ALEXANDER R. McBIRNEY
ELICITATION INTERVIEW FOR PVHA PROJECT

VOLCANIC/TECTONIC SETTING

The distribution of volcanism in space and time is governed by a combination of conditions in the mantle and overlying lithosphere. Deep-seated controls govern the long-term, regional patterns, whereas shallow structures influence local, short-term behavior. Most melting anomalies in the mantle are manifested in magmatism that takes advantage of structural pathways through the crust. The main spatial controls are structural features of the lithosphere; mantle conditions are reflected only in the broad, regional distribution of volcanism.

The Amargosa Valley Isotopic Province (AVIP) proposed by G. Yogodzinski (presentation at PVHA Workshop 3) is probably the surface expression of a melting anomaly in the mantle, but the resulting volcanism has an uneven spatial distribution within the broad outline of the province. Some areas, such as the Walker Lane, are totally devoid of volcanism; whereas others, such as the Death Valley region, have a dense cluster of eruptive centers. It does not seem to matter what is occurring in the mantle; if there are no favorable channelways to the surface, the magma is obstructed at depth and fails to reach the surface. Where the pattern of strain is favorable, particularly in terms of the orientation of faults with respect to regional stresses, the distribution of vents is mainly a function of conditions within each individual structural block.

The fault system around Yucca Mountain dates back at least to the Miocene (Ferrill et al., 1995). Owing to the large number of existing faults that can accommodate regional stresses, formation of new faults is less likely than reactivation of older ones. The interaction of stresses in the region is very complex, and the strain in individual structural zones cannot be measured accurately (thus, areas cannot be ranked quantitatively in terms of the ability of magma to open new vents). Nevertheless, the AVIP can be divided into a number of types of structural settings that can be ranked in a relative sense according to the likely frequency of eruptions (see section below on Spatial Models). The ranking is based on the general distribution of volcanism in the Basin and Range Province as a whole and is purely qualitative.

The record of volcanism for the past 10 my in the central Basin and Range region suggests that there has been a long-term decline in the rate of both volcanism and faulting and that this will continue to decrease over the next 10,000 years. The data are not sufficient, however, to make precise estimates of the rate of decline, and in view of the large short-term variations and episodic nature of activity, it is reasonable to assume that the rates will be essentially the same as they have been for the past 10,000 years.

EVENT DEFINITION

Temporal Aspects

A volcanic event, as defined for this PVHA, is an identifiable period that is limited by the time required for magma to rise to shallow levels of the crust and cool. It is normally of the order of a few tens of years (Williams and McBirney, 1979). Examples of such events are those of the young Nicaraguan volcano, Cerro Negro, where discrete eruptive events are separated by a few tens of years (Mooser et al., 1958). In other places where there is a longer history of activity, it is found that, although the frequency of eruptions may vary, the average production rate of magma over several cycles is relatively constant. This indicates that each event represents the release of magma that has accumulated during the preceding repose interval. The timing of eruptions is governed by a combination of tectonic strain rates and structural conditions in the volcano.

The long-term distribution of volcanism is governed by large-scale mantle conditions that tend to be episodic on a scale of a few million years. On a shorter time-scale, the timing of eruptions is probably related to the regional strain rate. Although magma may be produced at a more-or-less constant rate in the mantle, the strain conditions in the lithosphere govern the frequency with which magma is able to reach the surface. This is why the volumes of erupted magma tend to be larger after long periods of repose.

Spatial Aspects

The spatial dimensions of a volcanic event are generally those that are typical of a single basaltic dike (about 5 km long). However, a single event may consist of a fissure system that is as long as 15 km.

Geochemical Affinity

Eruptive products associated with an event are expected to have similar compositions, but little importance is given to geochemical affinities in defining events, because crustal contamination can lead to large variations, even during a single eruption. This was observed, for example, during the nine-year eruption of Paricutin volcano (McBirney et al., 1987).

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

REGION OF INTEREST

The region of interest is the area defined as the AVIP (described above). The Pliocene-and-younger volcanoes in this area have a regionally distinctive isotopic composition, which probably is inherited from a common mantle source. The most recent volcanic events in the AVIP have a wide areal distribution. The southern part of the AVIP is not included in this analysis for two reasons: (1) the presence of large active faults in this area may indicate differences in the spatial and temporal controls of volcanism; and (2) there has been a significant decline in the rate of volcanism from the Pliocene to the Quaternary, indicating that this activity has migrated to the north.

In the spatial models for the PVHA, the region of interest is subdivided into sub-regions according to their relative potentials for future volcanism. The criteria that are believed to be important for assessing future volcanism are geologic structure, the presence of young volcanic centers, and the age, and composition of the volcanic rocks. Of these criteria, geologic structures are the primary means by which the region has been subdivided for the probability analysis (Scott, 1990; Simonds et al., 1995).

The volcanism of Crater Flat and its relation to Yucca Mountain can be characterized in the general context of the regional tectonic conditions. All recent structural, neotectonic, and geophysical studies agree that the area is a pull-apart basin bounded on the west by the east-dipping Bare Mountain fault and on the east by two or more west-dipping faults (Ferrill et al., 1995; Fridrich, 1995). Although the surface trace of the Bare Mountain fault coincides with the western edge of the alluvial basin, the eastern boundary is more difficult to define. Some recent studies have placed it east of Yucca Mountain (Ferrill et.al., 1995; Fridrich, 1995), but the concentration of volcanism in Crater Flat clearly indicates that, so far as volcanism is concerned, the elevated and depressed blocks must be treated independently.

Faults, even where well defined, do not coincide exactly with the boundaries of volcanic domains. The dips of the fault planes decrease downward until they are nearly horizontal (Ferrill et al., 1995; Fridrich, 1995). They must extend beneath at least some of the volcanic centers. This is best seen from the 1995 deep reflection seismic profile across the valley (G. Thompson interpretation of T. Brocher work in presentation at PVHA Workshop 4) that shows that the feeder for Red Cone must have intersected the Bare Mountain fault. This must be true of the other cones as well. Thus, the structural control of the vents must lie at a deeper level, and the boundary of the Crater Flat domain is related only indirectly to the surface traces of faults.

This conclusion finds support in the observations that (a) the alluvial valley is the region of maximum extension and (b) the orientation of the dike system beneath the cones corresponds to a right-lateral component of offset seen in some of the faults. The north-northeast orientation of the line of cones is very close to the direction of maximum compressive stress and would be consistent with coupled right-lateral movement on the boundary faults. Opinions seem to differ regarding the amount of strike-slip motion that has occurred on these faults (Ferrill et al., 1995; Fridrich, 1995). Even though no motion of this kind has been found either in the seismic record or in exposures of the fault traces (Ferrill et al., 1995; Fridrich, 1995), this does not rule out a strike-slip component of earlier earthquakes. The proximity to the Walker Lane would make right-lateral displacement likely at depth, even if it is not seen at the surface.

If the main trend of the line of cones reflects stresses deeper in the lithosphere, the smaller dikes cutting individual cones are oriented normal to the inferred extension on the boundary faults. Thus, the major alignment is probably controlled by the regional stress field, while the subsidiary dikes reflect conditions in the shallow crust.

Although the Lathrop Wells center is included in the Crater Flat domain, it differs in several ways from the cones of Crater Flat. It is located within an area where several transcurrent faults appear to be converging (e.g., near the mapped southern limits of the Bare Mountain, Solitario Canyon, Stagecoach Road, and other faults). The history of repeated eruptions at Lathrop Wells may reflect periodic offset on one or more of these faults.

SPATIAL MODELS

Two approaches are used to define the future distribution of volcanism in the Yucca Mountain region (YMR, defined as the region within a 50-km radius of Yucca Mountain). The first, termed a "zonation" approach, divides the region into five different types of structural settings (Figure AM-2). These are listed in order of decreasing potential for future volcanism.

1. The most favorable condition is that of pull-apart basins, where eruptions occur along dilational fractures in fault-bounded valleys. If the stress regime is purely tensional, the fissures and dikes are parallel to the long axis of the valley, but if there is a strike-slip component, they may be at an oblique angle.

2. Intersections of strike-slip faults are favorable zones for volcanism, because the lateral offset where two faults cross tends to produce local fractures that can serve as channelways for rising magma.

3. The large calderas in this part of the Basin and Range province date from an earlier tectonic regime, and their magmatism is either terminated or in the final stages of decline. Eruptions associated with these features are located mainly along ring fractures, but a few may occur on radial fractures on the flanks. The magmas have compositions that are distinct from those of eruptions related to the AVIP.

4. Fault-bounded blocks of uplifted basement rock normally have fewer volcanoes and dikes than areas of lower elevation (Connor and Hill, 1995). There are, of course, exceptions to this generalization, but it is a pattern observed throughout the world (Connor and Hill, 1995). Because the boundary faults tend to isolate the interiors of such blocks from the regional strain, dilational fractures are less likely. In addition, the topographic elevation adds an additional vertical distance the magma must rise, and long dikes can find outlets at lower levels.

5. Large transcurrent fault systems have few volcanoes along their main trace. Eruptions are limited to areas of offsets or the ends of propagating branches of the main system.

The second spatial model, termed a "smoothing" approach, uses the spatial distribution of observed events to assess the probability of future events. The approach is essentially that given in Connor and Hill (1995). A Gaussian smoothing kernel is used, rather than the Epanechnikov kernel used by Connor and Hill, in order to allow for a longer tail on the probability distribution. To arrive at the same mean probabilities as Connor and Hill using the Gaussian kernel, the smoothing distances of Connor and Hill are decreased by a factor of 2.5. The resulting values of h are used: 6, 9, and 12 km. The three values are given equal weight because there is no strong preference for one over the other.

The relative weights assigned to the two alternative spatial models are: zonation approach (0.9), smoothing approach (0.1). The zonation approach is preferred because it has a stronger geologic basis that takes into account different structural provinces, faults, and their ages.

EVENT COUNTS

In accordance with the definition of volcanic "event" given earlier, the number of events and their uncertainties are assessed for each of the centers in the YMR. The event counts are assessed for the post 1-Ma period and for the post-5 Ma period. Event counts are summarized on Table AM-1.

Lathrop Wells

One to 4 events are represented at Lathrop Wells and the 3-event possibility is the most likely. A minimum of 1 event is based on chemical compositions for the identified chronostratigraphic units not being significantly different, the overlapping age determinations and homogeneous appearance of the cone being consistent with a monogenetic interpretation. Different lines of evidence, including stratigraphic, geomorphic, and soils data, suggest there have been 2 or more events: chronostratigraphic units Q1 and Q2 (Crowe et al., 1995) are more likely to be separate events than Q3 and Q4. Q3 is the most extensive unit, blanketing Q1 and Q2, and age dates for Q3 are significantly younger, supporting the separation from Q1 and Q2. The evidence for Q4 is considered relatively weak, as geochemical differences could reflect shallow crustal processes and the thermoluminescence dates are not reliable.

The following event counts and their relative weights are assigned for the Lathrop Wells center: 1 (0.3), 2 (0.2), 3 (0.4), and 4 (0.1).

Sleeping Butte

One to 3 events are represented at Sleeping Butte. Two events are most likely because Hidden Cone and Little Black Peak appear to have distinct ages. Alternatively, they could be part of the same event. Some geomorphic and possibly paleomagnetic data provide suggestive evidence for 2 events at Hidden Cone, giving some possibility to 3 events.

The event counts and their relative weights for the Sleeping Butte area are: 1 (0.05), 2 (0.8), and 3 (0.15).

1.0 Ma Crater Flat

The 1 Ma basalts of northern Crater Flat represent 1 to 5 events. One event is most likely because age determinations for the various cones overlap, and the cones appear to be located along a single fissure system. Two events are represented if Makani Cone is a separate event from the three cones to the south. Three events assumes that Black Cone and Red Cone form a single event, and the Makani and Little Cones are each separate events. Four events assumes Makani, Black, Red and Little Cones are all separate events. Five events assumes that each cone is a separate event and that there are two events at Little Cone.

The following event counts and their relative weights are assigned for northern Crater Flat: 1 (0.9), 2 (0.05), 3 (0.025), 4 (0.015), and 5 (0.01).

Buckboard Mesa

Zero to 2 events are represented at Buckboard Mesa. Zero events is most likely because the calc-alkaline basalts at Thirsty Mesa are unlike the other basalts in the AVIP. The difference in composition cannot be explained by contamination from the continental crust. However, the AVIP is defined to include them, so some weight is given to 1 or 2 events.

The following event counts and their relative weights are assigned for the Buckboard Mesa area: 0 (0.8), 1 (0.1), and 2 (0.1).

3.7 Ma Crater Flat

One to 6 events are represented at the 3.7 Ma area of Crater Flat. Two events is the most likely possibility, because the field relations suggest two en echelon fissure systems, but a single fissure system is possible. Three or more events are suggested by the detailed geologic relationships given by Crowe et al. (1995). Available geochronological data (Crowe et.al, 1995) suggest a single event but cannot preclude multiple events.

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 (0.05), 4 (0.05), 5 (0.05), 6 (0.05).

Amargosa Valley

Two to 8 events may be represented by the aeromagnetic anomalies in Amargosa Valley. Five events are most likely, because of the high confidence given to the five anomalies with strong dipole signatures (anomalies A, B, C, D, and E on the aeromagnetic map presented by V. Langenheim at PVHA Workshop 1). The minimum of 2 events is based on the basalts encountered in wells (anomalies B and D on the V. Langenheim aeromagnetic map); anomalies F and G most likely represent 1 event, but they could represent 0 or 2 events with equal likelihood; 6 events are obtained by combining anomalies F and G for 1 event and adding that event to the preferred interpretation of 5 events for anomalies A, B, C, D, and E.

The following event counts and their relative weights are assigned to the Amargosa Valley area: 2 (0.02), 3 (0.03), 4 (0.05), 5 (0.2), 6 (0.5), 7 (0.15), and 8 (0.05).

Thirsty Mesa

One or 2 events might be represented at Thirsty Mesa. The surface geology does not indicate that any interval of weathering or erosion separated the eruptions from this center. Because evidence for an earlier event could be concealed by the extensive products of the last eruption, allowance should be made for this possibility.

The following event counts and their relative weights are assigned for the Thirsty Mesa area: 1 (0.9), and 2 (0.1).

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 two time periods and for source zone types 1-5 (see summary in Table AM-2). The rates (number of events per square kilometer) are calculated by summing the counts for the centers within each zone, divided by the sum of the areas of zones of a particular type. For example, the post-1 Ma rate for the Zone 1 regions is derived from the sum of the counts at northern Crater Flat and Sleeping Butte, divided by the area of the Zone 1 regions.

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

Post-1 Ma (0.1)
Post-5 Ma (0.9)

The post-5 Ma period is given highest weight because it is a period during which similar tectonic processes have been operative. The post-1 Ma period is given relatively low weight because it excludes too many events that are believed to be significant to the potential for future volcanism (e.g., Crater Flat and Amargosa Valley).

Undetected Events

In addition to those events identified and interpreted at the surface, there is the potential for undetected events, the effects of which might be buried at depths of less than 300 m (depth of the repository) but not be represented at the surface. These events, which include both cones that were subsequently covered by younger materials and shallow dikes that did not erupt, should be added to the rates considered from surface observations.

For rates assessed for the post-1 Ma period, it is not necessary to consider additional undetected events, because there is a negligible chance of additional events within the 1 my time frame, given the extensive geologic and geophysical investigations that have been conducted within the area of interest.

For the post-5 Ma period, there is a finite possibility that there were events in addition to those recorded by their observed products. It is estimated that there may be an additional 10% of the observed counts (i.e., the observed post-5 Ma counts should be multiplied by 1.1 to arrive at the total counts).

TEMPORAL MODELS

One temporal model is considered appropriate: a homogeneous model that assumes the rate of occurrence of volcanic events is uniform through time. This is because the starting times of 1 Ma and 5 Ma are recent enough for the rate of volcanism to be considered homogeneous. If a longer time period were used (e.g., 10 Ma), a temporal model describing the waning of volcanic activity would be required.

EVENT GEOMETRIES

The dimensions of volcanic events are expected to be essentially the dimensions of basaltic dikes. Long dikes require large volumes of magma. In the YMR the volumes of eruptions are small, and dike dimensions are also expected to be small. The expected length of a dike is about 5 km; the minimum length is 3 km and the maximum length is 15 km. The maximum length would likely include a fissure system of multiple dikes, rather than a single dike. The lengths of dikes and their relative weights are the following: 3 km (0.3), 5 km (0.6), and 15 to 20 km (0.1). Equal weights are given to maximum values of 15 and 20 km.

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

The orientation of dikes is expected to be N30E, with an uncertainty of ± 45 degrees (representing 80% of the probability). This orientation is consistent with the NW orientation of the least horizontal compressive stress deduced from earthquake focal mechanisms and the orientation of normal faults.

Topographic relief has an effect on the ability of dikes to intrude shallow levels of the crust. Because magma is a liquid that flows from high to low elevations, long dikes are less likely to approach the surface of elevated blocks than valley floors. This is why volcanic cones and fissures are much less common on horsts than in grabens. Thus, even if a dike extends from Crater Flat into Yucca Mountain, the probability that it will rise to the level of the repository below the crest of the mountain is very low.

Given the center of an event, the probability distribution for the location of the event relative to the center is assumed to be trapezoidal, with 75% of the density between 0.2 and 0.8 of the dike length.

HYDROMAGMATIC ACTIVITY

Because the proposed repository site lies within the Yucca Mountain block, the potential for significant (large-volume) hydromagmatic activity is very low. It is estimated that 1 out of every 100 volcanic eruptions in the YMR will be associated with significant hydromagmatic activity.

TYPE OF ERUPTION

The expected type of eruption in the YMR is a small-volume basaltic eruption. Although there is no consistent pattern, many mature volcanic fields have had rhyolitic volcanism as well. The probability that the region will evolve into a period of rhyolitic volcanism is estimated to be 0.1 in 10,000 years. Given such a change, the probability of a significant rhyolitic volcanic event is 0.25. Therefore, the probability of a significant rhyolitic volcanic event is (0.1 x 0.25) = 0.025.

A R McBirney
29 April 1996

REFERENCES

Connor, C.B., and Hill, B.E., 1995, Three nonhomogeneous Poisson models for the probability of basaltic volcanism: Application to the Yucca Mountain region, Nevada, USA: Journal of Geophysical Research, v. 100, no. B6, p. 10,107-10,125.

Crowe, B.M., Perry, F.V., Geissman, J., McFadden, L., Wells, S., Murrell, M., Poths, J., Valentine, G.A., Bowker, L., and Finnegan, K., 1995, Status of volcanism studies for the Yucca Mountain site characterization projects: Los Alamos National Laboratory Report LA-12908-MS, March.

Ferrill, D.A., Stirewalt, G.L., Henderson, D.B., Stamatakos, J.A., Morris, A.P., Wernicke, B.P., and Spivey, K.H., 1995, Faulting in the Yucca Mountain region: Critical review and analyses of tectonic data from the central Basin and Range (CNWRA 95-017): prepared by the Center for Nuclear Waste Regulatory Analyses, San Antonio, Texas, for the Nuclear Regulatory Commission, August.

Fridrich, C.J., 1995, Characterization of detachment faults in the Yucca Mountain region, *in* Simonds et al. (eds.), Final report on detachment faulting: U.S. Geological Survey Administrative Report.

McBirney, A.R., 1959, Factors governing emplacement of volcanic necks: American Journal of Science, v. 257, p. 431-448.

McBirney, A.R., Taylor, H.P., and Armstrong, R.L., 1987, Paricutin re-examined: a classic example of crustal assimilation in calc-alkaline magmas: Contributions to Mineral Petrology, v. 95, p. 4-20.

Mooser, F., Meyer-Abich, H., and McBirney, A.R., 1958, Catalogue of the active volcanoes of the world - Part VI: Central America: International Association of Volcanologists, 146 p.

Scott, R.B., 1990, Tectonic setting of Yucca Mountain, southwest Nevada, *in* B.P. Wernicke (ed.), Basin and Range extensional tectonics near the latitude of Las Vegas, Nevada: Boulder, Colorado, Geological Society of America Memoir 176, p. 251-282.

Simonds, W.F., Whitney, J.W., Fox, K.F., Ramelli, A., Yount, J.C., Carr, M.D., Menges, C.M., and Dickerson, R., 1995, Map of fault activity in the Yucca Mountain area, Nye County, Nevada: U.S. Geological Survey Miscellaneous Investigations Series Map I-2520, scale 1:24,000.

Williams, H., and McBirney, A.R., 1979, Volcanology: Freeman & Cooper, 397 p.

TABLE AM-1
ALEXANDER R. McBIRNEY - EVENT COUNTS

LOCATION	COUNTS (CONES)	WEIGHT	NOTES
Lathrop Wells	1 (all) 2 (Q1, 2) 3 (Q1, 2, 3) 4 (Q1, 2, 3, 4)	(0.3) (0.2) (0.4) (0.1)	BC: Black Cone HC: Hidden Cone 2HC: 2 events at Hidden Cone LBP: Little Black Peak LC: Little Cones 2LC: 2 events at Little Cones M: Makani Cone Q1-4: Chronostratigraphic units of Crowe et al. (1995) RC: Red Cone
Sleeping Butte	1 (HC+LBP) 2 (HC, LBP) 3 (2HC, LBP)	(0.05) (0.8) (0.15)	
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)	(0.9) (0.05) (0.025) (0.015) (0.01)	
Buckboard Mesa	0 1 2	(0.8) (0.1) (0.1)	
3.7 Ma Crater Flat	1 2 3 4 5 6	(0.75) (0.05) (0.05) (0.05) (0.05) (0.05)	
Amargosa Valley	2 3 4 5 6 7 8	(0.02) (0.03) (0.05) (0.2) (0.5) (0.15) (0.05)	
Thirsty Mesa	1 2	(0.9) (0.1)	

TABLE AM-2
ALEXANDER R. McBIRNEY - RATES OF OCCURRENCE

TIME PERIOD	COUNT METHOD FOR ZONES	NOTES
Post 1 Ma (0.1)	Zone 1: (NCF+SB) Zone 2: (LW) Zone 3: Use Post-5 Ma rate Zone 4: Use Post-5 Ma rate Zone 5: Use Post-5 Ma rate	NCF: Northern (1.0 Ma) Crater Flat SB: Sleeping Butte LW: Lathrop Wells 3.7: 3.7 Ma Crater Flat TM: Thirsty Mesa AV: Amargosa Valley BM: Buckboard Mesa
Post 5 Ma (0.9)	Zone 1: (NCF+SB+3.7+TM) Zone 2: (LW+AV) Zone 3: (BM) Zone 4: (BM) Zone 5: 0.5 x rate of Zone 3	

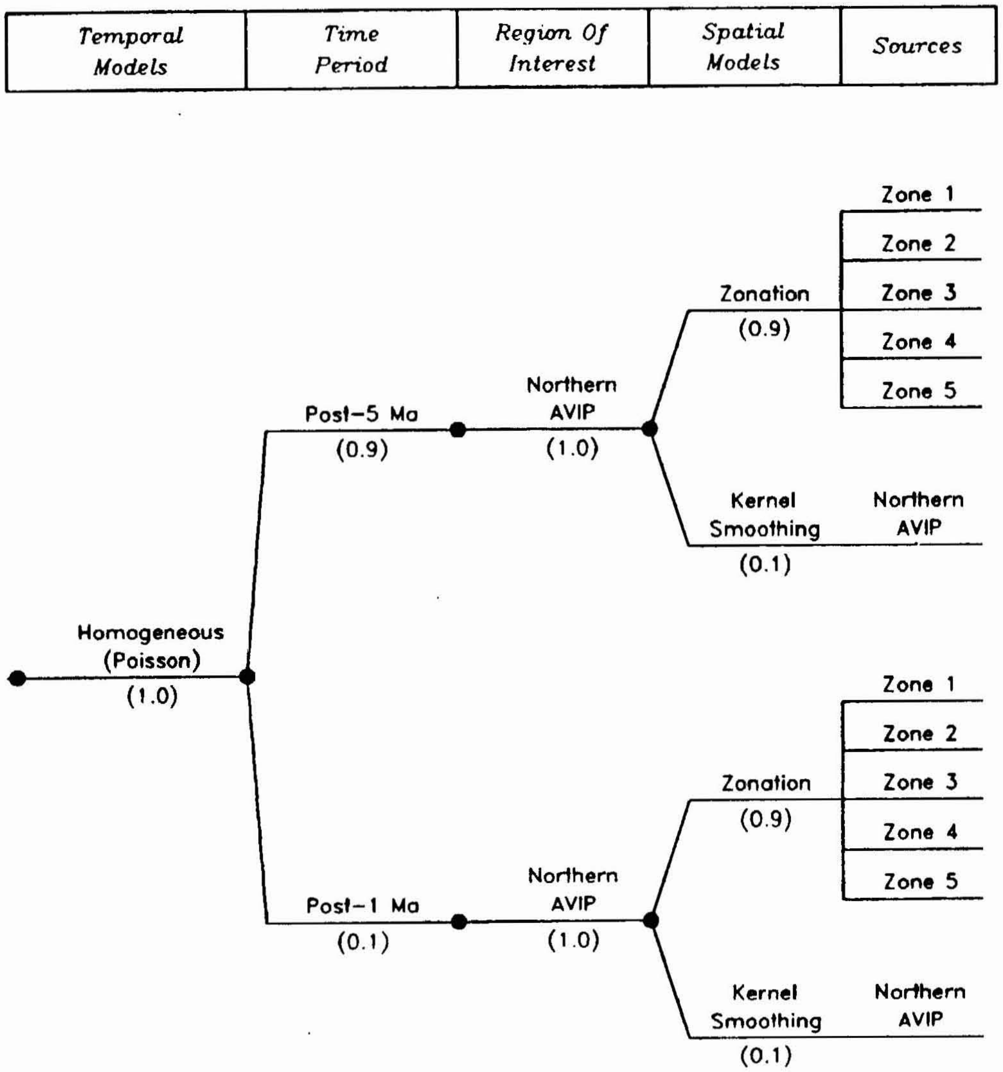
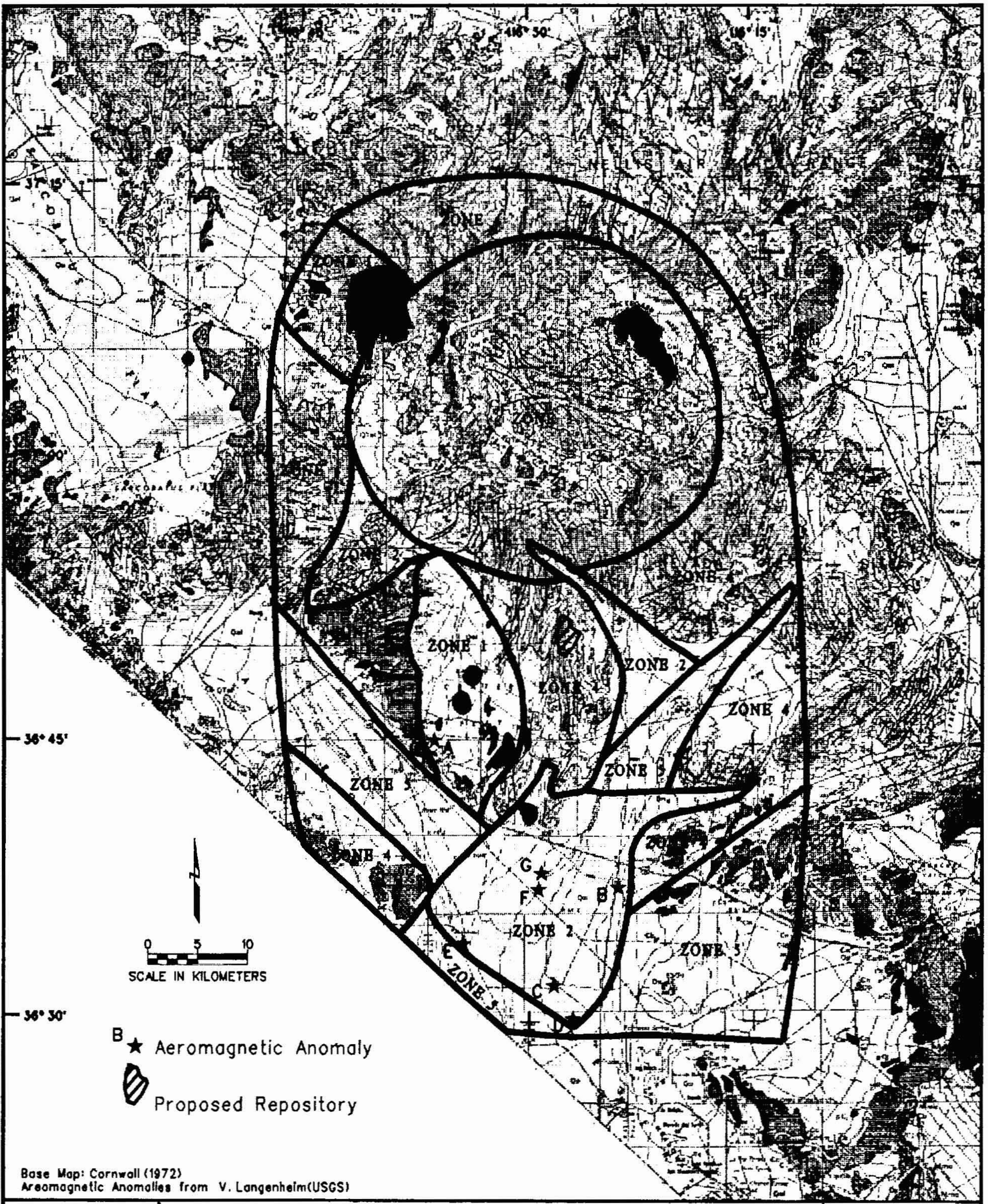


Figure AM-1 PVHA model logic tree developed by Alexander R. McBirney.



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GEOMATRIX

ALEXANDER R. McBIRNEY
LOCAL ZONES

Figure
AM-2

PVHA
Project

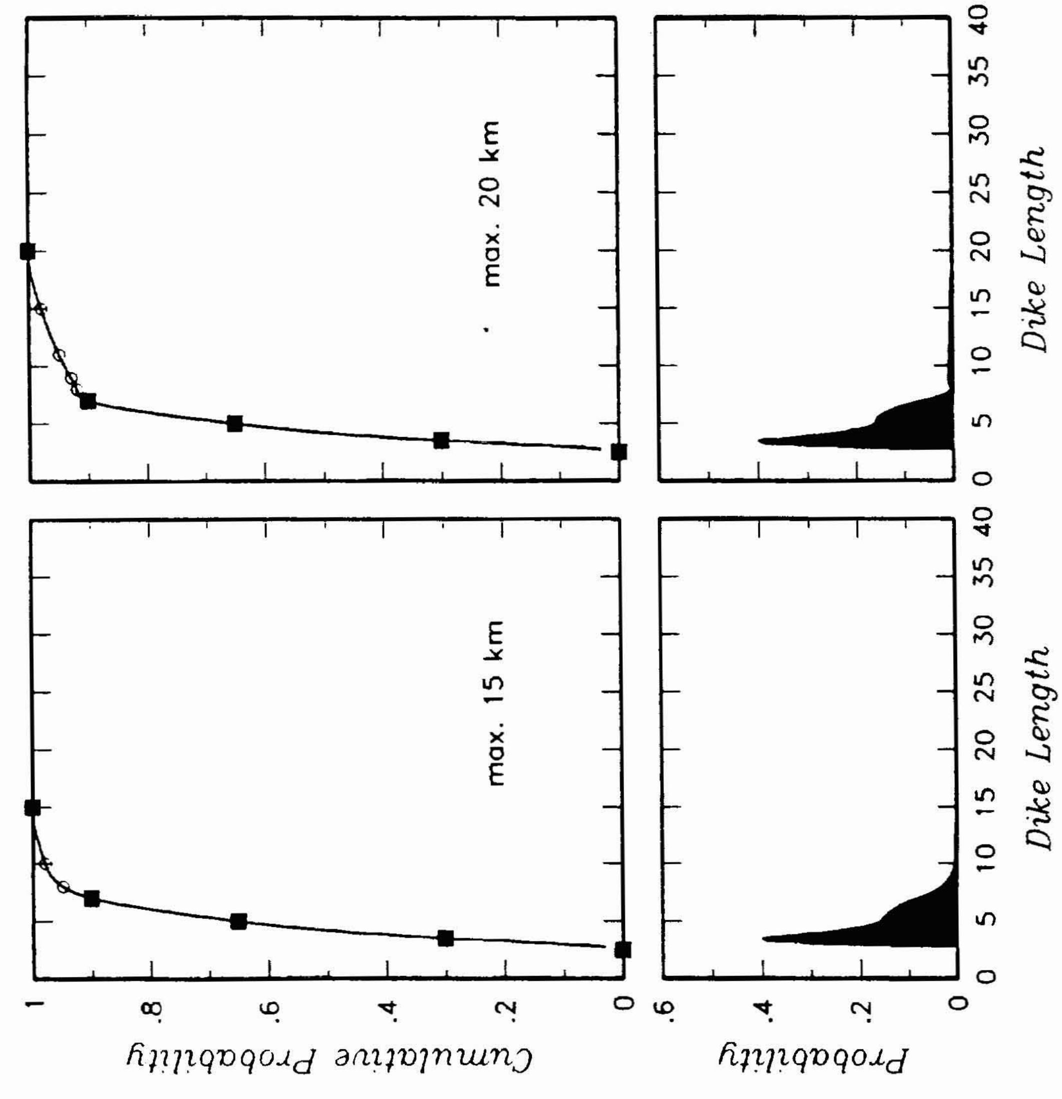


Figure AM-3 Dike length distribution developed by Alexander R. McBirney.

MICHAEL F. SHERIDAN
ELICITATION INTERVIEW FOR PVHA PROJECT

VOLCANIC/TECTONIC SETTING

Over the past 15 my, basaltic volcanism in the Basin and Range of the western U.S. has been episodic within defined fields; new fields have appeared randomly over a broad regional area during this time. Conditions for persistent basaltic volcanism were created by: (1) subduction of either the East Pacific Rise or new basaltic crust generated near the rise beneath the North American plate, which caused an abnormally high thermal regime within the lithosphere; (2) cessation of widespread subduction related rhyolitic volcanism, which produced ash-flow sheets and calderas; and (3) gradual separation of triple points along the western margin of North America, behind which an extensional tectonic regime allowed the rise to the surface of dominantly basaltic magmas. As the two triple points diverged along the western margin of the North American plate, subduction related effects died as extensional features developed (Atwater, 1970). The cessation of subduction related to plate impingement began about 20 Ma and the conditions for dominantly basaltic volcanism reached the Yucca Mountain area about 10 Ma. Extensional tectonism associated with basaltic volcanism continues to the present at this location (Christiansen and Lipman, 1972; Luedke and Smith, 1981). Because it is not clear whether volcanism has been waxing or waning in the vicinity of Yucca Mountain in the past 5 my, the more recent geologic record is considered to be the best indicator of what can be expected in the future.

Due to the strong clustering of mapped volcanoes, future volcanic eruptions in the western U.S. will most likely occur again within the boundaries of established fields. In particular, those fields with the highest recurrence rates are the most probable sites for future volcanism. Volcanic events outside known fields represent the initiation of a new field; an event much less likely than an another eruption within a field. Older calderas in the Basin and Range province could be responsible for localizing small basaltic fields or volcanic centers, provided that their silicic magmas have solidified (Smith and Bailey, 1968; Smith, 1979). This is due to the penetration of these structures through the crust, causing attendant fracturing and weakening of surrounding rocks. Basaltic fields such as Sleeping Butte, Thirsty Mesa, and Buckboard Mesa near the Timber Mountain caldera could be examples of such a mechanism, although this has yet to be proven in the region.

The basic process leading to volcanism involves generation of a melt from a source zone within the asthenosphere or lower lithosphere and migration of the magma to the surface where it erupts. At present there is not much spatial or temporal predictive power to magma generation models (i.e., they are not useful in predicting where and when future volcanoes will occur in the Basin and Range). The typical lifetime of late Cenozoic volcanic fields in the southern Basin and Range province is 1 to 15 my (Nealey and Sheridan, 1989), suggesting that source zones may be active for at least this duration. The reason repeated activity occurs within fields rather than being widely dispersed is not well understood. Volcano clusters may correspond to the distribution of melt source zones or they may be the location of leaky places in the system where magma can escape more easily.

The state of stress in the lithosphere is very important in assessing the near-surface locations of volcanism because the migration of basaltic magma to the surface is favored by extension (Delaney et al., 1986). Near-surface faults do not play a major role in the location of volcanic fields, but faults may have some influence on the locations of vents and cones. In general, the number of cones decreases with distance from faults. However, the use of faults in developing a spatial model of volcanism is not sufficiently understood to be warranted in a model of volcanic forecasting.

EVENT DEFINITION

Temporal Aspects

An event is equivalent to an "eruption cycle," or an "eruptive episode," in which active periods of eruptions occur between quiescent phases. An active period typically includes short pauses and may extend from several years to thousands of years. The spatial arrangement is the most important characteristic to consider in identifying events. The uncertainty associated with dating young basaltic volcanic rocks, such as those in the region of interest, is about 100,000 yr. Because of the large uncertainties of age-dates (Crowe et al., 1995), a long-duration and large-sized event was used for this analysis. Therefore, the time-frame for an event is assessed to be 100,000 yr.

Spatial Aspects

The spatial relationships among eruptive features are the most important criteria for identifying events in the region of interest because of the lower precision of geochronologic data. A single event may produce 0 to 5 or more cones. For example, the Paricutin eruption of 1943-52 produced several cones and exhibited many different phases (Foshag and Gonzalez, 1956). For my model, the cones must be associated with a single linear dike or a dike system with more complex geometry. If eruptions of similar ages (i.e., ±100,000 yr or less) cannot be linked by a single linear dike or dike system, then they are considered to be separate events. Dikes feeding individual cones have the most frequent dimension of about 1.0 to 2.5 km (Delaney et al., 1986; Sheridan, 1992), and dike systems feeding multiple cones may be as long as 15 km in the broad region of the western Great Basin. Longer dikes have been described in areas of rifting such as the eastern Snake River Plain and Iceland (Sigurdsson, 1987).

Geochemical Affinity

The role of chemical affinity in defining an event is complex. Greatly different magmas may erupt during the same event due to magma mixing or other processes. Such magmas may have different phenocryst suites, isotopic ratios, trace element patterns, and bulk major element chemistry. Thus, I do not believe that geochemistry is useful for distinguishing events in the region of interest, especially at Lathrop Wells. I do believe, however, that isotopes and trace elements can be useful in identifying broad source regions. Hence, I like the model of G. Yogodzinski (presentation at PVHA Workshop 3; Yogodzinski and Smith, 1995) that defines the Amargosa Valley Isotopic Province (AVIP) as the source region for all the young basalts in the region of interest. This concept is useful to confirm some bounds set on the region of interest. I favor his interpretation that the AVIP is an area underlain by cooler Proterozoic lithosphere that is the source for basaltic magmas responsible for the weak volcanism of this area.

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

REGION OF INTEREST

A key determinant in the decision regarding a relevant region of interest for the PVHA is the concept of volcanic fields (Schwartz et al., 1991). A field contains volcanic features that are spatially, temporally, and genetically related (i.e., formed by magma that is generated by melting in the lower lithosphere or upper asthenosphere and that migrates to the surface in a focused area). The length of basaltic fields in the western Great Basin and southern Basin and Range (Luedke and Smith, 1981; Lynch, 1989; Nealy and Sheridan, 1989) is on the order of 15-50 km. Basaltic volcanic fields in this area may be active for a duration of 1 my up to 15 my with an average life of 5 my (Christiansen and Lipman, 1968; Luedke and Smith, 1981; Lynch, 1989). Individual active phases may have time scales that last a few years to a few hundred years. Longer-period time scales are preferred to define events for the purpose of this analysis because of the large time span considered for the PVHA (10,000 yr) and the limitation of current radiometric dating techniques (± 100,000 yr). The location of renewed volcanic activity at the surface is unlikely to be at the exact location of a previous eruption (i.e., at the same cone), but it has a high probability of occurring within the defined boundaries of a field.

Considering the concept of volcanic fields as fundamental to descriptions of future locations of volcanoes (Sheridan, 1992), two alternative areas are evaluated (Figure MS-2): (1) volcanic fields in a regional area within a 200-km radius of Yucca Mountain, identified on the Luedke and Smith (1981) map and used to calculate the rate of birth of new volcanic fields; and (2) volcanic fields, events, and individual cones identified and counted in a local area within a radius of about 40 km of Yucca Mountain, here termed the "region of interest," used for event recurrence rate calculations. All of the region of interest lies within the AVIP, the suspected source region for all of the young basalts that it encompasses. Both the 200-km-radius region and the 40-km-radius region of interest are used to calculate probability in my model.

SPATIAL MODELS

Two alternative spatial models are used to assess the future locations of volcanic activity in the region of interest: (1) the volcanic field approach and (2) the volcanic zone approach. The field approach takes into consideration the general characteristics of other basaltic fields in the Basin and Range. The shape and distribution of volcanic features within a field are important in this model. The volcanic zone approach assumes a random distribution of volcanic events in time and space within the designated zone.

Based on studies of a large number of basaltic volcanic fields in the southwestern U.S., typical fields have an elliptical shape, with length-to-width aspect ratios of about 2:1, and the events within fields are assumed to follow a bivariate Gaussian distribution (Sheridan, 1992). In this analysis, the best fit of events to a bivariate Gaussian distribution is used to define the event probabilities of the single field closest to the site. This area, called the Crater Flat field, is defined by the distribution and uncertainties of surface and subsurface events younger than 5 Ma in Crater Flat and the Amargosa Desert. The large spatial separation of Sleeping Butte, Thirsty Mesa, and Buckboard Mesa from the Crater Flat field, and the complete absence of basaltic centers between them over the past 10 my, strongly argues for their being separate fields. Gaussian distributions centered on these distant fields have such low probabilities that they were not considered to be significant related to the proposed repository site.

In applying the field shape approach, events are represented as points, either centered on individual cones or the midpoint of clusters defined by multiple aligned cones. Because event points in the Crater Flat field are assumed to represent realizations of a bivariate Gaussian distribution, they are used directly to define the center, length, width, and orientation of this field by a mathematical best fit algorithm. The data set is too small to justify using non-homogeneous models in time and space such as those suggested by Ho (1991) and Connor and Hill (1993). These models are very sensitive to starting times and event definitions. The aspect ratio of fields is restricted to a maximum of 5 based on observations of existing, well-defined fields.

In the volcanic zone approach, or zonation model, the spatial probability distribution of future volcanic events is assumed to be uniform across a zone. The zone used for this analysis is the inner 40-km-radius area, and the rate is defined by event counts within the zone. Post-10 Ma volcanic rocks are used in this analysis only to help define the rate of birth of new fields in the region. The post-5 Ma events exclusively are used in defining rates of occurrence within the smaller 40-km region of interest.

Weights assigned to the field approach and zonation approach are 0.75 and 0.25, respectively. The field approach is given higher weight than the zonation approach because it is judged to have a stronger technical basis for assessing the future location of volcanism, one that takes into account observations of centers in the region of interest as well as the behavior of fields in analogue regions.

FIELD AND EVENT COUNTS

For both the field approach and the zonation approach, the number of events occurring over a particular time period must be specified. In addition, for the field approach, the number of fields must be counted.

EVENT COUNTS

Based on the definition of volcanic events given above, the number of events and their uncertainties are assessed for each of the centers in the inner 40-km-radius zone (Table MS-1). The event counts were made for the post-5 Ma time interval. This time interval, used in many publications on regional volcanism (e.g., Luedke and Smith, 1981), is sufficiently long to provide accurate rate data. It is the most appropriate time interval for evaluating rates because: (1) data for post-5 Ma events are more complete than for older events; (2) scoria cones and other eruptive features that are used to define events are preserved for up to about 5 my before their complete removal by erosion, thus event counts for older periods are difficult to make; and (3) counts made for a more recent period would include too few events to provide a meaningful estimate of the rate. The counts given here are based on interpretations of eruptive features at the surface reported in publications and noted by my personal field observations. Also considered are subsurface events that might exist at shallow depths but not at the surface (see following section "Undetected Events").

Lathrop Wells

The Lathrop Wells cone represents 1 cone and 1 event. The geologic history of the Lathrop Wells cone is complex, and we could still be within the active period of the "event" (see Rates of Occurrence, below). By my definition, Lathrop Wells would be only a single, albeit complex, event. The large ambiguity in the numerous radiometric and other dates and the geomorphic youth of this feature justify considering it to be a single event. The possible extremes of radiometric dates and the geomorphic complexity (Wells et al., 1990) make the continuing life of Lathrop Wells as a 2-event scenario a weak possibility.

The following event counts and their relative weights are assigned for the Lathrop Wells center: 1 (0.9), and 2 (0.1).

Sleeping Butte

Little Black Peak and Hidden Cone are most likely a single event connected by a NE-trending dike because of the closeness in their ages. With a lower probability, the cones could represent 2 events.

The event counts and their relative weights for Sleeping Butte are: 1 (0.67) and 2 (0.33).

1.0 Ma Crater Flat

The 1 Ma basalts of the surface cones in northern Crater Flat could represent from 1 to 3 events, with the most likely being 1 event. These features include Makani Cone, Black Cone, Red Cone, and two Little Cones. It is judged unlikely that all of these cones are separate events. The favored scenario is that all of the cones are related to a single dike or dike system having a northeast trend. The alignment of the surface cones and the consistent radiometric dating are the bases for the surface cones being a single event. Aeromagnetic anomaly A of V. Langenheim (presentation at PVHA Workshop 1), which is buried beneath the alluvium near the alignment of the 1 Ma chain, has a probable age of about 3.8 Ma and represents a unique event that is included with my analysis of the other buried events in the Amargosa Desert.

The probability of more than 3 events is assigned zero weight because of the large age difference required by my definition of an event (an age range or uncertainty of ± 400,000 years would be required). Two events assumes that Makani Cone was formed by a separate event, and 3 events assumes the two Little Cones formed as separate events.

The following event counts and their relative weights are assigned for northern Crater Flat: 1 (0.7), 2 (0.2) and 3 (0.1).

Buckboard Mesa

The geologic relationships at Buckboard Mesa suggest that it represents 1 event. Venting occurred at a single scoria cone and a fissure that extends to the SW (Lutton, 1968). However, there is uncertainty about the number of events at Buckboard Mesa. Because of the large volume of lava (1 km^3) and lack of detailed mapping or dating (Crowe et al., 1995), additional vents could be present. Because there is no direct basis for evaluation of uncertainty magnitude, as many as 6 events have been considered. The maximum number would assume an average event volume of lava of 0.13 km^3 and a possible cumulative age range uncertainty of ± 0.6 my. Each multiple event possibility was given an equal probability (0.05) because there is no justification for weighting them differently.

The following event counts and their relative weights are assigned to the Buckboard Mesa area: 1 (0.75), 2 (0.05), 3 (0.05), 4 (0.05), 5 (0.05), and 6 (0.05).

3.7 Ma Crater Flat

The 3.7 Ma basalts exposed at the surface of Crater Flat could represent from 1 to 6 events, with the 2 event scenario preferred. The basis for assuming a 2 event sequence is the location and geometry of two well-defined dikes trending N-S through this outcrop area. Radiometric dating cannot distinguish between events, and the only theoretical basis for assuming multiple events is the separation of the two large dike segments. Also, the suspected vents along the dikes seem to be well aligned in the N-S direction. More than 4 events are unlikely considering the age limitation of my definition (1.0 my of uncertainty is needed for 5 events). The higher probability assigned for 3 events is based on the possibility of a third dike system.

The following event counts and their relative weights are assigned for the 3.7 Ma area of Crater Flat: 1 (0.1), 2 (0.6), 3 (0.2) and 4 (0.1).

Amargosa Valley

The 7 aeromagnetic anomalies within Amargosa Valley and Crater Flat (V. Langenheim presentation at PVHA Workshop 1; Langenheim et al., 1993) might represent as few as 5 and as many as 7 events, with a preferred interpretation of 6 events. Anomalies B and D both have been drilled and confirmed to be basalt covered by about 100-200 m of Quaternary alluvium. Anomaly B is basalt dated at 3.84 Ma. Modeling of anomaly C suggests that it is also a basaltic cone buried about 200 m below the surface, consistent with a pre-Quaternary age.

Determination of the number and location of events in this area takes into account the location and potential orientation, as well as the magnetic polarity of the anomalies. Events A, D, and E are considered unique events in all scenarios due to their wide geographic spacing. Anomaly E is a separate event from anomalies F and G due to probable differences in polarity. In the 5-event scenario, anomalies F/G and B/C are assumed to be 2 separate events related to northeast-trending dikes. In the 6-event scenario anomalies B and C are considered to be separate events because of their geographic separation. The 7-event scenario considers all anomalies to represent separate events due to the high uncertainty in ages. The 6-event scenario is preferred because it assumes NE dike trends similar to the trend observed in the alignment of cones in northern Crater Flat. *(Note: Anomalies F and G on the unpublished aeromagnetic map presented by V. Langenheim at PVHA Workshop 1 correspond to anomaly A in the Langenheim et al. (1993) reference.)*

The following event counts and their relative weights are assigned to the Amargosa Valley area: 5 (0.25), 6 (0.5), and 7 (0.25).

Thirsty Mesa

The number of events at Thirsty Mesa could range from 1 to 4 events, based on the large volume of lava and the possibility of undetected events. Thirsty Mesa most likely represents 1 event, with low probabilities assigned to 2 to 4 events.

The event counts and their relative weights for Thirsty Mesa are: 1 (0.9), 2 (0.033), 3 (0.033) and 4 (0.033).

Field Counts

The field approach to the spatial distribution of volcanism requires that the rate of occurrence of volcanoes outside of the local fields (i.e., Crater Flat, Buckboard Mesa, and Sleeping Butte fields) be defined by the rate of formation of a new field. This rate is calculated by counting the number of fields that have formed between 0 and 5 Ma and between 5 and 10 Ma in the region of interest (both the 200-km-radius and the 40-km-radius regions). The locations and ages of fields are interpreted from the information given on the Luedke and Smith (1981) map. Within the 200-km-radius area, 30 fields are identified as younger than 10 Ma, and 16 fields are younger than 5 Ma. Within the 40-km-radius region of interest, 5 fields are younger than 10 Ma, and 2 fields are younger than 5 Ma (Crater Flat and Buckboard Mesa).

RATES OF OCCURRENCE

Event Rates

The rate of occurrence of volcanic events within fields is calculated from the counts over the post-5 Ma period in centers located within the 40-km-radius region of interest (the Crater Flat field, the Sleeping Butte/Thirsty Mesa field, and the Buckboard Mesa fields) (see summary on Table MS-2). Due to the youthfulness of the Lathrop Wells center, there is a possibility that we are still within the active period of an "event" and this is accounted for in assessing the rate. Approximately 125,000 yr have elapsed since the last eruption at Lathrop Wells. Given the definition of an event (i.e., can occur over 100,000 yr), it is judged that there is a 0.25 probability that we are still within the event giving rise to the most recent eruption at Lathrop Wells. There is a 0.75 probability that the event has ended and, in this case, the Lathrop Wells cone is simply counted as another event in the post-5 Ma time period.

In the case where the event is assumed to still be occurring, the following rate is derived. It is assumed that the full length of an event is 200,000 yr (± 100,000 yr). At the end of the 200,000 yr period, the probability of another eruption within this event will be zero. If 125,000 yr have elapsed, the probability of an event in the next 75,000 yr is simply 1/75,000. It is assumed that this represents an equivalent annual rate, given that we are still within the most recent event.

Rate of New Field Birth

The rates of formation of volcanic fields are assessed for two regions: a 200-km-radius circle from the site (given a weight of 0.75) and the inner 40-km-radius zone (given a weight of 0.25). The event counts are for two time periods: post-10 Ma and post-5 Ma. The post-10 Ma time period is given higher weight (0.75) because it is judged that the regional tectonic setting within the regions of interest has been relatively constant over this time period; the maps appear to be complete for volcanics of this age; and a larger, perhaps more significant, number of events is identified than for the post-5 Ma time period, thus providing a more stable rate estimate.

Undetected Events

This PVHA is focused on assessing the probability of intersection of the proposed repository (at a depth of approximately 300 m below the surface) with a volcanic event. The events discussed above are related to surface observations. It is also possible that some events may occur in the shallow subsurface but not be present at the surface. The aeromagnetic anomalies in the Amargosa Desert and Crater Flat are assumed to be scoria cones. These represent surface events that were buried but have been identified, hence they are not undetected events. The major type of undetected event in the northern Crater Flat area would be subsurface dikes which could be present within about 1 km of the valley floor and which may have a geometry that is difficult to recognize by current geophysical techniques (vertical thin sheet).

The technical justification for these features is related to the presentation of G. Thompson (at PVHA Workshop 2) on crustal extension that follows the model of Bursik and Sieh (1989): in a zone of extension the horizontal strain can be accomodated by either intrusion of dikes parallel to the plane of maximum extension or by normal faulting with both horizontal and vertical components of displacement. According to Bursik (1993), density plays a major role that inhibits the vertical extent of lava in dikes. Magma within the dikes would have a tendency to move down-hill and break to the surface at some point lower than its maximum elevation. Eruptions on Hawaii are good examples of this hypothesis.

The present Yucca Mountain block apparently has had no dikes emplaced during the past 5 my, and its tectonic response has been uplift as a more-or-less rigid block bounded by normal faults. The deep structure of the adjacent Crater Flat basin is not clear, and several models were presented at the PVHA workshops (e.g., G. Thompson presentation at Workshop 4). The model I favor is a pull-apart basin with a horizontal strain accommodated by dike intrusion. Using this model, the subsurface dike system of the 1.0 Ma cones is a manifestation of one or more deeper dike systems. This would also apply to the 3.7 Ma volcanic features in Crater Flat and the young cones of Lathrop Wells.

To estimate undetected events, using my definition of an event as having ± 100,000 year life span, there could be as many as 25 events in the 5 Ma under consideration. This number, minus the number of recognized events, yields the number of undetected dikes in the subsurface. For the Crater Flat field, in which there are 15 recognized events, this simplifies to about 10 undetected events ± 5 at the 90% confidence level. The computed rates, based on observations, should then be multiplied by factors of 1.33 [(15+5)/15], 1.67 [15+10)/15], or 2.0 [(15+5]/15] with weights of: 0.185, 0.63, and 0.185, respectively.

TEMPORAL MODELS

The temporal distribution of the occurrence of field formation and of volcanic events is assumed to be homogeneous. Non-homogeneous models, such as the Weibull model, are not considered to be appropriate because of the low numbers of events and because such models are highly sensitive to the "start times" that are assumed. By examining the data for field formation during both the post-10 Ma and post-5 Ma periods, and the post-5 Ma period for events within volcanic fields, the assumption of a homogeneous process seems to be reasonable.

EVENT GEOMETRIES

The geometry of events is a function of the type of event being considered. Cone-type events (defined by a single cone) will have dike lengths that are typical of those measured in the San Rafael Swell by Delaney and Gartner (1995) [mean of 1.03 +1.74 - 0.65, log normal] and the field observations made in several basalt fields reported by Sheridan (1992) [2.5 km ±0.8 km, Gaussian]. For "lumped" events (defined as more than one cone or eruptive feature on a dike system), the distribution of event lengths is taken from the actual dimensions of volcanic features mapped in the region of interest. The mean length is 5 km and the lognormal variance ranges about +7 km to -3 km for the 90th and 10th percentiles. There is a ± 25% uncertainty on the mean and on the standard deviation. These are models with weights of 0.185, 0.63, and 0.185. The event location on the dike will have a preference for the middle point and can be modeled by a triangular distribution.

Note: The resulting cumulative distributions and density functions for dike length are shown on Figure MS-3.

The interpretation of the orientation is also a function of the event type. For cone-type events, the dike orientation is parallel to the maximum horizontal compression direction (Pollard, 1987). This direction is N30E defined from earthquake focal mechanisms, in-situ stress measurements, and strain accumulation (Savage et al., in press). One standard deviation uncertainty is estimated to be ±20 degrees. In the case of "lumped" events, the orientation comes from the mean direction of observed surface features and is based on assumptions of Delaney et al. (1986). This methodology also gives a direction of N30E with a standard deviation of ± 15 degrees.

HYDROMAGMATIC ACTIVITY

Hydrovolcanic explosions require a specific range of hydrologic and volcanic conditions (Sheridan and Wohletz, 1981; 1983). One of the best means of estimating the probability of hydrovolcanic events is to count the number of tuff rings and tuff cones relative to the scoria cones in volcanic fields (Wohletz and Sheridan, 1982). The number of tuff cones and scoria cones in Plio-Pleistocene volcanic fields in Arizona is tabulated by Lynch (1989). Low numbers of tuff cones and tuff rings (maars) also occur in the Lunar Crater and Cima volcanic fields. There are none in the 40-km-radius region of interest near Yucca Mountain. Given a dike injection in the vicinity of the site, the probability of a significant hydromagmatic explosion with a large volume of ejected materials (defined as more than 10^6 m^3) is estimated at 0.01 - 0.02, or 1-2 maar or tuff cone for every 100 scoria cones. This estimate is based on the ratio of cone counts from scoria eruptions versus those related to hydromagmatic processes within analogue regions in the southern Basin and Range.

TYPES OF ERUPTION

The most likely type of eruption expected in the future would be a small scoria cone and associated lava flows. In this type of event, roughly equal amounts of scoria (explosive products) and lava (effusive products) would total about 0.1 km^3 (order of magnitude) of magma. Another, but less probable, type of event would be the formation of a basaltic lava shield composed mostly of thin flows. Such volcanoes would have a volume of about 1.0 km^3, but the probability of this type of event would be about 1/10 that of the small scoria cone. A third possibility would be a hydromagmatic explosion, with the formation of a crater and tuff ring with only about 0.01 km^3 of juvenile magma but about 0.1 km^3 of surrounding accidental material. The conditional probability of such explosions given a volcanic event would be about 0.01. A final possibility would be the eruption of more evolved magma to form an explosive ash-flow deposit of large volume. The conditional probability of such an event in the region of interest is estimated to be about 10^{-4} compared with that of a scoria cone and lava event.

Michael J Sheridan 5/16/96

REFERENCES

Atwater, T., 1970, Implications of plate tectonics for the Cenozoic tectonic evolution of western North America: Geological Society of America Bulletin, v. 81, p. 3513-3536.

Bursik, M., 1993, Subplinian eruption mechanisms inferred from volatile and clast dispersal data: Journal of Volcanology and Geothermal Research, v. 57, p. 57-70.

Bursik, M., and Sieh, K., 1989, Range front volcanism in the Mono Basin, eastern California: Journal of Geophysical Research, v. 94, p. 15,587-15,609.

Christiansen, R.L. and Lipman, P.W., 1972, Cenozoic volcanism and plate tectonic evolution of the western United Sates, II, late Cenozoic: Philosophical Transactions Royal Society London Series A, v. 271, p. 249-284.

Connor, C.B., and Hill, B.E., 1993, Estimating the probability of volcanic disruption of the candidate Yucca Mountain repository using spatially and temporally non-homogeneous Poisson models: Proceedings, Site Characterization and Model Validation Focus '93 Symposium Volume, American Nuclear Society, La Grange Park, Illinois, p. 174-181.

Crowe, B., Perry, F., Geissman, J., McFadden, L., Wells, S., Murrell, M., Poths, J., Valentine, G.A., Bowker, L., and Finnegan., K., 1995, Status of volcanism studies for the Yucca Mountain Site Characterization Project: Los Alamos National Laboratories Report LA-12908-MS, March 1995.

Delaney, P.T., and Gartner, A.E., 1995, Physical processes of shallow mafic dike emplacement near the San Rafael Swell, Utah: U.S. Geological Survey Open-File Report 95-491, 47 p.

Delaney, P.T., Pollard, D.D., Ziony, J.I., and McKee, E.H., 1986, Field relations between dikes and joints: Emplacement processes and paleostress analysis: Journal of Geophysical Research, v. 91, p. 4920-4938.

Foshag, W.F., and Gonzalez, J., 1956, Birth and development of Paricutin Volcano, Mexico: U.S. Geological Survey Bulletin 965-D, 489 p.

Ho, C.H., 1991, Time trend analysis of basaltic volcanism for the Yucca Mountain Site. Journal of Volcanology and Geothermal Research, v. 46, p 61-72.

Langenheim, V.E., Kirchoff-Stein, K.S., and Oliver, H.W., 1993, Geophysical investigations of buried volcanic centers near Yucca Mountain, southwest Nevada: Proceedings, High Level Radioactive Waste Management Conference, Las Vegas, Nevada, American Nuclear Society, La Grange Park, Illinois, p. 1840-1846.

Luedke, R.G., and Smith, R.L., 1981, Map showing distribution, composition, and age of late Cenozoic volcanic centers in California and Nevada: U.S. Geological Survey Miscellaneous Investigation Series Map I-1090-C.

Lutton, R.J., 1968, Internal structure of the Buckboard Mesa basalt: Bulletin of Volcanology, p. 579-593

Lynch, D.J., 1989, Neogene volcanism in Arizona: the recognizable volcanoes, *in* Jenny, J.P., and Reynolds, S.J. (eds), Arizona Geological Society Digest, v. 17, p. 681-700.

Nealey, L.D., and Sheridan, M.F., 1989, Post-Laramide volcanic rocks of Arizona and northern Sonora, Mexico and their inclusions, *in* Jenny, J.P. and Reynolds, S.J. (eds), Arizona Geological Society Digest, v. 17, p. 609-647.

Pollard D.D., 1987, Elementary fracture mechanics applied to the structural interpretation of dykes, *in* Halls, H.C. and Fahrig, W.F. (eds), Mafic Dyke Swarms: Geological Association of Canada Special Paper 34, p. 5-24.

Savage, J.C., Lisowski, M., Scarc, J.L., and Gross, W.K., in press, Strain accumulation across the central Nevada seismic zone, 1973-1994: Journal of Geophysical Research.

Schwartz, F.W., McGuire, R.K., Bullen, D.B., Cook, N., Coppersmith, K.J., Kemeny, J., Long, A., Pearson, F.J. Jr., Sheridan, M.F., and Youngs, R.R., 1991, Demonstration of a decision analysis methodology for assessing the performance of the Yucca Mountain site in southern Nevada: Waste Management, v. 11, p. 287-306.

Sheridan, M.F., 1992, A Monte Carlo technique to estimate the probability of volcanic dikes: Proceedings, High Level Radioactive Waste Management Conference, Las Vegas, Nevada, American Nuclear Society, La Grange Park, Illinois, v. 2, p. 1840-1846.

Sheridan, M.F., and Wohletz, K.H., 1981, Hydrovolcanic explosions, the systematics of water-tephra equilibrations: Science, v. 212, p. 1387-1389.

Sheridan, M.F., and Wohletz, K.H., 1983, Explosive hydrovolcanism: basic considerations and review, *in* Sheridan, M.F., and Barberi, F. (eds), Explosive Volcanism: Journal of Volcanology Geothermal Research, v. 17, p. 1-29.

Sigurdsson, H., 1987, Dyke injection in Iceland: A review, *in* Halls, H.C., and Fahrig, W.F. (eds.), Mafic Dyke Swarms: Geological Association of Canada Special Paper 34, p. 55-64.

Smith, R.L., 1979, Ash-flow magmatism, *in* Chapin, C.E. and Elston, W.E. (eds), Ash Flow Tuffs: Geological Society of America Special Paper 180, p. 5-27.

Smith, R.L., and Bailey, R.A., 1968, Resurgent Cauldrons, *in* Coats, R.R., et al. (eds), Studies in Volcanology: Geological Society of America Memoir 116, p. 153-210.

Wells S.G., McFadden, L.D., Renault, C.E., and Crowe, B.M., 1990, Geomorphic assessment of late Quaternary volcanism in the Yucca Mountain area, southern Nevada: implications for the proposed high-level radioactive waste repository: Geology, v. 19, p 549-553.

Wohletz, K.H., and Sheridan M.F., 1982, Evolution of tuff cones and tuff rings: American Journal of Science, v. 283, p. 385-413.

Yogodzinski, G.M., and Smith, E.I., 1995, Isotopic domains and the area of interest for volcanic hazard assessment in the Yucca Mountain area: Abstract, Eos, Transactions, American Geophysical Union, 1995 Fall Meeting, p. F669.

TABLE MS-1
MICHAEL F. SHERIDAN - EVENT COUNTS

EVENT COUNTS

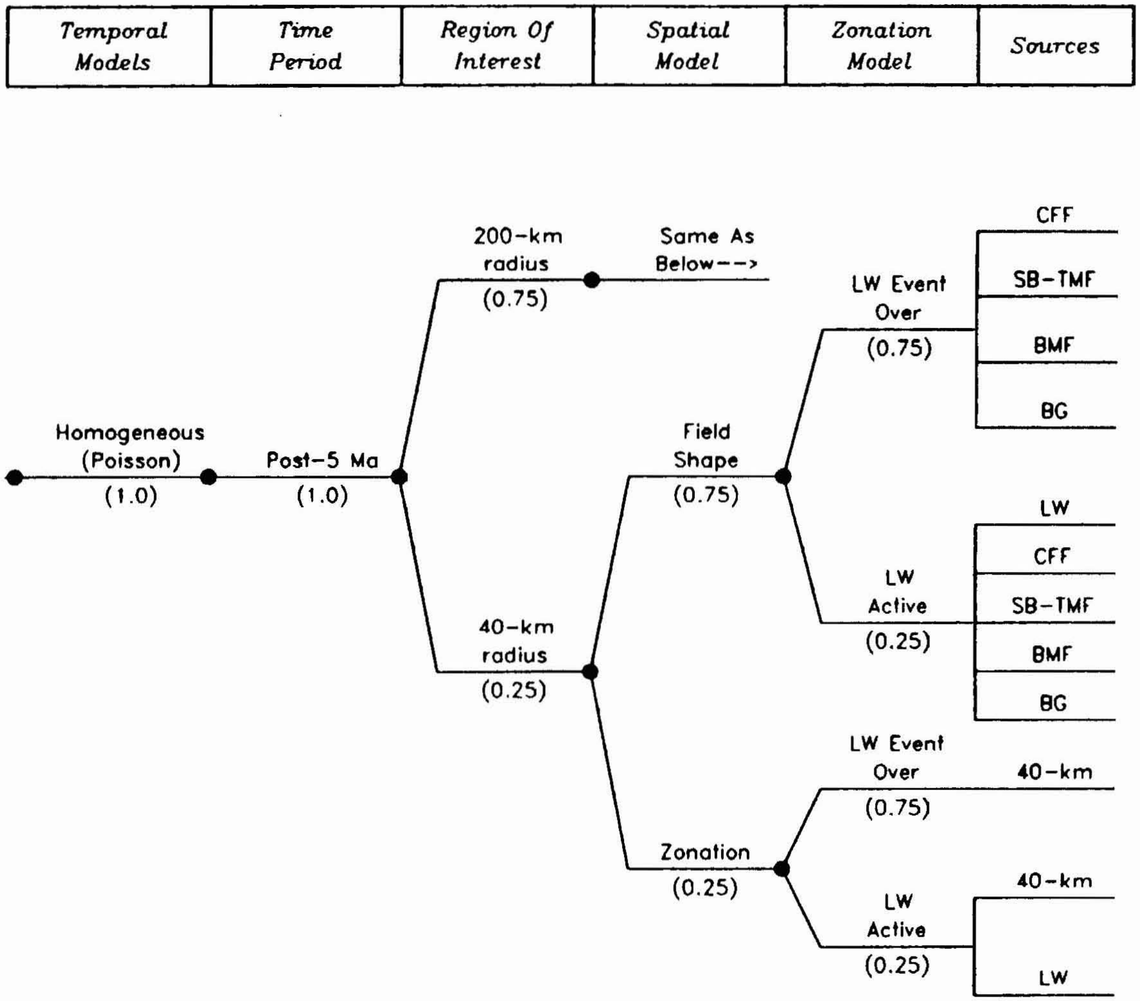
LOCATION	COUNTS (CONES)	WEIGHT	NOTES
Lathrop Wells	1 2	(0.9) (0.1)	
Sleeping Butte	1 2	(0.67) (0.33)	
1.0 Ma Crater Flat	1 2 3	(0.7) (0.2) (0.1)	
Buckboard Mesa	1 2 3 4 5 6	(0.75) (0.05) (0.05) (0.05) (0.05) (0.05)	
3.7 Ma Crater Flat	1 2 3 4	(0.1) (0.6) (0.2) (0.1)	
Amargosa Valley	5 6 7	(0.25) (0.5) (0.25)	
Thirsty Mesa	1 2 3 4	(0.9) (0.033) (0.034) (0.033)	

FIELD COUNTS

REGION	TIME PERIOD	COUNTS	WEIGHT
Within 200 km	Post 10 Ma	30	(1.0)
	Post 5 Ma	16	(1.0)
Within 40 km	Post 10 Ma	5	(1.0)
	Post 5 Ma	2	(1.0)

TABLE MS-2
MICHAEL F. SHERIDAN - RATES OF OCCURRENCE

TIME PERIOD	COUNT METHOD FOR FIELDS	NOTES
5 MA		
(1.0)	CFF: (LW+3.7+NCF, AV)	CFF: Crater Flat Field
		SBTMF: Sleeping Butte/Thirsty Mesa Field
	SBTMF: (SB+TM)	BMF: Buckboard Mesa Field
		NCF: Northern (1.0 Ma) Crater Flat
	BMF: (BM)	3.7: 3.7 Ma Crater Flat
		LW: Lathrop Wells
	200 km: 10 Ma (0.75)	TM: Thirsty Mesa
	5 Ma (0.25)	SB: Sleeping Butte
		AV: Amargosa Valley
	40 km: 10 km (0.75)	BM: Buckboard Mesa
	5 Ma (0.25)	200 km: 200 km Radius
		40 km: 40 km Radius



CFF: Crater Flat Field

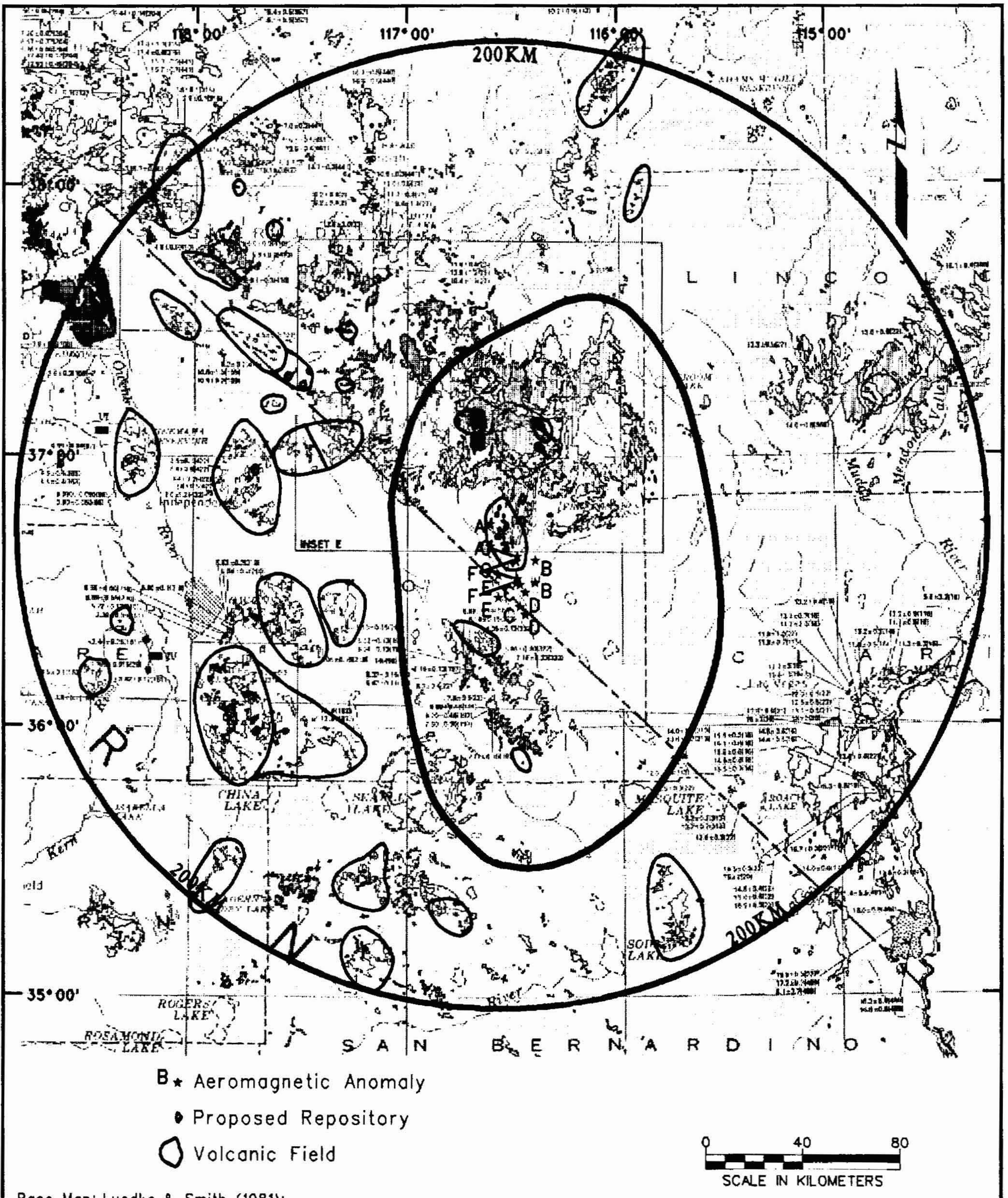
SB-TMF: Sleeping Butte-Thirsty Mesa Field

BMF: Buckboard Mesa Field

LWF: Lathrop Wells

BG: Background

Figure MS-1 PVHA model logic tree developed by Michael F. Sheridan.



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

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GEOMATRIX

MICHAEL F. SHERIDAN
REGIONAL BACKGROUND ZONES
AND VOLCANIC FIELDS

Figure
MS-2

PVHA
Project

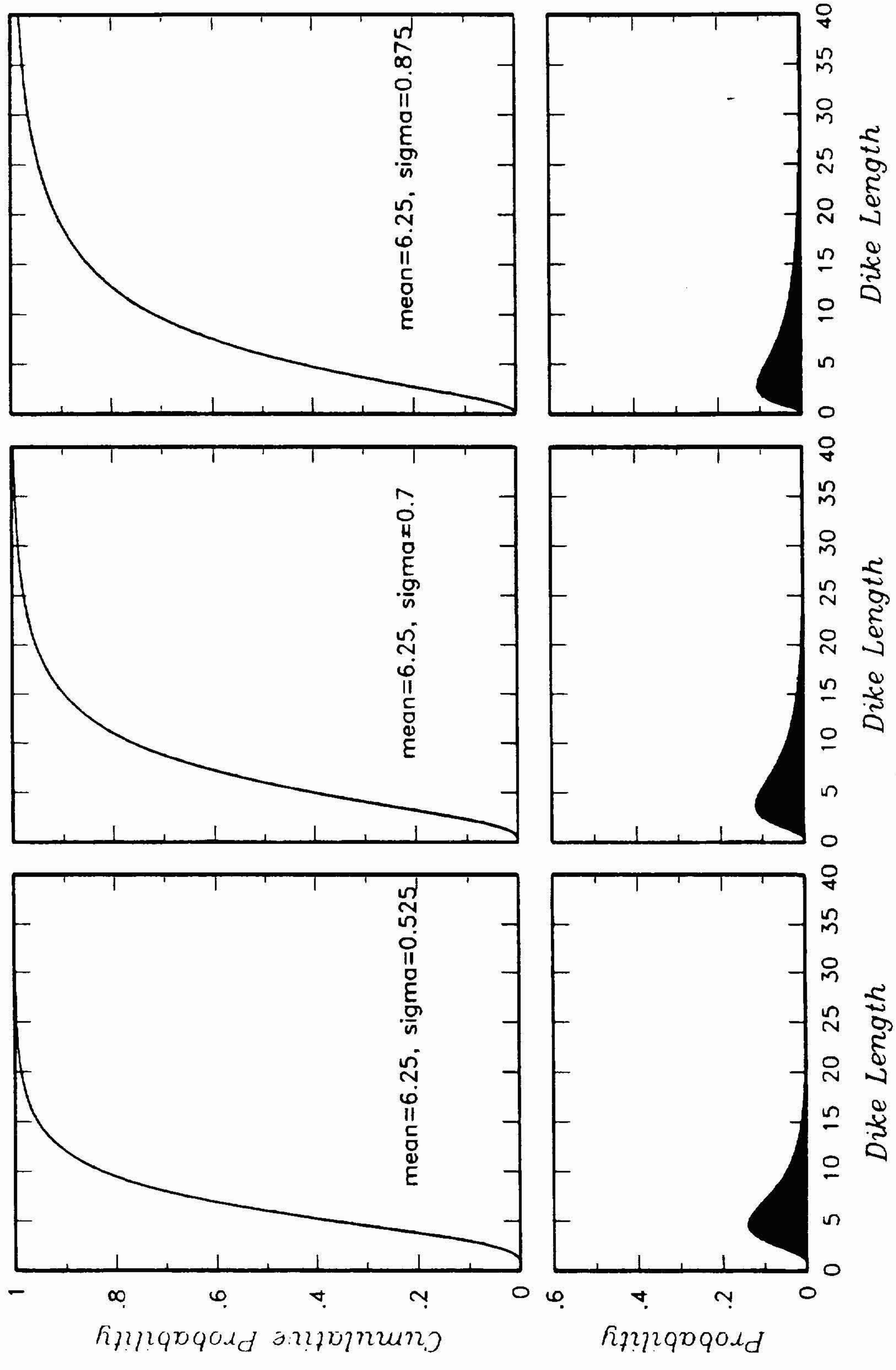


Figure MS-3 Dike length distribution developed by Michael F. Sheridan.

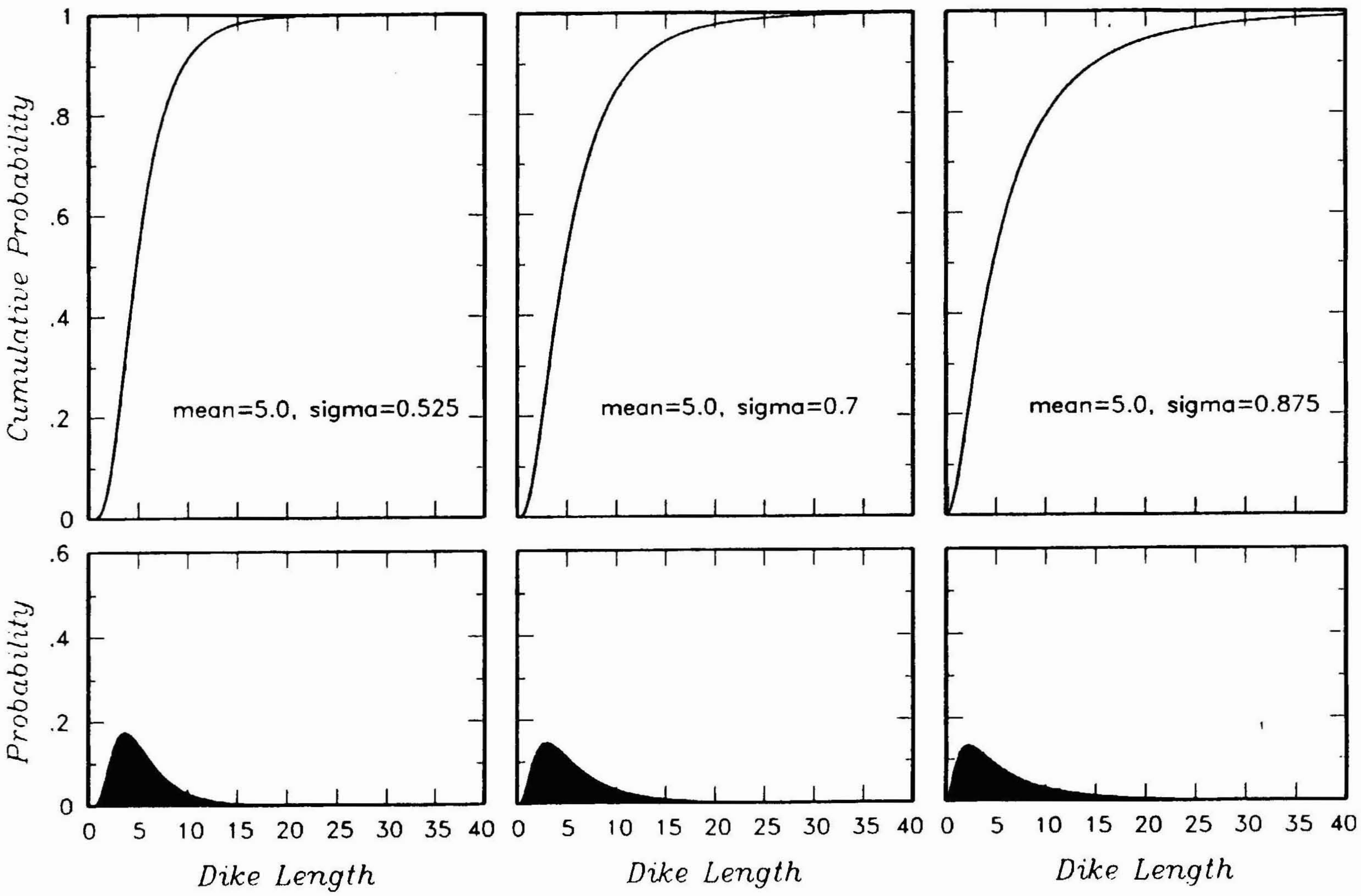


Figure MS-3 (Cont'd) Dike length distribution developed by Michael F. Sheridan.

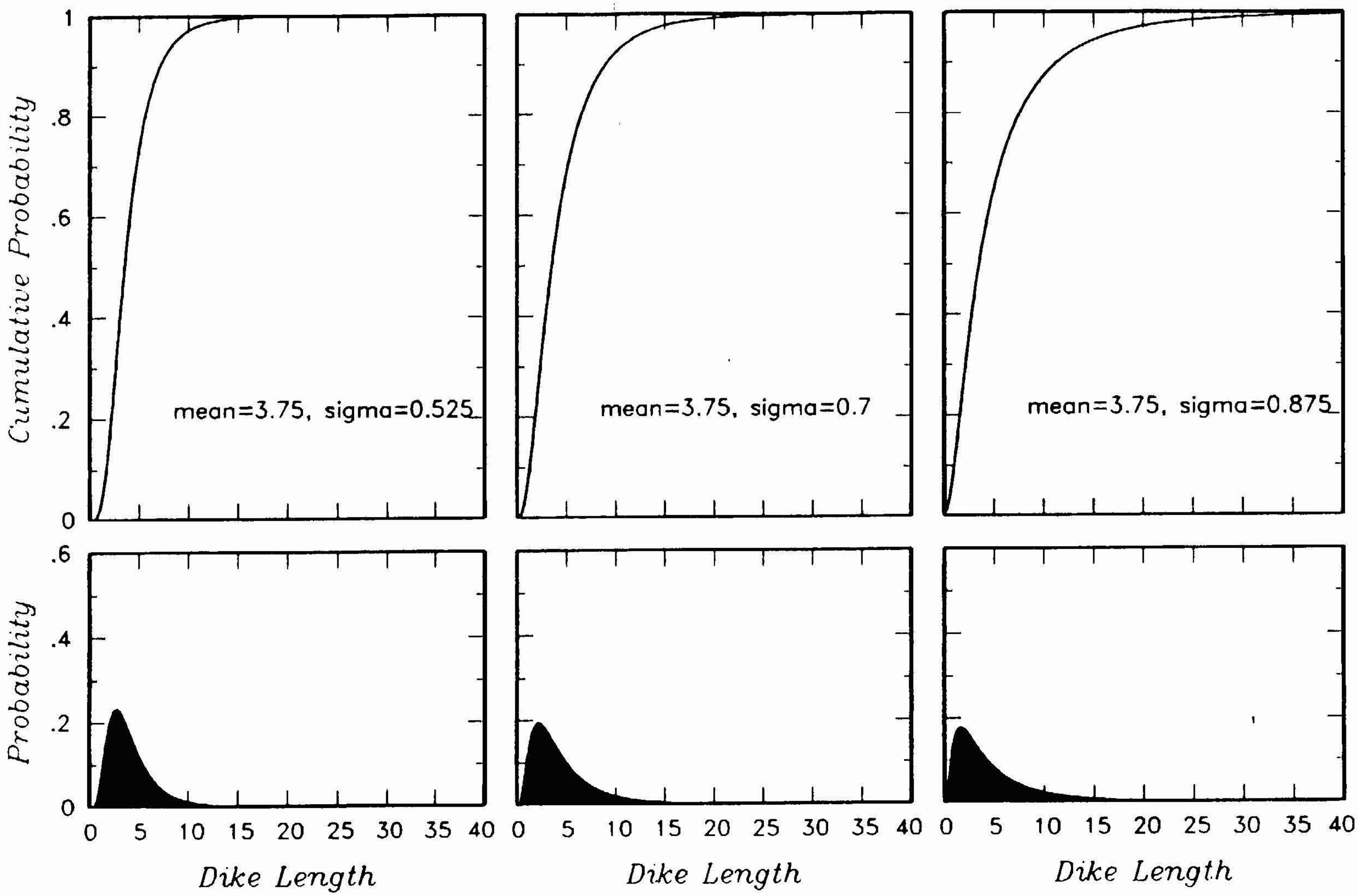


Figure MS-3 (Cont'd) Dike length distribution developed by Michael F. Sheridan.

GEORGE A. THOMPSON
ELICITATION INTERVIEW FOR PVHA PROJECT

VOLCANIC/TECTONIC SETTING

The Yucca Mountain region (YMR, defined as the region within a radius of about 50 km centered on Yucca Mountain) is located on the boundary between the Basin and Range province, characterized by extension, and the Walker Lane belt, characterized by oblique-normal and strike-slip movement. Most of the tectonism within the Basin and Range province appears to be nearly pure extension, expressed as either normal faulting or dike emplacement (strike-slip is locally important). The local picture in the region of interest (Bare Mountain, Crater Flat, Yucca Mountain) is consistent with the broad picture in this part of the Basin and Range: the cone alignment in northern Crater Flat is parallel to the maximum compressional stress direction of about NNE, and the Lathrop Wells cone lies at the southern end of Quaternary faults.

Dike emplacement and normal faulting both are mechanisms for accommodating regional extension. In places where magma supply is high, volcanism will occur; where supply is low, faulting will occur. In the same way that coseismic fault displacement relieves accumulated stress, dikes are emplaced quickly and extensional stresses are relieved. The Paiute Ridge area northeast of Yucca Mountain (Byers and Barnes, 1967; Crowe et al., 1995) provides insights into the interplay between normal faults and dikes. This area contains a complex graben, where about 0.5 km of erosion has exposed dikes and volcanic features. Some dikes are replaced by normal faults along strike, verifying that dike emplacement and faulting are both accomplishing net extension. The interspacing and dip of faults can provide information on the depth to the dikes.

A key part of the interpretation of the Basin and Range tectonics is the close temporal relationship between normal faulting and dike emplacement (Parsons and Thompson, 1991). Because both normal faults and dikes are relieving extensional stress, those areas with evidence of young faulting will often be associated with volcanism. For example, the Lathrop Wells cone erupted about 100,000 years ago just south of a series of faults that display evidence of multiple displacements in late Quaternary time (Frizzel and Shulters, 1990). In contrast, the faults within Bare Mountain do not show evidence of late Cenozoic displacement, and the most recent dikes are about 14 Ma (Monsen et al., 1992).

The southern end of Yucca Mountain has been rotated in a clockwise direction, based on paleomagnetic data (O'Neill et al., 1992). The left-lateral component of shear exhibited on the regional faults is consistent with a "book shelf type of deformation" imposed by the right-lateral regional shear of the Walker Lane. However, the extensional component of strain on these faults is the most important for accommodating regional extension.

Areas where active extension is occurring, as indicated by recent faulting and dike emplacement, are the most favorable sites for future volcanism. Inherently, extensional features tend to be concentrated in basins because normal faults that formed the basins generally dip inward and converge downward beneath the basins. During the past 2 my, fault rupture has occurred on several faults in the vicinity of Yucca Mountain, including the Solitario Canyon and Bow Ridge faults. The preferred orientation of dikes is roughly parallel with the trends of active fault systems. It is unlikely that future volcanism will occur within structural blocks that have not been faulted in the late Cenozoic. The proposed repository site in the Yucca Mountain block has revealed no evidence of late Cenozoic faulting, and is much less likely to be disrupted than faulted areas to the south. The Lathrop Wells area is the most likely site for future volcanism, as the area contains a temporal association between recent faulting and volcanism. Specifically, faults responding to the regional stress system could be underlain by dikes that have erupted at Lathrop Wells. In contrast, the Bare Mountain block exhibits no internal evidence of late Cenozoic activity other than tilting and is considered to have a low potential for future volcanism. The Bare Mountain fault is roughly parallel to the 14 Ma dikes in the area.

EVENT DEFINITION

Temporal Aspects

A volcanic event occurs within the time required to solidify a feeder dike, roughly on the order of a few years (it is acknowledged that rapid continuous flow with accompanying heat input may prevent solidification). In some cases where multiple dikes are emplaced as part of a dike set and where multiple cones are formed, the time may be as long as several hundred years. The short time period is due to the lack of crustal storage and the short time it takes to freeze a basaltic dike. It is acknowledged that available age dating methods do not allow sufficient resolution to differentiate between two events separated by less than several thousand years. This uncertainty is accounted for in estimating the number of events at any given volcanic center.

Spatial Aspects

Generally, an event has dimensions associated with the length of a dike, which is about 1 to 5 km. In some cases, a dike set may be as long as 10 to 15 km. The cones in northern Crater Flat may be related to a single event and, if so, would represent an event with a length of 12 km. Most likely, such an event would be the result of a set of dikes, and not a single dike. Longer event lengths would require significantly larger volumes than observed or expected in the YMR.

Geochemical Affinity

The geochemistry of volcanic deposits can provide useful information on the magma source (e.g., depth) and residence time in the crust. However, geochemistry is not judged to be particularly useful in identifying individual events.

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

REGION OF INTEREST

The region of interest is the area defined as the Amargosa Valley Isotopic Province (AVIP) by G. Yogodzinski (presentation at PVHA Workshop 3). This area includes young faults, and the isotopic data may distinguish between crustal and mantle sources. The isotopic data suggest a common magma source for the AVIP that is distinct from surrounding regions.

An alternative region of interest is that defined by a 200-km radius from Yucca Mountain, as characterized by M. Sheridan (presentation at PVHA Workshop 4). The alternative zone includes several volcanic fields that are distinct from those in the YMR. As discussed below, the number of fields in the 200-km region is used to define the rate of occurrence of volcanism within this region.

The 200-km radius captures basalt vent clusters or fields within the age range of 0-5 Ma, which tend to be spaced roughly 50-100 km apart (Luedke and Smith, 1981); this is also the scale of lithosphere dimensions. From a geophysical perspective the spacing may reflect withdrawal of heat and magma from widespread incipient melt in the Basin and Range mantle; that is, a critical volume of melt needs to be gathered from an extended area in order for it to rise into and through the crust. The probability of eruptions between fields may be much diminished because of depletion of magma and heat.

The regions of interest defined by the AVIP and by the 200-km radius serve as "background" zones in the PVHA. The relative weight given to the background alternatives are: AVIP (0.7), radius approach (0.3). The AVIP approach is preferred because it takes into account the geologic characteristics of the volcanic fields in the region.

A "local region of interest" is also defined, as discussed below in the context of source zones.

SPATIAL MODELS

The spatial model that is used is a zonation of the region into zones that have different rates of occurrence of volcanic events. The basis for these zones comes from a consideration of age of tectonism and the style (i.e., volcanism versus faulting).

The background zones are described above in the section on the region of interest. These zones are regional in extent and serve to provide a regional rate of occurrence of volcanism in the part of the Basin and Range province of significance to the site.

Within the background zone, three local zones are assessed. The first is a Local Domain zone (Figure GT-2), which encloses an area south of the Timber Mountain caldera complex and east of the Bare Mountain uplifted block, and encloses the uplifted Yucca Mountain block and the Amargosa Valley. It is not judged to be appropriate for the Local Domain zone to include the Sleeping Butte region to the northwest because of the large spatial separation with Crater Flat. This separation has persisted for at least the past 8 my, suggesting that the two areas are separate volcanic fields.

Within the Local Domain are the "Volcanic Domain" zone, which includes the Quaternary volcanoes of Crater Flat and Lathrop Wells, as well as the Pliocene events in the Amargosa Valley, and the "Quaternary Faulting Domain," which includes the Quaternary faults in the YMR. These two local zones are interpreted to represent two different mechanisms for accomplishing extension: extension by dike emplacement and by normal faulting. The two domains overlap in the region of the 3.7 Ma volcanics, suggesting that Quaternary faulting replaced volcanism as the primary mechanism for extension in this region. The boundaries of the two sources differ, depending on the time period being considered. When the 1 Ma time period is considered, faulting is the controlling process in the area of overlap, and the source zones are the Quaternary Faulting Domain and that portion of the Volcanic Domain lying outside the Quaternary Faulting

Domain. When the 4 Ma time period is considered, volcanic processes are dominant in the area of overlap, and the source zones are the Volcanic Domain and the area of the Quaternary Faulting Domain outside the Volcanic Domain. The eastern edge of the Volcanic Domain may represent a hard boundary, or the rate density will decay linearly over a distance of 5 km. The relative weights assigned to these two models are: hard boundary (0.67) and transition zone (0.33).

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 (Table GT-1). The number of events is assessed for the past 4 my, which is judged to be the time period of most relevance to estimates of future hazard. In addition, the event counts are assessed for the past 1 my.

Lathrop Wells

The relationships at Lathrop Wells suggest from 1 to 4 events (Crowe et al., 1995); one event is preferred simply because most of the volume is attributed to one event and age dates do not unequivocally separate the events. Spatially, all of the deposits occurred at essentially the same place; therefore, differences in timing are the most important aspects in defining separate events (recall that geochemical differences are not relied on for identifying events). The radiometric age estimates are very uncertain, but stratigraphic and soils evidence are suggestive of satellite eruptions that may have been well separated in time.

The following event counts and their relative weights are assigned for the Lathrop Wells center: 1 (0.75), 2 (0.08), 3 (0.08), and 4 (0.08).

1.0 Ma Crater Flat

The 1 Ma basalts of northern Crater Flat may represent 1 to 5 events, with 4 events most likely. Stress changes could have resulted in pulses of small-volume eruptions that formed cones propagating towards the NE. Possible connecting dikes, if only a meter or so in width, will be difficult to identify in the subsurface because magnetic surveys can resolve them only to a depth of a few meters in the presence of background noise (basalt flows and float in the area).

In the 2-event scenario, the Makani Cone is considered a separate event (based on distance) from the combined event represented by the Black, Red, and Little Cones to the south. For the 3-event scenario, Red and Black cones are combined and Makani and Little Cones each represent separate events. For the 4-event scenario, Makani, Red, Black and Little Cones each represent separate events; for 5 events, Little Cone represents 2 events.

The following event counts and their relative weights are assigned for northern Crater Flat: 1 (0.2), 2 (0.15), 3 (0.1), 4 (0.5), and 5 (0.05).

3.7 Ma Crater Flat

The 3.7 Ma basalts are most likely to represent 1 or 2 events that have subsequently been disaggregated by local faulting, erosion, and alluvial deposition (Crowe et al., 1995). The center seems to be more voluminous than other centers in the region. The dike feeders appear to have an orientation of N-S to NNE. There is no strong evidence for more than 1 event; however, up to 6 events could be represented, as described by Crowe et al. (1995, p. 7-31).

The following event counts and their relative weights are assigned for the 3.7 Ma area of Crater Flat: 1 (0.4), 2 (0.5), 3 (0.04), 4 (0.03), 5 (0.02), and 6 (0.01).

Amargosa Valley

Five to 7 events might be represented in Amargosa Valley based on interpretation of aeromagnetic anomalies (V. Langenheim presentation at PVHA Workshop 1). The most likely scenario of 5 events is based on the interpretation that anomalies A, B, C, D, and E (on the aeromagnetic map presented by V. Langenheim at PVHA Workshop 1) are cones, as indicated by their strong, bipolar aeromagnetic signatures. Interpretation of the origin of anomalies F and G is more uncertain.

The following event counts and their relative weights are assigned to the Amargosa Valley area: 5 (0.9), and 7 (0.1).

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 GT-2).

For the Volcanic Domain zone and the Quaternary Faulting Domain zone, rates are calculated over two time periods: the past 1 my and the past 4 my. Higher weight is given to the past 4 my (0.7) than 1 my (0.3) because this includes a period of significant volcanism at 3.7 Ma. However, the past 1 my is probably more significant to the period of Quaternary faulting.

In assessing rates for the post-4 Ma time period, the counts for the regional background zones are assumed to be those estimated by Crowe et al. (1995) for AVIP and by Sheridan for the 200-km radius circle (M. Sheridan presentation at PVHA Workshop 4). The Local Domain outside of the Quaternary Faulting and Volcanic domains is assumed to have a rate comparable to the background zones. The Volcanic Domain rates are based on counts for the 1 Ma area of Crater Flat, the 3.7 Ma area, Lathrop Wells, and Amargosa Valley. For the post-1 Ma period, the Quaternary Faulting Domain includes the area of the 3.7 Ma basalts of Crater Flat, but, because they are older, does not include additional event counts. The rate for the Quaternary Faulting Domain is based on the relative likelihood of undetected events in the two domains discussed below. That is, the rate in the Quaternary Faulting Domain is 0.1 times the rate of the Volcanic Domain.

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 of less than 300 m (depth of the proposed repository) but not be represented at the surface.

In the YMR, the surface distribution of dikes may not be a good indicator of dike distribution at depths of about 1 km; dikes could extend to within a few hundred meters of the ground surface but not be exposed at the surface. The spacing of dikes (exposed or within about 1 km of the surface) may be equivalent to the 1-km spacing of faults in the YMR. Dike conduits may not be vertical (Parsons and Thompson, 1991). In addition to dikes, sills may be present in the area, but formation of sills is most likely when the magma supply exceeds the amount of regional extension that is accommodating dike emplacement. This is unlikely to be the case in the YMR, where magma volumes are low.

The number of undetected events is judged to be different in the Volcanic Domain and the Quaternary Faulting Domain. In the Volcanic Domain, no extensional features (e.g., faults) that could indicate the presence of undetected or buried dikes have been observed in the Crater Flat area, suggesting that the level of resolution is too low to identify these features (Frizzel and Shulters, 1990; T. Brocher, pers. comm., 1995). It is estimated that there is approximately equal probability that the number of undetected events in the domain ranges from zero to equal to the number of observed events (0.5 and 0.5 probabilities, respectively). Recent seismic reflection results show continuous, unbroken basalt of 3.7 Ma under western Crater Flat, indicating no Quaternary fault activity (T. Brocher, pers. comm., 1995).

In the Quaternary Faulting Domain, the number of undetected events is expected to be far less than the Volcanic Domain. This is supported by the small number of events observed within this domain over the past 10 my, despite the fact that this region has been uplifted and eroded (the 11 Ma dike in Solitario Canyon may represent such an event). The author has been a reviewer of the T. Brocher manuscript describing the analysis of the 1995 deep reflection seismic line across Crater Flat. Within the resolution of the reflection data (a few meters) the 3.7 Ma basalt reflection is unbroken and thus precludes Quaternary fault offsets in that part of Crater Flat. The reflection data generally support the earlier gravity and refraction seismic modeling of the subsurface structure of Crater Flat by Langenheim et al. (1991) but add considerably to the resolution and to the depth variation of the basement surface. The ages of several faults are constrained to be pre-Quaternary. It is estimated that the ratio of undetected events in the Quaternary Faulting Domain relative to the Volcanic Domain is 1:10.

TEMPORAL MODELS

Two start times are assessed for the Volcanic Domain and the Quaternary Faulting Domain zones: 1 Ma and 4 Ma, with probabilities of (0.3) and (0.7), respectively. A homogeneous temporal Poisson model is assumed because this model adequately fits the data.

EVENT GEOMETRIES

Event lengths and widths should be consistent with the dike data reported by Delaney and Gartner (1995): 1 to 5 km long and 1.1 m wide. The dike length data were compiled by Delaney and Gartner for mafic dikes and are considered to be good analogs to the YMR (relative to the very long lengths of dike swarms present in the northern Nevada Rift, Canadian shield areas, etc.). Because the magma volumes in the YMR are expected to be small volumes, volcanic events are expected to be essentially single basaltic dikes. However, it is also possible, but improbable, that some events will be represented by multiple dikes forming a dike set. The maximum length of such a dike set is 10 to 12 km, such as that possibly represented by the volcanoes in northern Crater Flat. Ninety percent of the probability density lies between an event length of 1 to 5 km; a low probability tail exists out to lengths of 10 to 12 km. Equal weights (0.5 and 0.5) are given to maximum lengths of 10 and 12 km. Events are assumed to be more likely to occur near the center of dikes, and a triangular distribution is used to model event geometries.

Note: *At the request of Dr. Thompson, 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 GT-3.*

Dike orientations are consistent with the maximum horizontal stress orientations inferred from earthquake focal mechanisms and in-situ stress measurements (e.g., Stock and Healey, 1988). A N30°E direction is preferred, plus or minus 15 degrees (95% interval).

HYDROMAGMATIC ACTIVITY

A shallow water table and the proper overburden of rock is necessary to generate a significant hydromagmatic explosion. Where such conditions are favorable, about 1 in 1,000 eruptions will show significant hydromagmatic activity. Given the conditions of a low water table at the site, the chances are 1 in 1,000,000.

TYPE OF ERUPTION

The most likely style of future volcanism is the type that has occurred in the past 4 Ma in the region. The termination of silicic volcanism is clearly linked to the change in the subducting plate margin, and therefore, is very unlikely to reoccur. The evidence suggests that the recent volcanism is related to magmas coming from the mantle, and there is no evidence for crustal melts that would give rise to rhyolitic domes.

George A. Thompson 4-15-96

REFERENCES

Byers, F.M., Jr., and Barnes, H., 1967, Geologic map of the Paiute Ridge quadrangle: U.S. Geological Survey Map GQ-577.

Crowe, B.M., Perry, F.V., Geissman, J., McFadden, L., Wells, S., Murrell, M., Poths, J., Valentine, G.A., Bowker, L., and Finnegan, K., 1995, Status of volcanism studies for the Yucca Mountain site characterization projects: Los Alamos National Laboratory Report LA-12101-MS, March 1995.

Delaney, P.T., and Gartner, A.E., 1995, Physical processes of shallow mafic dike emplacement near the San Rafael Swell, Utah: U.S. Geological Survey Open-File Report 95-491, 47 p.

Frizzel, V.A., Jr., and Shulters, J., 1990, Geologic map of the Nevada Test Site, southern Nevada: U.S. Geological Survey Miscellaneous Investigations Series Map I-2046.

Langenheim, V.E., Carle, S.F., Ponce, D.A., and Phillips, J.D., 1991, Revision of an aeromagnetic survey of the Lathrop Wells area, Nevada: U.S. Geological Survey Open-File Report 91-46.

Luedke, R.G., and Smith, R.L., 1981, Map showing distribution, composition, and age of late Cenozoic volcanic centers in California and Nevada: U.S. Geological Survey Miscellaneous Investigations Series Map I-1091-C.

Monsen, S.A., Carr, M.D., Reheis, M.C., and Orkild, P.P., 1992, Geologic map of Bare Mountain, Nye County, Nevada: U.S. Geological Survey Miscellaneous Investigations Series Map I-2201.

O'Neill, J.M., Whitney, J.W., and Hudson, M.R., 1992, Photogeologic and kinematic analysis of lineaments at Yucca Mountain, Nevada: Implications for strike-slip faulting and oroclinal bending: U.S. Geological Survey Open-File Report 91-623, 24 p.

Parsons, T., and Thompson, G.A., 1991, The role of magma overpressure in suppressing earthquakes and topography: worldwide examples: Science, v. 253, p. 1399-1402.

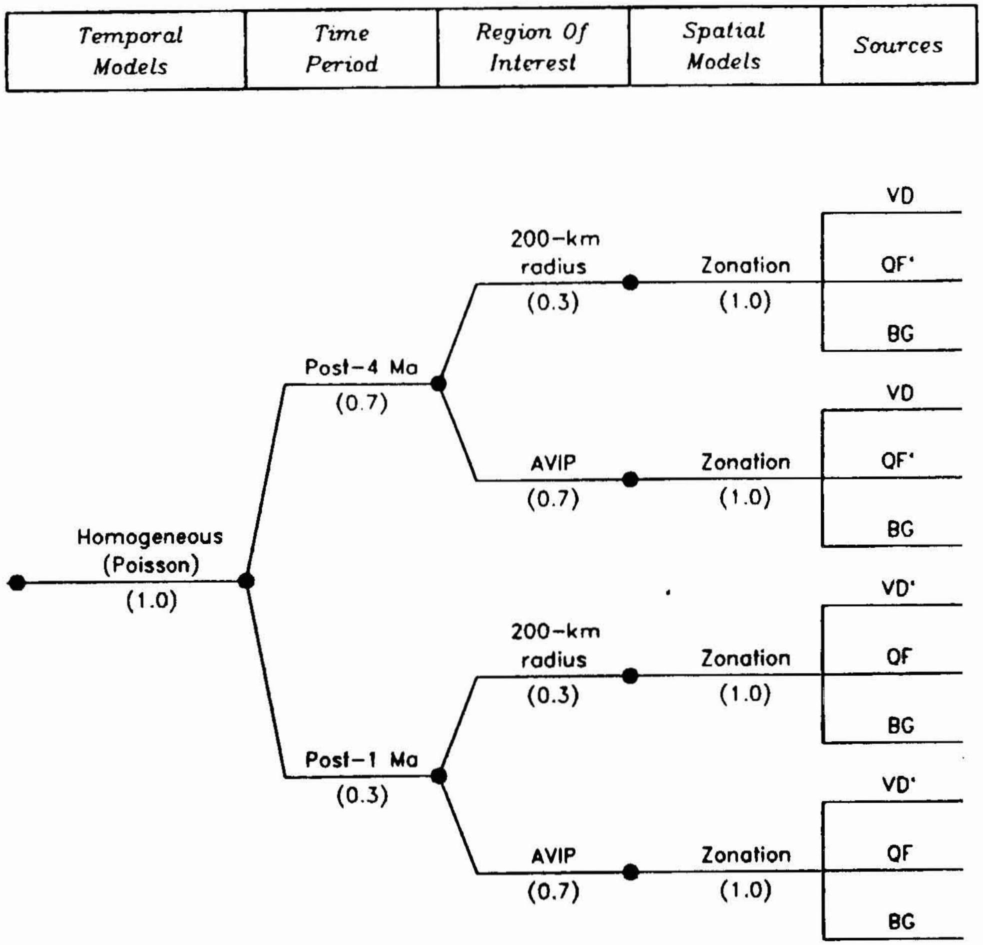
Stock, J.M., and Healy, J.H., 1988, Stress field at Yucca Mountain, Nevada, *in*, Carr, M.D., and Yount, J.C., eds., Geologic and hydrologic investigations of a potential nuclear waste disposal site at Yucca Mountain, southern Nevada: U.S. Geological Survey Bulletin 1790, p. 87-93.

TABLE GT-1
GEORGE A. THOMPSON - EVENT COUNTS

LOCATION	COUNTS (CONES)	WEIGHT	NOTES
Lathrop Wells	1	(0.75)	BC: Black Cone LC: Little Cones 2LC: 2 separate Little Cones M: Makani Cone RC: Red Cone SB: Shoreline Butte SC: Split Cone
	2	(0.09)	
	3	(0.08)	
	4	(0.08)	
Sleeping Butte	1	(0.35)	
	2	(0.65)	
1.0 Ma Crater Flat	1 (all)	(0.2)	
	2 (LC+RC+BC, M)	(0.15)	
	3 (LC, RC+BC, M)	(0.1)	
	4 (LC, RC, BC, M)	(0.5)	
	5 (2LC, RC, BC, M)	(0.05)	
Buckboard Mesa	1	(0.7)	
	2	(0.3)	
3.7 Ma Crater Flat	1	(0.4)	
	2	(0.5)	
	3	(0.04)	
	4	(0.03)	
	5	(0.02)	
	6	(0.01)	
Amargosa Valley	5	(0.9)	
	7	(0.1)	
Background 200 km radius	16 in 5 Ma	(1.0)	
Background AVIP (1 Ma)	1 in 1 Ma (SC)	(1.0)	
Background AVIP (4 Ma)	2 (SC+SB)	(0.35)	
	3 (SC+2SB)	(0.35)	
	4 (SC+3SB)	(0.30)	

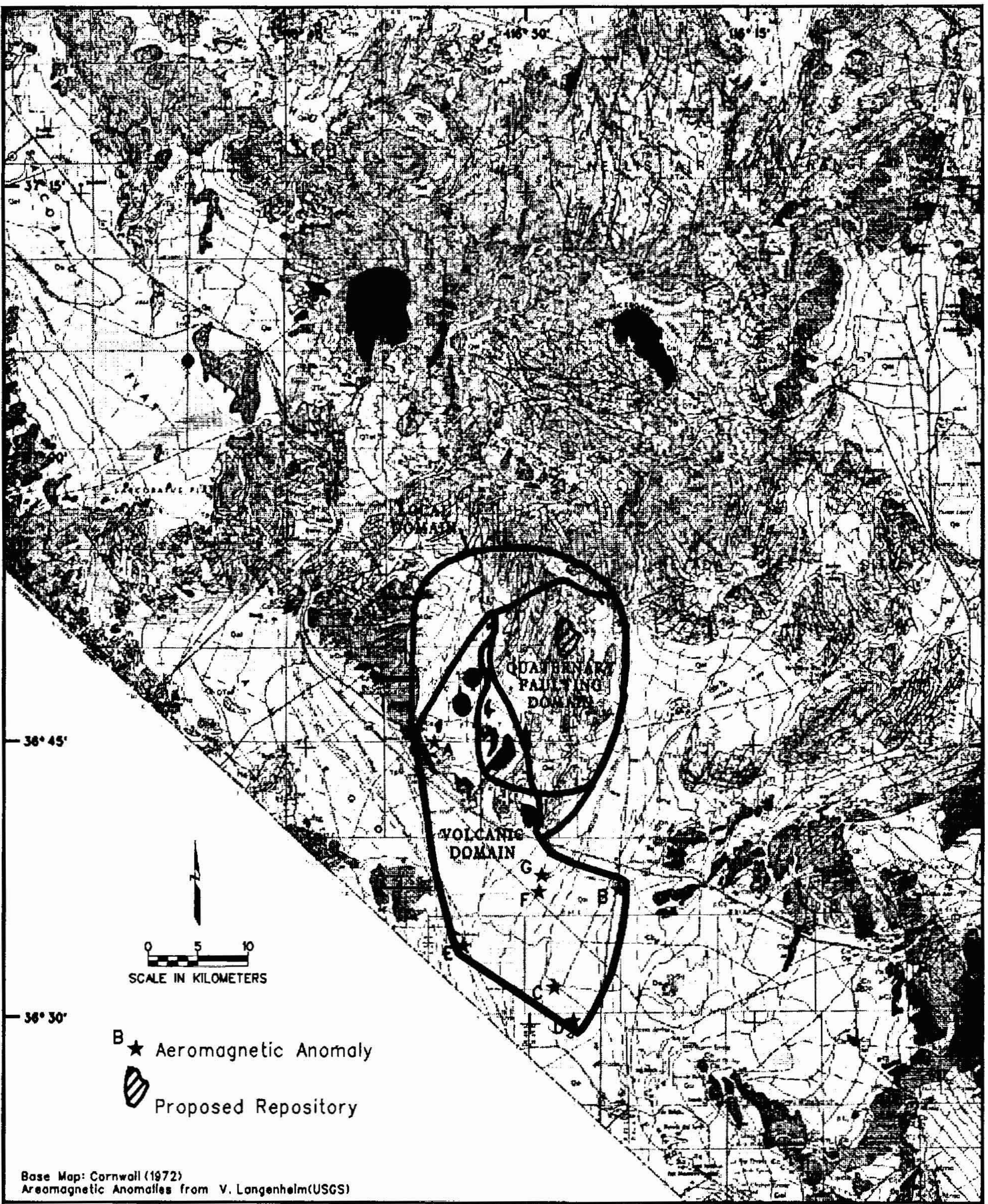
TABLE GT-2
GEORGE A. THOMPSON - RATES OF OCCURRENCE

TIME PERIOD	COUNT METHOD FOR ZONES	NOTES
Post 1 Ma (0.3)	VD: (LW+NCF) QFD: 1/10 VD B200 km: (200 k) BAVIP: (SB+DV1)	AV: Amargosa Valley BAVIP: Background, Amargosa Valley Isotopic Province B200 km: Background, 200 km Radius BM: Buckboard Mesa DV1: Death Valley 1 Ma DV4: Death Valley 4 Ma LW: Lathrop Wells NAVIP: Northern Amargosa Valley Isotopic Province of Yogodzinski (1995) NCF: Northern (1.0 Ma) Crater Flat QFD: Quaternary Faulting Domain SB: Sleeping Butte VD: Volcanic Domain 3.7: 3.7 Ma Crater Flat 200 km: 200 km Radius Field Counts
Post 4 Ma (0.7)	VD: (LW+NCF+3.7+AV) QFD: 1/10 VD B200 km: (200 k) NAVIP: (SB+BM+DV4)	



VD: Volcanic Domain
QF: Quaternary Faulting Domain
VD': Volcanic Domain Outside of Quaternary Faulting Domain
QF': Quaternary Faulting Domain Outside of Volcanic Domain
BG: Background

Figure GT-1 PVHA model logic tree developed by George A. Thompson.



Base Map: Cornwall (1972)
Areomagnetic Anomalies from V. Langenheim(USGS)

GEOMATRIX

GEORGE A. THOMPSON
LOCAL ZONES

Figure GT-2

PVHA Project

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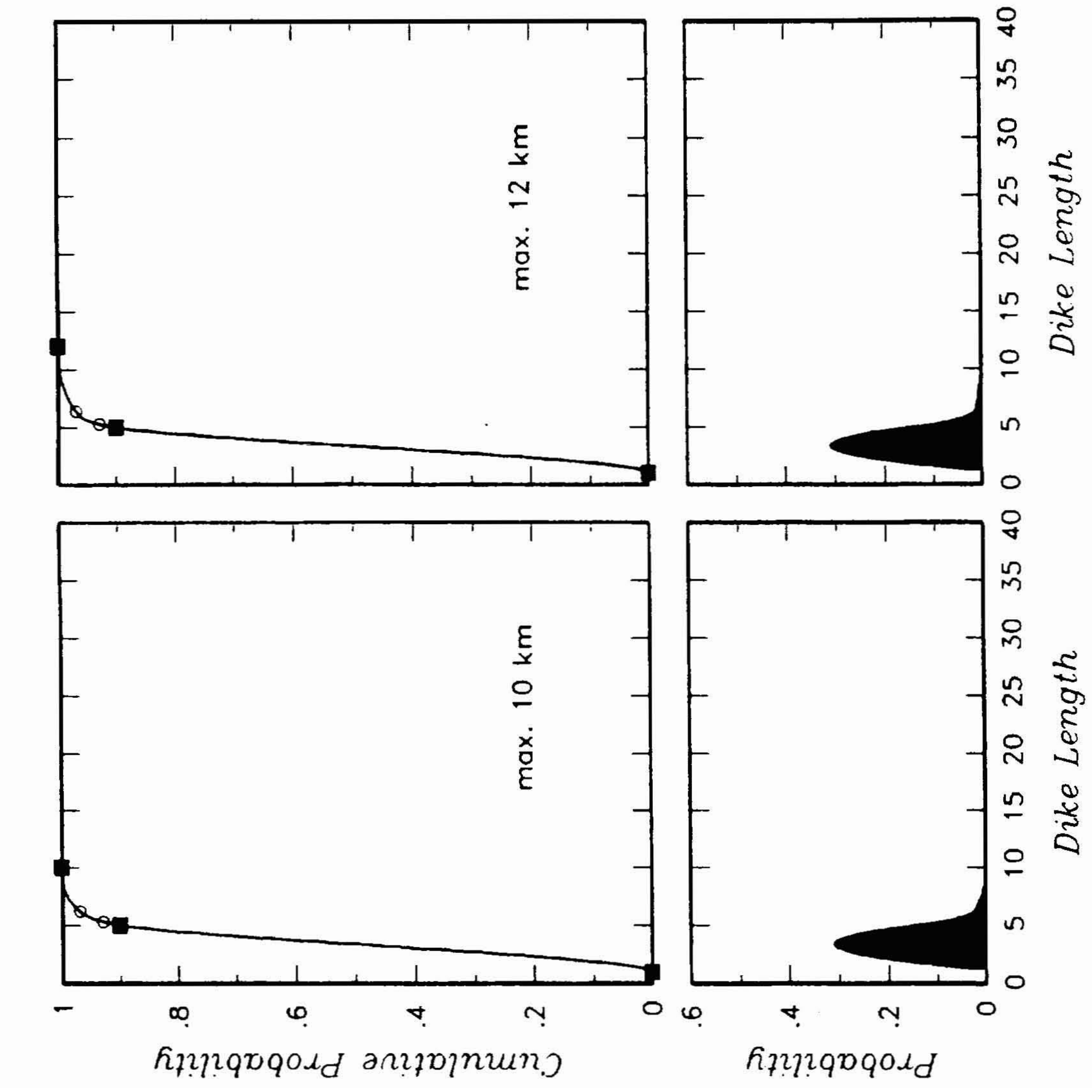

Figure GT-3 Dike length distribution developed by George A. Thompson.