# PVHA_YM VERSION 1.0—PROBABILISTIC VOLCANIC HAZARD ASSESSMENT METHODS FOR A PROPOSED HIGH-LEVEL RADIOACTIVE WASTE REPOSITORY AT YUCCA MOUNTAIN, NEVADA

*Prepared for*

**Nuclear Regulatory Commission
Contract NRC-02-97-009**

*Prepared by*

**Center for Nuclear Waste Regulatory Analyses
San Antonio, Texas**

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# ABSTRACT

The assessment of long-term performance of the proposed high-level radioactive waste repository at Yucca Mountain, Nevada, requires the use of mathematical models to consider the probability of disruptive scenarios. Volcanism is one important disruptive scenario to consider in site evaluation. The purpose of the PVHA_YM software is to provide and document mathematical models developed to assist staff in the probabilistic volcanic hazards assessment (PVHA) of the Yucca Mountain (YM) site.

PVHA_YM is intended to be launched from a standard web browser. PVHA_YM includes java applets that can be used to estimate the probability of a volcanic event occurring within a effective area about the repository using kernel density estimators to smooth the point pattern map distribution of previous volcanic events in the region. Two types of kernel density estimators are included: Gaussian and Epanechnikov. These density estimators are used to calculate the probability of volcanic events at the site, and to plot conditional probability maps of the location of volcanic events, given the occurrence of a volcanic event in the magmatic system. Articles are included that provide an overview of basaltic volcanism, summarize the application of kernel density estimators to the YM PVHA, and illustrate their application in analogous volcanic fields.

# CONTENTS

# FIGURE

# ACKNOWLEDGMENTS

# QUALITY OF DATA, ANALYSES, AND CODE DEVELOPMENT

**DATA:** No CNWRA-generated original data are contained in this report. Sources for other data should be consulted for determining the level of quality for those data.

**CODES:** The PVHA code Version 1.0, including the java applets Prob1Graph, Prob2Graph, ProbMap1, and ProbMap2, has been developed following the procedures described in the CNWRA Technical Operating Procedure (TOP)–018, Development and Control of Scientific and Engineering Software, which implements the quality assurance (QA) guidance contained in CNWRA QA manual.

# 1 OVERVIEW OF PVHA_YM

The purpose of this document is to present codes and procedures used by the Nuclear Regulatory Commission (NRC) and the Center for Nuclear Waste Regulatory Analyses (CNWRA) staff to perform an independent probabilistic volcanic hazard assessment (PVHA) for the proposed high-level radioactive waste repository at Yucca Mountain, Nevada. NRC and CNWRA staff will use the PVHA_YM codes to review the PVHA performed by the U.S. Department of Energy (DOE) as part of their license application (LA) to NRC for construction of the proposed repository. Specifically, PVHA_YM codes have been developed as part of the igneous activity key technical issue (IA KTI) with the goal of streamlining LA review. During the LA review process, PVHA_YM will be used to assist NRC review of expected post-closure performance and to evaluate DOE compliance with 10 CFR 63.113.

Volcanic hazards at the proposed site stem from the proximity of Yucca Mountain (YM) to small-volume basaltic volcanoes (figure 1-1, map showing the distribution of volcanoes in the area). Because of the potential of adversely affecting the long-term performance of the repository, basaltic volcanism is considered a disruptive scenario in total-system performance assessments (TPAs) of the site. Results of the PVHA are incorporated in TPA estimates of radiological dose to a critical group, and ultimately into a risk assessment based on the expected radiological dose to this group. In this context, PVHA_YM has been developed as a tool to assist the NRC in their mission to assure public health and safety.

This document includes several articles that describe the geologic and statistical basis for the PVHA. The PVHA relies on the distribution and ages of these basaltic volcanoes as indictors of the expected rate of volcanic activity and the expected distribution of future volcanic events in the YM region.

The PVHA_YM document is contained on a CDROM included with this report and is intended to be viewed and used within a web browser. Printed documentation is only provided to create a document that is easily referenced. Four computer programs (java applets) are used to estimate the probability of volcanic eruptions at the site using Gaussian and Epanechnikov kernels, and to create maps of the probable distribution of future volcanic events using the same two kernels. Instructions in the use of these codes are provided.

PVHA_YM requires Java Virtual Machine language version 1.1 or higher enabled on the web browser. This software has been tested using Netscape versions 4.5, 4.6 and 4.7 on Windows NT, Linux, SGI, and Sun operating systems.
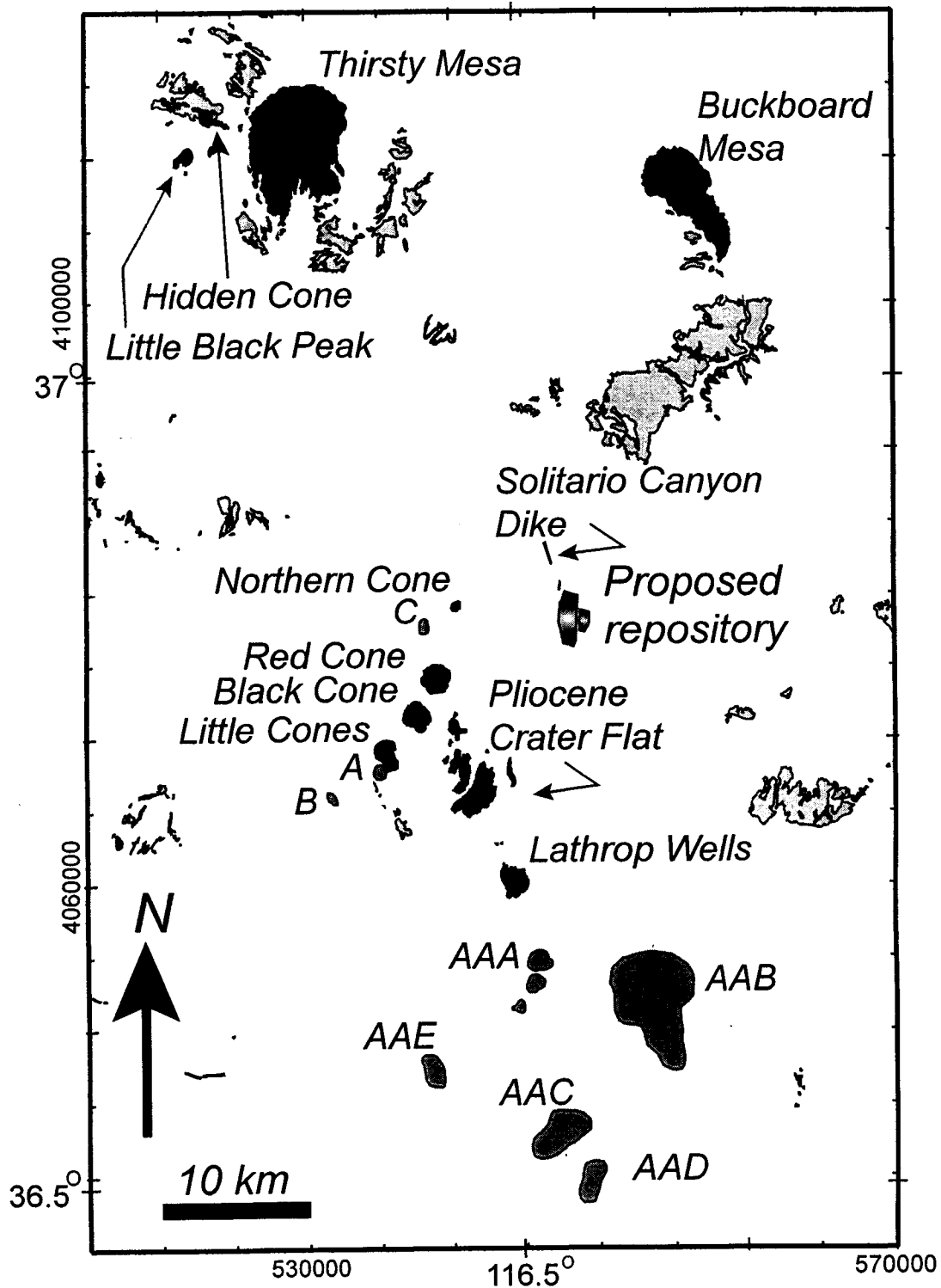
**Figure 1-1.** Locations of the basaltic volcanoes in the Yucca Mountain region. Black-Quaternary volcanoes, dark shade-Pliocene, light shade Miocene volcanoes. Lettered areas are magnetic anomalies.

# 2 DEFINITION OF VOLCANIC EVENTS

It is crucial to define volcanic events explicitly in PVHA. In this PVHA for the YM site, the definition of a volcanic event is limited to extrusive eruptions that result in the formation of basaltic vents as indicated by cinder cones, spatter mounds, and/or lava flows. A complete compilation of basaltic vents in the YM region is provided in data table contained in PVHA_YM on the CDROM. Estimates of the probability of dike injection, without volcanic activity, are not considered explicitly in this PVHA.

Even using this restricted definition, it is possible to define volcanic events in various ways. Individual vents can be considered to be volcanic events, or closely spaced and similarly aged vents can be grouped together. Furthermore, only cones younger than a specific age might be included in the analysis as volcanic events. Because vents may be grouped together into volcanic events in varying ways depending their timing and distribution, several data sets were defined. Formally, each volcanic event in the following data sets is considered to be independent of the other volcanic events in the data set.

The regional recurrence rate used to estimate probability also depends on the definition of volcanic events. For example, grouping volcanic vents by alignments in the YM region results in fewer Quaternary volcanic events, and consequently a lower regional recurrence rate, than results from treating individual vents as independent volcanic events. In practice, a range of recurrence rates must be considered in the PVHA because of uncertainties about the appropriate values to use. Volcanism in the YM region may be episodic or respond to external factors, such as geologic strain rate, in ways not well understood at the present (Connor and Conway, 2000) (see articles). Furthermore, the area likely affected by volcanic events varies with the definition of volcanic events. Therefore, a range of parameters is used in the PVHA (Connor and Hill, 1995; Connor et al., 2000) (see articles).

Data set 1 includes known Miocene through Quaternary vents mapped in the YM region, including several magnetic anomalies, assumed to be Miocene or younger in age, that have not been drilled. See the data table for details. This data set does not include some petrologically distinct basalts of Miocene age, such as the 11.2 Ma Solitario Canyon dike. The number of volcanic events is 47 in data set 1. An average regional recurrence rate for this data set is approximately 5 events per million years. This data set corresponds to data set 1 used in Connor and Hill (1995) (see articles) and treats individual volcanic vents as independent volcanic events. See the data table for details.

Data set 2 includes all known Pliocene—Quaternary vents mapped in the YM region, including several magnetic anomalies, assumed to be Miocene or younger in age, that have not been drilled. Several closely spaced vents have been grouped, and are treated as single volcanic events. For example, the two Little Cones are treated as a single volcanic event in this data set. The number of volcanic events is 20 in data set 2. This data set corresponds to data set 2 used in Connor and Hill (1995) (see articles). Use of this data set implies that the distribution of Miocene vents has little influence on potential patterns of basaltic volcanism during the performance period of the repository. An average regional recurrence rate for this data set is approximately 6 volcanic events per million years. See the data table for details.

Data set 3 includes all known Quaternary vents mapped in the YM region. Magnetic anomalies are not included in this data set. Use of this data set implies that the expected distribution of future volcanic activity is best defined by the distribution of volcanism in the recent geologic past (last one million years), and that older volcanic vents are not relevant to the analysis. The number of volcanic events is 8 in data set 3. An

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average regional recurrence rate for data set 3 is 8 volcanic events per million years. See the data table for details.

Data set 4 includes three events. These are the Quaternary Crater Flat volcano alignment, taken as centered on Red Cone, the Sleeping Butte alignment, taken as centered on Hidden Cone, and Lathrop Wells. Use of this definition implies that vents that form alignments are not independent volcanic events, and that Quaternary volcanism is the best guide to future volcanic activity. The distribution of older volcanoes or volcanic alignments is not considered as part of calculations using this data set. An average recurrence rate for this data set is 3 volcanic events per million years. See the data table for details.

Data set 5 includes all of the vent locations reported in the data table. The number of volcanic events is 64 in data set 5. An average recurrence rate for this data set is 6 volcanic events per million years.

## 2.1 BASIS FOR THE PROBABILISTIC VOLCANIC HAZARD ASSESSMENT

The geologic and statistical basis for the PVHA for the YM site is provided in Connor and Hill (1995) and Connor et al. (2000) (see articles). Briefly, kernel density estimators are used to calculate a probability surface directly from the location and timing of past, discrete volcanic events. As a result, kernel estimators are sensitive to patterns, such as vent clustering, commonly observed in basaltic volcano distributions. Furthermore, the resulting probability surfaces do not have the abrupt changes in probability that must be introduced in spatially homogeneous Poisson models. Thus, the kernel methods eliminate the need to define zones of volcanic activity *a priori*.

Two types of kernel density functions are provided: Gaussian and Epanechnikov kernels. The Gaussian kernel is defined as:

$$k_i = 2\pi \exp\left[ \frac{-1}{2} \left( \frac{d_i}{h} \right)^2 \right] \tag{2-1}$$

where $d_i$ is the distance from the point s to the $i^{th}$ volcano and $h$ is the smoothing parameter.

The Epanechnikov kernel is defined as

$$k_i = \frac{2}{\pi}\left[ 1 - \left( \frac{d_i}{h} \right)^2 \right], \quad \text{if } \left( \frac{d_i}{h} \right)^2 < 1 \tag{2-2}$$

$$k_i = 0, \quad \text{otherwise}$$

In each case, the spatial recurrence rate of volcanic events in the 1 × 1 km area about the point *s*, given the occurrence of a volcanic event in the system is given by

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$$\lambda_s = \frac{1}{nh^2} \sum_{i=1}^{n} k_i \qquad (2\text{-}3)$$

The probability of a volcanic event within the area of the repository site is then

$$P[N \geq 1] = 1 - \exp\left[ -t\lambda_t \sum_a \lambda_s \right] \qquad (2\text{-}4)$$

where $t$ is the time interval of interest, $\lambda_t$ is the temporal recurrence rate of volcanic events in the magmatic system, and $a$ is the effective area, an area within which a volcanic event might occur and disrupt the repository.

Assuming that $\lambda_s$ does not vary on the scale of the repository

$$P[N \geq 1] = 1 - \exp\left[ -t\lambda_t a\lambda_s \right] \qquad (2\text{-}5)$$

These techniques have been tested using the recurrence rates of volcanism and patterns of volcanic activity in other volcanic fields. In particular, these models have been tested in the Springerville volcanic field, Arizona (see articles) An introduction to basaltic volcanic fields is given in Connor and Conway (2000) (see articles).

## 2.2    EXPLANATION OF PARAMETERS USED IN PVHA_YM

Several parameters may be varied in the analysis. These parameters include the smoothing factor used in the kernel functions, the regional recurrence rate of volcanic activity, the effective area of the repository, and the time interval for which probability calculations are made.

The smoothing factor controls how probability is distributed about existing volcanic events, which are treated as a point process. Using a small smoothing factor tends to concentrate probability near existing volcanoes; a large smoothing factor results in a more even distribution of probability across the map area. The two kernel estimators, Gaussian and Epanechnikov, rely on different functions and, as a result, the smoothing factor has a different effect in each case. In the Gaussian kernel, the smoothing factor is equivalent to the standard deviation of a symmetric, bivariate Gaussian distribution. For an Epanechnikov kernel, the smoothing factor determines the radius of the Epanechnikov distribution function about each point. The probability is zero at distances greater than the smoothing factor from the point, and nonzero at distances less than the smoothing factor from the point (i.e., volcanic event).

Methods of estimating the smoothing factor are described in Connor et al. (2000) (see articles). The kernel function (Gaussian or Epanechnikov) may be recast in polar coordinates as a cumulative distribution function. In this form, the cumulative kernel function can then be compared to observed nearest-neighbor distances between volcanic events. Using this approach, Connor et al. (2000) (see articles) found that values of the smoothing factor greater than 7 km for the Gaussian kernel yield conservative estimates of probability.

For Epanechnikov kernels, a smoothing factor greater than 18 km yields conservative results. The larger value for the Epanechnikov kernel compared to the Gaussian kernel results from the definition of the smoothing factor as the limit of the probability distribution in the former case, and the standard deviation of the probability distribution in the latter case.

Probability models rely on estimates of the expected regional recurrence rate of volcanism in order to estimate the probability of future volcanic activity. In the YM region, estimates of the regional recurrence rate vary between 2 and 12 volcanic events per million years, with variations in the definitions of volcanic events accounting for at least part of this range. Furthermore, it is uncertain whether the rate of volcanic activity in the YM region is stationary, nonstationary, or episodic. As a result, uncertainty in the regional recurrence rate of volcanism is significant.

The effective area of the repository includes the actual footprint of the repository, plus the area within which a volcanic event may occur and cause volcanic disruption of the repository. This additional area is included because volcanic events are treated as points in the analysis, but in reality affect an area about that point, due to dike injection and the formation of multiple vents. For data sets 1 and 2, Connor and Hill (1995) (see articles) used an effective area of 8 sq km. If alignments are treated as single events, such as in data set 4, significantly larger areas should be used (e.g., 20–30 sq km). Alternatively, vent alignment length and orientation may be considered explicitly (Connor et al., 2000) (see articles), but this feature has not been implemented in version 1.0 of PVHA_YM.

The time interval for which probability is estimated may be varied to calculate annual probabilities, or to calculate probabilities of volcanic disruption of the proposed site for different performance periods. The probability calculation assumes that the time interval considered and the regional recurrence rate are independent.

# 3 APPLETS

PVHA_YM calculations are performed using the following java applets.

## 3.1 Prob1Graph

Prob1Graph calculates the probability of a volcanic event in an effective area about the repository, given a temporal recurrence rate, time interval of interest, and selected data set. This estimate uses a Gaussian kernel and plots probability as a function of the smoothing parameter.

## 3.2 Prob2Graph

Prob2Graph calculates the probability of a volcanic event in an effective area about the repository, given a temporal recurrence rate, time interval of interest, and selected data set. This estimate uses an Epanechnikov kernel and plots probability as a function of the smoothing parameter.

## 3.3 ProbMap1

ProbMap1 calculates the probability surface for the YM region using a selected data set and smoothing parameter. This estimate uses a Gaussian kernel and plots the conditional probability of a volcanic event within a $1 \times 1$ km area, given an event in the magmatic system.

## 3.4 ProbMap2

ProbMap 2 calculates the probability surface for the YM region using a selected data set and smoothing parameter. This estimate uses an Epanechnikov kernel and plots the conditional probability of a volcanic event within a $1 \times 1$ km area, given an event in the magmatic system.

# 4 ARTICLES

Two articles are included in this document that describe the development of kernel density estimators and their application to the CNWRA PVHA for YM. These articles are

Connor et al., 2000, Geologic Factors controlling patterns of small volume basaltic volcanism: Application to a volcanic hazards assessment at Yucca Mountain, Nevada

Connor and Hill, 1995, Three nonhomogeneous Poisson models for the probability of basaltic volcanism: Application to Yucca Mountain, Nevada

Application of PVHA techniques to analogous basaltic volcanic fields, for the purposes of validating the use of density kernels in PVHA, is described in

Condit and Connor, 1996, Recurrence rates of basaltic volcanism: An example from the Springerville volcanic field, Arizona.

An introduction to basaltic volcanic fields is provided in: Connor and Conway, 2000, Basaltic volcanic fields.

The intent of this article is to provide background on the nature of basaltic volcanic fields, their physical characteristics, evolution, and origins.

# 5 CODE LIMITATIONS

PVHA_YM contains codes used to estimate probabilities of volcanic events within the area of the proposed YM repository to assist in reviewing the anticipated DOE LA. Nevertheless, a complete PVHA analysis for the proposed repository cannot be accomplished using PVHA_YM alone. For example, Connor et al. (2000) (see articles) showed that geologic structure plays an important role in controlling the distribution of basaltic volcanism in the YM region. Their analysis showed the affect of including geologic structure in the PVHA was to increase the probability of volcanic disruption of the site (Connor et al. , 2000) (see articles). The influence of geologic structure is not incorporated in version 1.0 of PVHA_YM. Furthermore, volcanic events may effect a larger area than represented by a single vent. In basaltic volcanic fields, volcanic events may be defined as volcanic alignments, with length and orientation. For example, in Data set 4, the Quaternary Crater Flat alignment is treated as a single volcanic event. The areal dimension of volcanic events is not incorporated explicitly in version 1.0 of PVHA_YM, although the effective area parameter may be changed to help illustrate the influence of event area on probability estimates.

# 6 REFERENCES

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Connor, C.B., and B.E. Hill. Three nonhomogeneous Poisson models for the probability of basaltic volcanism: Application to Yucca Mountain, Nevada. *Journal of Geophysical Research* 100 (B6): 10,107–10,125 1995.

# ADDITIONAL INFORMATION FOR PVHA_YM Version 1.0

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|---|---|
| **Document Date:** | 12/03/1999 |
| **Availability:** | Southwest Research Institute® <br> Center for Nuclear Waste Regulatory Analyses <br> 6220 Culebra Road <br> San Antonio, Texas 78228 |
| **Contact:** | Southwest Research Institute® <br> Center for Nuclear Waste Regulatory Analyses <br> 6220 Culebra Road <br> San Antonio, TX 78228-5166 <br> Attn.: Director of Administration <br> 210.522.5054 |
| **Data Sensitivity:** | ■"Non-Sensitive"  □ Sensitive <br> □"Non-Sensitive - Copyright"  □ Sensitive - Copyright |
| **Date Generated:** | 12/03/1999 |
| **Operating System:** (including version number) | Windows |
| **Application Used:** (including version number) | PVHA Code Version 1.0 including java applets Prob1Graph, Prob2Graph, ProbMap1, and ProbMap2 |
| **Media Type:** (CDs, 3 1/2, 5 1/4 disks, etc.) | 1 CD |
| **File Types:** (.exe, .bat, .zip, etc.) | Various |
| **Remarks:** (computer runs, etc.) | Media contains: PVHA_YM code is to be launched from a standard web browser that can be used to estimate the probability of a volcanic event occurring within an effective area about the repository using kernel density estimators to smooth the point pattern map distribution of previous volcanic events in the region. |