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SCPB: NA
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Civilian Radioactive Waste Management System
Management and Operating Contractor

Probabilistic Volcanic Hazard Analysis for Yucca Mountain, Nevada

BA0000000-1717-2200-00082, Rev. 0

June 1996

Prepared for:

U.S. Department of Energy
Yucca Mountain Site Characterization Project
P.O. Box 98608
Las Vegas, Nevada 89193-8608

Prepared by:

Geomatrix Consultants, Inc.
100 Pine Street, 10th Floor
San Francisco, CA 94111

and

TRW
1261 Town Center Drive
Las Vegas, Nevada 89134

Under Contract Number
DE-AC01-91RW00134

102-8

SCPB: NA
QA: L

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Prepared by: Kevin J. Coppersmith — Date: 6/24/96

Prepared by: Roseanne C. Perman — Date: 6/25/96

Accepted by: Martha W. Pendleton, Leader
Technical Evaluation Team — Date: 6/26/96

Approved by: Jean L. Younker, Manager of
Suitability and Licensing Operations — Date: 6/26/96

YUCCA MOUNTAIN
PROBABILISTIC VOLCANIC HAZARD ANALYSIS

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1.0 INTRODUCTION

1.1 PROJECT OBJECTIVES

This report presents the results of the Probabilistic Volcanic Hazard Analysis (PVHA) project at Yucca Mountain, Nevada, sponsored by the U.S. Department of Energy (DOE) and managed by Geomatrix Consultants, Inc. (Geomatrix). The objectives of this project were to assess the probability of disruption by a volcanic event of the proposed high level waste repository at Yucca Mountain and to quantify the uncertainties associated with this assessment. In this context, *disruption* means the physical intersection of magma with the potential repository volume; *volcanic event* includes both eruptive and intrusive features; and *probability* is defined as an annual frequency.

A major goal of the project was to capture the uncertainties that are involved in the assessment of the volcanic hazard, including uncertainty in both the *models* used to represent the key physical controls on volcanism and the *parameter values* used in the models. To ensure that a wide range of perspectives was considered in the hazard analysis, individual judgments were elicited from members of an expert panel. The experts on the panel were not independent peer reviewers. They were convened to represent a range of experience and expertise and consisted of experts from within and outside the Yucca Mountain project. A deliberate process was followed in facilitating interactions among the experts, in training them to express their uncertainties, and in eliciting their interpretations. The resulting probability distribution, therefore, provides a reasonable representation of the knowledge and uncertainty about the volcanic hazard at the proposed Yucca Mountain site. Because of the careful process followed in selecting, training, facilitating, and eliciting the experts, it is concluded that this distribution represents a reasonable representation of the views of the larger, informed technical community on this specific issue (see discussion below in Section 2.3).

The results obtained for this PVHA provide direct input into an assessment of occurrence probability for disruptive events in the Total System Performance Assessment for the proposed repository system. The results are expressed as *annual* frequencies (probabilities) of intersection. During the course of the elicitations, the experts were asked to consider the future 10,000-year period as the time period of interest for the assessment, As such, the assessed frequencies are believed to be appropriate annual frequencies over the next 10,000 years. This would include, for example, the 0-100 year pre-closure period. In the course of the discussions, consideration was given to the manner in which changes might occur in the frequency estimates if they were assessed for a longer time period (e.g., 1,000,000 years). For example, some experts discussed possible secular trends in occurrence rates (waxing or waning) that might be important in considering a longer time period such as 1,000,000 years. Despite this consideration and discussion, no formal assessments of occurrence rates or frequencies were conducted for time periods longer than 10,000 years as part of this PVHA.

1.2 RELATIONSHIP OF PVHA PROJECT TO YUCCA MOUNTAIN VOLCANISM PROGRAM

Volcanism studies for the DOE Yucca Mountain Site Characterization Project (YMP) began in 1979, and numerous researchers from a variety of organizations and institutions have conducted studies in the region. Los Alamos National Laboratory (LANL) has conducted extensive volcanism studies for DOE to provide a scientific basis for volcanic hazard assessment and to assist in applying those data to the regulatory requirements for siting a potential repository at Yucca Mountain. Study Plan 8.3.1.8.1.1, Probability of Magmatic Disruption of the Repository, identifies the application of expert judgment to probabilistic volcanic hazard analysis for the proposed Yucca Mountain site. An appendix to this Study Plan describes the general procedures to be followed for the expert judgment elicitation process. The three major goals cited for the use of expert judgment are: (1) to review all data and develop or refine models for evaluating the future locations and recurrence of volcanism; (2) to assign weights to the various models to arrive at representative cumulative probability distributions for probabilistic variables; and (3) to evaluate all the appropriate variables for each model and to quantify the uncertainties associated with each parameter value.

The PVHA project is a natural follow-up to the many years of data collection that have occurred during the Yucca Mountain project, and is a culmination of the assessments of volcanic hazard that have been conducted. The studies conducted to date have focused on gathering information on a number of important issues, including: the spatial distribution of volcanism in the region (Figure 1-1), the geologic history of volcanic activity, time-dependent changes in the nature of volcanism and the relationship to changes in the tectonic regime, detailed mapping of individual volcanic centers in the Yucca Mountain region (YMR), geochronologic and geochemical analyses of individual centers to understand their genesis and recurrence history, and interpretation of eruptive volumes and event chronologies to provide input to volcanic hazard analyses (see Crowe et al., 1995 for an overview of these studies and information on the geologic setting of the YMR).

During the entire volcanism data-collection process, volcanic hazard analyses have been conducted (e.g., Crowe et al., 1982; 1995). The focus of these probabilistic analyses has been to provide preliminary assessments of the disruption probabilities and, perhaps more importantly, to provide a focus to the data collection activities such that the data and information of most importance to the hazard assessment would be gathered. The focus on the data collection program over the past decade has benefited the PVHA project by providing a comprehensive, thoroughly documented data base that is particularly pertinent to the issues of most importance to hazard analysis.

The probabilistic volcanic hazard analyses conducted by the project prior to the PVHA were for a different purpose than the PVHA and should be considered separate, but complementary, activities. As mentioned, the volcanic hazard analyses focused on providing preliminary hazard estimates (e.g., disruption probabilities). The most recent volcanic hazard assessments (Crowe et al., 1995) also provided a systematic assessment and comparison of hazard using all published input models and methodologies. Further, the analysis presented the range of possible results based on the judged minimum, best estimate, and maximum values for various parameter values (e.g., minimum, best estimate, and maximum numbers of events that might be interpreted at a particular volcanic center). This analysis provided valuable insights into the sensitivity that various approaches, models, and parameter values might have to the calculated results. However, the purpose of the Crowe et al. (1995) hazard studies was *not* to fully characterize uncertainties or to arrive at a final hazard result that incorporated these uncertainties. In the previous studies, alternative models and parameter values were not evaluated, assigned weights, or combined into a final result.

The PVHA study is the next logical step in the volcanism program for the Yucca Mountain project. Its purpose is—explicitly—to characterize the uncertainties in the hazard analysis. As such, the project takes advantage of all the data collection that has preceded it and the insights provided by previous hazard assessments. The use of multiple experts in the PVHA is part of an attempt to fully characterize uncertainties. Likewise, each expert provided weighted alternative models and parameter values, expressing his degree of belief that they were, in fact, the correct models and values. Consequently, the PVHA results and process should not be viewed as "agreeing or disagreeing" with the various approaches—the two exercises are simply different and complementary.

1.3 PROJECT ORGANIZATION

The PVHA project was organized into four primary groups: the PVHA contractor, the Methodology Development Team (MDT), the expert panel, and the technical specialists. The principal responsibilities of each of these groups are described here, and the technical roles of each group are described in detail in Section 2.3 of this report.

- **PVHA Contractor:** Under contract with TRW, the PVHA Contractor, Geomatrix, was responsible for conducting all aspects of the project and for delivery of this report describing the methodology and the results. The PVHA Contractor personnel also were members of the MDT.

- **Methodology Development Team (MDT):** As a group, the MDT served the roles of both actively carrying out the project and reviewing the progress of the project. The participation role included developing a strategic plan, facilitating workshops, eliciting members of the expert panel, performing calculations, and documenting methodology and results. The review role included reviewing the progress of the study and recommending mid-course adjustments to ensure that the study met its objectives.

- **Expert Panel:** The ten widely recognized, professional earth scientists on the expert panel were responsible for providing and documenting their interpretations of the volcanic hazard at Yucca Mountain.

- **Technical Specialists:** Numerous technical specialists participated in the project by presenting specialized data, interpretations, or training to the experts as part of workshops and field trips.

The members of the MDT and their responsibilities for the PVHA project are summarized in Table 1-1. Brief biographies for each MDT member are provided in Appendix A.

The members of the expert panel (subject matter experts) were responsible for developing the interpretations that form the technical substance of the PVHA project. Table 1-2 lists the experts on the panel and their affiliations. Brief biographies for members of the expert panel are provided in Appendix A.

The manner in which the experts on the panel were selected, their roles and responsibilities, and each of their interpretations are discussed extensively in subsequent sections of this report.

Numerous technical specialists from many different organizations provided information to the expert panel through presentations at workshops and participation on field trips. A list of the technical specialists for each workshop or field trip and their affiliations are given in Table 1-3.

1.4 PRODUCTS OF STUDY AND STRUCTURE OF REPORT

The PVHA study occurred over a period of approximately 18 months. The project began with the development of a strategic plan for the course of the study, identifying the goals to be accomplished and methodologies to be implemented in meeting these goals. Next, the MDT developed and implemented a process for selecting the members of the expert panel, resulting in the selection of ten experts. The bulk of the study was centered around four workshops and two field trips. These activities were designed specifically to facilitate interaction among the experts, provide all data needed for the assessment, and provide a forum for discussion of a full range of technical interpretations. Between the third and fourth workshops, the interpretations of each expert were elicited in individual interviews and documented in elicitation summaries. Following feedback and discussion among the experts of all interpretations made, the experts finalized their assessments, and the MDT performed the final calculations.

The products of the activities of the PVHA project outlined above all are contained in this report. Section 2 describes in detail the process that was followed in eliciting the PVHA expert interpretations, focusing first on the attributes of the methodology (Section 2.2) and then on its implementation (Section 2.3). Appendices B, C, and D provide summaries of the references provided to the experts, the four workshops, and the two field trips. This information provides written documentation of the technical data discussed by the panel, the formats and content of interpretations presented by a number of outside technical specialists during the study, and the preliminary interpretations made by the panel prior to finalizing their assessments.

Section 3 of this report provides a detailed discussion of the computational models used to capture spatial and temporal aspects of the PVHA (Section 3.1) and the expert-specific mathematical formulations and models used to represent the interpretations of each expert (Section 3.2). The results of the PVHA are provided in Section 4.0. References are listed in Section 5.0. Both the results for each of the 10 individual experts (Section 4.1) and the aggregated results (Section 4.2) are provided. Key products of the study are the written elicitation summaries prepared by each expert, which are provided in Appendix E. The experts expended considerable effort to ensure that their summaries provide a reasonably complete record of the thought processes they followed in arriving at their interpretations. Appendix F contains additional details of the mathematical formulation used to compute the volcanic hazard. Calculation illustrations can be found in Appendix G. Information related to Quality Assurance is provided in Appendix H.

TABLE 1-1
METHODOLOGY DEVELOPMENT TEAM MEMBERS AND THEIR PRINCIPAL RESPONSIBILITIES

NAME	AFFILIATION	RESPONSIBILITIES
Kevin J. Coppersmith	Geomatrix	Project management and planning; methodology development; facilitating workshops; expert elicitation; documentation of procedures
Roseanne C. Perman	Geomatrix	Project planning and methodology development; organizing workshops and field trips; elicitation documentation
Robert R. Youngs	Geomatrix	Interactions with experts on PVHA modeling issues; eliciting and formulating alternative models; calculation and documentation of results/sensitivity
Peter A. Morris	Applied Decision Analysis, Inc.	Project planning and methodology development; peer review of project direction; expert elicitation methodologies
C. Allin Cornell	Stanford University; CAC Co.	Review of project direction; review of alternative PVHA models; advice regarding technical facilitation
J. Carl Stepp	Woodward-Clyde Federal Services	Review of project direction; peer review of expert interaction process; review of elicitation documentation
Richard P. Smith	Idaho National Engineering Laboratory	Review of project direction; trial elicitation; technical review of expert interpretations
Stephen T. Nelson	Woodward-Clyde Federal Services	Project planning and oversight; expert selection process; review of project direction
Timothy Sullivan	U.S. Department of Energy	Project planning and oversight; review of project direction
Jeanne Nesbit	U.S. Department of Energy	Project planning and oversight; expert selection process; review of project direction

TABLE 1-2
EXPERT PANEL MEMBERS

EXPERT	AFFILIATION
Dr. Richard W. Carlson	Carnegie Institution of Washington
Dr. Bruce M. Crowe	Los Alamos National Laboratory
Dr. Wendell A. Duffield	U.S. Geological Survey
Dr. Richard V. Fisher	University of California, Santa Barbara (Emeritus)
Dr. William R. Hackett	WRH Associates
Dr. Mel A. Kuntz	U.S. Geological Survey
Dr. Alexander R. McBirney	University of Oregon (Emeritus)
Dr. Michael F. Sheridan	State University of New York, Buffalo
Dr. George A. Thompson	Stanford University
Dr. George P.L. Walker	University of Hawaii

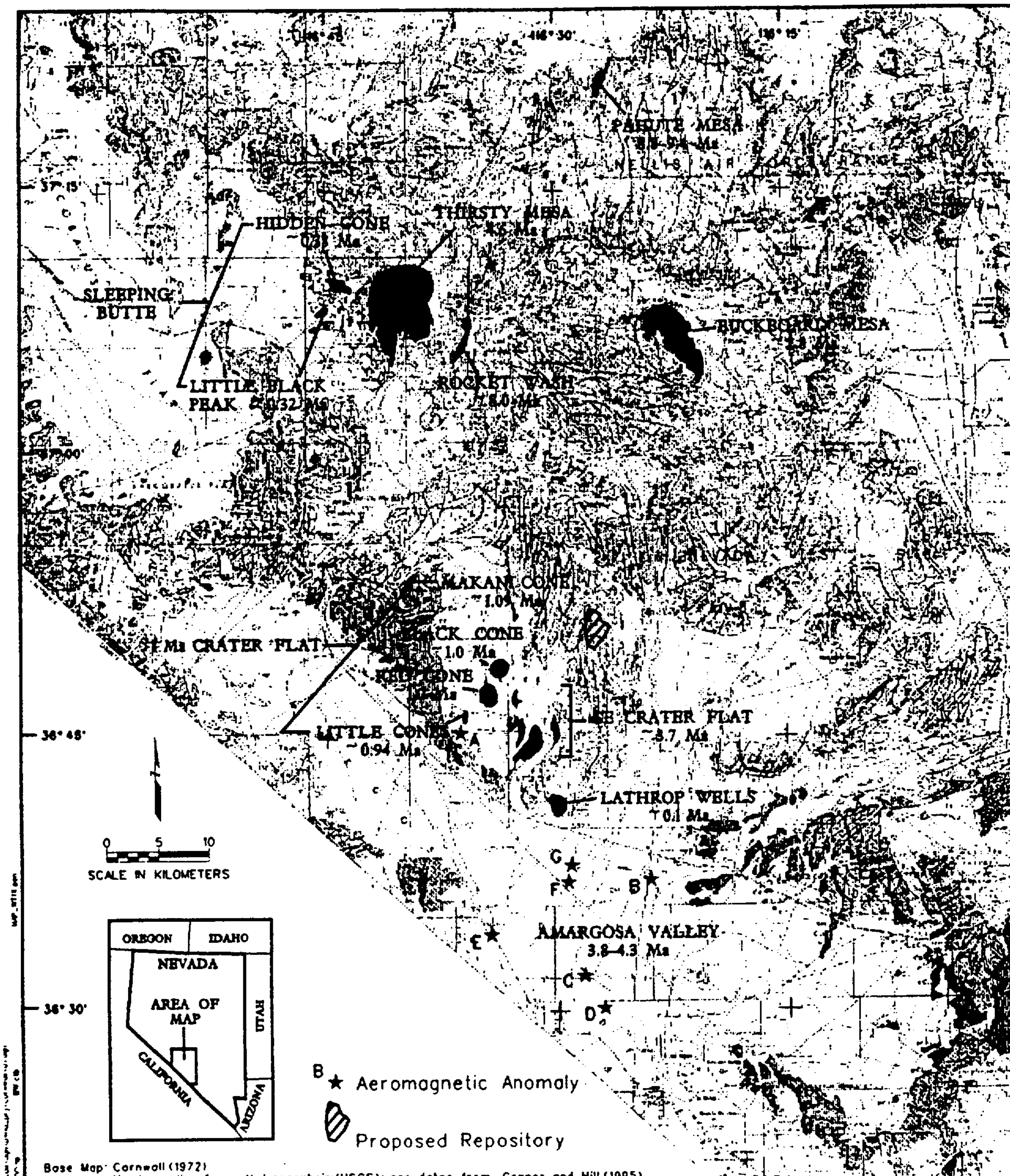
TABLE 1-3
TECHNICAL SPECIALISTS PARTICIPATING IN PVHA WORKSHOPS AND FIELD TRIPS

Workshop 1 - Identification of Data Needs	
Charles B. Connor	Center for Nuclear Waste Regulatory Analyses
Richard P. Smith	Idaho National Engineering Laboratory
Eugene I. Smith	University of Nevada, Las Vegas
Brent D. Turrin	U.S. Geological Survey
Frank V. Perry	Los Alamos National Laboratory
Victoria E. Langenheim	U.S. Geological Survey
Workshop 2 - Alternative Hazard Models Workshop	
Chih-Hsiang Ho	University of Nevada, Las Vegas
Eugene I. Smith	University of Nevada, Las Vegas
Paul T. Delaney	U.S. Geological Survey
Charles B. Connor	Center for Nuclear Waste Regulatory Analyses
C. Allin Cornell	Stanford University
Workship 3 - Alternative Interpretations and Elicitation Training	
Bruce R. Judd	Strategic Decision Group, Inc.
Peter A. Morris	Applied Decision Analysis, Inc.
Gene M. Yogodzinski	University of Nevada, Las Vegas
Duane E. Champion	U.S. Geological Survey
John H. Stewart	U.S. Geological Survey
John R. Wesling	Geomatrix Consultants, Inc.
James E. Faulds	University of Iowa
John W. Geissman	University of New Mexico

**TABLE 1-3 (Cont'd.)
TECHNICAL SPECIALISTS PARTICIPATING IN
PVHA WORKSHOPS AND FIELD TRIPS**

Field Trips (Crater Flat/Lathrop Wells/Sleeping Butte)	
Chris J. Fridrich	U.S. Geological Survey
Scott A. Minor	U.S. Geological Survey
Paul P. Orkild	U.S. Geological Survey
Duane E. Champion	U.S. Geological Survey
Robert J. Fleck	U.S. Geological Survey
Chris M. Menges	U.S. Geological Survey
Frank V. Perry	Los Alamos National Laboratory
Eugene I. Smith	University of Nevada, Las Vegas
Charles B. Connor	Center for Nuclear Waste Regulatory Analyses
Brittain E. Hill	Center for Nuclear Waste Regulatory Analyses
Steven G. Wells	University of California, Riverside
Leslie D. McFadden	University of New Mexico

The roles of the technical specialists are discussed in more detail in Section 2.2.3 of this report.



GEOMATRIX

BASALTIC VOLCANIC CENTERS
AND AEROMAGNETIC ANOMALIES
IN THE VICINITY OF YUCCA MOUNTAIN, NEVADA

Figure 1-1

PVHA Project

2.0 PROCESS FOR ELICITING PVHA EXPERT JUDGMENTS

2.1 INTRODUCTION

This section provides a summary of the process or methodology that was followed in carrying out the PVHA project. It is our belief that to be credible and useful, a hazard analysis such as the PVHA must: (1) be based on sound technical information and interpretations, (2) follow a process that provides for consideration of all available data, and (3) provide for incorporation of uncertainties in the assessments. A key mechanism used in the PVHA to quantify uncertainties is the use of multiple expert judgments. The *process* used to select the experts, facilitate their interaction and mutual education, and elicit their judgments is just as important as the technical content of their interpretations. We agree with the assertion of the Senior Seismic Hazard Analysis Committee (SSHAC, 1995) in their discussion of issues related to probabilistic seismic hazard analysis (PSHA):

> "In the course of our review, we concluded that many of the major potential pitfalls in executing a successful PSHA are *procedural* rather than technical in character. One of the most difficult challenges for the PSHA analyst is properly representing the wide diversity of expert judgments about the technical issues in PSHA in an acceptable analytical result, including addressing the large uncertainties...
>
> This also explains why we believe that *how a PSHA is structured* is as critical to its success as the technical aspects—perhaps more critical because the procedural pitfalls can sometimes be harder to avoid and harder to uncover in an independent review than the pitfalls in the technical aspects." (Executive Summary, p. xvi)

From a procedural standpoint, the issues for seismic hazard analysis are identical to those for volcanic hazard analysis. The uncertainties are comparable and the processes that can be used to capture uncertainties are common to both types of analyses.

Because of the importance of process issues, a MDT was established at the outset of the project with acknowledged experience in developing guidance for and implementing multi-expert hazard studies. For example, Drs. Coppersmith, Cornell, and Morris were members of the SSHAC; Dr. Stepp represented the Electric Power Research Institute (EPRI) as a sponsor of SSHAC and directed the large EPRI multi-expert hazard study in the eastern U.S.; Dr. Youngs participated on the EPRI methodology team and has conducted large multi-expert hazard studies throughout the U.S.; and

Dr. Smith participated as one of several experts on a seismic hazard analysis for the Idaho National Engineering Laboratory (INEL). The cumulative experience gained over the past 10 to 15 years by these individuals, as well as the written procedural guidance for the use of expert judgment (discussed below), provides the basis for the formulation and implementation of the PVHA process.

The discussion of the PVHA process is divided into two parts: specification of the *attributes* of the methodology (Section 2.2) and discussion of the *implementation* of the methodology (Section 2.3).

2.1.1 Pertinent Guidance Regarding Expert Judgment

In the study of any complex technical problem—such as volcanic hazard at Yucca Mountain—expert judgment is used. Generally, the pertinent data themselves do not provide an interpretation of the hazard. For example, data regarding the mapped location of volcanoes, and their estimated ages and geochemical signatures do not provide direct estimates—or even direct inputs to—a volcanic hazard analysis. The mapped data must be interpreted (by experts) to assess the geologic history, volumes, and locations of past events. Age estimates, considering analytical uncertainties and sampling density, must be interpreted to provide indications of the timing of volcanic events and, in turn, the frequency of occurrence. The geochemical data, together with physical models of the evolution of magmas, must be interpreted before assessments can be made of future eruptive styles, volumes, and locations. Through the scientific process, experts integrate and evaluate data in order to arrive at conclusions that are meaningful to hazard analysis. This process is the same regardless of the abundance or scarcity of data. In this sense, expert judgment is not a "substitute for data"; it is a process by which data are evaluated and interpreted. If data are scarce and uncertainties are high, the range of expert judgments should reflect this high degree of uncertainty.

Despite the fact that expert judgment is used in any technical assessment, this judgment is often implicit and undocumented. The PVHA project *explicitly* includes judgments of multiple experts to represent the range of scientific views and *documents* the reasoning on which the judgments are based. To do so, the project has taken advantage of several recent efforts to develop guidance for eliciting and documenting expert judgment.

The procedures and approaches to eliciting expert judgments, developed through the experience of conducting many studies, are being formalized in guidance documents. DOE has recently developed guidance for the formal use of expert judgment by the YMP (DOE, 1995), and the Nuclear Regulatory Commission (NRC) staff has issued a draft Branch Technical Position (BTP) on use of expert elicitation in the high level waste program (Kotra et al., 1996). Comprehensive guidance on expert judgment elicitation for seismic hazards has recently been set forth by the SSHAC in a study sponsored by DOE, EPRI, and Lawrence Livermore National Laboratory (LLNL) (SSHAC, 1995). Each of these guidance documents is discussed briefly below.

Guidance entitled "Principles and Guidelines for Formal Use of Expert Judgment by the Yucca Mountain Site Characterization Project" has recently been developed by DOE (1995). The guidance is higher-level policy guidance, rather than detailed procedural guidance. The guidance establishes circumstances when formal applications of expert judgment (elicitations and peer reviews) might be appropriate, the principles expected in applications (e.g., each application must be systematic and open to scrutiny), general guidelines for conducting applications, and expectations for resulting documentation. The guidelines for conduct of elicitations address planning/procedure, selection of number of experts, general selection criteria, independence of experts, qualifications and balance, and documentation. The process followed for the PVHA project is consistent with the DOE guidance.

The NRC staff is developing a BTP on the use of expert elicitation in the high level waste program (Kotra et al., 1996). A draft of the BTP was released for public comment in February 1996, and the final guidance should be published in summer 1996. NRC has developed the BTP in anticipation of the "DOE using expert judgments to complement and supplement other sources of scientific and technical information, such as data collection, analyses, and experimentation" (Kotra et al., 1996). The BTP notes that the NRC traditionally has accepted for review expert judgments to evaluate factual data bases for license applications, and will likely do so for a license application for the high level waste repository. The purpose of the BTP is to:

> "(1) provide general guidelines on those circumstances that may warrant the use of a formal process for obtaining the judgments of more than one expert (i.e., expert elicitation); and (2) describe acceptable procedures for conducting expert elicitation when formally elicited judgments are used to support a demonstration of compliance with NRC's geologic disposal regulation, currently set forth in 10 CFR Part 60" (Kotra et al., 1996, p. iv).

While acknowledging that there may be many cases where informal expert judgment may be appropriate, the BTP discusses conditions that may warrant consideration of a formal process of expert elicitation. These conditions include one or more of the following: empirical data are not reasonably obtainable or the analyses are not practical to perform; uncertainties are large and significant to a demonstration of compliance; more than one conceptual model can explain, and be consistent with, the available data; and technical judgments are required to assess whether bounding assumptions or calculations are appropriately conservative. Clearly, one or more of the above conditions exist in the case of volcanic hazard analysis at Yucca Mountain.

An acceptable procedure for formal expert elicitation that follows a consistent, documented, stepwise procedure is outlined in Kotra et al. (1996). While allowing for flexibility in application, the procedure includes the following nine steps: definition of objectives, selection of experts, identification of issues and problem decomposition, assembly and dissemination of basic information, pre-elicitation training, elicitation of judgments, post-elicitation feedback, aggregation of judgments (including treatment of disparate views), and documentation. These steps were developed from a review of a number of other expert elicitation studies and recent guidance developed by the NRC and other groups. Each of the nine steps in the BTP has been followed in the PVHA, as will be discussed in more detail below in this section.

A status report on the development of the BTP was presented by the NRC before the Nuclear Waste Technical Review Board (NWTRB) full board meeting on January 11, 1996, in Las Vegas, Nevada. During that meeting, the study conducted by the Center for Nuclear Waste Regulatory Analyses (CNWRA) on climate change (DeWispelare et al., 1993) was cited as a demonstration of a process that is consistent with the NRC guidelines.

The SSHAC study (SSHAC, 1995) provides perhaps the most detailed guidance on uncertainty and the use of experts that has yet been developed. Motivated by the significant uncertainties in assessing seismic hazards—particularly in the central and eastern U.S.—formal expert judgment has been used in the seismic hazard field since the early 1980s. At the same time, it has been seen that the various methods and procedures for eliciting these judgments have led to differences in the hazard results. Through the experience of many PSHAs—both large and small—over the past decade or so, the seismic hazard analysis community is in a position to describe detailed guidance for carrying out a PSHA that best characterizes uncertainties and utilizes expert judgments.

The SSHAC study is an attempt to define guidance in enough detail that it can be used to guide the process of future hazard analyses. Some basic tenets of the SSHAC process are the following. A key goal of any PSHA—regardless of its scale—should be to "represent the center, the body, and the range of technical interpretations that the larger informed technical community would have if they were to conduct the study" (SSHAC, 1995, p. 21). "Informed" in this case means familiar with the site-specific data bases and other pertinent information. A "community" distribution can be assessed in a variety of ways, ranging from using a single *Technical Integrator* who gathers and integrates information, to a *Technical Facilitator/Integrator* who facilitates the interactions of multiple experts and elicits their interpretations to represent the community distribution.

SSHAC defines different expert roles including *proponents, evaluators,* and *integrators.* A proponent is an advocate of a particular technical view or interpretation; an evaluator evaluates and weighs the relative merits of alternative views; and an integrator combines the alternative views into a composite, or aggregate, distribution that includes uncertainties. Expert interactions are deemed to be very important in the SSHAC process and need to be properly facilitated. Four *levels of study* are defined—implying increasing degrees of formalism—depending on the complexity of the technical issues, their degree of controversy, and their significance to the hazard result. Finally, the SSHAC process allows for integration (aggregation) of multiple expert views using a "weighing" approach rather than a weighting approach, when necessary. Individual *weights* can be applied to each expert's interpretation (as was done in the PVHA), or an interactive process can be followed whereby the technical facilitator/integrator *weighs* the various interpretations and develops an assessment that he believes best captures the range of views and uncertainties.

The PVHA study closely follows the procedural guidance set forth in the SSHAC study, both in spirit (e.g., facilitated expert interactions are important) and, in many cases, in detailed implementation recommendations (e.g., conduct of elicitation interviews). For example, the PVHA process was designed—in accordance with SSHAC guidance—to result in a probability distribution that represents the "range of technical interpretations that the larger informed technical community would have if they were to conduct the study."

However, inasmuch as the SSHAC process professes to be "non-prescriptive" in specifying a single way of implementing various aspects, it would be inappropriate to say that the PVHA conforms exactly to the SSHAC process. In some cases, the PVHA process followed approaches that were more appropriate for a site-specific volcanic hazard analysis and included some innovative procedures that proved to be effective (e.g., a trial elicitation prior to the actual elicitation interviews). The detailed PVHA implementation will be discussed below in this section, and comparisons to SSHAC recommendations will be made throughout the discussion.

The goal of all of the guidance documents described is not to set out a rigid set of rules for how to elicit expert judgment; rather, it is to draw from the experience gained—both successes and failures—to provide criteria for when expert judgment should be used and to outline alternative approaches to motivating, eliciting, and documenting the judgments made by the experts. Other documents in the literature provide alternative approaches to the formal or informal use of expert judgment (e.g., Meyer and Booker, 1991).

2.1.2 Previous Focused Technical Hazard Studies Using Expert Judgment Elicitation

In recent years, focused technical hazard studies have been conducted that explicitly include expert judgment, incorporate the judgment of multiple experts, and provide various levels of documentation of the reasoning on which the judgments are based. These studies are a subset of a much larger set of studies that have utilized expert judgment to arrive at estimates of risk or performance assessment. These studies are mentioned briefly below. Some of the hazard studies that are pertinent to the process followed in the PVHA study are then summarized.

In a large study designed to estimate the uncertainties and consequences of severe core damage accidents in selected nuclear power plants (NUREG 1150), seven panels of experts were involved in an extensive expert judgment process (NRC, 1990). Complete probabilistic risk assessments were conducted for each of five nuclear power plants having different plant and containment designs. A formal expert judgment elicitation process also was followed to assess the long-term radionuclide releases from the Waste Isolation Pilot Plant (WIPP), an underground radioactive waste repository in southeastern New Mexico (Trauth et al., 1991). A performance assessment was conducted by four experts, who also developed probability distributions for the concentrations of dissolved radionuclides at the WIPP.

Two large probabilistic seismic hazard studies were conducted to assess the hazard at commercial power plant sites in the central and eastern United States (EPRI, 1986; Bernreuter et al., 1989). Both studies utilized multiple experts to capture the uncertainties associated with earthquake hazards, although slightly different approaches were used to elicit the expert judgments. For example, in the EPRI study the experts were arranged into six "earth science teams," each having a range of expertise. Multiple workshops were held to discuss technical issues, and each team arrived at consensus estimates of the uncertainties associated with seismic source characterizations and documented the technical basis for their assessments. The NRC-sponsored study carried out by LLNL (Bernreuter et al., 1989) elicited individual expert judgments, rather than those of teams, did not include workshops or other interactions among the experts, and, although elicited parameters were documented for each expert, the technical *basis* for the parameters was not documented.

Uncertainties associated with the earthquake potential of the Cascadia subduction zone and associated ground motions at a nuclear power plant site in western Washington were assessed using multiple experts (Geomatrix, 1988; Coppersmith and Youngs, 1990). Fourteen experts were elicited in interviews, and the judgments and technical basis for their assessments were documented. Similar seismic hazard studies were completed as part of the New Production Reactor program for the INEL and the Savannah River Site (Savy et al., 1992). These studies utilized workshops, and the expert elicitations were conducted through individual interviews.

The CNWRA conducted a formal expert elicitation to estimate the future climate in the YMR (DeWispelare et al., 1993). The objectives of this study included acquiring expertise in the expert elicitation process to aid in reviews of DOE's use of expert elicitation, investigating aggregation and consensus-building techniques for expert panels, and contributing to the development of NRC guidance on expert judgment elicitation. Future climate was selected for study because the uncertainties associated with this topic are large considering climate variance during the Quaternary period, and the climatic impact on infiltration can be important to repository performance. Five panel members participated in the study and developed probability distributions for a variety of issues including precipitation, temperature, and storm intensity in the vicinity of Yucca Mountain at various time periods between 100 and 10,000 years in the future. Each panel member prepared a position paper describing their judgments and the technical basis for the judgments.

The EPRI sponsored a study to demonstrate a methodology for evaluating fault displacement through the proposed Yucca Mountain repository using expert judgment (Coppersmith et al., 1993). This study was part of EPRI's High Level Waste (HLW) performance assessment project, and was centered around two workshops in which various technical issues were identified and discussed. An expert panel comprised of seven geologists and seismologists from a variety of institutions was convened for the study. The EPRI study utilized a probabilistic approach and included explicit uncertainty treatment. A variety of approaches to assessing fault displacement hazard at the Yucca Mountain site were identified by the panel members. The judgments of each panel member were elicited in individual interviews. The procedural and technical aspects of this study were thoroughly documented, including the experts' bases for each assessment.

Based on the experience gained from the studies described above, as well as many others, there were several "lessons learned" that apply to developing a process to be followed for the PVHA study. Some of these lessons are:

- All of the experts should be provided with, or have access to, a uniform data base.
- Workshops or other meetings where interactions can take place are important to allow the experts to discuss data bases, clarify their interpretations, and challenge the interpretations of others.

- The optimal number of experts for geologic hazard assessments is variable, but should be in the range of 4 to 12 individuals.
- Workshops provide an opportunity to share and challenge interpretations; however, the best vehicle for the actual elicitation is individual interviews.
- Interviews should include the technical expert, a normative expert (trained in probability), and a generalist to help translate between the two.
- Each expert should have the opportunity to review the documentation of his or her assessments prior to actual calculations and aggregation of results across multiple experts.
- The technical basis for the expert judgments should be documented in sufficient detail that a third party can understand the data, models, and thought processes used by the expert to arrive at the judgments.

The PVHA process attempts to take advantage of these lessons learned, the guidance discussed previously, and additional considerations identified by the MDT during the course of the project. The attributes of the resulting methodology are described below.

2.2 PVHA METHODOLOGY ATTRIBUTES

In this section we identify the particular attributes of the methodology, or process, followed, to show that each of these features was given considerable thought before and during its implementation. In some cases, methods were followed that have been shown to be successful in similar projects. Likewise, certain approaches were avoided that have been shown to be ineffective in other studies.

A large multi-expert study like the PVHA is dynamic, and based on the personalities and desires of the panel members, it is necessary to have the flexibility to make changes during the study. For example, the members of the PVHA expert panel greatly benefitted from the first field trip (to Crater Flat) and found it highly educational to observe field relationships first-hand. After the trip, they expressed a desire to have a second field trip (to Sleeping Butte and Lathrop Wells) to observe the remaining young basaltic centers in the region. The project was able to accommodate this request and to involve additional technical specialists as field trip leaders. Several other "mid-course corrections" were implemented to ensure that the goals of the project were met. Such flexibility is required and must be anticipated in a study of this kind.

Several of the key attributes of the PVHA process, or methodology, are described in this section.

2.2.1 Interaction and Structured Debate

A basic premise of the PVHA process is that the assessment is fundamentally a scientific process. Data of several types are interpreted using various (and sometimes competing) models; hypotheses are advocated and tested relative to site-specific and analogue data gathered at other volcanic regions; tentative interpretations and conclusions are developed and presented to technical peers on the panel for their review; and experts consider the credibility of the various models and parameters based on the data and their experience.

Fundamental to this type of scientific exchange are interaction and communication among the experts on the panel. During their professional careers, earth scientists interact on a regular basis at professional society meetings, field trips, etc. During these times, new findings are discussed, hypotheses are advanced, and, ultimately, defendable technical interpretations and conclusions are documented in the professional literature. Because this is a common process, the PVHA attempts to follow the same process as well. In addition, because the PVHA is focused on obtaining (in a timely manner) specific interpretations from the experts related to volcanic hazard at Yucca Mountain, the interactions must be structured and facilitated.

Considerable effort was devoted to facilitation in the PVHA workshops, which were the primary mechanisms for expert interaction on the project. Each workshop was designed to achieve certain goals, which were communicated to the experts well in advance (specific workshops are discussed in Section 2.3.3). Ground rules were discussed at the beginning of each workshop to ensure that all discussions were kept at the highest professional level. These ground rules are listed in Figure 2-1, which is a copy of the viewgraph presented at each workshop. A variety of presenters participated, including many technical specialists who were not members of the panel. On controversial technical issues, advocates of alternative viewpoints provided presentations and focused, structured technical debates on the issues were conducted. The technical facilitation process followed is that recommended in the SSHAC guidance (SSHAC, 1995).

2.2.2 Types of Participation

A large number of individuals participated in the PVHA project. The types of participation are described below.

- **Members of Expert Panel**—These experts (also called subject matter experts) were the principal focus of the study. The experts reviewed all available data bases, prepared for presentations and discussions at workshops, prepared for and participated in individual elicitations, and documented their interpretations. (The expert panel members are listed in Table 1-2.)

- **Workshop/Field Trip Presenters**—A number of technical specialists participated as presenters at the workshops or by discussing their investigations on the field trips. This process allowed the experts the opportunity to have first-hand access to data being developed, to hear about—and weigh—models and interpretations being advocated, and to formally and informally communicate with their technical peers. Some of the presenters were individuals who were invited to be members of the expert panel but were unable to do so because of potential conflicts of interest. (A list of presenters is given in Table 1-3.)

- **Methodology Development Team**—The MDT participated in the project by developing the strategic plan, planning and facilitating workshops and field trips, making data available to the panel, eliciting the experts, and documenting the project. Some members of the MDT provided periodic peer review of the project and made recommendations for project direction and activities. (The MDT members are listed in Table 1-1.)

- **Observers**—Observers were invited to attend the workshops and field trips by the MDT. Observers included knowledgeable individuals from the various review groups (NRC, ACNW, CNWRA, NWTRB), affected units of government (State of Nevada, affected counties and Native American groups) and project participants (DOE, M&O, EPRI). The observers had opportunities to comment and ask questions at the workshops.

2.2.3 Roles of Proponents, Specialists, Evaluators, and the Technical Facilitator/Integrator

Individuals on the PVHA project played several different roles; in some cases, certain individuals played more than one role. Although the terms used are slightly different, the roles of the individuals defined here are very similar to the roles described in the SSHAC guidance (SSHAC, 1995, p.24). The roles of proponents, specialists, evaluators, and the technical facilitator/integrator (TFI) are described below.

A *proponent* is a technical expert who advocates a particular hypothesis or technical position. Proponents participated in the PVHA project primarily through presentations at workshops and field trips. For example, two proponents (Drs. D. Champion and J. Geissman) described their paleomagnetic data from the Lathrop Wells cone and their interpretation of the age and eruptive history of the cone. Another proponent (Dr. C.-H. Ho) presented his published method for characterizing the temporal distribution of volcanic events in the region. Another proponent (Dr. G. Yogodzinski) described his interpretation of the geochemical affinities and differences in the region and the implications to magmatic sources. The proponent role is common in the earth sciences, and a proponent's position is usually published in the literature. In some cases, members of the expert panel were asked to play the role of proponents (i.e., Dr. M. Sheridan advocated his parametric volcanic "field shape" approach to assessing spatial distributions; Dr. B. Crowe defended an interpretation of polygenetic volcanism at the Lathrop Wells volcanic center). The proposent role that is quite different from that of an evaluator (described below).

A technical *specialist* is a resource expert who has particular knowledge of a particular data set of importance to the hazard analysis. The specialist makes his/her data available to the experts and discusses issues related to data uncertainties and resolution. A number of technical specialists participated on the PVHA project, providing information that had been gathered in the YMR and in analogous regions. For example, Dr. E. Smith (UNLV) presented his field and geochemical data from Red Cone and Black Cone in northern Crater Flat; Dr. P. Delaney (USGS) presented his data bases and interpretations of volcanic dikes; and Dr. F. Perry (LANL) presented his geochemical analyses of volcanic rocks throughout the YMR. Key advantages of having technical specialists involved in the project are that they can update the panel on data sets that may not yet be available in the professional literature and provide their unique perspective on the "quality" of the data.

The *evaluator* on the PVHA project is one who is capable of evaluating the relative credibility of multiple alternative hypotheses. Although some members of the expert panel were asked to play the role of proponents or technical specialists, all members of the panel were required to play the role of evaluator. The expert panel members often had strong personal preferences for various volcanic models, however, they were also independent thinkers and proved capable of coming to conclusions after evaluating all of the available data. "To evaluate the alternatives, the evaluator considers the available data, listens to proponents and other evaluators, questions the technical basis for their conclusions, and challenges the proponents' positions" (SSHAC, 1995, p.24). In arriving at his/her representation of uncertainty, the evaluator must consider the interpretations of the larger technical community. The evaluator makes a concerted attempt to quantify and incorporate a full range of uncertainties.

The role of *technical facilitator/integrator* (TFI) is key to facilitating the interactions among the experts, eliciting the expert judgments, and ultimately integrating the assessments into a single quantitative result. As discussed previously, expert interaction was an important attribute of the PVHA project, and this interaction occurred in a structured, focused way. The facilitator is a technical individual who is responsible for facilitating this interaction by: providing for proper preparation by the experts, ensuring that two-way communication occurs during discussions, promoting technical challenge of ideas, providing a hazard focus to the technical discussions, defusing tensions and personal confrontations, leading the elicitations, and ensuring complete documentation by the experts. The "integrator" role of the TFI refers to the process of aggregating the assessments of the panel into an overall probability distribution. Provision is made in the SSHAC guidance for the TFI to exercise a variety of methods to integrate the judgments of multiple experts, including "weighing" rather than weighting, their assessments or applying differential weights because of any of a variety of problems. However, as discussed later in Section 2.2.11, the PVHA project did not experience these problems and followed a process that ensured that all of the expert interpretations could be integrated using equal weights.

2.2.4 Focus on Technical Issues Important to Hazard

Certain aspects of the volcanism issue in the YMR have been contentious in the past. Further, because of the many years of intensive data collection efforts, much of the contention has centered around details of the data and alternative ways of interpreting the data. For example, the issue of the uncertain number, genesis, and age of eruptions at Lathrop Wells has sparked considerable debate by those conducting geochronolgic analyses, mapping field relationships, conducting geochemical analyses, studying analogue regions, etc. Although this debate may have intrinsic value in dealing with a difficult scientific issue, it may not be particularly significant from the standpoint of the PVHA.

Although the expert panel brought to the PVHA a broad range and depth of expertise in various aspects of volcanism, it was emphasized that the issue of volcanic hazard at Yucca Mountain draws on only a subset of that knowledge. Some issues were important to the assessment (e.g., factors related to the spatial distribution and frequency of occurrence of volcanic events in the YMR), but many other issues were not significant. Likewise, some data sets were more useful for the analysis than others. As will be discussed below, the project attempted to provide a focus on PVHA issues from the beginning. The data needs for the assessment were identified only *after* the issues important to the hazard analysis were originally identified. Following the elicitations, calculations and sensitivity analyses were conducted to further define those issues of most importance to the results (e.g., the location of the eastern boundary of source zones including Crater Flat volcanoes). Plus, issues that affect the uncertainties in the hazard results were identified, such that their uncertainties would be provided emphasis and focus (e.g., the length and orientation of volcanic events). By maintaining a focus on the hazard analysis throughout the project, extraneous issues could be avoided and proper effort could be devoted to those key issues of importance.

2.2.5 Availability of Data Bases and Field Observations

Data pertinent to a site-specific assessment of volcanic hazard at Yucca Mountain have been gathered for more than a decade. Because nearly all of the experts on the panel had no significant prior experience with these data, it was important to make all pertinent data available to them. Efforts to compile data, including large numbers of published papers, began well in advance of the first workshop, and distribution continued throughout the project. Members of the MDT were responsible for accommodating all requests by the panel for data. Fortunately, the Yucca Mountain volcanism program has recently completed significant data synthesis efforts, and synthesis reports could be made available to the experts (e.g., Crowe et al., 1995).

In some cases, recently gathered data—both from the YMR and other analogue areas—were presented in workshops and/or made available to the experts in preliminary form for their review. An example of this type of data is the regional seismic reflection line recently run across Crater Flat and Yucca Mountain. The line was described during the Crater Flat field trip by C. Fridrich and G. Thompson also discussed it at PVHA Workshop 4, including the current interpretation of the reflection profile being developed by the USGS. The interpretations were discussed again later in Workshop 4 in the context of the uncertainties in the eastern boundary of the Crater Flat "source zone." Another example of a new data base was the ground magnetic survey being developed by the CNWRA in northern Crater Flat. C. Connor presented his preliminary findings at the Crater Flat field trip regarding subsurface expression of dikes.

It should be noted that the PVHA experts devoted considerable effort and "did their homework" to prepare for workshops, field trips, and their elicitations. In every case, the experts showed clear evidence of having reviewed available data. Further, most of the experts used data from analogous regions worldwide in developing their interpretations for the YMR.

In addition to documented data bases, the experts also relied to a significant extent on the "data base" associated with their observations in the field during field trips. Many of the experts are field geologists and considered the opportunity to observe field relationships first-hand an important part of formulating their ideas. These trips were greatly facilitated by presentations and discussions by the geologists who had conducted investigations in the region.

2.2.6 Uncertainty Treatment

As discussed in the Introduction to this report, a key product of the PVHA project is a complete and documented expression of uncertainty. Clearly, assessments of the probability (or, more properly, annual frequency) of intersection of volcanic events with the repository contain uncertainties. These uncertainties are derived from uncertainties in models that describe the future locations of volcanic events and models that describe the temporal distribution or rate of events. Likewise, even given that a model is correct, the parameters of these models are uncertain. A key concept used in the PVHA and in many similar studies is that the total uncertainty in the hazard result can be captured by careful consideration of uncertainties in the components of the assessment. That is, by breaking down the assessment into pieces that are small enough to be evaluated confidently by the expert and defining uncertainties at this level, the pieces can be reassembled into an overall distribution that properly defines the total uncertainty.

In general, the volcanic hazard analysis was broken down into components describing the spatial and temporal distribution of volcanism. The spatial distribution defines the future location of volcanic events; the temporal distribution defines the timing and recurrence rate of volcanic events. A variety of spatial models were usually considered by each expert, with weights assigned to express the relative credibility of the models (modeling uncertainty), and alternative parameter values assigned to the variables operating each model (parameter uncertainty). A tool used to express these uncertainties is the logic tree. (See Section 3.2 for a discussion of PVHA logic trees.) Logic trees are convenient for sequencing the series of assessments that might be required by a model and for accounting for dependencies in the assessments. For example, most experts developed models of the future spatial distribution of volcanism dependent on the geologic time period considered. Thus, one set of "source zones" might be appropriate for an assumed post-5 Ma time period, and another set of zones for a post-2 Ma period. Given this dependency and uncertainties in both the appropriate time period and the proper source zones, the assessment of the time period would appear as a node on the logic tree before the node for source zones. In some cases, the experts expressed their parameter uncertainty as a continuous probability distribution, rather than as discrete values that form the branches of a logic tree.

The MDT made an effort to ensure that both *aleatory* uncertainties and *epistemic* uncertainties were incorporated into the assessments (see SSHAC, 1995, p. 12-13 for discussion of these terms). Aleatory uncertainties are related to the random variability in a parameter or process. Examples of aleatory uncertainties include the timing of the next volcanic eruption, the length of the next dike to erupt in Crater Flat, and the future location of volcanoes within Crater Flat over the next one million years. Epistemic uncertainties are related to our lack of knowledge about a parameter or process. Examples of epistemic uncertainties include the number of volcanic events represented at a particular volcanic center, the length of dikes associated with volcanic events in Crater Flat, and alternative models for representing the future spatial distribution of volcanism. In concept, aleatory uncertainties are not reducible with the consideration of new data; epistemic uncertainties are reducible with the introduction of new data. For example, the experts provided a probability distribution expressing their uncertainty in the length of dikes that might occur in the YMR. The experts were reminded to include not only the (aleatory) uncertainty in length associated with an individual event, but also the (epistemic) uncertainty in the probability distribution for the population of dikes (e.g., mean length, standard deviation, maximum length).

2.2.7 Feedback and Revision

A basic premise of the PVHA project was that the assessments by the experts should be reviewed, discussed, and challenged by other members of the panel before being finalized. This is a natural part of developing scientific interpretations: an expert evaluates data and other information using his/her past experience; hypotheses are advanced that express models and conclusions that are consistent with the data and experience; the hypotheses are presented and debated among peers, who likely have a different experience base, interpret the data differently, etc.; and the expert modifies and otherwise strengthens his/her interpretation based on the input received.

This process was followed in the PVHA: various data sets, methodologies, and existing/published alternative interpretations of data were presented to the experts and discussed in the early workshops and field trips; the experts were then elicited individually to provide their own interpretations; the experts presented their interpretations to the rest of the panel in a workshop where they were encouraged to ask questions and technically challenge each other's views; and in light of the feedback, the experts finalized their assessments and documented them.

The PVHA feedback process also included two additional important features. First, because this study focused on assessments of volcanic *hazard*, the feedback of the interpretations made by the experts included feedback on the relative importance of their assessments to the hazard results. For example, the experts were told—as a group—which elements of their assessments were most important to the final results (e.g., spatial models, event geometry) and which elements were less significant (e.g., event counts at distant centers). In addition, the experts were informed individually of the sensitivity of various parts of their assessments to the hazard results. This knowledge of the importance of various components of the assessment allowed the experts to focus on these particular issues in considering possible revisions to their interpretations.

A second important consideration in the feedback process is the fact that the experts are expressing not only their preferred models and parameter values, but also their uncertainties (i.e., alternative weighted models and parameter values). As a result, in their review and challenge of the interpretations of others, each expert is considering how his expression of uncertainty might be revised. For example, an expert might decide, after review of another expert's model or approach, to include that model (perhaps as a lesser weighted alternative) in their assessment. Further, the MDT quizzed the experts at the feedback workshop to ensure that they fully captured their uncertainties, both aleatory and epistemic.

2.2.8 Diversity of the Expert Panel

The PVHA arrives at a probability distribution that incorporates the interpretations and uncertainties that each expert expresses (within-expert uncertainty) and the diversity of views across the panel as a whole (expert-to-expert uncertainty). In combination, the distribution is judged to be representative of the larger informed technical community. Part of the basis for this judgment is the fact that the expert panel includes a wide range of expertise, experience, and institutions (the expert selection process is discussed in Section 2.3.2). Plus, in addition to being exposed to the views of others on the panel, the experts were exposed to the views of a large number of other proponents and technical specialists. This exposure to a variety of views purposely was designed to promote a broadening of the perspectives of each expert. Also, the experts were trained in ways to express their uncertainties and encouraged to do so. In this way, each expert played the role of an *evaluator* of alternative hypotheses.

At the final workshop, the experts were presented with their individual calculated probability distributions, as well as the aggregated distribution across all of the panel. In the discussion, they were asked if they felt that, as a subset of those capable of participating in a PVHA for Yucca Mountain, their interpretations provided a reasonable representation of the diversity of views in the "larger informed technical community." (Clearly, this question is hypothetical, because, to make the assessment, the others in the community would need to become "informed" by following the same process of data review and interaction as this panel.) The panel responded in the affirmative. Also, when asked, they concluded that there was no systematic bias between the interpretations of this panel and that of the larger community. It is concluded that the diversity in the total probability distribution is reasonable and representative.

2.2.9 Documentation by the Experts

In addition to each expert's quantitative assessments that provide inputs to the calculated results, a key product of the PVHA project is the documentation prepared by each expert to describe the technical basis for their interpretations. Experience on past multi-expert studies has shown that proper documentation allows third parties to review and understand the thought processes followed by the experts. Further, the *process* of documentation can help the experts to organize their thoughts, consider the strengths and weaknesses of their arguments, and properly express their uncertainties.

As described in Section 2.3.5, the documentation process followed in the PVHA began with written notes taken by the MDT during the elicitations and preparation of draft summaries. The experts were then responsible for revising the draft summaries, updating them following the workshop, reviewing them for completeness, and finalizing them for the Final Report. The final elicitation summaries are authored and signed by each expert and represent their principal contribution to the project (Appendix E).

2.2.10 Availability of Modeling "Tools"

A number of approaches are available to model the spatial and temporal distribution of volcanism in the YMR. Specific applications of some of these approaches have been published by various researchers. For example, C. Connor and B. Hill of the CNWRA have published an approach to modeling the spatial distribution of volcanic events that "smooths" the location of observed volcanic centers (Connor and Hill, 1995). This approach uses a specific set of observed volcanic locations, a particular type of smoothing operator, and particular smoothing distances. Many experts on the PVHA panel found the general smoothing approach to be preferable, but wanted to consider applications different from those used by Connor and Hill (i.e., different smoothing operators, different smoothing distances, different event locations).

The MDT made a concerted attempt to make a wide variety of modeling "tools" available to the experts and to have sufficient flexibility to provide for any new models that might be specified by the experts. By doing so, the experts were free to be creative in their assessments and to focus on the technical basis for their models and not on the potential difficulties in modeling them. This was particularly important for those experts whose expertise lay more in understanding the physical processes controlling volcanism, and less in formulating quantitative probabilistic models and calculating results. In many cases, the experts specified particular approaches to modeling the spatial or temporal aspects of the problem and reviewed the calculated results of each approach before refining the models and assigning relative weights. Some experts carried out calculations themselves; others specified approaches and reviewed calculations made for them by the MDT.

2.2.11 Process Aggregation

Aggregation refers to the process of combining or aggregating the individual assessments made by the experts. Although the individual expert assessments are important and are included in this report, aggregation is necessary to arrive at a calculated result that can be used for subsequent analyses (e.g., performance assessment). The approach used in the PVHA is termed "process aggregation" and is based on the following premise: the target, or goal, for the aggregation procedure is one of weighting the experts equally; therefore, actions are taken throughout the entire process to create the proper conditions where equal weights are appropriate. The actions taken include the following:

- Carefully selecting highly qualified experts who represent diverse views and experience
- Establishing the commitment of each expert to provide appropriate time and effort throughout the project
- Identifying and disseminating a comprehensive and uniform data base to all experts
- Educating the experts in all aspects of issues important to PVHA and training the experts in elicitation methodologies
- Facilitating interaction of the experts in workshops and field trips such that a free exchange of data and interpretations and scientific debate of all hypotheses occurs
- Establishing criteria for removing an expert from the panel and enforcing those criteria
- Providing feedback and sensitivity analyses to the experts, checking for unintentional errors, and facilitating discussion and challenge to preliminary interpretations
- Providing an opportunity for experts to revise their assessments in light of feedback
- Obtaining agreement from the each expert that the other experts' interpretations are understood and are valid alternative interpretations
- Establishing agreement that the panel is representative of the larger informed technical community so that another expert panel from the community would reach the same conclusions.

Problems have occurred on other multi-expert studies, which have led to the need in some cases to consider alternatives to equal weights (SSHAC, 1995, p.33-34). These problems include: experts playing the role of a proponent and being unwilling to evaluate alternative interpretations; outlier experts whose interpretation is extreme relative to the larger technical community and may be over-represented on a small expert panel; insufficient expert interaction such that experts misunderstand the hypotheses presented by others; uneven access to pertinent data sets such that the experts are relying on different data to arrive at their interpretations without knowledge of other data; and insufficient feedback such that the experts are not aware of the significant issues or the relative impact of each part of their assessments. None of these problems occurred on the PVHA project because a deliberate effort was made throughout the entire process to mitigate them. Further, the experts themselves agreed in the course of discussions at the workshop that an equal-weighting aggregation scheme was most appropriate.

2.2.12 Participatory Peer Review

Two types of peer review are defined in SSHAC (1995): a *participatory peer review* is an ongoing review that provides the peer reviewers with full and frequent access throughout the entire project. A *late-stage peer review* is a review that occurs only after the project has been almost completed, usually when a draft report has been submitted or the project's results are close to being in final form. There are advantages and disadvantages to both types of peer review, but a participatory review is clearly preferred by SSHAC (1995) for most situations. The term "peer review"—as used in the SSHAC guidance—is not necessarily the same as defined more narrowly in the Yucca Mountain project procedure for peer review.

A common means of implementing a participatory peer review is a "consulting board" or "advisory board" that periodically meets and reviews the progress of the project. In the same way, Drs. Stepp, Cornell and Smith met periodically throughout the course of the project to discuss strategy with the Geomatrix group managing the study and to provide advice on the project direction. For example, they met with the Geomatrix group after each day of the workshops to plan a strategy for the following day, to suggest adjustments to the agenda or format to help achieve the workshop goals, and to provide other suggestions on overall workshop management. As another example, Dr. Cornell met with Drs. C.-H. Ho and E. Smith of UNLV to understand their temporal and spatial models and to ensure that these models were properly represented to the experts as possible models for their use. During the documentation phase of the elicitation, Dr. Smith and Dr. Stepp conducted detailed reviews of the expert elicitation summaries and provided their comments to the experts to assist them in providing more complete documentation. This "participation" in the peer review process is critically important to maintaining a focused, high-quality project.

2.3 METHODOLOGY IMPLEMENTATION

This section of the report summarizes the manner in which the PVHA methodology was implemented. It begins with an overview of the important steps in the process, followed by a detailed discussion of those steps.

2.3.1 Steps in the Methodology

The PVHA project followed a number of steps in implementing the methodology whose attributes were described in Section 2.2. The principal steps are described below.

(1) **Development of Strategic Plan.** As a first step in the project, a strategic plan was developed by the MDT that would provide an outline of the goals and key elements of the project, timing of significant activities such as workshops, topics to be covered at and between workshops, and significant milestones. The plan provided a useful planning tool to help prepare for long lead-time activities such as data compilation and dissemination. During the course of the project, the strategic plan was updated to ensure that goals were achieved and that the plan reflected the actual course of the project.

(2) **Selection of the Expert Panel.** Criteria were established by the MDT for participation on the expert panel. These criteria were intended to ensure a high-quality panel having significant stature and diversity. Several well-known volcanologists were asked for their nominations to the panel, resulting in about 70 nominations. From this list of nominees, 10 experts were selected and agreed to participate. (The expert selection process is discussed in detail in Section 2.3.2.)

(3) **Data Compilation and Dissemination.** The process of compiling and distributing pertinent data bases, including published reference material, began early in the project and continued throughout. Prior to the first workshop, the experts were sent a number of data sets and publications and were provided access by request to all Yucca Mountain data gathered as part of the volcanism project.

(4) **Workshop on Data Needs (Workshop 1).** The first workshop was designed to identify the significant issues that need to be addressed for a PVHA, characterize the various types of data available from the Yucca Mountain project and analogous regions, and identify the data needed by the experts to develop their interpretations. The workshop ended with a clear set of data needs for the MDT to collect and distribute to the panel.

(5) **Field Trip to Crater Flat (Field Trip 1).** A one-day field trip to Crater Flat was held to provide the expert panel an opportunity to observe first-hand the field relationships at the 1 Ma centers in northern Crater Flat and the 3.7 Ma centers in southern Crater Flat. From the standpoint of the project, this trip provided field "data" to the experts, which were supplemented with other mapped and analytical data developed by DOE, University of Nevada, and USGS researchers. The field trip leaders were earth scientists with considerable experience in the area and from a variety of institutions and disciplines.

(6) **Workshop on Alternative Hazard Models (Workshop 2).** The purpose of this meeting was to explore the several volcanic hazard models that had been proposed for Yucca Mountain or other analogous regions. Researchers from CNWRA, Nevada, LANL, USGS, and several universities discussed their models for characterizing the future spatial and temporal distribution of volcanism. The experts were able to ask

questions about the models and the data used by the authors to implement them. Discussion began on the ways that the models might be modified or refined.

(7) **Field Trip to Sleeping Butte and Lathrop Wells (Field Trip 2).** A two-day field trip was held to allow the experts an opportunity to observe the field relationships and to hear from researchers who have worked in the Sleeping Butte and Lathrop Wells areas. At both locations, interpretations of the number and genesis of events were discussed relative to the available data. Discussion also included the implications of the interpretations to hazard analysis and the nature of the uncertainties.

(8) **Interactive Meeting on Hazard Methods.** A one-day informal meeting was held to provide discussion among the panel members on the various probabilistic methods available to model the spatial and temporal aspects of hazard analysis. Experience from seismic hazard analysis was discussed and an influence diagram was developed to express the general relationships among the various components of probabilistic volcanic hazard analysis.

(9) **Workshop on Elicitation Training and Alternative Interpretations (Workshop 3).** The first part of this workshop consisted of elicitation training to educate the experts on issues of eliciting probabilities, ways to express uncertainties, cognitive and motivational biases, and the manner in which their interpretations would be elicited following the workshop. The second part of the workshop was a final opportunity for presentation by various proponents of a number of alternative technical interpretations. The goal was to allow the experts to understand the technical bases for the interpretations being espoused and their uncertainties.

(10) **Trial Elicitation.** The MDT conducted a one-day trial elicitation with one of its members, Dr. R. Smith. The purpose was to gain insight into the structuring of the assessment, sequencing of questions, methods to capture uncertainties, data and maps to have available, and documentation procedures. The insights gained provided a framework for the actual elicitations of the experts.

(11) **Elicitation of Experts.** Two-day individual elicitation interviews were held with each member of the expert panel. Through facilitated discussion by the elicitation team, the expert provided his interpretations, expressed his uncertainties, and specified the technical basis for his assessments. Maps were prepared showing the source zones for the spatial distribution of volcanic events. The elicitation was documented by the elicitation team during the interview. The experts then reviewed, revised, and supplemented the summary prepared by the elicitation team.

(12) **Calculation of Preliminary Results.** Based on the elicitations, preliminary calculations were carried out by the MDT, and sensitivity analyses were conducted.

In addition, each elicitation was reviewed for logical consistency to ensure that the sequence of models, components, and parameters was logical and complete.

(13) **Workshop to Review Preliminary Assessments (Workshop 4).** A final "feedback" workshop was held to provide a summary of the assessments of all of the experts, to provide each expert an opportunity to present his interpretations, to encourage debate and technical challenge of expert interpretations, and to ensure that uncertainties were being completely incorporated. In addition, the aggregation process was discussed.

(14) **Finalization of Expert Assessments.** Following the final workshop, the experts reviewed the data, sensitivity analyses of their calculated results, and the presentations and conclusions of the other experts. The experts then developed a final draft of their elicitation summary. This draft was reviewed for completeness and clarity in providing the technical basis for the interpretations. Following this review, the experts prepared their final reports (included in Appendix E to this report).

(15) **Preparation of Project Report.** This report was developed to provide documentation of the process followed, the expert elicitation summaries, and the calculation methodologies and results.

The remainder of Section 2.3 describes in more detail the key activities involved in implementing the PVHA methodology.

2.3.2 Selection of Members of the Expert Panel

The process of selecting members of the expert panel involved four steps: (1) developing selection criteria; (2) obtaining nominations from knowledgeable individuals; (3) selecting and inviting the candidates to participate; and (4) acceptance by the candidates to participate.

Guidelines or criteria for selection of members of the expert panel were developed by the MDT. The following criteria were used in selecting expert panel members:

(1) Earth scientist having a good professional reputation and widely recognized competence based on academic training and relevant experience. Tangible evidence of expertise, such as written documentation of research in refereed journals and reviewed reports is required.

(2) Understanding of the general problem area through experience collecting and analyzing research data for relevant volcanic studies in the southern Great Basin or similar extensional tectonic environments; prior familiarity with the data available for the proposed Yucca Mountain site will be an asset, but not a requirement for participation.

(3) Availability and willingness to participate as a named panel member, including a commitment to devoting the necessary time and effort to the project and a willingness to explain and defend technical positions.

(4) Personal attributes that include strong communication and interpersonal skills, flexibility and impartiality, and the ability to simplify; individuals will be asked specifically not to act as representatives of technical positions taken by their organizations, but rather to provide their own technical interpretations and uncertainties.

(5) Help to provide a panel balanced to include experts with diverse opinions, areas of technical expertise, and institutional/organizational backgrounds (e.g., from government agencies, academic institutions, and private industry). The panel should include some researchers who have worked in the YMR and some who have not.

A broad search was conducted to obtain nominations for the expert panel. Letters requesting nominations were mailed to 22 earth scientists identified by the MDT. The letters requesting nominations contained a brief description of the project and included the guidelines for selection of panel members, presented above. Written responses containing nominations were received from 13 individuals and a verbal response from one; a small number of additional nominations were supplied by the MDT. More than 70 individuals were nominated and considered in the selection process.

The candidates for the expert panel were chosen by the MDT in accordance with the selection guidelines. Careful consideration was given to balancing the panel to be consistent with the 5th selection guideline, cited above. Individuals were selected to obtain a balance with respect to areas of technical expertise, including physical volcanology, isotope geology and geochemistry, and structural geology, as well as to include individuals from varied institutional/organizational backgrounds, including the federal government, state government, universities, and private practice.

The candidates were contacted by telephone and invited to participate. They were informed that the estimated level of participation was 25 days (by the end of the project, many of the experts had spent significantly more time.) Most accepted during the initial phone call; others requested time to consider potential conflicts of interest or schedule/time conflicts. A total of 17 individuals were invited to join the expert panel; ten accepted, three (including individuals from the CNWRA and the University of Nevada) declined, citing potential conflicts of interest, and four declined due to extensive travel plans or other schedule conflicts.

It is important to emphasize that the criteria for selection of the experts were reviewed with each expert prior to their making a commitment. In particular it was felt that each expert would need to commit a significant portion of time, would need to prepare for and attend all meetings, and would be required to exhibit the highest levels of professional behavior. Throughout the project, the experts were reminded of their commitment to the project and their agreement to the standards of behavior stated in the selection criteria.

The experts were also informed of the role that they would play in the PVHA assessment as an expert *evaluator* who considers a variety of viewpoints, challenges the interpretations of others, and arrives at a reasoned position that includes a representation of the uncertainties. The resulting panel consisted not only of experts of considerable stature and prominence in the volcanological community, but individuals with reputations for being independent thinkers capable of coming to conclusions after evaluating all of the available data. Throughout the project the panel members proved to be fully capable—and willing—to evaluate alternative hypotheses and to provide the technical basis for their interpretations and uncertainties.

2.3.3 Review of Technical Issues/Expert Interaction

Technical issues related to the PVHA project were identified by the experts in the first workshop and reviewed throughout the course of the project. The multiple workshops and field trips provided an opportunity for technical discussion and interaction, with an objective of ensuring a common understanding of the issues to be assessed and the data sets available to provide the technical basis for assessment.

Maps and literature pertaining to geologic issues relevant to assessing future volcanic hazard were sent to members of the expert panel throughout the project. A list of the references distributed to the expert panel members is provided in Appendix B; this list was also made available to workshop observers during the course of the project. Prior to the first workshop, a number of references (maps and literature) pertaining to the geology of the YMR were sent to the experts for their review, along with a comprehensive reference list from which the experts could request other publications if they desired. In addition, two background reports prepared by Geomatrix were distributed to the experts to provide them with an overview of certain technical topics relevant to the PVHA project. These reports, entitled "Overview of Volcanism in the Yucca Mountain Region" and "Status of Geochronological Methods for Dating Quaternary Volcanic Deposits and Landforms" summarized interpretations and highlighted pertinent references related to these specific topics. These materials were provided to the experts as a starting point for reviewing a number of technical issues of importance to the Yucca Mountain PVHA. A third background report, "Miscellaneous Geology Topics" that addressed the generalized stratigraphy of the YMR and some geophysical issues, was distributed to the expert panel following Workshop 3.

The following sections summarize the various activities (workshops and field trips) conducted during the project. These are summarized under the topic of Review of Technical Issues/Expert Interaction because the workshops and field trips were the primary vehicle for accomplishing these activities. Summaries of the workshops and field trips are included in Appendices C and D, respectively.

2.3.3.1 Workshop on Data Needs. The Workshop on Data Needs was the first of four workshops conducted for the PVHA project. The goal of this workshop was to identify specific data needed to make probabilistic assessments of volcanic hazard at Yucca Mountain. The approach to the workshop was to: (1) identify the technical issues of most significance to PVHA, (2) establish linkages between the important issues and the data needed to address the issues, (3) specify pertinent data available for the YMR, and (4) identify the particular data that are required by the experts to make hazard assessments. During a discussion that followed presentations by several technical specialists at the workshop, the issues deemed most important to assessing the volcanic hazard at Yucca Mountain were identified by the expert panel. The identification of technical issues was essential for identifying the types of data needed to conduct the PVHA. The discussion also helped to ensure a common understanding among the experts of the important elements that can directly or indirectly influence future volcanic hazard at Yucca Mountain.

Some of the major technical issues identified by the experts included: (1) the type and nature of eruptions, (2) structural control of volcanism in the YMR, (3) spatial and temporal relationships number of events at a particular center, (6) the reliability/uncertainty of age determinations, (7) the orientations of feeder dikes, and (8) appropriate analogue regions. A complete list of the technical issues identified by the expert panel is included in the Workshop on Data Needs summary in Appendix C.

The focus on the second day of the workshop was on relating each of the technical issues identified the previous day to data that can provide information to address that issue. A comprehensive list of specific data needs was compiled by the expert panel and MDT, and is included with the Workshop on Data Needs summary in Appendix C. In the days immediately following the workshop, available data sets specific to the YMR, including geochemical, geochronological, geophysical, geological (mapping, etc.), and seismological data, were compiled from the technical presentations given at the workshop. In addition, data sets specific to individual volcanic centers (Thirsty Mesa, Sleeping Butte, Buckboard Mesa, Crater Flat, and Lathrop Wells) were compiled from the workshop presentations and various other sources. The compiled lists were then distributed to the experts so they could choose the data they wanted to receive. Geomatrix served as a clearinghouse for requests for and dissemination of data. Many of the technical specialists who gave presentations at the workshop, including scientists from the USGS, LANL, and the University of Nevada, offered to provide unpublished data to the experts by request, either through Geomatrix or via personal communication.

2.3.3.2 Field Trip to Crater Flat. The Crater Flat field trip was held after the first workshop to provide the expert panel members an opportunity to observe first-hand the volcanic geology at the various Crater Flat volcanic centers. The field trip was led by several earth scientists who have carried out extensive mapping and/or research in the Crater Flat area, including scientists from the State of Nevada, USGS, CNWRA, and LANL (see field trip summary in Appendix D). Field trip stops were made at locations where key outcrops of the geology could be observed, and discussions focused primarily on the following issues: (1) the nature of the volcanic deposits (i.e, the types of eruptions), (2) polygenetic vs. monogenetic volcanism, (3) structural control of volcanism, (4) the number of events, (5) feeder dike geometries, and (6) field relationships at each of the volcanic centers. The field trip provided the experts an opportunity to understand the interpretations of other investigators, while forming interpretations of their own based on their observations.

2.3.3.3 Workshop on Alternative Hazard Models. The Workshop on Alternative Hazard Models was the second workshop conducted for the PVHA project. This workshop was designed to review the alternative methods and models for assessing probabilistic volcanic hazard, and to evaluate their applicability to Yucca Mountain. The purpose of this review was to provide the experts an opportunity to better understand the available models for characterizing the spatial and temporal aspects of volcanic hazard analysis. The various approaches were presented by the researchers who have developed them.

The workshop began with a discussion of the general spatial and temporal aspects of natural phenomena hazard modeling, drawing on experience from seismic hazard analysis. This discussion was led by C. Allin Cornell, who has widely recognized expertise in hazard analysis, probability, and statistics. He also discussed ways of capturing, or quantifying, uncertainty in the data by applying various relative weights to alternative models or hypotheses.

Workshop presenters then described a variety of methods for characterizing the recurrence rate of volcanism and for modeling the spatial and temporal distribution of future volcanism at Yucca Mountain. The types of spatial models discussed included spatially homogenous "source zone" models, non-uniform parametric models, and nonhomogeneous spatial clustering models. Homogeneous and non-homogeneous temporal models also were discussed. Each presenter discussed the assumptions inherent in their models, the data required, the procedures, the model uncertainties, and the strengths and weaknesses of the method. Following the presentations, the experts and MDT discussed the relative merits and applicability of the alternative approaches. During this discussion, the experts compiled a list of technical issues to be discussed at the next workshop. The list included the regional and local tectonic regimes, the regional volcanic history (including pre-Pliocene volcanism), the geometry of magma bodies, and paleomagnetic data for the YMR.

2.3.3.4 Field Trip to Lathrop Wells and Sleeping Butte. The two-day field trip to Lathrop Wells and Sleeping Butte (Hidden Cone and Little Black Peak) was organized by the MDT at the request of the expert panel members, who wanted to observe first-hand the volcanic geology at each of the volcanic centers. The field trip was led by earth scientists from LANL and the USGS who have carried out extensive mapping and/or research in the two areas (see Appendix D). Field trip stops were made at locations where key outcrops of the geology could be observed. Discussions at Lathrop Wells focused primarily on geomorphic relationships, the age and distribution of mapped units, and the number of events at the center. At the Sleeping Butte centers, discussions focused on the ages of the cones, the number of events based on paleomagnetic and geomorphic data, and the local and regional geology. The field trip provided the experts an opportunity to understand interpretations made by other geologists and to make their own observations from the standpoint of their impending task of quantitative assessment of the volcanic hazard at Yucca Mountain.

2.3.3.5 Interactive Meeting. An interactive meeting attended by the expert panel and MDT was held one day prior to the Workshop on Elicitation Training and Alternative Interpretations. This was an informal meeting held for the benefit of the expert panel, as some members of the panel had expressed an interest in obtaining a greater understanding of the available probabilistic models. The meeting began with an introduction to probability and uncertainty treatment, which led to the development of an influence diagram for PVHA (Figure 2-2) showing the essential elements of the analysis and where different data are used. The interactive discussions then focused on the various methods that can be used for hazard analysis, progressing from simple to complex models and considering both spatial and temporal aspects. The purpose of these discussions was to allow the experts to understand the various "tools" available to them to construct their volcanic hazard models. Further, the relationships between various models and physical processes of volcanism were discussed. For example, the implications of spatial models that "smooth" the locations of observed volcanic centers were discussed, as was the importance of the "start-time" for real-time Weibull temporal models.

2.3.3.6 Workshop on Elicitation Training and Alternative Interpretations. The Workshop on Elicitation Training and Alternative Interpretations was the third workshop conducted for the project. The purpose of this workshop was to provide probability assessment and elicitation training to the expert panel—to prepare them for their elicitations—and to review a variety of topics of potential significance to the Yucca Mountain PVHA. The workshop began with a half-day training session on probability assessment and quantifying uncertainties, taught by Dr. Bruce Judd (Strategic Decisions Group), a renowned educator and consultant in decision analysis. The process for assessing probabilities and recognizing and minimizing motivational and cognitive biases were the focus of discussions. The training session included several exercises that demonstrated the value of widening probability distributions when there is uncertainty, and how anchoring and inadequate adjustment for cognitive biases can lead to inadequate expressions of uncertainty. Techniques for eliciting probabilities were also demonstrated, as preparation for the elicitation interview sessions to follow the workshop.

The remainder of the workshop consisted of a series of technical presentations on topics relevant to the PVHA identified at the previous workshop by the expert panel and MDT. The presentations included discussions of the local and regional tectonic regime, the character and geometry of analogous volcanic fields, the history of volcanism in the YMR and southern Basin and Range, geochemistry of the southern Great Basin, and paleomagnetic data gathered at Lathrop Wells. The discussions covered a wide range of topics and were designed to allow a final examination of all pertinent issues and data bases—including those issues that had been controversial or subject to alternative interpretations.

2.3.3.7 Workshop to Review Preliminary Assessments. Between the third and fourth workshops, the experts were elicited (see Section 2.3.4 below). The Workshop to Review Preliminary Assessments occurred after the elicitations and was the final workshop conducted for the PVHA project. The workshop allowed the experts to present and discuss elements of their preliminary assessments. Preliminary hazard calculations based on the expert interpretations also were presented, along with sensitivity analyses. Sensitivity analyses identified the most important technical issues to the PVHA results. In general, the spatial aspects were more important than temporal parts of the PVHA. The important spatial issues included whether or not the repository site lies within a zone of high activity, the length of an event vs. distance to more active sources, the use of source zones vs. spatial smoothing, and smoothing distance factors. Important temporal issues included the volcanic event counts and the use of a homogeneous vs. a nonhomogeneous recurrence model.

The discussion of the hazard model sensitivities was intended to provide the experts with a focus for evaluating and revising their initial assessments. For example, considerable discussion occurred at the workshop on the nature of the eastern boundary of source zones developed for Crater Flat. Various data bases related to interpretations of this boundary were discussed, including the newly-acquired seismic reflection profile and previously interpreted geophysical data including gravity and aeromagnetic data, geologic mapping, etc. Methods for quantifying uncertainties in the eastern boundary also were discussed, including spatial smoothing, parametric field shape (i.e., bivariate Gaussian), multiple alternative source zones, and "soft" zone boundaries. All of the experts were strongly encouraged to adopt one or more methods to capture their uncertainties in this important issue. (As discussed in Section 3, the experts used a variety of approaches to quantify their uncertainties in this issue.)

The workshop provided an opportunity for the experts to present, defend, and question the preliminary interpretations that they had made in their elicitations. The experts had been provided with the written draft summaries of the elicitations for each of the panel members. The source zone maps and other mapped materials were posted in the meeting room for review by the panel. Topics discussed included the spatial approaches used to represent the future distribution of volcanism (e.g., homogenous source zones, spatial smoothing, parametric approaches), background source zones, local source zones, the "event counts" at various volcanic centers in the YMR, dike lengths and orientations, and the various temporal models used in the hazard analysis. Other issues discussed were the tectonic setting of Yucca Mountain, the experts' definition of a volcanic "event," undetected or hidden events, time periods of interest, and ways of capturing uncertainty in the assessments. The MDT discussed the importance of capturing both the aleatory and epistemic uncertainties in their assessments of event geometries (length and orientation).

The workshop also included a discussion by P. Morris and C. A. Cornell of the process to be used to aggregate the expert assessments. They noted that, from the outset of the project, the process followed was designed to create the proper conditions for equal weights among the expert assessments. The experts were asked to consider if they believed the panel to be representative of the larger community, or if they might have a systematic bias relative to that community.

In addition, a brief feedback session with the experts was held. Some of the feedback comments highlighted the importance of the field trips and training in estimating uncertainties. It was also suggested that an initial elicitation early in the project might help to improve the elicitation process, by helping the experts to organize and focus their thoughts on the most relevant hazard issues.

2.3.4 Elicitation of Experts

The elicitation is the process of obtaining the experts' interpretations of the PVHA at Yucca Mountain. The elicitations involved a series of activities, which can be grouped into three steps: (1) preparation for the elicitation, (2) the elicitation interview, and (3) documentation and review.

2.3.4.1 Preparation for the Elicitation. Elicitation training was provided at the third workshop. The objectives of the training were to demonstrate how to quantify uncertainties using probabilities, to recognize common cognitive biases and compensate for them, and to present examples of the types of assessments that would be made at the elicitation (e.g., continuous variables, discrete hypotheses, and associated weights). The training was designed to allow the experts to be comfortable with the *process* of eliciting their judgments, so that the elicitation interview itself could focus on the *technical issues* of importance to the PVHA.

Following Workshop 3 and the elicitation training session, the MDT conducted a trial elicitation of R. Smith, a member of the MDT who was technically qualified to serve as a member of the expert panel. The one-day trial elicitation consisted of walking through the various spatial and temporal components of the PVHA. Dr. Smith presented the technical basis for his assessments and discussed the alternative approaches that members of the expert panel might take during their elicitations. The trial elicitation helped develop a sequence of the elicitation that began with the tectonic setting of the YMR, regional controls on the spatial distribution of volcanism, alternative spatial models and their parameters, temporal models and their parameters, and event geometries. The trial elicitation allowed the MDT to better understand the nature of the technical issues, the approaches likely to be taken by the experts, the sequence of the assessments, the manner in which uncertainties should be expressed, and the overall time involved in the elicitation. As a result, the actual elicitations were conducted more efficiently.

A memorandum was sent to the expert panel members to assist them in preparing for the elicitation interview. This memo stated that, although the expert's particular approach to the problem would determine the specific model parameters required, a minimum set of questions should be considered in preparing for the elicitation. These questions are provided in Table 2-1. The purpose of providing these questions was not to preclude flexibility in the approaches that the experts might want to follow in their PVHA assessments. Rather, it was intended to help the experts prepare, to focus their data review on the topics of most significance, and to ensure that all important issues were addressed by all experts. The memo reiterated the process that would be followed to document the judgments in the elicitation, including feedback at Workshop 4 and the opportunity to revise assessments following the workshop.

2.3.4.2 The Elicitation Interview. The elicitations of the expert panel members took place in individual interviews in the San Francisco office of Geomatrix. All interviews were conducted by a Geomatrix elicitation team composed of K. Coppersmith, R. Youngs, and R. Perman. In addition, P. Morris, the normative expert for the project, attended most of the elicitation interviews. The interviews were essentially completed within the two-day period (about 90 percent complete), with some follow-up by phone or by meeting usually required after supplemental information was provided (e.g., one expert wanted to delineate different structural settings in the region of interest, so Geomatrix prepared a GIS-based map that merged bedrock geology and the most recently available fault information).

All data sets provided or made available to the experts during the course of the project were present during the elicitations. Some of the experts brought maps and written descriptions of their models to the interviews, although this was not required. The elicitation interview followed a logical sequence from general assessments to more specific assessments and, typically, from spatial issues to temporal issues. Alternative models, approaches, and hypotheses were discussed and relative weights assigned to the alternatives to express the uncertainties. Parameter uncertainties were represented by discrete weighted alternatives or by continuous probability distributions, depending on the desires of the expert. Each expert represented the spatial distribution of future volcanism on maps, which they prepared during the elicitation. As discussed below, written notes of all assessments were taken by the Geomatrix team during the interviews.

2.3.4.3 Documentation and Review. Documentation of the expert elicitations began with notes taken by the elicitation team during the course of the interviews. Experience on several other expert assessment projects has shown that other documentation methods are less effective (e.g., written questionnaires, experts writing their interpretations following the interview, etc.). During the two-day interview, each PVHA expert was asked to make a large number of assessments, to quantify his uncertainties, and, most importantly, to provide the technical basis for his interpretations. By having the elicitation team—not the expert—take notes, the expert was free to focus on thinking through his answers and expressing his interpretations thoroughly. Plus, the elicitation often followed a circuitous path—touching on and later returning to particular topics—following the logic comfortable to the expert. The experience of the elicitation team on similar elicitation interviews and documentation allowed them to be flexible in the elicitation sequence while ensuring that all elements were covered.

Following the elicitation interviews, the elicitation team provided each expert with written documentation of the interview, organized by model component. The experts were instructed to review, revise, and expand the preliminary assessments in this "First Draft" documentation summary so that it fully reflected their interpretations. The summaries revised by each expert became the "Second Draft" document. Next, the technical consistency and clarity of the judgments were reviewed by MDT member R. Smith. Inconsistencies (e.g., typographical errors such as substituting "northwest" for "northeast" and probabilities that summed to 0.95 instead of 1.0) were discussed over the telephone with each expert and revised as necessary.

The "Second Draft" summaries from each expert were then distributed to all members of the expert panel prior to Workshop 4 so that each expert could review the judgments of others and the technical basis of each judgment.

The Workshop to Review Preliminary Assessments provided feedback to the experts and is viewed as a continuation of the elicitation process. It was emphasized at the start of the workshop that the experts would have the opportunity to revise their assessments in light of the feedback and discussions (see discussion of Workshop 4 in Section 2.3.3.7). The importance of incorporating a full range of uncertainty in each model parameter was stressed at the workshop, as was the need for each expert to thoroughly document the technical basis for his judgment.

After Workshop 4, the experts made additional revisions to their elicitation summaries to reflect any changes in their judgments following the interactions with the other panel members. These revised summaries became the "Third Draft" set. Also following Workshop 4, sensitivity information on each expert's assessment was provided so that the individual could better understand the implications of the various components of his assessments. When the "Third Draft" summaries, with their revised model parameters, were received by the Geomatrix elicitation team, a telephone call was made to each expert to discuss any missing or inconsistent element(s) and confirm that the expert was confident that each element accurately reflected his best judgments.

The "Third Draft" summaries were reviewed for thoroughness of documentation by MDT member J. C. Stepp. Dr. Stepp's experience both as a former member of the NRC and as an applicant before the NRC make him uniquely qualified to comment on this aspect of the project. Dr. Stepp stated that excellent documentation is necessary because future reviewers would require that the technical bases (i.e., processes, models, data) for the interpretations and conclusions (i.e., weights on alternatives) are supported by adequate investigations and data.

All of the experts responded to the comments made by Dr. Stepp, and their revisions resulted in "Fourth Draft" elicitation summaries. These summaries were reviewed by the MDT elicitation team for thoroughness, clarity, and editorial consistency, and "Fifth Drafts" were returned to each expert for review and approval. The approved summaries, which included any revisions indicated by the expert, are the elicitation summaries provided in Appendix E.

2.3.4.4 Feedback and Sensitivity. In an overall sense, feedback to the experts occurred throughout the PVHA project, primarily through the process of expert interaction. By making presentations at workshops and otherwise presenting ideas for general consideration, the experts received feedback from their peers on their models and interpretations.

More formal feedback loops, including sensitivity analyses, occurred throughout the elicitation process. These feedback loops are summarized as the following:

- Written elicitation summaries were reviewed by R.Smith, MDT, for technical consistency and clarity.

- Written elicitation summaries were provided to all panel members for their review and discussion at Workshop 4.

- The experts presented their interpretations on key issues to the panel for their review (including maps on display) at Workshop 4. Discussion included the technical basis for the interpretations.

- Preliminary PVHA results were shown and the relative importance of various elements of the assessment were identified at Workshop 4. The experts were asked to focus on the key elements in the revision of their assessments.

- Immediately following Workshop 4, each expert was provided with information and sensitivity analyses that allowed him to better understand the implications of his assessments. Examples of this feedback for a single expert are shown on Figures 2-3 and 2-4. These figures show the effect of alternative spatial smoothing parameters on the predicted spatial density of future volcanic events (Figure 2-3) and on the estimate of the volcanic hazard at the repository site (Figure 2-4).

- Written elicitation summaries were reviewed by J. C. Stepp, MDT, from the standpoint of the adequacy and completeness of documentation of the technical basis for judgments.

- Final review of elicitation summaries by MDT to ensure accuracy and clarity.

The feedback-revision process for reviewing and documenting the expert assessments was rigorous and placed considerable burden on the experts to defend/revise their assessments and to provide appropriate documentation. In all cases, the experts on the panel responded positively to technical criticisms of their interpretations and to reviews of their documentation. The resulting assessments and summaries reflect the significant effort provided by each member of the expert panel.

2.3.4.5 Aggregation of Expert Assessments. As discussed in Section 2.2.11, the approach taken for the combination, or aggregation, of the expert assessments is equal weighting. Importantly, this approach was not a "default" but was a goal throughout the project. Accordingly, the proper conditions were created throughout the project to ensure that a deliberate, defensible decision could be made to use equal weights. Section 2.2.11 summarizes the actions that were taken to create these conditions.

It should be noted that, in accordance with the guidance provided by the SSHAC study (SSHAC, 1995), conditions could have been such that differential weights may have been necessary. For example, if a member of the expert panel has been unwilling to forsake the role of a *proponent*, who advocates a singular viewpoint, for that of an *evaluator*, who is able to consider multiple alternative viewpoints, the expert may have been given less weight or removed from the panel entirely. Or the interpretations of a member of the panel would be given less weight if he were declared by the rest of the panel to have extreme, outlier views relative to **both** the views of the rest of the panel and the larger technical community as well. In this case, a weight of 1/10 (1 view in 10 on the panel) would be excessive relative to the true weight of his views when compared to the larger community (say, 1 in 100 might share the view).

Another alternative to a "mechanical" weighting scheme was considered: that of "behavioral" aggregation through development of a consensus assessment (an example of this approach for earthquake ground motions is given in SSHAC, 1995). This approach is particularly suited to common assessments across a group of experts. For example, a probability distribution function (PDF) defining the value of a continuous parameter could be elicited from a group of experts. The elicitation could occur in a group setting with a technical facilitator/integrator (TFI) ensuring that the PDF captured the range of estimates provided by the experts and "weighing" (rather than numerically weighting) the various expert assessments until a PDF was developed that all of the experts would agree properly captures their assessments *as a group.*

Although this approach has considerable appeal and could be potentially applied to a few assessments the PVHA experts had in common, the approach could not be generally applied to this project. This is because most aspects of the PVHA were very specific to the expert's interpretation. For example, each expert had a slightly different definition of a volcanic "event" and, therefore, the event counts at different locations (although a continuous parameter value) were based on each expert's definition. Also, the descriptions of the spatial occurrence of future volcanic events were based on either the location of volcanic events—again based on a particular event definition—or each expert's particular maps of source zones. Parameter values (e.g., rates) that characterize the zones are source-specific. As a result of these basic differences in the approaches and assessments among the experts, there was no real opportunity to conduct a facilitated behavioral aggregation. It should be noted, however, that the intensive interactions among the experts throughout the project provided a considerable element of informal behavioral aggregation.

TABLE 2-1
QUESTIONS TO CONSIDER
IN PREPARING FOR PVHA ELICITATIONS

- *What is your overall conceptual model(s) for the occurrence of volcanism in the Yucca Mountain region* (including volcanic history, tectonic regime, magma dynamics and sources, etc.)?
- *What is your relevant region(s) of interest for evaluating PVHA at Yucca Mountain* (indicate on map and discuss rationale)?
- *What is your definition of volcanic "event"* (including consideration of spatial proximity, timing, geochemical affinities, etc.)?
- *What other definitions are particularly relevant to your assessment* (e.g., volcanic "center," eruptive episode, etc.)?
- *What method(s) do you choose to portray the future spatial location of volcanism* (alternative spatial methods discussed include a large homogeneous region, source zones defining areas of different rates from a background zone, parametric approaches to source zones, and non-parametric approaches)?
- *For your selected spatial method(s), provide the interpretations and parameters required* (e.g., map of the relevant region, zone configurations shown on maps, functional form of field configuration, smoothing assumptions, etc.).
- *What method(s) do you choose to define the recurrence rate of future volcanic activity* (e.g., event counts, time-predictable methods, temporal homogeneity, non-homogeneity, etc.)?
- *For your selected recurrence method(s), provide the parameters that define the model* (e.g., relevant time period for event counting, event counts for region and for zones, Weibull parameters, time to next event, etc.).
- *What types of volcanic events do you feel could occur and what are their likelihoods* (e.g., dike intrusion, scoria cones, hydro-magmatic, etc.)?
- *For each type of volcanic event that you feel could occur, what are the dimensions of that event* (e.g., length, width, orientation of dikes; scoria cone dimensions; depth/volume of hydro-magmatic explosion, etc. all defined in terms of distributions)?

FIGURE 2-1
GROUND RULES FOR WORKSHOPS

1. The workshops are an opportunity for the Expert Panel to:

   Exchange data
   Present interpretations
   Challenge and defend technical hypotheses
   Be trained in elicitation procedures
   Gain information on the project
   Interact and ask questions

   Therefore, the focus of each workshop is the *Expert Panel*

2. The Methodology Development Team (MDT) runs the workshops and is responsible for keeping to the schedule, logistics, etc.

3. The conduct of the technical discussions at the workshops will be at the highest professional level. Personal attacks or confrontations will not be permitted (even those directed at the MDT).

4. Discussions will be among the Expert Panel and the Presenters.

5. Observers are provided with a period each day for brief statements or questions (3 minutes each).

6. If an Observer has a burning question, please write it down and give to a member of the MDT; they will attempt to have it answered during the course of the discussions.

7. The data bases supplied to the Expert Panel will not be supplied to the Presenters or Observers; a list of all materials supplied will be available.

8. A workshop summary will be supplied to all workshop participants who have signed in.

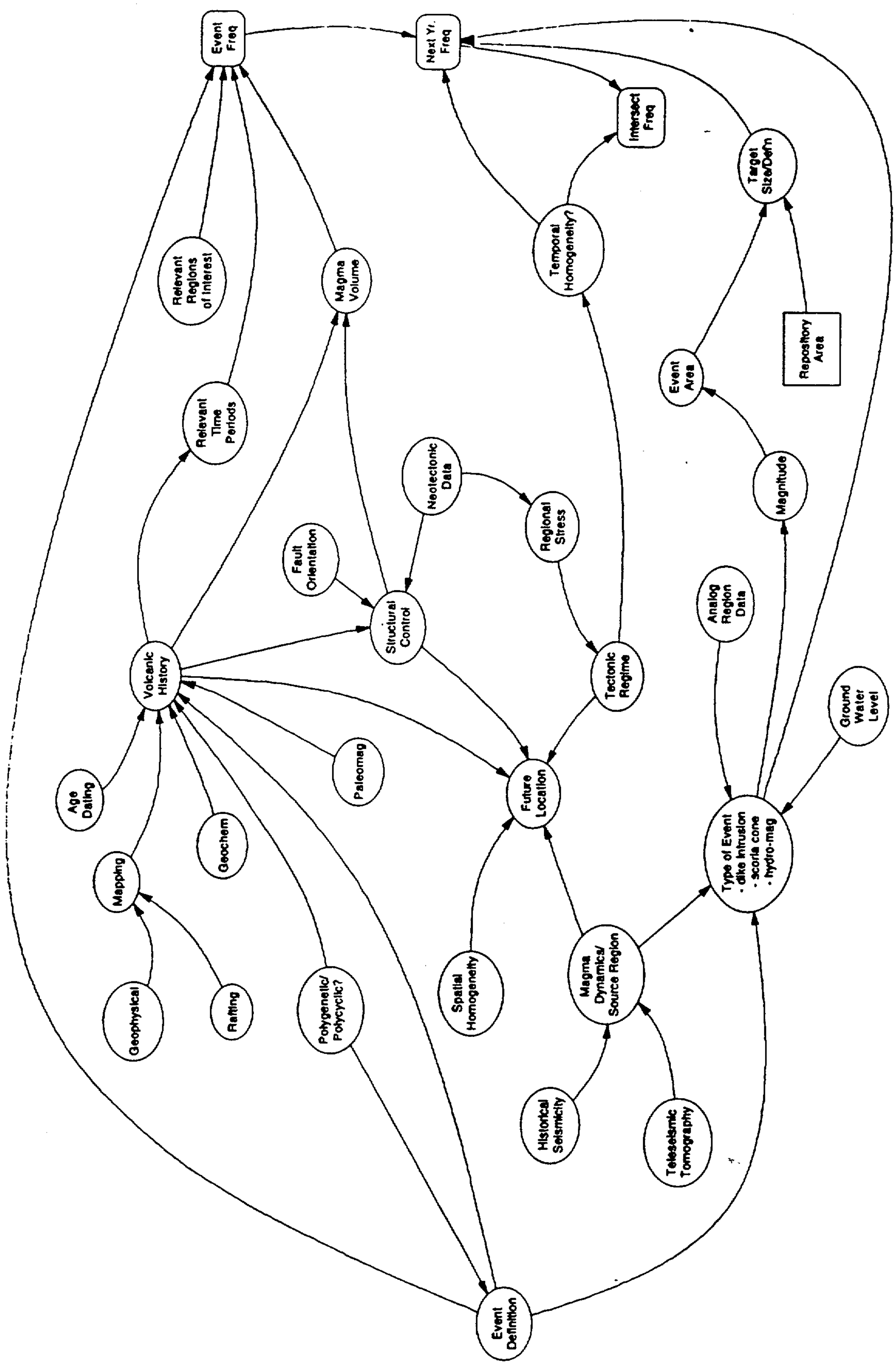


Figure 2-2 Influence diagram developed by the expert panel for the Yucca Mountain PVHA.

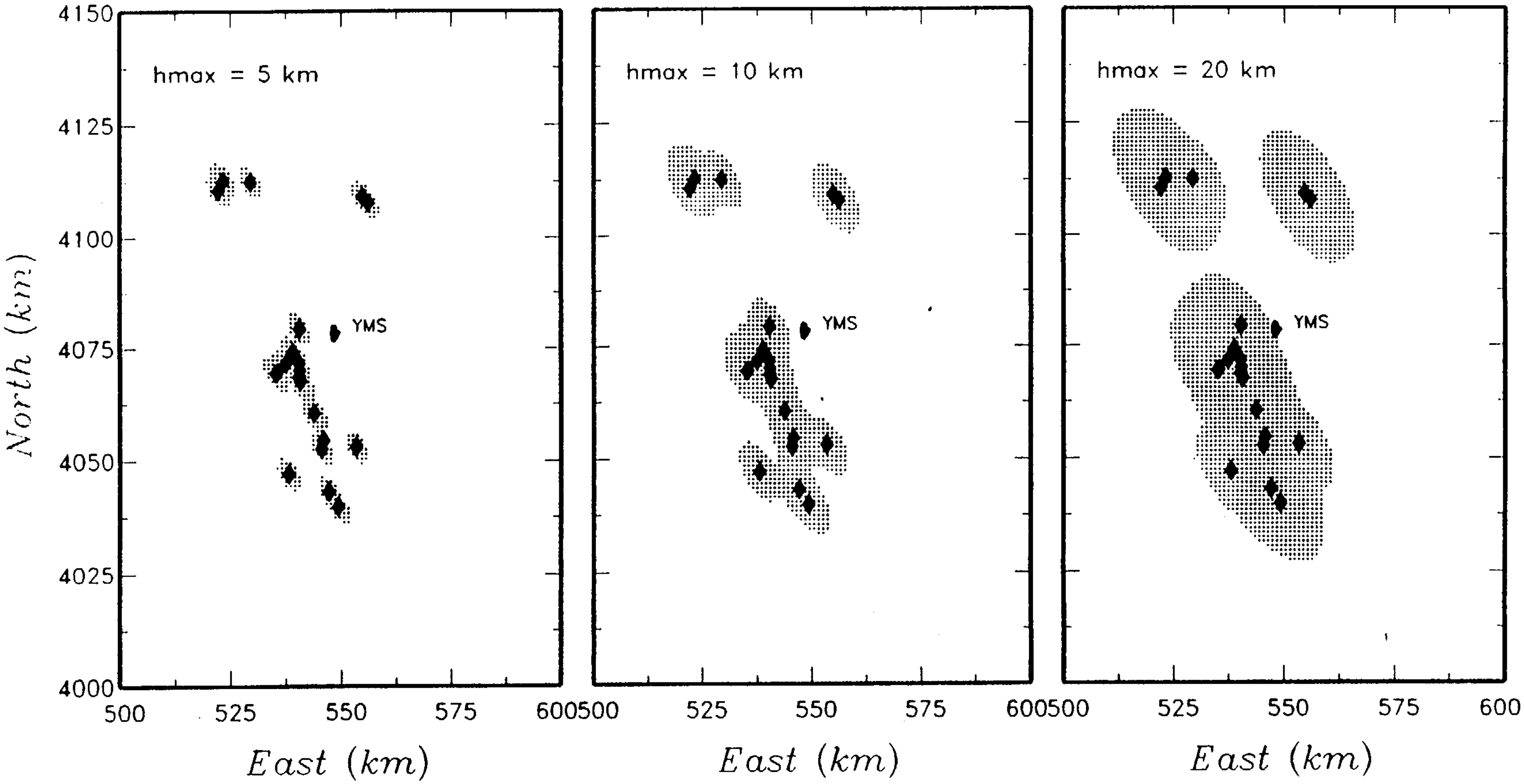


Figure 2-3 Kernel density estimates of the spatial distribution of future volcanic events. Stippled areas show the 95 percent density region computed using smoothing parameters of 5, 10, and 20 km. The density estimates were computed using the maximum number of events assessed for the post-5 Ma time period. YMS refers to the proposed Yucca Mountain repository site.

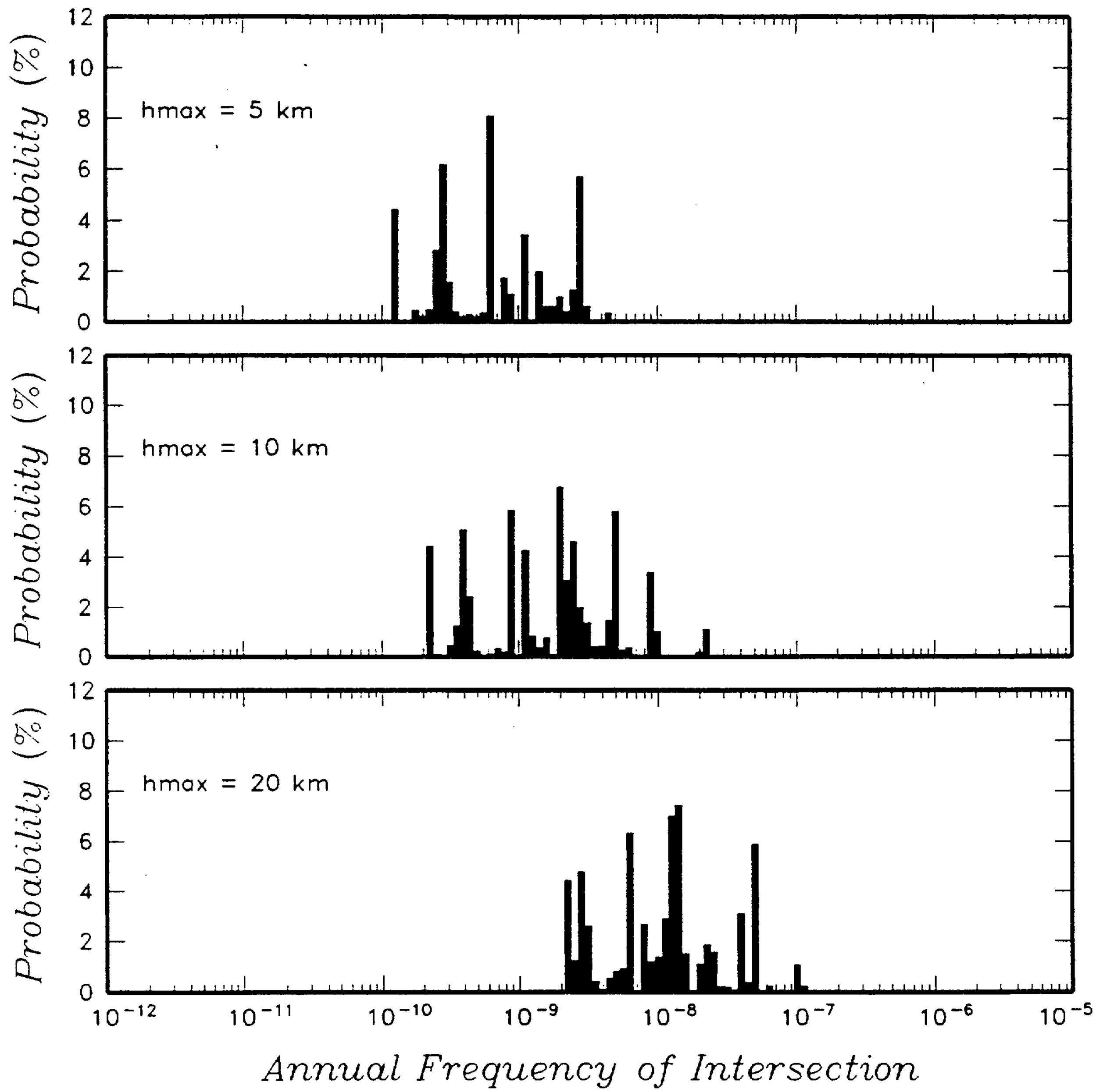


Figure 2-4 Effect of alternative values for the smoothing parameter on the computed distribution for annual frequency of intersecting the repository site. The hazard distributions were computed using the kernel density approach and smoothing parameters of 5, 10, and 20 km.

3.0 VOLCANIC HAZARD ANALYSIS

This section presents the probabilistic volcanic hazard analysis (PVHA) model developed for this study. Section 3.1 describes the mathematical formulation for the PVHA. Details of the mathematical model are developed in Appendix F. Section 3.2 translates the individual experts' assessments into a common hazard model format and summarizes their assessments of various components of the model. The results of the hazard analysis are presented in Section 4.

3.1 VOLCANIC HAZARD MODEL FORMULATION

3.1.1 Basic Formulation

The quantitative product of the PVHA study is the probability that the proposed repository site will be intersected by a volcanic event during the next 10,000 years. Because the probability is small it can be estimated to a very close (and conservative) approximation by the expected number of intersections regardless of the appropriate temporal model for volcanic event occurrence.[1] The specific measure of volcanic hazard used in this analysis is the mean number of intersections per year or mean annual frequency of intersection, termed ν_I. Given the fact that the time period of interest for the PVHA assessment is very small compared to the time scale for changes in volcanic rates (millions of years), the mean annual frequency of intersection is not expected to vary significantly during 10,000 years. Thus the mean number of intersections is very close to $\nu_I \cdot 10^{-4}$, which is, in turn, slightly greater than the probability of intersection. For simplicity, we shall refer below to this "mean annual frequency" as the "frequency."

The frequency of intersection can be represented as the product of two quantities, the frequency of occurrence and the likelihood that the event will intersect the repository. Figure 3-1 shows schematically the basic formulation for PVHA calculation. If one assumes that volcanic events occur randomly in time with a constant rate, then a natural estimate of the frequency of occurrence is the number of observed events divided by the time period of observation. If one assumes that volcanic events occur randomly within a region *R* with uniform spatial density, then a natural

1 This is shown by comparing the mean number of intersections [equal to $0 \cdot P(0)+1 \cdot P(1)+2 \cdot P(2)+....$] to the probability of one or more intersections [equal to $P(1)+P(2)+....$]. When P(2) is much smaller than P(1), which is the case for rare events, the mean number if events is close to P(1 event).

estimate of the spatial density of events is one over the area of region R. Using these estimates, the estimated annual frequency of intersection, ν_I, is given by the expression

$$\nu_I = \frac{N(R,T)}{T} \cdot \frac{a_r^e}{A_R} \tag{3-1}$$

where $N(R,T)$ is the number of events that have occurred in region R in time period T, A_R is the area of region R, and a_r^e is the area of the repository, adjusted for the dimensions of the effect of the event. For example, if the repository were circular, with radius r_r, and events that occur within a distance d_e of the repository result in intersection, then $a_r^e = \pi(r_r+d_e)^2$ (see Figure 3-1).

The members of the expert panel used a variety of methods to model the volcanic hazard at the proposed Yucca Mountain repository site. All of these models can be represented by a generalized form of Equation **(3-1)**:

$$\nu_I(t) = \iint_R \lambda(x,y,t) \cdot P_I(x,y)\, dx\, dy \tag{3-2}$$

In Equation **(3-2)** $\lambda(x,y,t)$ is the rate density (frequency of events per unit time, per unit area) at point (x,y) and time t in the region of interest, R, and $P_I(x,y)$ is the conditional probability that a volcanic event occurring at point (x,y) will intersect the repository. The generalized model allows for a spatially and temporally varying rate of volcanic events.

The generalized model of Equation **(3-2)** can be related to the basic model of Figure 3-1 and Equation **(3-1)** by considering the rate density of volcanic events to be uniform over region R and time T. Thus the estimate of $\lambda(x,y,t)$ is $N(R,T)/(T \cdot A_R)$, a constant value independent of location in region R and independent of time within time period T. The conditional probability of intersection becomes a step function, $P_I(x,y) = 1$ for (x,y) inside of the effective region of the repository, r^e, and 0 everywhere else. As a result:

$$\nu_I(t) = \iint_R \lambda(x,y,t) P_I(x,y)\, dx\, dy = \frac{N(R,T)}{TA_R} \iint_{r^e} dx\, dy = \frac{N(R,T)}{TA_R} a_r^e \tag{3-3}$$

The generalized model of Equation **(3-2)** used in this analysis separates the PVHA into two parts: (1) an assessment of the spatial and temporal frequency of volcanic events, and (2) an assessment of the spatial extent of an event, given that it occurs. This separation provides a means of easily incorporating the variety of approaches to volcanic hazard published in the literature (and used by the experts) into the common model. The published approaches (e.g., Crowe et al., 1982, 1992; Ho et al., 1991; Sheridan, 1992; Connor and Hill, 1995) consider volcanic events to be represented by points and use various point process methods to model the distribution of future events in time and space. For the most part, these models consider the temporal and spatial aspects of the problem in such a way that the rate density parameter, $\lambda(x,y,t)$, can be written as the product of a rate parameter, $\lambda(t)$, and a spatial density, $f(x,y)$. The generalized model of Equation **(3-2)** becomes:

$$\nu_I(t) = \iint_R \lambda(t) \cdot f(x,y) \cdot P_I(x,y)\, dx\, dy \qquad \textbf{(3-4)}$$

Referring again to the simple example of Figure 3-1, the estimate of $\lambda(t)$ is $N(R,T)/T$ and the estimate of $f(x,y)$ is $1/A_R$.

Below, we describe the various models used by the experts to represent the temporal and spatial distribution of future volcanic events in the following sections of the report. First, however, we discuss the approach used to address the uncertainty in specifying volcanic hazard models and model parameters.

3.1.2 Treatment of Uncertainty

The PVHA model of Equation **(3-2)** or **(3-4)** represents the randomness inherent in the natural phenomena of the occurrence of volcanic events. In all assessments of the effects of rare phenomena one is faced with considerable uncertainty in selecting the appropriate models and model parameters arising from limited data and/or alternative interpretations of the available data. It has become a standard-of-practice to explicitly incorporate these additional uncertainties into probabilistic hazard assessments. The most prominent example is probabilistic seismic hazard analysis (PSHA) methodologies used for hazard assessments at critical facilities (National Research Council, 1988).

For this study, we employ the logic tree methodology to incorporate the uncertainty in modeling the spatial and temporal distribution of future volcanic events in the region surrounding the proposed Yucca Mountain site. The logic tree formulation has been well developed for probabilistic seismic hazard analysis (e.g., Kulkarni et al., 1984; Coppersmith and Youngs, 1986; EPRI, 1987; National Research Council, 1988, SSHAC, 1995). The methodology involves setting out the sequence of assessments that must be made in order to perform the analysis and then addressing the uncertainties in each of these assessments in a sequential manner. The logic tree allows for alternative models, hypotheses, and parameter values to be weighted and incorporated into the analysis in a logical and transparent way. Thus, it provides a convenient approach for breaking a large, complex assessment into a sequence of smaller, simpler components that can be more easily addressed.[2]

The simple volcanic hazard model shown on Figure 3-1 will be used to illustrate the logic tree methodology. The three parameters of the hazard model are the time period, T, over which the rate of occurrence of volcanic events is assumed to be constant and representative of the current rate, the region, R, over which the spatial distribution of volcanic events can be considered uniform during time period T, and the actual number of events, $N(R,T)$, that have occurred in region R in time period T. Figure 3-2 shows the alternative assessments that could be made. These involve considering alternative time periods, alternative regions, and the uncertainty in determining the actual number of events that have occurred in the past.

The general structure of a logic tree is shown on Figure 3-3. The logic tree is composed of a series of nodes and branches. Each node represents an assessment of a state of nature (e.g., alternative models or hypotheses) or an input parameter value that must be made to perform the analysis. Each branch leading from the node represents one possible discrete alternative for the state of nature or parameter value being addressed. If the variable in question is continuous, it can be discretized at a suitable increment. The branches at each node are intended to represent mutually exclusive and collectively exhaustive states of the input parameter. In practice, a sufficient number of branches are placed at a given node to adequately represent the uncertainty in the parameter estimation.

Probabilities are assigned to each branch that represent the relative likelihood or degree of belief that the branch represents the correct value or state of the input parameter. These probabilities are assessed conditional on the assumption that all the branches leading to that node represent the true state of the preceding parameters. Because they are conditional probabilities for an assumed mutually exclusive and collectively exhaustive set of values, the sum of the conditional probabilities at each node is unity. The probabilities depend strongly upon expert judgment

2 Note that, although it is similar in appearance, the logic tree is neither an "event" tree nor a "decision" tree; the logic tree deals solely with model and parameter uncertainty associated with limited information.

(subjective probabilities) because the available data are too limited to allow for objective statistical analysis, and because scientific judgment is needed to weigh alternative scientific interpretations of the available data. The logic tree approach simplifies these subjective assessments because the uncertainty in a single parameter is considered individually with all other parameters leading up to that parameter assessment assumed to be known with certainty. Thus, the nodes of the logic tree are sequenced to provide for the conditional aspects or dependencies among the parameters and to provide a logical progression of assumptions from the general to the specific in defining the input parameters for an evaluation. So, for example, the distribution for N, the number of past events, depends on what time period T (e.g., 2 Ma vs. 5 Ma) and region R (R_1 vs. R_2) are under consideration at the node (Figure 3-3).

In most cases, the probabilities assigned to the branches at a node are in units of tenths, unless there is a basis for finer resolution. Usually the weights represent one of two types of probability assessments. In the first, a range or distribution of parameter values is represented by the logic tree branches for that parameter and their associated weights. For example, the volume of basalt erupted during a single past volcanic event is uncertain because of uncertainties in geochronologic analyses of materials and in interpreting eroded land forms. The resulting volume may be represented by a preferred value and a range of higher and lower values, similar to a normal or log normal statistical distribution. This type of distribution can be represented by three (or more) branches of a logic tree. Keefer and Bodily (1983) have shown that most distributions can be reliably represented by three values: the median estimate (with a weight of 0.63) and a higher and lower value (each with weights of 0.185) that represent the 5^{th} and 95^{th} percentiles (e.g., plus or minus 1.65 standard deviations for a normal distribution). Although a large number of branches for an individual assessment can be included on a logic tree, usually the results are not sensitive to having more than about three branches at any one node in a logic tree having many nodes. If the assessments are provided in the form of a specific probability density function or in the form of a cumulative probability distribution, the assessment can be discretized into a suitable increment for input into the logic tree format.

In some instances, the uncertainty in a parameter assessment can be estimated using formal statistical estimation techniques and the resulting continuous distribution discretized for use in the logic tree formulation. For example, the rate of occurrence of volcanic events in Equation (3-1) is estimated by the quantity N/T. If one assumes that the occurrence of volcanic events conforms to a Poisson process, then there are explicit probabilistic models that describe the probability distribution for the rate parameter of a Poisson process estimated from a data set of finite size.

Appendix F describes the procedure used in this study to develop a discrete distribution describing the uncertainty in the rate of occurrence estimated from an observed number of events.

A second type of probability assessment to which logic trees are suited is in indicating a relative preference for, or degree of belief in, two (or more) alternative hypotheses. For example, the appropriate geologic time period for assessing the current rate of volcanic events is uncertain. Two possible alternatives might be the Quaternary period (past 2 million years) or the Pliocene and Quaternary (past 5 million years). Based on the pertinent data, a relative preference for these alternatives can be expressed by the logic tree weights. A strong preference for one over the other is usually represented by weights such as 0.9 and 0.1 for the two alternatives. If there is no preference for either hypothesis, they are usually assigned equal weights (0.5 and 0.5 for two hypotheses). Increasing the weight assigned to one hypothesis from 0.5 to 0.9+ reflects an increasing preference for that alternative. Although the logic tree weights are ultimately subjective judgments based on available information, it is important to document the data and interpretations that led to the assessment of the alternatives being considered and the assignment of weights in order that the process can be reviewed by others.

The example logic tree shown on Figure 3-3a contains three nodes, one for each of the three parameters of the simplified model of Equation **(3-2)**. In this example, the parameter that is clearly dependent on the other assessments is the event counts, $N(R,T)$, which is a function of the time period and region. Therefore, this node is logically placed last (farthest to the right) in the logic tree. However, the sequence of the nodes is not fixed and is decided primarily as a matter of convenience in making the assessments. Once a logic tree has been developed, one can invert the order of the nodes, as will be illustrated later in Section 3.2.

The simplified model shown on Figures 3-2 and 3-3a considered two alternative time periods (3.2 and 10.0 My) and two alternative regions (R_1 with area 10,000 km^2 and R_2 with area 5,000 km^2). The assessment has been made that the shorter time period is strongly preferred (probability 0.8) to the longer time period (0.2) and that region R_1 is slightly preferred (probability 0.6) to region R_2 (0.4). For each combination of T and R, two alternative values of $N(R,T)$ have been assessed. These alternatives are based on the assumption that the larger volcanic centers represent one or more events. Two hypotheses are considered, all of the larger centers represent single events or all of the centers represent multiple (2 or 3) events. These two hypotheses are considered equally likely to represent the true history of volcanism in the region and are given equal weight.

The logic tree shown on part (a) of Figure 3-3 defines a discrete distribution for the frequency of intersection, ν_I, computed using Equation **(3-2)**. The eight possible parameter combinations, the probability of each parameter combination, and the resulting frequency of intersection are listed on part (b) of Figure 3-3 for an effective repository area, a_r^e of 10 km^2. The resulting distribution is shown on part (c) of Figure 3-3. The probability that the frequency of intersection will take one of the eight possible values is equal to the joint probability of the set of parameters *T*, *R*, and *N(T,R)* being the true parameter values and is equal to the product of the conditional probabilities following a particular path through the logic tree. For example, the probability that the frequency of intersection equals $4 \cdot 10^{-9}$ equals the product of the probability that *T* should be 3.2 Ma, the probability that R_I is the appropriate region, and that *N(T,R)* equals 13 events.

The discrete distribution for the frequency of intersection shown on part (c) of Figure 3-3 can be used to compute the expected or mean value of ν_I given the uncertainty in the input parameters *T*, *R*, and *N(T,R)*. The expected value, $E[\nu_I]$, is obtained by summing the individual estimates of ν_I multiplied by the probability that they are the "correct" estimate:

$$\begin{aligned} E[\nu_I] &= 0.24 \cdot 4.0 \cdot 10^{-9} + 0.24 \cdot 3.8 \cdot 10^{-9} + 0.16 \cdot 6.9 \cdot 10^{-9} + 0.16 \cdot 6.3 \cdot 10^{-9} + \\ &\quad 0.06 \cdot 2.0 \cdot 10^{-9} + 0.06 \cdot 1.5 \cdot 10^{-9} + 0.04 \cdot 3.2 \cdot 10^{-9} + 0.04 \cdot 2.4 \cdot 10^{-9} \\ &= 4.4 \cdot 10^{-9} \text{ events/year} \end{aligned}$$

Formally, this is given by the equation

$$E[\nu_I] = \sum_i \sum_j \sum_k \frac{N_k(T_i,R_j)}{T_i \cdot A_{R_j}} \cdot P(T=T_i) \cdot P(R=R_j) \cdot P(N=N_k \mid T_i,R_j) \tag{3-5}$$

The variance in the estimate of ν_I is computed in a similar fashion and is defined formally by:

$$Var[\nu_I] = \sum_i \sum_j \sum_k \left(\frac{N_k(T_i,R_j)}{T_i \cdot A_{R_j}} - E[\nu_I] \right)^2 \cdot P(T=T_i) \cdot P(R=R_j) \cdot P(N=N_k \mid T_i,R_j) \tag{3-6}$$

The resulting coefficient of variation (square root of the variance/mean) is 0.37.

Part (d) of Figure 3-3 shows the cumulative distribution for the frequency of intersection, ν_I, developed from the discrete distribution shown on part (c). This distribution can be used to obtain confidence intervals for the frequency of intersection that reflect the uncertainties in defining the hazard analysis models and parameters. The actual logic trees developed to represent the volcanic hazard models of each of the experts have thousands of branches, resulting much smoother density estimates that those show on Figure 3-3 for this simple example.

In the following sections the various hazard models used by the experts are described in terms of the basic formulation and the treatment of uncertainty. Details of the mathematical formulations are provided in Appendix F.

3.1.3 Locally Homogeneous Spatial and Temporal Model

The basic assumption of the homogeneous model is that one can identify a region where the rate of occurrence of volcanic events can be considered uniform in both time and space over the time period of interest to the hazard assessment. The simplified hazard model of Figure 3-1 is an example of a homogeneous spatial and temporal model. It is of course recognized that the rate of volcanic events is not spatially and temporally homogeneous over the entire western United States. One must identify zones where the assumption of homogeneity can be applied. Therefore, we use the term "locally homogeneous" to describe the model in which the region of interest is divided into one or more zones, each with its own homogeneous rate of volcanic events.

The assumption of a uniform spatial and temporal rate density of volcanic events within a locally homogeneous zone is consistent with a homogeneous Poisson process. Homogeneous Poisson models are commonly used to represent the hazard from rare events. In particular, the Poisson model forms the basis of the probabilistic seismic hazard methodology developed by Cornell (1968, 1971). It has also been shown that the Poisson model provides a reasonable representation for the combined effects of the contributions from multiple independent processes, even when the individual processes are non-Poisson in nature (Brillinger, 1982).

The locally homogeneous spatial and temporal model is implemented by dividing the region of interest into a number of non-overlapping zones, Z_i, $i = 1$ to n. Figure 3-4 shows an example of subdividing the region shown on Figure 3-1 into two zones, a large region with diffuse activity, Zone A, and a smaller region with a concentration of activity, Zone B. In this type of zonation the larger zone is often called a background zone that is used to represent a "background" rate of activity in the region outside of the more active volcanic fields.

Within each zone the rate density of volcanic events can be modeled by separating the temporal and spatial aspects using Equation **(3-4)**. Given the assumption of a uniform spatial density, the density parameter is equal to the inverse of the zone area, A_i [$f(x,y) = 1/A_i$]. If the rate of occurrence, λ, is to be estimated from the observed data for the zone, then the maximum likelihood estimate is given by the number of observed events within a specified time interval, $N(Z_i,T)$, divided by the time interval, T [$\lambda = N(Z_i,T)/T$]. The frequency of intersection due to the occurrence of volcanic events in zone i is thus given by

$$\nu_{I_i} = \frac{N(Z_i,T)}{T}\iint_{Z_i}\frac{1}{A_i}\cdot P_I(x,y)\,dx\,dy = \frac{N(Z_i,T)}{T}\cdot(\bar{P}_I)_i \qquad \textbf{(3-7)}$$

where $(\bar{P}_I)_i$ is the spatial average of the conditional probability of intersection within zone i. The total hazard is obtained by summing the hazard contributed by each zone

$$\nu_I = \sum_{i=1}^{n}\frac{N(Z_i,T)}{T}\cdot(\bar{P}_I)_i \qquad \textbf{(3-8)}$$

The boundary between two zones represents a point where there is an abrupt step function in the volcanic event rate density. Several of the experts chose to consider a gradual transition between zones in areas where there was a large change in rate density and the modeling of this change is important to the site hazard. The eastern edge of Crater Flat is an example in which the hazard is very sensitive to the manner of the rate density changes. The gradual transition was implemented by assuming that the rate density within zone i decays linearly to zero with distance from the zone boundary over a specified distance, h. The effect is an increase in the area of the zone approximately equal to $h/2$ times the length of the zone perimeter along the portion of the zone where a gradual transition is assumed to occur, and an increase in the area over which the spatial average of P_I is computed (see Appendix F).

The uncertainties in the homogeneous spatial and temporal model include defining the appropriate zones, defining the appropriate time period, and estimating the number of events that have occurred within that time period. These uncertainties are modeled in the PVHA by considering alternative zonations, alternative time periods, alternative estimates of the number of events that have occurred at each volcanic center, and alternative boundary conditions (abrupt versus gradual transition). In addition, there is uncertainty in estimating the true rate of volcanic events given that there is only a limited data set. The uncertainty in the rate parameter, λ, can be estimated using objective statistical techniques. Weichert (1980) presents a method of estimating confidence intervals for a Poisson rate. His approach (described in Appendix F) uses a χ^2 distribution to represent the confidence interval in λ. In the PVHA, the uncertainty in λ was represented by the three point approximation of Keefer and Bodily (1983) discussed above. The maximum likelihood value, $N(Z_i, T)/T$, was given a weight of 0.63. The 5th and 95th percentiles of the confidence interval for λ were estimated using Weichert's χ^2 approach and each was given a weight of 0.185.

3.1.4 Nonhomogeneous Spatial Models

Nonhomogeneous spatial models provide a means of specifying a smooth variation of the spatial density of volcanic events, $f(x,y)$, within the region of interest. Two types of nonhomogeneous spatial models were used by the experts, parametric models and nonparametric models.

Parametric Spatial Density Function. Sheridan (1992) has developed a model for volcanic fields in which the spatial density of events is represented by a bivariate Gaussian distribution. The resulting volcanic field has an elliptical shape defined by five parameters, the coordinates of the center of the field, the length of the major and minor axes, and the orientation of the major axis. Figure 3-5 shows an example of a bivariate Gaussian field representation of the volcanic events in Crater Flat. The spatial density of future events associated with the field is given by the expression

$$f(x,y) = \frac{e^{-[(\mathbf{x}-\boldsymbol{\mu})^T\Sigma^{-1}(\mathbf{x}-\boldsymbol{\mu})]/2}}{2\pi|\Sigma|^{1/2}} \qquad \textbf{(3-9)}$$

where $\mathbf{x}$ is the location of point (x,y), $\boldsymbol{\mu}$ is the location of the center of the field (mean of x and y for all past and future events) and Σ is the covariance matrix describing the distribution about the field center for the x and y locations of all past and future events associated with the field. The covariance matrix defines the size and shape of the field. For example, the ellipse that encloses 50 percent of the density of the field has dimensions that are approximately 1.2 times the standard deviation of the x and y coordinates of the population of events within the field.

The specification of the Gaussian field parameters can be through reference to better developed fields considered analogous (e.g. Sheridan, 1992; Crowe et al., 1995) or they can be estimated directly from the observed events associated with the field. The experts chose to estimate the parameters of Gaussian volcanic fields from the local data using two approaches.

In the first approach, a set of volcanic events that constitute a field was identified. The five parameters of a bivariate Gaussian distribution were then estimated directly from the x and y locations of the observed events using standard maximum likelihood estimators of the mean of x and y and the covariance matrix of x and y. These parameters provide a best estimate of the field and Equation **(3-9)** can then be used to compute the spatial density function for future events associated with the field.

Uncertainty in the field parameters results from uncertainty in defining the appropriate set of volcanic events that constitute the field. In addition, there is uncertainty in estimating the field parameters because of the limited size of the data set. This uncertainty was incorporated into the PVHA by defining a joint distribution for the five field parameters. Asymptotic standard errors were estimated for each of the field parameters from the maximum likelihood fit to the observed data. The five parameters were then varied by ±one standard error to create 3^5 (243) possible sets of field parameters. The likelihood that each parameter set describes the population producing the observed field data was then computed and the resulting set of likelihoods were normalized to define relative weights to assign to each parameter set. For example, Figure 3-6 shows the set of possible field shapes obtained from fitting the data shown on Figure 3-5 in Crater Flat. Shown are only the 27 field shapes arising from uncertainty in the field size and shape parameters defined by the three parameters of the covariance matrix of x and y.

The second approach for specifying the field parameters is based on the use of the local geology to define the likely geometry of a field. For example, a zone may be defined that is considered to represent a volcanic field. However, instead of assuming that the zone represents a locally homogeneous field, it is assumed that the zone boundary approximately defines a specified density contour of the field (such as the 90^{th} percentile). A set of field parameters is then found that minimizes the difference between the defined approximate field boundary and the bivariate Gaussian ellipse that encompasses the specified density percentile. Figure 3-7 shows an example of fitting a 95^{th} percentile density ellipse to a specified field boundary. Uncertainty in the field parameters defined in this approach was specified by considering alternative zone boundaries and/or alternative values for the density percentile contained within the specified boundary.

The bivariate Gaussian volcanic field model defines the spatial density of future events associated with a field. The rate of occurrence of the events can be computed using the number of observed events in the field and the homogeneous temporal model defined above. The frequency of intersection is then computed using Equation **(3-4)**. It application, the volcanic field was often considered to be superimposed on a larger spatially homogeneous background zone representing the hazard from random volcanic events not associated with an identifiable field.

Nonparametric Spatial Density Function. Nonparametric spatial densities of events can be estimated using various types of smoothing operators combined with the observed data. Connor and Hill (1995) present three types of nonhomogeneous spatial models for estimating volcanic hazards, spatial-temporal nearest neighbor density estimation, kernel density estimation, and nearest neighbor kernel density estimation. Of the three, the kernel density estimation technique probably is the most widely used in the general field of density estimation, and was the method selected by the experts for nonparametric estimation of the spatial density of future volcanic events.

Nonparametric density estimation assumes that future events are likely to occur "near" the existing events. In the kernel density estimation technique, near is defined by a parametric density function, with characteristic dimension h, centered on each event. The process is illustrated in one dimension on Figure 3-8. Three events are located along the x axis, as indicated on plot (a) of the figure. At the location of each event a parametric kernel function is placed. The kernel has the properties of a symmetric probability density function such that the area under each kernel equals unity. The combined density function at a point is computed by summing the values of the individual kernel density functions at that point. The function is then normalized by its integral, which is equal to the number of points for infinite boundary conditions. The resulting density function is shown on plot (b) of Figure 3-8.

A wide variety of kernel functions have been developed for density estimation. Two common forms are the Epanechnikov and Gaussian kernels. The Epanechnikov kernel was used by Connor and Hill (1995) and has the following form for two-dimensional density estimation
(Silverman, 1986)

$$K^E(d_i) = \frac{2}{\pi h^2}\left[1 - \frac{d_i^T d_i}{h^2}\right] \quad \text{for } \frac{d_i^T d_i}{h^2} < 1 \qquad \textbf{(3-10)}$$

$$= 0 \qquad \text{otherwise}$$

where $d_i^T d_i$ is the distance between point (x,y) and event i (d_i is the vector of relative coordinates), and h is the smoothing constant. The Epanechnikov kernel is shown on plot (a) of Figure 3-9 for h equal to 1. The Epanechnikov kernel has an abrupt termination at a distance h from each data point (volcanic event) and thus results in zero density at distances greater than h from all data points.

The Gaussian kernel has the form of a two-dimensional Gaussian density function:

$$K^G(d_i) = \frac{e^{-d_i^T d_i / 2h^2}}{2\pi h^2} \tag{3-11}$$

The parameter h in the Gaussian kernel represents one standard deviation of a normal distribution. Plot (b) of Figure 3-9 shows a Gaussian kernel with h also equal to 1. The Gaussian kernel does not have the abrupt edge of the Epanechnikov kernel and is much more diffuse for the same value of h.

Silverman (1986) indicates that similar results can be achieved with a variety of kernel types, with the choice primarily motivated by ease of computation. In particular, Silverman indicates that equivalent results can be achieved using the Gaussian and Epanechnikov kernels if the value of h used with the Gaussian kernel is a factor of ~2.5 times smaller than the value of h used with the Epanechnikov kernel. Plot (c) on Figure 3-9 shows a Gaussian kernel with h equal to 0.4. The resulting kernel density function has approximately 99 percent of density with the limits of ±1, compared to 100 percent for the Epanechnikov kernel with h equal to 1.

The kernel functions defined by Equations **(3-10)** and **(3-11)** are axisymmetric. However, anisotropic kernel functions can be used to introduce a preferred orientation for smoothing, perhaps representing the interpretation of an underlying structural control. In this approach a covariance matrix is defined to describe the shape of the kernel density function in a similar manner to the parametric Gaussian field model defined in Equation **(3-9)**. The details of the use of an anisotropic kernel are presented in Appendix F. Using the kernel smoothing approach, the spatial density of volcanic events in the region is given by:

$$f(x,y) = \frac{1}{N(R,T)} \sum_{i=1}^{N(R,T)} K(d_i,h) \tag{3-12}$$

The normalizing constant of $1/N(R,T)$ is introduced to make $f(x,y)$ a density function that integrates to unity.

If the kernel density function is to be limited to the boundaries of a specific zone, Z, then the normalizing constant is replaced by the integral of the smoothing function over the source zone and Equation **(3-12)** becomes:

$$f(x,y) = \frac{\sum_{i=1}^{N(R,T)} K(d_i,h)}{\iint_Z \sum_{i=1}^{N(R,T)} K(d_i,h)\,dx\,dy} \quad \textbf{(3-13)}$$

This is the edge effect discussed by Connor and Hill (1995).

The primary issue in applying kernel density estimation is the selection of the appropriate value of the smoothing constant, h. Silverman (1986) discusses multiple approaches for selecting h, including subjective judgment, simple formulas based on the scatter in the data, and various statistical methods. Connor and Hill (1995) use cluster analysis techniques to identify maximum cluster lengths in the Yucca Mountain data. They then use these lengths as smoothing distances for the Epanechnikov kernel, which has an abrupt edge or limiting distance.

The volcanic experts used two approaches for selecting h. They either used physical arguments, such as those employed by Connor and Hill (1995), or used a technique similar to that illustrated on Figure 3-7 for the parametric Gaussian field. In the second approach, a zone boundary is defined that is assumed to approximate a specified density contour of all past and future events associated with a local volcanic field. The mapped volcanic events associated with the field are then used to construct kernel density functions using a range of values for h. The appropriate value of h is selected to be the one that results in the minimum difference between the zone boundary and the specified density contour computed from the data. This method is completely analogous to that used for the Gaussian field except that the overall field shape is defined by the distribution of the data. Figure 3-10 illustrates the application of this method to the zone boundary shown on Figure 3-7 with a set of possible events that have occurred within the zone. Examples are shown for both the Epanechnikov and Gaussian kernels. The values of h resulting in the best fits are 5.3, and 2.0, respectively. The ratio of the two is 2.6, consistent with the relative values for h discussed by Silverman (1986).

The nonparametric spatial density function defined by Equations **(3-12)** or **(3-13)** is then used to compute the hazard using Equation **(3-4)**. Uncertainty in the density function is modeled by the uncertainty in the event data and by specifying weighted alternative values of h.

3.1.5 Nonhomogeneous Temporal Models

Nonhomogeneous temporal models provide a means of allowing for a time varying rate of volcanic events, $\lambda(t)$, within a zone or region of interest. To a first approximation, this is achieved by considering alternative time periods for the homogeneous Poisson model, assuming that the instantaneous rate changes very slowly (over millions of years). Nonhomogeneous temporal models provide an approach for estimating the instantaneous rate of volcanic events when it is assumed to vary over time scales on the order of the period of interest for hazard estimation. The nonhomogeneous temporal models considered by the experts were of the general form that defines a monotonic change in the rate with time. Two models were considered, the nonhomogeneous Poisson process with a Weibull rate function (Ho, 1991, 1992), and a volume predictable model.

Nonhomogeneous (Weibull) Poisson Process Ho (1991, 1992) proposed that the rate of volcanic activity in the Yucca Mountain region was not stationary in time and that the time varying rate could be modeled as a nonhomogeneous Poisson process with the time varying rate, $\lambda(t)$ represented by the Weibull function

$$\lambda(t) = \frac{\beta}{\theta}\left(\frac{t}{\theta}\right)^{\beta-1} \qquad \textbf{(3-14)}$$

where t is time measured from t_0 when the process starts, and β and θ are parameters. The homogeneous Poisson process is a special case of Equation **(3-14)** with β equal to 1. The instantaneous rate increases with time when β is greater than 1 and decreases with time for β less than 1. Ho (1991, 1992) presents maximum likelihood relationships for estimating the parameters β and θ (see Appendix F).

Uncertainty in the volcanic event rate is incorporated in the PVHA through uncertainty in the event counts and considering alternative start times, t_0. In addition, the confidence intervals in the Weibull rate parameter were estimated using the formulation developed by Crow (1982) (see Appendix F). In the same manner as discussed above for the homogeneous rate parameter, a three point discrete distribution was used to model the uncertainty in the instantaneous rate parameter. The maximum likelihood value was given a weight of 0.63 and the end points of the 90-percentile confidence interval (the 5^{th} and 95^{th} percentiles) were each given weights of 0.185.

Instantaneous Volume Predictable Rate Crowe et al. (1995) present estimates of the rate of volcanic events based on the model

$$\lambda(t) = \frac{\dot{V}_M(t)}{V_E(t)} \tag{3-15}$$

where $\dot{V}_M(t)$ is the instantaneous rate of magma production and $V_E(t)$ is the time varying volume per volcanic event. One of the volcanic experts adapted this general approach for estimating the instantaneous rate by specifying parametric formulations for $\dot{V}_M(t)$ and $V_E(t)$ and estimating the model parameters by regression analysis. The particular functional forms used are discussed below in the section describing the individual expert's model. Uncertainty in $\lambda(t)$ was modeled by developing three point representations of the uncertainty in both $\dot{V}_M(t)$ and $V_E(t)$ from the regression analyses and then using the resulting nine possible values assuming the two parameters are independent.

The above set of spatial and temporal models were used by the experts in various combinations by substituting the desired relationships for $\lambda(t)$ and $f(x,y)$ into Equation **(3-4)**. The specific models developed by each of the experts are presented in Section 3.2.

3.1.6 Conditional Probability of Intersection

The remaining piece of the hazard model is the computation of the probability that a volcanic event occurring at point (x,y) will produce an intersection of the repository. The conditional probability of intersection, $P_I(x,y)$, depends on the geometry assumed for an event. Most previous PVHA analyses have used a point representation for events [Figure 3-11, part (a)] and have accounted for the dimensions of the event through an increase in the effective area of the repository used in the hazard calculation (e.g., Crowe et al., 1982, 1992; Ho et al., 1991; Connor and Hill, 1995). Using this representation, $P_I(x,y)$ will be 1 within the effective footprint of the repository, and 0 everywhere else.

Sheridan (1992) developed an alternative approach to PVHA in which events are explicitly modeled as linear dike-like features centered on the point representation of the event [Figure 3-11, part (b)]. This approach provides a more physically realistic model of basaltic volcanic events and allows the distribution of possible event lengths and event orientations to be incorporated into the computation of the conditional likelihood that an event will intersect the repository. Thus, $P_I(x,y)$ will vary with both distance and azimuth from the repository.

For this study we have extended the linear dike model to consider the dike to be randomly placed on the point event [Figure 3-11, part (c)]. The parameters of an event thus are the event length, the event azimuth, and the relative location of the dike on the event. These parameters all are modeled as probability density functions defined by the experts. The event length probability distributions were supplied either in the form of a standard probability function (such as a lognormal distribution) or as a subjectively defined cumulative density function. The event azimuths were defined by the experts typically as normally distributed with a specified mean azimuth and a standard deviation. These distributions were then modeled as doubly truncated normal density functions with truncation points at ±90° from the mean azimuth. In some cases, bimodal density distributions were defined for event azimuth. The placement of the dike on the event was modeled by a symmetric density function.

The general procedure for computing $P_I(x,y)$ is illustrated on Figure 3-12. A dike extending length l from point (x,y) will intersect the repository over the azimuth range ϕ_1 to ϕ_2. The probability

that a dike extending length l toward the repository will intersect is equal to the probability that its azimuth will fall in range of ϕ_1 to ϕ_2. This is given by

$$P_I(x,y|l) = \int_{\phi_1|x,y,l}^{\phi_2|x,y,l} f(\phi)d\phi \tag{3-16}$$

where $f(\phi)$ is the dike azimuth distribution function defined by the experts. As indicated in Equation **(3-16)**, this probability is conditional on the point (x,y) and on l through the range of possible azimuths for intersection. The process is repeated for all possible values of l, each being multiplied by the probability that the dike will extend a distance l beyond the event, yielding the relationship

$$P_I(x,y) = \int_0^{L_{max}} f(l) \cdot \int_{\phi_1|x,y,l}^{\phi_2|x,y,l} f(\phi)d\phi \, dl \tag{3-17}$$

The density function $f(l)$ defines the probability that a dike will extend a distance l toward the repository. This probability is a function of how the event is represented. If the dikes are assumed to be centered on the events, then l represents a half-length of an event and $f(l)$ is obtained directly from the density function for total event length. For the randomly placed dikes, the density function $f(l)$ is obtained by convolving the event length and event placement distributions. Figure

3-13 shows examples of expert-specified density functions for dike length and dike location on an event. In this example, the expert developed a cumulative distribution for total dike length. This distribution was fit with a smooth interpolation curve to develop the density function.

Figure 3-14 shows examples of the computation of the conditional probability of intersection, $P_I(x,y)$, using the event length distributions shown on Figure 3-13. Results are shown for both unimodal and bimodal event azimuth distributions. The effect of considering randomly placed dikes is to extend the area of influence where the conditional probability of intersection is very low (<0.001). The area enclosed within the 0.001 probability contour is similar for both event representations.

The probability functions used in Equation **(3-17)** to compute the conditional probability of intersection model the placement of a random dike or dike set, given that an event occurs at point *(x,y)*. These probability functions are considered to represent the randomness inherent in the physical process of emplacement of basaltic dikes. In addition, there is scientific uncertainty in specifying the parameters of the process. This uncertainty is expressed by defining alternative probability functions for the length and orientation of the dikes associated with basaltic volcanic events and assigning relative weights to the alternatives.

3.2 EXPERT VOLCANIC HAZARD MODELS FOR YUCCA MOUNTAIN

The previous section describes the set of spatial and temporal models used to define the occurrence frequency of volcanic events in the Yucca Mountain region and the model used to compute the probability that a event occurring at point *(x,y)* will intersect the repository footprint. This section presents the ways in which the experts used these models to assess the volcanic hazard at the proposed Yucca Mountain repository site. First, the general logic tree framework for treatment of uncertainty in the PVHA is developed. Then the individual expert's PVHA models presented in Appendix E are translated into this common framework. Finally, the experts' assessments of key components of the PVHA model are compared.

3.2.1 Logic Tree Structure For PVHA Model

The PVHA models developed by each of the experts were transformed into a common logic tree structure for clarity of presentation and convenience in performing sensitivity analyses. Figures 3-15 and 3-16 show the general logic tree structure used to represent the scientific uncertainties in the PVHA computation. The logic tree is structured to move from the assessment of the general framework on the left (Figure 3-15) to specific assessments of individual volcanic zones and volcanic centers on the right (Figure 3-16). The specific definition of a specific zone or estimation of the number of events that may have occurred at a volcanic center commonly are dependent upon more general assessments of the appropriate time period or region of interest. Thus, the dependent assessments are placed to the right, and the independent assessments are placed to the left. However, the specific order of the nodes in the tree is purely a matter of convenience in conforming to an expert's thought process. The sequence of the nodes can be easily inverted, as will be demonstrated below in translating some of the experts' hazard models into the general framework of Figure 3-15.

The first two nodes of the logic tree address specification of alternative distributions for the length and orientation of dikes associated with the events. These parameters are used to compute the conditional probability of intersection, $P_I(x,y)$. The assessments of these two distributions are placed first in the logic tree because it is assumed that whichever models are the "correct" models for the dike length and dike orientation distributions, they apply to all events that may occur in the region.

The next two nodes address the assessment of the appropriate temporal models. The first node considers the uncertainty in whether homogeneous or nonhomogeneous temporal models are appropriate. Then, given the appropriate model, the following node addresses the uncertainty in selecting the appropriate time period over which the model parameters are to be evaluated.

The next four nodes address the assessment of the appropriate spatial models. The first node addresses identification of the appropriate region of interest. This region functions as a background volcanic source zone. The second node of this set addresses the uncertainty in specifying the appropriate form of the spatial density of future events. The alternatives considered by the experts include spatially homogeneous over the entire region of interest, locally homogenous within specific zones, or parametric and nonparametric nonhomogeneous spatial models. Given the selection of the region of interest and the appropriate spatial model, the next two nodes addresses specification of the appropriate zonation of the region. Alternative zonations usually are considered only when using the locally homogeneous, or "zonation," approach to spatial modeling.

At this point, the logic tree is expanded into subtrees, one for each of the identified volcanic sources. The vertical bar without a dot denotes additive hazard from multiple sources, (e.g., a local source zone and a background source). To the right of this point of the logic tree the parameter distributions for each source is considered to be probabilistically independent from those of the other sources, and the distribution in the total computed hazard is obtained by convolving the independent hazard distributions obtained for each source.

The logic tree structure for each volcanic source subtree is shown on Figure 3-16. The first node of the subtree addresses consideration of alternative age estimates of volcanic events in the source zone. Alternative age estimates may impact the rate estimates obtained using the Weibull process nonhomogeneous Poisson model.

The next two nodes address the parameters of the spatial models. The first deals with the treatment of the boundary of the source zone in the locally homogeneous spatial model. Alternatives considered by the experts were either an abrupt or a gradual change in the rate density of events across the boundary between zones of high and low activity. The second node addresses uncertainty in the specification of the basic parameters of the nonhomogeneous spatial models. If a parametric Gaussian field is to be fit to a specified zone boundary, then the uncertainty in specifying the density level represented by the boundary is addressed at this node. Similarly, the uncertainty in specifying the smoothing parameter of the nonparametric spatial models is addressed at this node.

The next two nodes address the basis for establishing the rate of activity in the source, given the appropriate temporal model. In most cases, this is just the event counts at the volcanic centers contained within the source for the specified time period. However, some source zones do not contain mapped events within the appropriate time period, and the experts used other means of specifying the rate of events, either comparisons to other zones or the use of other time periods. The second node is used for those cases where the rate of activity in a specific source zone is estimated from other source zones or time periods. The node addresses the uncertainty in specifying the appropriate multiplying factor to scale the rate from one zone to another.

The next seven nodes address the uncertainty in estimating the number of events that have occurred at each of the seven volcanic centers of primary interest to assessing the hazard at the repository: Lathrop Wells (LW), northwestern Crater Flat (NWCF), southeastern Crater Flat (SECF), the Amargosa Valley aeromagnetic anomalies (AV), Sleeping Butte (SM), Thirsty Mesa (TM), and Buckboard Mesa (BM). These assessments are represented individually in the logic tree so that the contribution of the uncertainty in the event counts at specific centers to the uncertainty in the total hazard can be readily identified. This approach also allows for explicit treatment of the impact of alternative event counts on application of the nonhomogeneous spatial models.

The next node of the logic tree addresses the statistical uncertainty in the parameters of the Gaussian field model [Equation (3-9)]. As discussed above in Section 3.1, a joint distribution for the five parameters of the Gaussian field model is computed from relative likelihood estimates using the observed events in the field. This node is placed at this point because the field parameters are conditional on the specific set of events that make up the field.

The next two nodes address uncertainty in the event counts at other volcanic centers and uncertainty in specifying the amount of additional events that may be undetected in the source region—so-called "hidden" events. The effect of hidden events is typically modeled as a range of possible multiples of the rate of activity computed from the observed events.

The final node addresses the statistical uncertainty in estimating the volcanic rate parameter for the given temporal model and data set. This includes the uncertainty in the homogenous or nonhomogeneous Poisson rates and the uncertainty in the volume predictable rate.

3.2.2 Individual Expert PVHA Models

This section presents a translation of the experts' assessments into the common logic tree framework of Figures 3-15 and 3-16. The models are listed in alphabetical order by first initial: Alexander McBirney, Bruce Crowe, George Thompson, George Walker, Mel Kuntz, Michael Sheridan, Richard Carlson, Richard Fisher, Wendell Duffield, and William Hackett. Appendix E contains summaries of the elicitation of each of the experts documenting the basis for the development of each PVHA model.

Alexander McBirney Figure 3-17 presents the logic tree that describes the basic framework for the PVHA model developed by Alexander McBirney (AM). Uncertainty in the size and orientation of dikes associated with the events is modeled by alternative maximum dike lengths of 15 and 20 km. Figure 3-18 shows the resulting distributions for $f(l)$ used to compute the conditional probability of intersection, $P_I(x,y)$.

A single temporal model, the homogeneous Poisson model, is used with two alternative time periods, post-1 Ma and post-5 Ma. A single region of interest is defined and two alternative spatial models are considered: the zonation (locally homogeneous) approach and the kernel smoothing approach. Following the zonation approach, a single zonation model is proposed. Figure 3-19 shows the zonation model proposed by AM. It consists of five zone types distinguished by differences in geology. The transition in the rate density across zone boundaries was assumed to be abrupt for all zones.

Table 3-1 summarizes the data used to define volcanic event rates for the individual source zones for both the zonation and kernel smoothing approaches. Zone types 4 and 5 do not contain any mapped volcanic events for the post-5 Ma time periods and the rate of volcanic events is based on other zones, as indicated. For the post-1 Ma time period, the rate of events in Zone types 3, 4, and 5 is assumed to be the same as that for the post-5 Ma time period. Table 3-2 summarizes the uncertainties in the event counts at each of the volcanic centers. The rate factors to account for hidden events were assessed to be 1.0 for the post-1 Ma time period and 1.1 for the post-5 Ma time period.

Following the kernel smoothing approach, three alternative values of the smoothing parameter h were selected. These values initially were chosen to span the range of 15 to 30 km used by Connor and Hill (1995) with the Epanechnikov kernel. However, AM chose to use a Gaussian kernel and the corresponding values of h were reduced by a factor of 2.5. Kernel density estimates were computed using three equally weighted values for h of 6, 9, and 12 km. The density estimates were computed for all possible combinations of the event counts in the northern AVIP zone for both time periods. Figure 3-20 shows an example of the kernel density estimate obtained using the most likely (highest probability) event counts for the post-5 Ma time period and a smoothing parameter of 9 km.

Bruce Crowe Figure 3-21 presents the logic tree that describes the basic framework for the PVHA model developed by Bruce Crowe (BC). Uncertainty in the size and orientation of dikes associated with the events is modeled by two alternative distributions for total event length. Figure 3-22 shows the resulting distributions for $f(l)$ used to compute the conditional probability of intersection, $P_I(x,y)$. A bimodal density function was specified for dike azimuth.

Two alternative temporal models are considered, the homogeneous Poisson model and the Weibull process nonhomogeneous Poisson model. Because the development of the PVHA model presented in BC's elicitation summary (Figure BC-1 of Appendix E) follows a different order than that of the general model shown on Figure 3-15, the remaining levels of the logic tree must be reordered from the assessments presented in the elicitation summary. This reordering was accomplished using Bayes' Theorem. Bayes' Theorem states that if one defines two types of events, A and B, each with several possible values (A_i and B_j), and provides probability assessments for the different values of

A, $P(A_i)$ and for different values of B conditional on the value of A, $P(B_j|A_i)$, then one can compute the conditional probability $P(A_i|B_j)$ by the expression

$$P(A_i|B_j) = \frac{P(B_j|A_i)\cdot P(A_i)}{\sum_k P(B_k|A_i)\cdot P(A_i)} \tag{3-18}$$

For example, in Figure BC-1 of Appendix E, the first assessment is the appropriate type of zonation model, one based on volcanic event distributions (ED) or one based on structural models (S). The probability assessments for the zonation type are $P(\text{ED})=0.4$, and $P(\text{S})=0.6$. The appropriate time period for computing event rates is assessed conditionally on the type of zonation model. Three time periods are considered: the Quaternary (Q) time period (post-1.15 Ma), the Plio-Quaternary (PQ) time period (post-5.05 Ma), and the Mio-Plio-Quaternary (MPQ) time period (post-9.15 Ma). If we place the assessment of time period before the assessment of zonation type in the logic tree, then we need to compute the probability of the zonation type conditionally on the time period. The following example illustrates computation of the probability of zonation type, either event-distribution (ED) based or structurally (S) based, conditional on time period Q being the appropriate time period.

Given zonation type ED, the probability assigned to time period Q is

$$P(\text{Q}|\text{ED}) = 0.8\cdot 0.5 = 0.4$$

and given zonation type A, the probability assigned to time period Q is the sum of the assessments for the various Quaternary zones.

$$P(\text{Q}|\text{S}) = 0.6\cdot 0.33+0.6\cdot 0.33+0.25\cdot 0.5+0.15\cdot 0.5 = 0.6$$

The probabilities assigned to the zonation models ED and S, given time period Q are obtained using Equation **(3-18)**.

$$P(\text{ED}|\text{Q}) = 0.4\cdot 0.4/(0.4\cdot 0.4+0.6\cdot 0.6) = 0.308$$
$$P(\text{S}|\text{Q}) = 0.6\cdot 0.6/(0.4\cdot 0.4+0.6\cdot 0.6) = 0.692$$

Proceeding in this manner, the logic tree shown on Figure BC-1 of Appendix A was transformed into that shown on Figure 3-21.

Three alternative regions of interest are considered for the PQ and MPQ time periods (Figure 3-23). The smallest of the tree, the post-caldera basalt zone (PCB) is not considered appropriate for computing background event rates for the Q time period because it does not contain any events.

Only the locally homogeneous, or zonation, spatial model is used in the assessment. Two alternative methods of defining zones are used, one based on event distributions and one based on structural considerations. The relative weights assigned to these two models display a shift in preference from the structural approach toward the event distribution approach as longer time periods are considered. Given the time period and the type of zonation model, various alternative source zones are defined. Figures 3-24 and 3-25 show the alternative zones for the Q and PQ time periods, respectively. Only the PCB zone (Figure 3-23) is used for the MPQ time period. The transition in the rate density across zone boundaries was assumed to be abrupt for all zones.

Table 3-3 summarizes the data to define the volcanic event rates for the individual source zones. Note that the full length of the Quaternary (2 My) is used to define the rate of events in the background zones for the Q time period models. Table 3-4 summarizes the uncertainties in the event counts at each of the volcanic centers. Bruce Crowe explicitly provided estimates of the number of hidden events at each volcanic center rather than general rate factors to multiply the rates computed from observed events. Three equally weighted alternative sets of event ages are defined in the elicitation summary for use in the nonhomogeneous Weibull process model. The resulting average values of parameter β computed over all alternative estimates of event counts and ages were 0.69 ±0.16 for the Q time period, 0.90 ±0.11 for the PQ time period, and 0.67 ±0.25 for the MPQ time period.

George Thompson Figure 3-26 presents the logic tree that describes the basic framework for the PVHA model developed by George Thompson (GT). Uncertainty in the size and orientation of dikes associated with the events is modeled by alternative maximum dike lengths of 10 and 12 km. Figure 3-27 shows the resulting distributions for $f(l)$ used to compute the conditional probability of intersection, $P_I(x,y)$.

A single temporal model, the homogeneous Poisson model, is used with two alternative time periods, post-1 Ma and post-4 Ma. Two alternative regions of interest are defined (see Figure 3-28). Only the zonation (locally homogeneous) approach is considered in the PVHA model. Two overlapping zones, a volcanic domain (VD) and a Quaternary faulting domain (QF) are specified. The controlling source zone in the region of overlap depends on the time period considered appropriate, as illustrated on Figure 3-29. Assuming that the post-1 Ma time period is appropriate, the Quaternary faulting zone is the dominant source. If the 4 Ma time period is considered to be the appropriate time period, the volcanic domain is the dominant source. Two alternatives are considered for the transition in the rate density across the boundary of the volcanic and Quaternary faulting zones, one in which there is an abrupt transition (weight 0.67) and one in which there is a gradual transition over a distance of 5 km (weight 0.33).

Table 3-5 summarizes the data used to define volcanic event rates for the individual source zones. The Quaternary faulting zone does not contain any mapped volcanic events, and the rate of volcanic events is assessed to be one-tenth of the rate in the volcanic domain. Table 3-6 summarizes the uncertainties in the event counts at each of the volcanic centers. The rate factors to account for hidden events were assessed to be 1.0 (weight 0.5) or 2.0 (weight 0.5).

George Walker Figure 3-30 presents the logic tree that describes the basic framework for the PVHA model developed by George Walker (GW). Uncertainty in the size and orientation of dikes associated with the events is modeled by alternative maximum dike lengths of 15 and 20 km. Figure 3-31 shows the resulting distributions for $f(l)$ used to compute the conditional probability of intersection, $P_I(x,y)$. A bimodal distribution for dike azimuths is specified.

A single temporal model—the homogeneous Poisson model— is used with a single time period of post-5 Ma. A single region of interest is defined containing one source zone (Figure 3-32). Three alternative approaches to spatial modeling are considered, the zonation (locally homogeneous) approach, Epanechnikov kernel smoothing, and fitting a Gaussian field to the observed volcanic events. Both the kernel smoothing and the Gaussian field approaches are applied to the events in the Crater Flat Volcanic Zone (CFVZ) shown on Figure 3-32. The smoothing parameter h for the kernel density estimate is estimated by minimizing the difference between the 90 percent density contour and the CFVZ boundary. The transition in the rate density across the CFVZ boundary is assumed to be abrupt.

Table 3-7 summarizes the data used to define volcanic event rates for the CFVZ and background source zones. Table 3-8 summarizes the uncertainties in the event counts at each of the volcanic centers. Kernel density estimates and Gaussian volcanic fields were computed for all possible combinations of the event counts in the CFVZ. The mean value of the smoothing parameter computed over all possible combinations of event counts is 6.0 ±0.4 km. Figure 3-33 shows an example of the kernel density estimate obtained using the most likely event counts. Figure 3-34 shows an example of a Gaussian field fit to the most likely event counts in the CFVZ.

The rate factors to account for hidden events were assessed to be 1.0 (0.3), 2.0 (0.2), 3 (0.167), 4 (0.166), or 5 (0.167).

Mel Kuntz Figure 3-35 presents the logic tree that describes the basic framework for the PVHA model developed by Mel Kuntz (MK). Uncertainty in the size and orientation of dikes associated with the events is modeled by alternative maximum dike lengths of 10, 12, 15, and 18 km. Figure 3-36 shows the resulting distributions for $f(l)$ used to compute the conditional probability of intersection, $P_I(x,y)$. A bimodal distribution for dike azimuths is specified.

Two alternative temporal models are considered, the homogeneous Poisson model (weight 0.8) and the Weibull process nonhomogeneous Poisson model (weight 0.2). Alternative time periods of post-2 Ma, post-5 Ma and post-11 Ma are considered in the analysis. A single region of interest is considered (Region A on Figure 3-37). Four alternative approaches to spatial modeling are considered, a uniform model within the region of interest, the zonation (locally homogeneous) approach, Gaussian kernel smoothing, and fitting a Gaussian field to the observed volcanic events. Five source zones are defined for the zonation model (Zones B through F on Figure 3-37). The transition in the rate density across the boundary between Zone C (Crater Flat) and Zone E to the east is modeled as being either abrupt (weight 0.5) or gradual over a distance of 5 km (weight 0.5). Both the kernel smoothing and the Gaussian field approaches are applied to the events in Zone C of the zonation mode shown on Figure 3-37. The smoothing parameter for the kernel density, h, is estimated by minimizing the difference between 90 percent (weight 0.6) or 95 percent (weight 0.4) density contours and the Zone C boundary.

Table 3-9 summarizes the data used to define volcanic event rates for the various source zones. Several of the source zones do not contain events in certain time periods, and the event rates are specified as multiples of the rates for other zones. Table 3-10 summarizes the uncertainties in the event counts at each of the volcanic centers. The resulting average values of parameter β computed over all alternative estimates of event counts and ages were 2.36 ±0.51 for the post-2 Ma time period, 1.05 ±0.13 for the post-5 Ma time period, and 3.02 ±0.92 for the post-11 Ma time period. Kernel density estimates and Gaussian volcanic fields were computed for all possible combinations of the event counts in Zone C. The mean values of the smoothing parameter computed over all possible combinations of event counts and time periods are 3.1 ±0.3 km for the 90 percent density constraint and 2.9 ±0.5 km for the 95 percent density constraint. Figure 3-38 shows an example of the kernel density estimate obtained using the most likely event counts for the post-2 Ma time period and the 90 percent density constraint. Figure 3-39 shows an example of a Gaussian field fit to the same data.

The rate factors to account for hidden events were assessed to be 1.0 (0.25), 1.1 (0.5), 1.5 (0.2), or 2 (0.05).

Michael Sheridan Figure 3-40 presents the logic tree that describes the basic framework for the PVHA model developed by Michael Sheridan (MS). Uncertainty in the size and orientation of dikes associated with the events is modeled by nine alternative lognormal distributions for dike length. Figure 3-41 shows the resulting distributions for $f(l)$ used to compute the conditional probability of intersection, $P_I(x,y)$.

The homogeneous Poisson model is considered the appropriate temporal model and the post-5 Ma time period is considered the appropriate time period. Two regions of interest are considered, the region within 200 km of the proposed Yucca Mountain site and the region within 40 km of the site (Figure 3-42). Two alternative approaches to spatial modeling are considered, a uniform model within the 40-km region of interest and fitting a Gaussian field to the observed volcanic events in three specified fields, Crater Flat, Sleeping Butte/Thirsty Mesa, and Buckboard Mesa. In addition, there is a 0.25 probability that the event at Lathrop Wells is still continuing. This is modeled by placing a point source at Lathrop Wells with the specified event frequency of 1 event in 100,000 years, MS's specified duration of an event.

Table 3-11 summarizes the data used to define volcanic event rates. When using the Gaussian field approach, the rate of events outside of the three fields is specified as the frequency of new field occurrence. Table 3-12 summarizes the uncertainties in the event counts at each of the volcanic centers and the rate of new field occurrence in the regions of interest. Gaussian volcanic fields were computed for all possible combinations of the event counts in each of the field areas. Figure 3-43 shows an example of Gaussian fields fit to the most likely event counts at each of the three fields. Because of the limited spatial extent of events at the Sleeping Butte/Thirsty Mesa field, the aspect ratio was fixed at 3.0. The events at Buckboard Mesa are very closely spaced and a circular field with standard error of 1 km was used to define the field.

The rate factors to account for hidden events were assessed to be 1.33 (0.185), 1.67 (0.63), or 2 (0.185).

Richard Carlson Figure 3-44 presents the logic tree that describes the basic framework for the PVHA model developed by Richard Carlson (RC). Uncertainty in the size and orientation of dikes associated with the events is modeled by three alternative maximum dike lengths. Figure 3-45 shows the resulting distributions for *f(l)* used to compute the conditional probability of intersection, $P_I(x,y)$.

Two alternative temporal models are included in the hazard model, a homogeneous Poisson model applicable for the post-1 Ma time period, and a volume predictable model applicable for the post-5 Ma time period. Two regions of interest are considered (Figure 3-46), the Amargosa Valley Isotopic Province (AVIP) for the post-1 Ma time period and the northern portion of AVIP for the post-5 Ma time period. Two alternative approaches to spatial modeling are considered, a uniform model within the region of interest and kernel smoothing using a fixed Epanechnikov kernel with an aspect ratio of 2:1 and an orientation of N20°W. Uncertainty in the smoothing parameter, *h*, was modeled by considering alternative values for the major axis value of *h*.

Table 3-13 summarizes the data used to define volcanic event rates. Table 3-14 summarizes the uncertainties in the event counts in the regions of interest. Kernel density functions were computed for all possible combinations of the event counts. Figure 3-47 shows an example for *h* equal to 10 km and the most likely event counts for the post-5 Ma time period.

Richard Carlson's PVHA model incorporates the volume predictable rate model defined by Equation **(3-15)**. The rate of magma generation in the northern AVIP zone was specified by fitting the following functional form to the cumulative volume data.

$$V_M(t) = C_1 + C_2 \cdot (C_3 - t)^{1/2} \qquad \textbf{(3-19)}$$

In Equation **(3-19)**, time is measured from the present and parameter C_3 acts as a starting time. This formulation was fit to the data by nonlinear least squares using the data given in RC's elicitation. The result is the relationship $V_M(t) = 2.288 + 1.400 \cdot (5.026 - t)^{1/2}$. Figure 3-48 shows the resulting fit. Differentiation of this relationship yields the rate of magma generation today, $\dot{V}_M(t=0)$, of 0.312 km^3/Ma. Using the asymptotic errors obtained from the fit of the data, 5th and 95th percentiles of $\dot{V}_M(t=0)$ were computed to be 0.105 km^3/Ma and 0.515 km^3/Ma, respectively. These three values were used with weights of 0.63 for the best estimate and 0.185 for the 5th and 95th percentiles to compute the volume predictable rates.

The volume per event, $V_E(t)$, was obtained by fitting a relationship of the form

$$V_E(t) = C_4 \cdot (C_3 - t)^{C_5} \qquad \textbf{(3-20)}$$

where C_3 was fixed at the value of 5.026 obtained from the fit to the cumulative volume data. The cumulative volume data for the region consists of volumes estimated for each center, e.g. 0.92 km^3 for the basalts of Buckboard Mesa. Thus, the volume per event data depends on how many events have occurred at each center. For the hazard analysis, the volume per event was computed for every possible combination of event counts in the northern AVIP region by a least squares fit of the log of Equation **(3-20)** to the volume per event data resulting from dividing the volume at each center by the number of events estimated to have occurred at the center. Figure 3-48 shows an example of the fit to the most likely counts in the region. In this example $V_E(t=0)$ is 0.096 km^3 with a 90-percent confidence interval of 0.030 to 0.306 km^3. Uncertainty in the volume predictable rate for each possible event count was modeled be considering the three possible values for $V_M(t=0)$ listed above and a similar three point distribution for $V_E(t=0)$ estimated from the regression fit to the specific event counts. The weighted average over all possible event counts of the volume per event was 0.080 km^3.

The rate factors to account for hidden events were assessed to be 1.1 for both the post-1 Ma and post-5 Ma time periods.

Richard Fisher Figure 3-49 presents the logic tree that describes the basic framework for the PVHA model developed by Richard Fisher (RF). Uncertainty in the size and orientation of dikes associated with the events is modeled by alternative maximum dike lengths of 20 and 25 km. Figure 3-50 shows the resulting distributions for $f(l)$ used to compute the conditional probability of intersection, $P_I(x,y)$. A bimodal distribution for dike azimuths is specified.

The homogeneous Poisson model is used to compute the event rates for alternative time periods of post-1 Ma and post-2 Ma. Two alternative regions of interest were considered (Figure 3-51). Three alternative approaches to spatial modeling are considered, the zonation (locally homogeneous) approach using the zones shown on Figure 3-52, Epanechnikov kernel smoothing, and fitting Gaussian field shapes to the Crater Flat and Sleeping Butte zones shown on Figure 3-52. The transition in the rate density across the boundary between zones was assumed to be abrupt. The smoothing parameter for the kernel density h and the Gaussian field shape parameters were estimated by minimizing the difference between 90 percent (0.8), 95 percent (0.1), or 98 percent (0.1) density contours and the Crater Flat boundary.

Table 3-15 summarizes the data used to define volcanic event rates for the various source zones. Table 3-16 summarizes the uncertainties in the event counts at each of the volcanic centers. Kernel density estimates and Gaussian volcanic fields were computed for all possible combinations of the event counts in the Crater Flat zone. The mean values of the smoothing parameter computed over all possible combinations of event counts and time periods are 9.9 ±0.6 km for the 90 percent density constraint, 9.2 ±0.7 km for the 95 percent density constraint, and 8.7 ±0.6 km for the 98 percent density constraint. Figure 3-53 shows an example of the kernel density estimate obtained using the most likely event counts for the post-2 Ma time period and the 90 percent density constraint. Figure 3-54 shows an example of a Gaussian field fit to the Crater Flat zone boundary.

The rate factors to account for hidden events were assessed to be 1.15 (0.25), 1.32 (0.25), 1.5 (0.25), or 2 (0.25).

Wendell Duffield Figure 3-55 presents the logic tree that describes the basic framework for the PVHA model developed by Wendell Duffield (WD). Uncertainty in the size and orientation of dikes associated with the events is modeled by alternative maximum dike lengths of 20, 30, and 40 km. Figure 3-56 shows the resulting distributions for $f(l)$ used to compute the conditional probability of intersection, $P_I(x,y)$.

A single temporal model, the homogeneous Poisson model, is used with a single time period of post-1 Ma. The region of interest is defined as the region within 40 km of the repository (Figure 3-57). Only the zonation (locally homogeneous) approach is considered in the PVHA model. Figure 3-57 shows the defined source zones. Two alternatives are considered, one with separate zones B and C_n, and one in which these two zones are combined. The transition in the rate density across the boundary of the zones is considered to be abrupt.

Table 3-17 summarizes the data used to define volcanic event rates for the individual source zones. The rate for those zones that do not contain any mapped volcanic events is based on estimates of the number of undetected events or a multiple of the rate in other zones. Table 3-18 summarizes the uncertainties in the event counts at each of the volcanic centers. The number of hidden events in the region for the time frame of interest (1 Ma) were assessed to be either 0 (weight 0.99) or 1 (weight 0.01).

William Hackett Figure 3-58 presents the logic tree that describes the basic framework for the PVHA model developed by William Hackett (WH). Uncertainty in the size and orientation of dikes associated with the events is modeled by alternative maximum dike lengths of 20, 30, and 40 km. Figure 3-59 shows the resulting distributions for $f(l)$ used to compute the conditional probability of intersection, $P_I(x,y)$. A bimodal distribution for dike azimuths is specified.

The homogeneous Poisson model is used to compute the event rates for alternative time periods of post-1 Ma, post-5 Ma and post-11 Ma. A single region of interest is defined (Figure 3-60). Two alternative approaches to spatial modeling are considered, the zonation (locally homogeneous) approach and Gaussian kernel smoothing. The zonation models are dependent on the time period considered appropriate (Figure 3-60). The transition in the rate density across the boundary between zones was assumed to be abrupt. The smoothing parameter for the kernel density, h, was specified as alternative values of 3.2 km (0.5), 6.4 km (0.4), and 9.6 km (0.1).

Table 3-19 summarizes the data used to define volcanic event rates for the various source zones. Table 3-20 summarizes the uncertainties in the event counts at each of the volcanic centers. The potential for hidden events are accounted for in defining the distribution of event counts at each center. Kernel density estimates were computed for all possible combinations of the event counts in the appropriate time period. Figure 3-61 shows an example of the kernel density estimate obtained using the most likely event counts for the post-1 Ma time period.

3.2.3 Summary of Assessments

Figures 3-62 and 3-63 present summaries of the experts' assessments of various components of the PVHA model. The summaries are in the form of histograms with the histogram bins defining alternative models or parameter values. The probability assigned to each bin is the equally weighted average of the probabilities specified by the experts. For example, the top plot on Figure 3-62 shows the aggregate relative preference for the four types of spatial models. In aggregate, the experts preferred the use of locally homogeneous zonation models to represent the spatial distribution of future volcanic events. The least favored model is the uniform model that assumes the spatial density is homogeneous throughout the region. The homogeneous temporal model is strongly favored with the preferred time periods of post-1 Ma or post-5 Ma. The experts also indicate that the number of hidden events in the region is likely to be less than the number of observed events. There is a wide distribution for the maximum length of a dike or dike set associated with an individual event. This wide distribution reflects the large uncertainties for maximum dike length specified individually by the experts. Figure 3-63 shows the aggregate distributions for the event counts at the seven primary volcanic centers. The aggregate distributions are generally similar to those developed individually by the experts.

TABLE 3-1
DATA USED TO DEFINE VOLCANIC EVENT RATES FOR SOURCE ZONES
ALEXANDER R. MCBIRNEY SOURCE MODEL

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	

TABLE 3-2
ESTIMATED UNCERTAINTIES IN EVENT COUNTS
ALEXANDER R. McBIRNEY SOURCE MODEL

LOCATION	COUNTS (CONES)	WEIGHT	NOTES
Lathrop Wells	1 I - IV 2 I, II 3 I, II, III 4 I, II, III, IV	(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 I - IV: 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 3-3
DATA USED TO DEFINE VOLCANIC EVENT RATES FOR SOURCE ZONES
BRUCE M. CROWE SOURCE MODEL

TIME PERIOD	COUNT METHOD FOR ZONES	NOTES
Quaternary (post-1.15 Ma)	CF: (LW+NCF+SB) PA: (LW+NCF) WL: (LW+NCF+SB) NE: (LW+NCF) SGB: (DV2+U+CV) AVIP: (DV2)	AV: Amargosa Valley AVIP: Amargosa Valley Isotopic Province of Yogodzinski (1995) BM: Buckboard Mesa CF: Crater Flat CV: Clayton Valley DV2: Death Valley (2 Ma) DV5: Death Valley (3-5 Ma) GV: Grapevine Canyon LW: Lathrop Wells NC: Nye Canyon NCF: Northern (1.0 Ma) Crater Flat NE: North East PCB: Post Caldera Basalts PA: Pull apart and Pull apart with fault PM: Pahute Mesa PR: Paiute Ridge RW: Rocket Wash SB: Sleeping Butte SC: Scarp Canyon SGB: Southern Great Basin TM: Thirsty Mesa TP: Towne Pass U: Ubehebe WL: Walker Lane YF: Yucca Flat YPCB: Younger Post-Caldera Basalts 3.7: 3.7 Ma Crater Flat
Plio-Quaternary (post-5.05 Ma)	CF: (LW+NCF+3.7+AV+SB+TM) YPCB: (LW+NCF+3.7+AV+SB+TM +BM) PA: (LW+NCF+3.7+AV) WL: (LW+NCF+3.7+AV+SB+TM) NE: (LW+NCF+3.7+AV+BM) SGB: (DV2+DV5+U+CV+TP+GV) AVIP: (DV2+DV5)	
Mio-Plio-Quaternary (post-9.05 Ma)	PCB: (LW+NCF+3.7+AV+SB+TM +BM+PM+PR+SC+RW+YF +NC)	

TABLE 3-4
ESTIMATED UNCERTAINTIES IN EVENT COUNTS
BRUCE M. CROWE SOURCE MODEL

LOCATION	COUNTS (CONES)	WEIGHT
Lathrop Wells	1	(0.9)
	2	(0.06)
	3	(0.03)
	4	(0.01)
Sleeping Butte	1 (LBP+HC)	(0.35)
	2 (LBP, HC)	(0.45)
	3 (LBP, 2HC)	(0.2)
1.0 Ma Crater Flat	1 (all)	(0.1)
	2 (RC+LC,BC+M)	(0.1)
	3 (LC, RC+BC, M)	(0.45)
	4 (LC,RC,BC,M)	(0.2)
	5 (2LC, RC, BC, M)	(0.1)
	6 (A, RC, BC, M, 2LC)	(0.025)
	7 (u)	(0.025)
Buckboard Mesa	1	(0.7)
	2	(0.25)
	3 (u)	(0.05)
3.7 Ma Crater Flat	1	(0.1)
	2	(0.25)
	3	(0.25)
	4	(0.1)
	5	(0.1)
	6	(0.1)
	7 (u)	(0.05)
	8 (2u)	(0.05)
Amargosa Valley	3	(0.05)
	4	(0.12)
	5	(0.2)
	6	(0.2)
	7 (u)	(0.2)
	8 (u)	(0.1)
	9 (2u)	(0.07)
	10 (3u)	(0.03)
	11 (4u)	(0.02)
	12 (5u)	(0.01)
Thirsty Mesa	1	(0.85)
	2	(0.09)
	3	(0.06)

NOTES

A-G: Aeromagnetic anomalies of V. Langenheim, USGS
BC: Black Cone
HC: Hidden Cone
2HC: 2 events at Hidden Cone
LBP: Little Black Peak
LC: Little Cones
2LC: 2 events at Little Cone
M: Makani Cone
RC: Red Cone
SC: Split Cone
SB: Shoreline Butte
2SB: 2 events at Shoreline Butte
3SB: 3 events at Shoreline Butte
u: undetected

TABLE 3-4 (Continued)
ESTIMATED UNCERTAINTIES IN EVENT COUNTS
BRUCE M. CROWE SOURCE MODEL

LOCATION	COUNTS (CONES)	WEIGHT	NOTES
Death Valley (2 Ma)	2 (SC, SB) 3 (2SB, SC) 4 (3SB, SC) 5 (3SB, SC+u) 6 (3SB, SC +2u)	(0.3) (0.3) (0.25) (0.1) (0.05)	
Death Valley (3-5 Ma)	22 Density Estimates 44 " " 89 " "	(0.185) (0.63) (0.185)	
Clayton Valley	1 2 (u) 3 (2u)	(0.85) (0.1) (0.05)	
Ubehebe	1 2 3 4 5 (u) 6 (2u)	(0.6) (0.15) (0.1)	
Towne Pass	11 Density Estimates 22 " " 44 " "	(0.185) (0.63) (0.185)	
Grapevine Canyon	6 Density Estimates 12 " " 24 " "	(0.185) (0.63) (0.185)	
Nye Canyon	1 2 3 4 5 6 (u) 7 (2u) 8 (3u) 9 (4u)	(0.02) (0.2) (0.2) (0.16) (0.16) (0.12) (0.08) (0.04) (0.02)	

TABLE 3-4 (Continued)
ESTIMATED UNCERTAINTIES IN EVENT COUNTS
BRUCE M. CROWE SOURCE MODEL

LOCATION	COUNTS (CONES)	WEIGHT	NOTES
Paiute Ridge	1 2 3 4 5 (u)	(0.35) (0.35) (0.15) (0.1) (0.05)	
Yucca Flat	1 2 3 (u)	(0.4) (0.4) (0.2)	
Pahute Mesa	3 4 5 6 (u) 7 (u)	(0.5) (0.2) (0.15) (0.1) (0.05)	

TABLE 3-5
DATA USED TO DEFINE VOLCANIC EVENT RATES FOR SOURCE ZONES
GEORGE A. THOMPSON SOURCE MODEL

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)	

TABLE 3-6
ESTIMATED UNCERTAINTIES IN EVENT COUNTS
GEORGE A. THOMPSON SOURCE MODEL

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

TABLE 3-7
DATA USED TO DEFINE VOLCANIC EVENT RATES FOR SOURCE ZONES
GEORGE P.L. WALKER SOURCE MODEL

TIME PERIOD	COUNT METHOD FOR ZONES	NOTES
Post 4.6 Ma (1.0)	- CFVZ zone: NCF, 3.7, LW, TM, SB, AV - Background Node: BM	NCF: Northern (1.0 Ma) Crater Flat 3.7: 3.7 Ma Crater Flat LW: Lathrop Wells TM: Thirsty Mesa SB: Sleeping Butte AV: Amargosa Valley BM: Buckboard Mesa

TABLE 3-8
ESTIMATED UNCERTAINTIES IN EVENT COUNTS
GEORGE P.L. WALKER SOURCE MODEL

LOCATION	COUNTS (CONES)	WEIGHT	NOTES
Lathrop Wells	1 2 3 4	(0.9) (0.07) (0.02) (0.01)	BC: Black Cone LC: Little Cones M: Makani Cone RC: Red Cone
Sleeping Butte	1 2	(0.4) (0.6)	
1.0 Ma Crater Flat	1 (all) 3 (LC, RC+BC, M) 4 (LC, RC, BC, M)	(0.1) (0.35) (0.55)	
Buckboard Mesa	1 2	(0.75) (0.25)	
3.7 Ma Crater Flat	2 3 4 5	(0.5) (0.25) (0.2) (0.05)	
Amargosa Valley	2 3 5 6	(0.3) (0.4) (0.15) (0.15)	
Thirsty Mesa	1 2 3	(0.85) (0.09) (0.06)	

TABLE 3-9
DATA USED TO DEFINE VOLCANIC EVENT RATES FOR SOURCE ZONES
MEL A. KUNTZ SOURCE MODEL

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

TABLE 3-10
ESTIMATED UNCERTAINTIES IN EVENT COUNTS
MEL A. KUNTZ SOURCE MODEL

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

TABLE 3-11
DATA USED TO DEFINE VOLCANIC EVENT RATES FOR SOURCE ZONES
MICHAEL F. SHERIDAN SOURCE MODEL

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

TABLE 3-12
ESTIMATED UNCERTAINTIES IN EVENT COUNTS
MICHAEL F. SHERIDAN SOURCE MODEL

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)

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)	

TABLE 3-13
DATA USED TO DEFINE VOLCANIC EVENT RATES FOR SOURCE ZONES
RICHARD W. CARLSON SOURCE MODEL

TIME PERIOD	COUNT METHOD FOR ZONES	NOTES
1.0 Ma (0.3)	AVIP: (LW+SB+NCF+DV)	AVIP: Amargosa Valley Isotopic Province of Yogodzinski (1995) AV: Amargosa Valley BM: Buckboard Mesa DV: Death Valley LW: Lathrop Wells NCF: Northern (1.0 Ma) Crater Flat NAVIP: Northern Amargosa Valley Isotopic Province TM: Thirsty Mesa SB: Sleeping Butte 3.7: 3.7 Ma Crater Flat
5.0 Ma (0.7)	NAVIP: (LW+SB+NCF+3.7+AV+TM+BM)	

TABLE 3-14
ESTIMATED UNCERTAINTIES IN EVENT COUNTS
RICHARD W. CARLSON SOURCE MODEL

LOCATION	COUNTS (CONES)	WEIGHT	NOTES
Lathrop Wells	1 2	(0.95) (0.05)	BC: Black Cone B-G: Aeromagnetic anomalies of V. Langenheim, USGS 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 RC: Red Cone SC: Split Cone
Sleeping Butte	1 (LBP+HC) 2 (LBP, HC) 3 (LBP, 2HC)	(0.7) (0.2) (0.1)	
1.0 Ma Crater Flat	1 (all) 3 (LC, RC+BC, M) 5 (2LC, RC, BC, M)	(0.6) (0.3) (0.1)	
Buckboard Mesa	1 2	(0.9) (0.1)	
3.7 Ma Crater Flat	1 2 3 4 5 6	(0.8) (0.1) (0.05) (0.02) (0.02) (0.01)	
Amargosa Valley	3 (B,C,D) 4 (B,C,D,E) 5 (B,C,D,E,F) 6 (B,C,D,E,F,G)	(0.3) (0.5) (0.1) (0.1)	
Thirsty Mesa	1 2	(0.9) (0.1)	
Death Valley (1 Ma)	1 (SC)	(1.0)	

TABLE 3-15
DATA USED TO DEFINE VOLCANIC EVENT RATES FOR SOURCE ZONES
RICHARD V. FISHER SOURCE MODEL

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

TABLE 3-16
ESTIMAZTED UNCERTAINTIES IN EVENT COUNTS
RICHARD V. FISHER SOURCE MODEL

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

TABLE 3-17
DATA USED TO DEFINE VOLCANIC EVENT RATES FOR SOURCE ZONES
WENDELL A. DUFFIELD SOURCE MODEL

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

TABLE 3-18
ESTIMATED UNCERTAINTIES IN EVENT COUNTS
WENDELL A. DUFFIELD SOURCE MODEL

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

TABLE 3-19
DATA USED TO DEFINE VOLCANIC EVENT RATES FOR SOURCE ZONES
WILLIAM R. HACKETT SOURCE MODEL

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

TABLE 3-20
ESTIMATED UNCERTAINTIES IN EVENT COUNTS
WILLIAM R. HACKETT SOURCE MODEL

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

**TABLE 3-20 (Cont'd)
ESTIMATED UNCERTAINTIES IN EVENT COUNTS
WILLIAM R. HACKETT SOURCE MODELS**

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

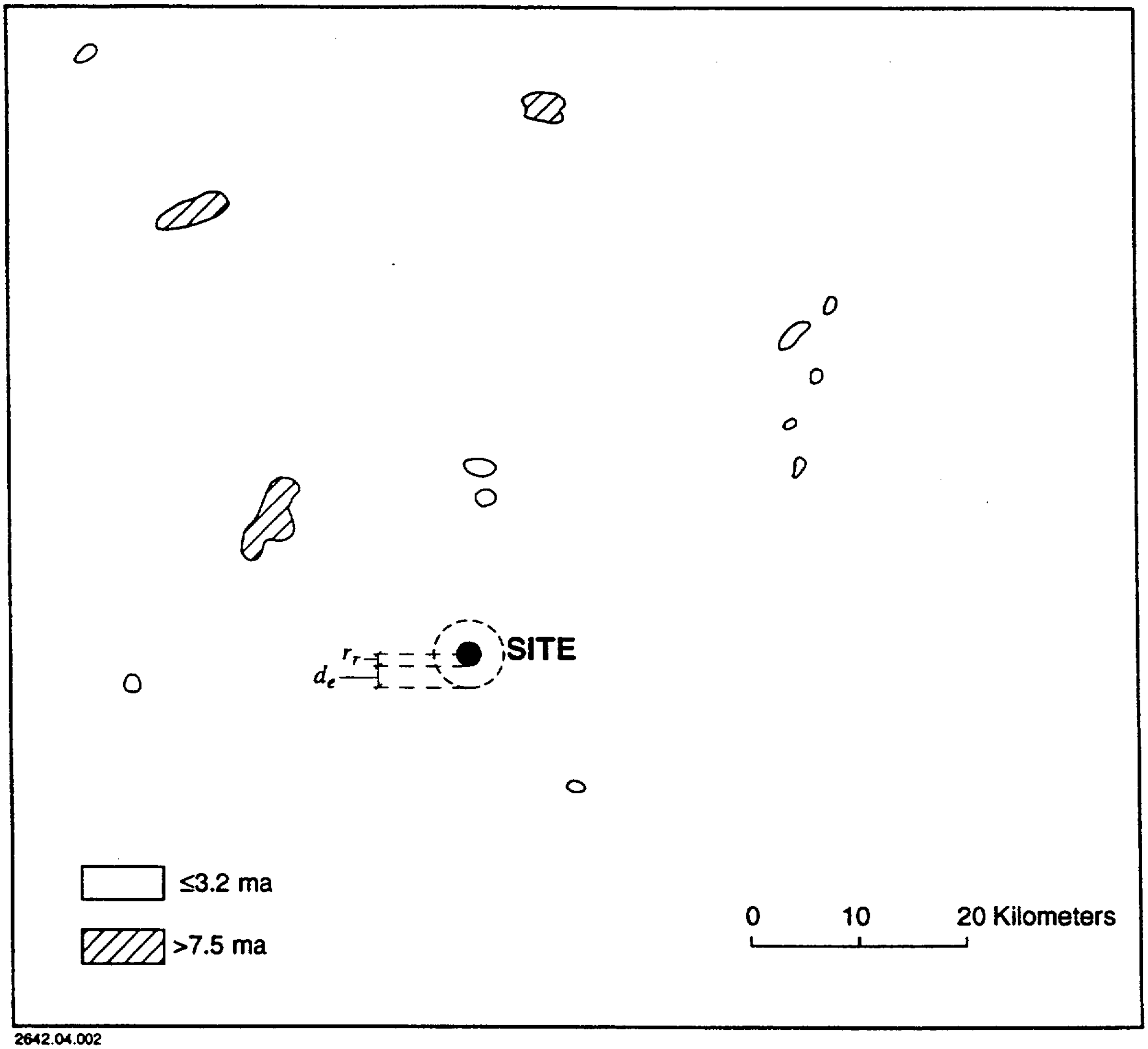


Figure 3-1 Example of simplified volcanic hazard model for a region R. Volcanic events are denoted by the irregular patches.

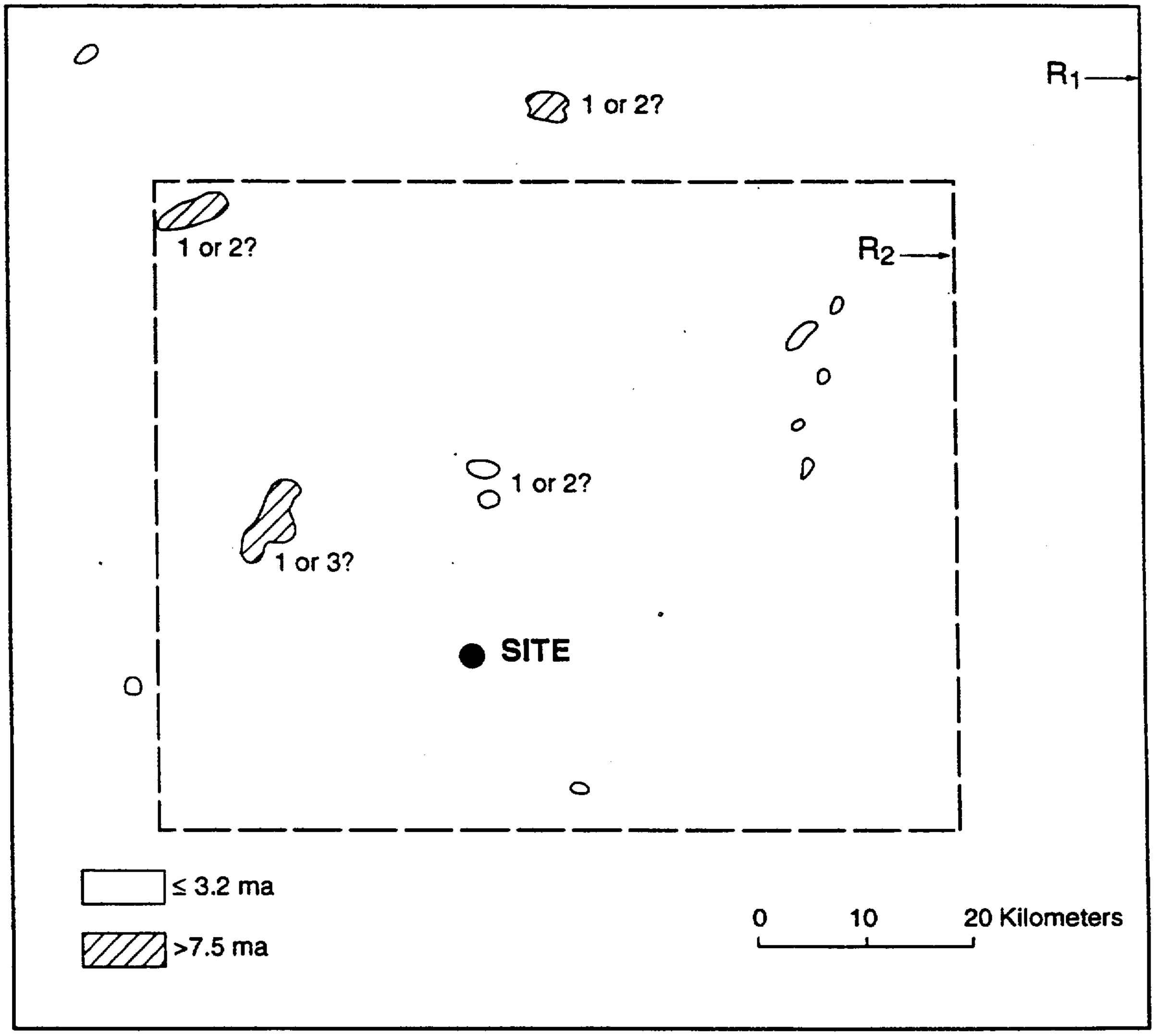
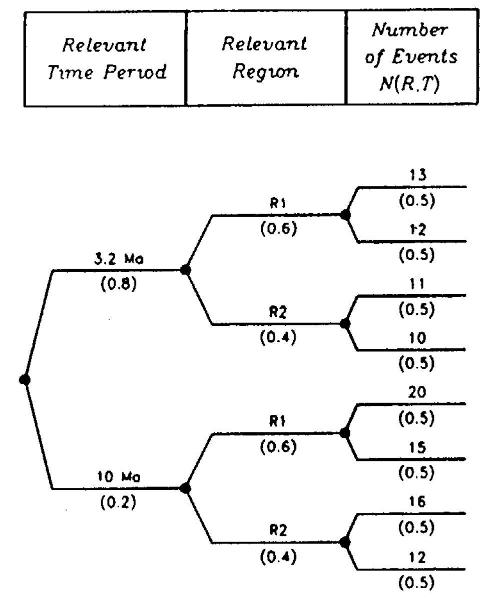


Figure 3-2 Alternative interpretations of the parameters of the simplified volcanic hazard model of Figure 3-1. Shown are alternative definitions of the region of interest and alternative estimates of the numbers of events at various volcanic centers.

(a)



(b)

T (my)	Area of R (sq. km)	N	v	P(v)
3.2	10^4	13	$4.0 \cdot 10^{-9}$	0.24
3.2	10^4	12	$3.8 \cdot 10^{-9}$	0.24
3.2	$0.5 \cdot 10^4$	11	$6.9 \cdot 10^{-9}$	0.16
3.2	$0.5 \cdot 10^4$	10	$6.3 \cdot 10^{-9}$	0.16
10	10^4	20	$2.0 \cdot 10^{-9}$	0.06
10	10^4	15	$1.5 \cdot 10^{-9}$	0.06
10	$0.5 \cdot 10^4$	16	$3.2 \cdot 10^{-9}$	0.04
10	$0.5 \cdot 10^4$	12	$2.4 \cdot 10^{-9}$	0.04

(c)

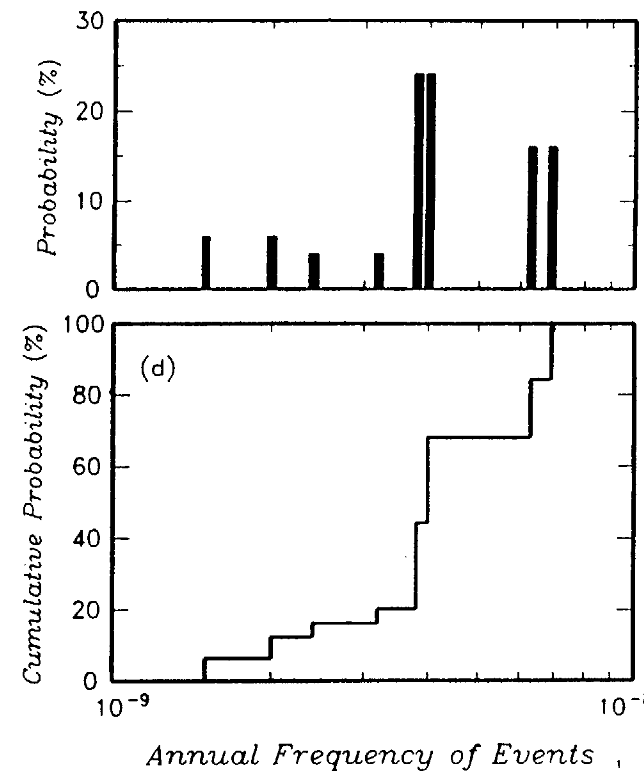


Figure 3-3 Example of logic tree formulation for treatment of uncertainty in PVHA. (a) Logic tree representing uncertainty in region of interest, time period, and event counts. (b) Table of alternate computed hazard estimates. (c) Resulting discrete distribution for frequency of intersection. (d) Cummulative distribution of frequency of intersection.

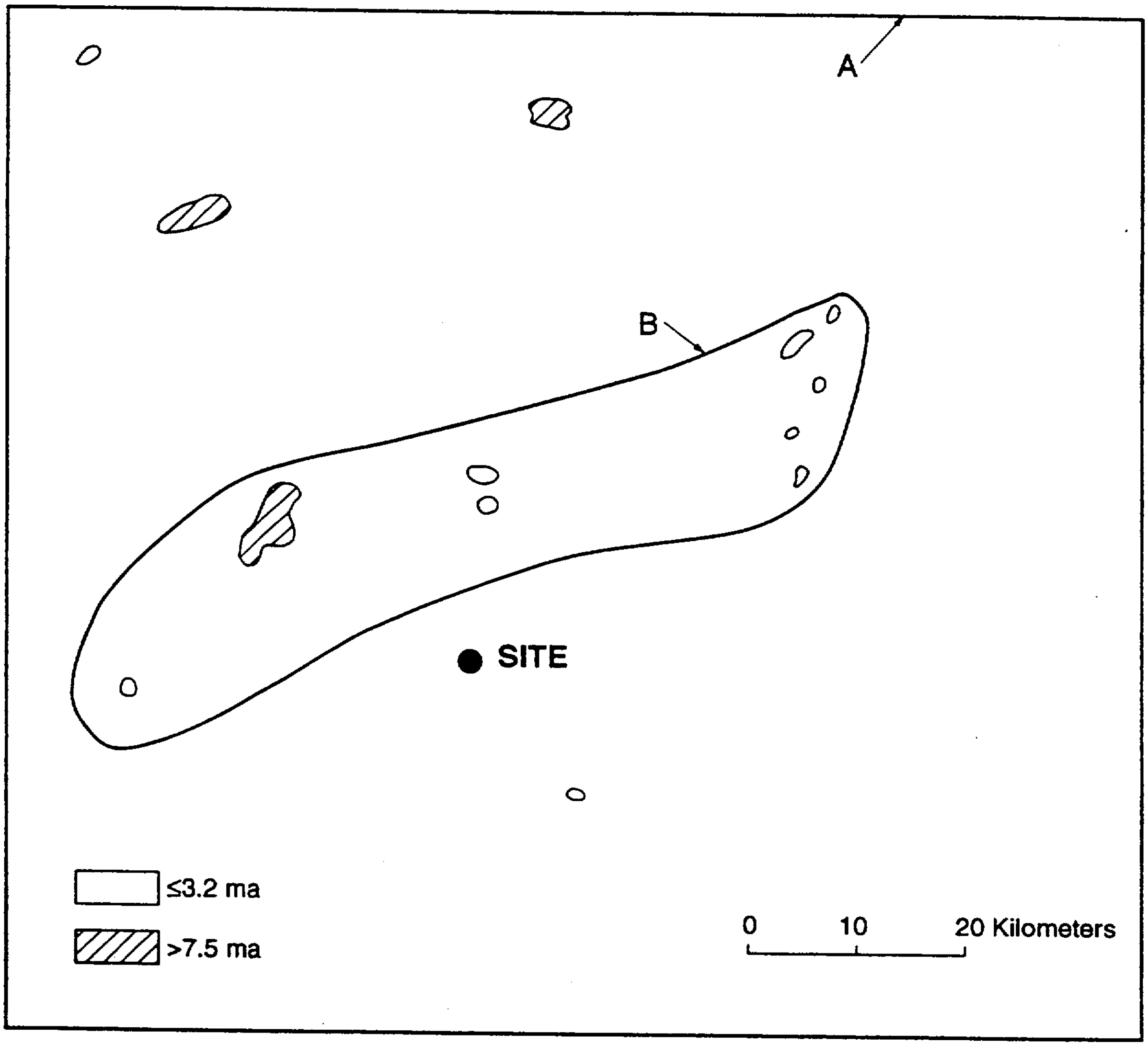


Figure 3-4 Example of subdividing the region of Figure 3-1 into locally homogeneous zones.

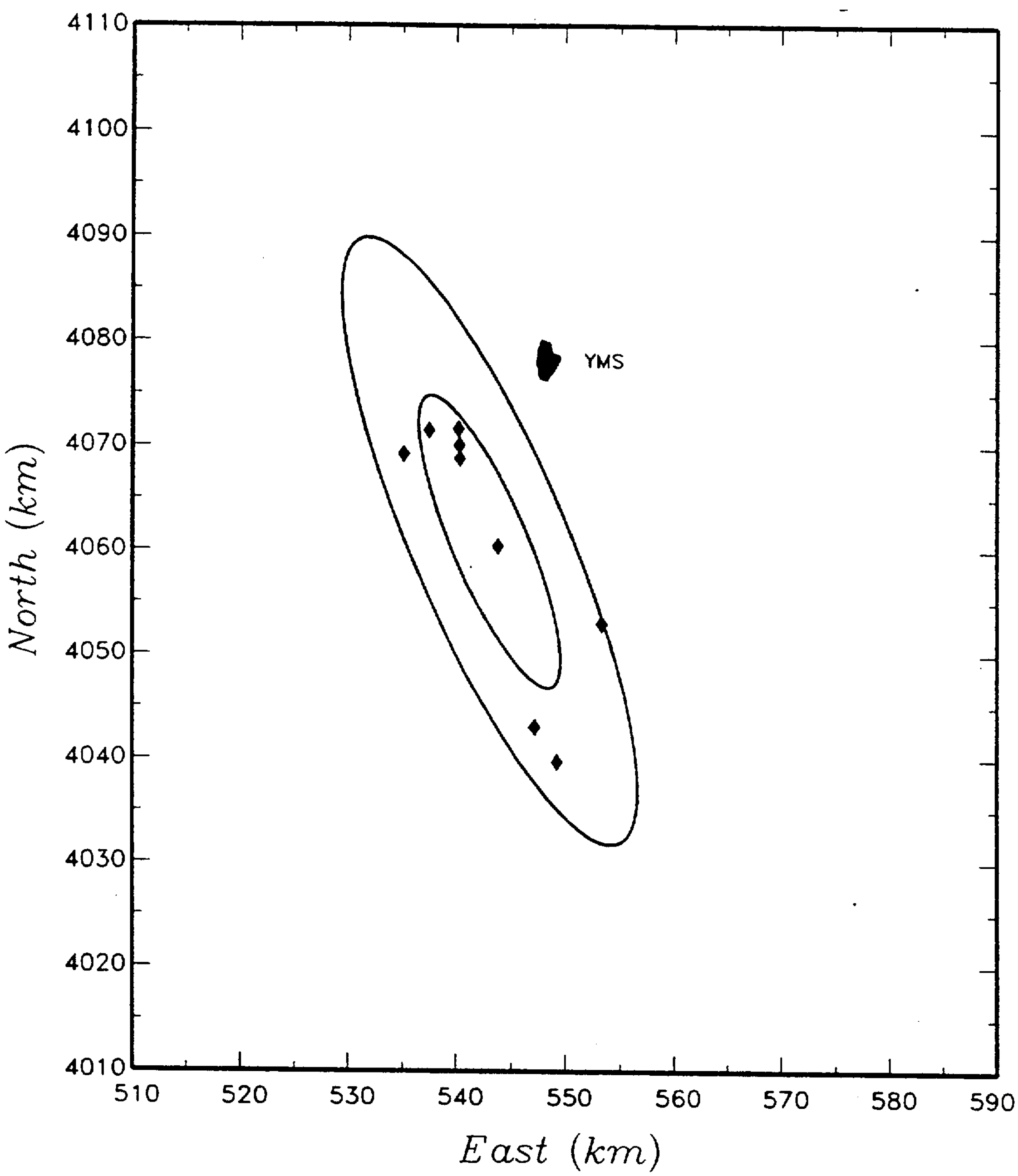


Figure 3-5 Representation of the volcanic events in Crater Flat by a bivariate Gaussian field. Lines enclose regions expected to contain 50 and 95-percent of future events associated with the field. YMS refers to the proposed Yucca Mountain repository site.

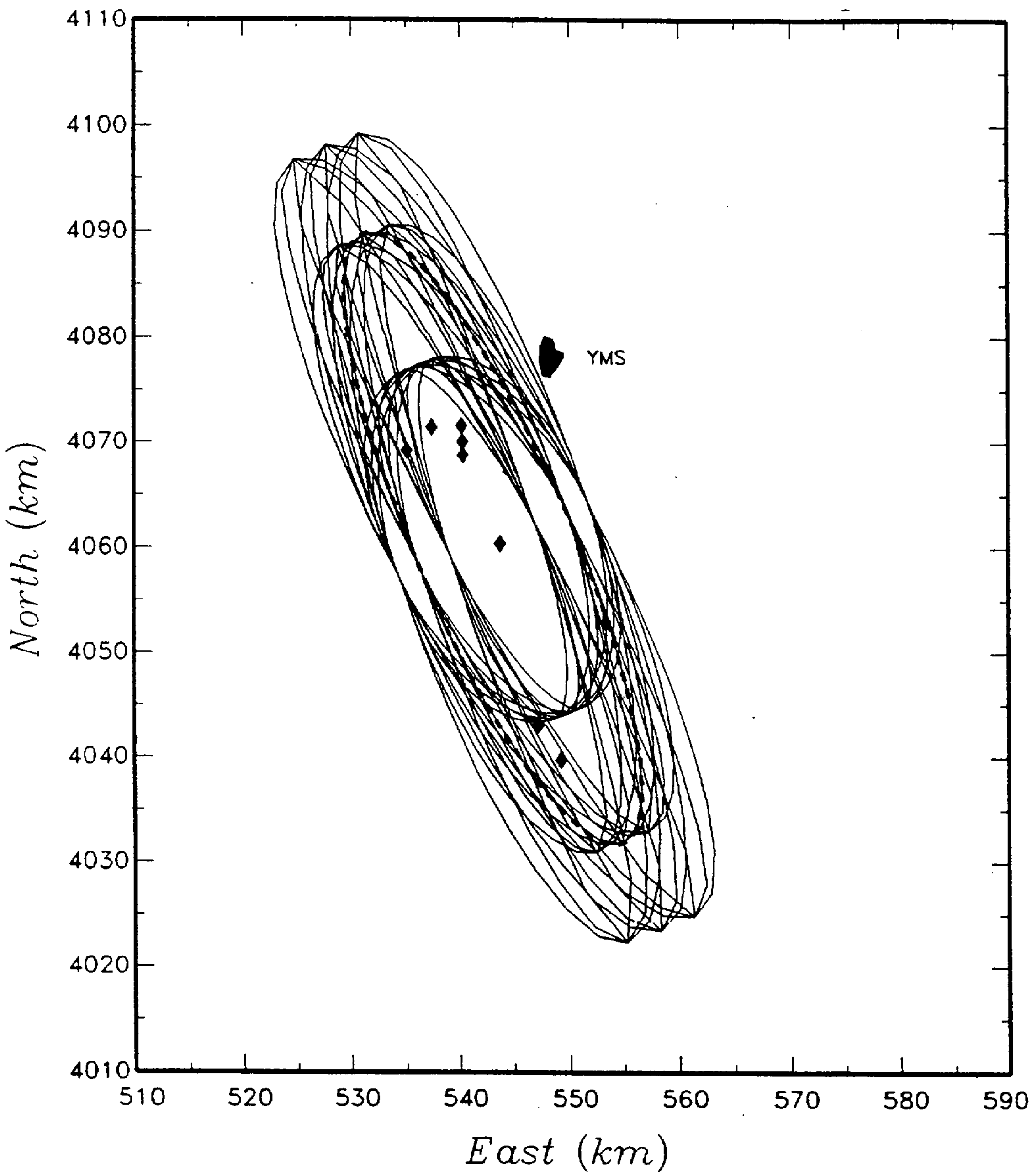


Figure 3-6 Example of set of 27 possible Gaussian volcanic fields considering uncertainty in field size and orientation (covariance of *x* and *y*). Each curve is a possible 95-percent density ellipse for the field. The heavy dashed curve denotes the maximum likelihood 95-percent density ellipse. YMS refers to the proposed Yucca Mountain repository site.

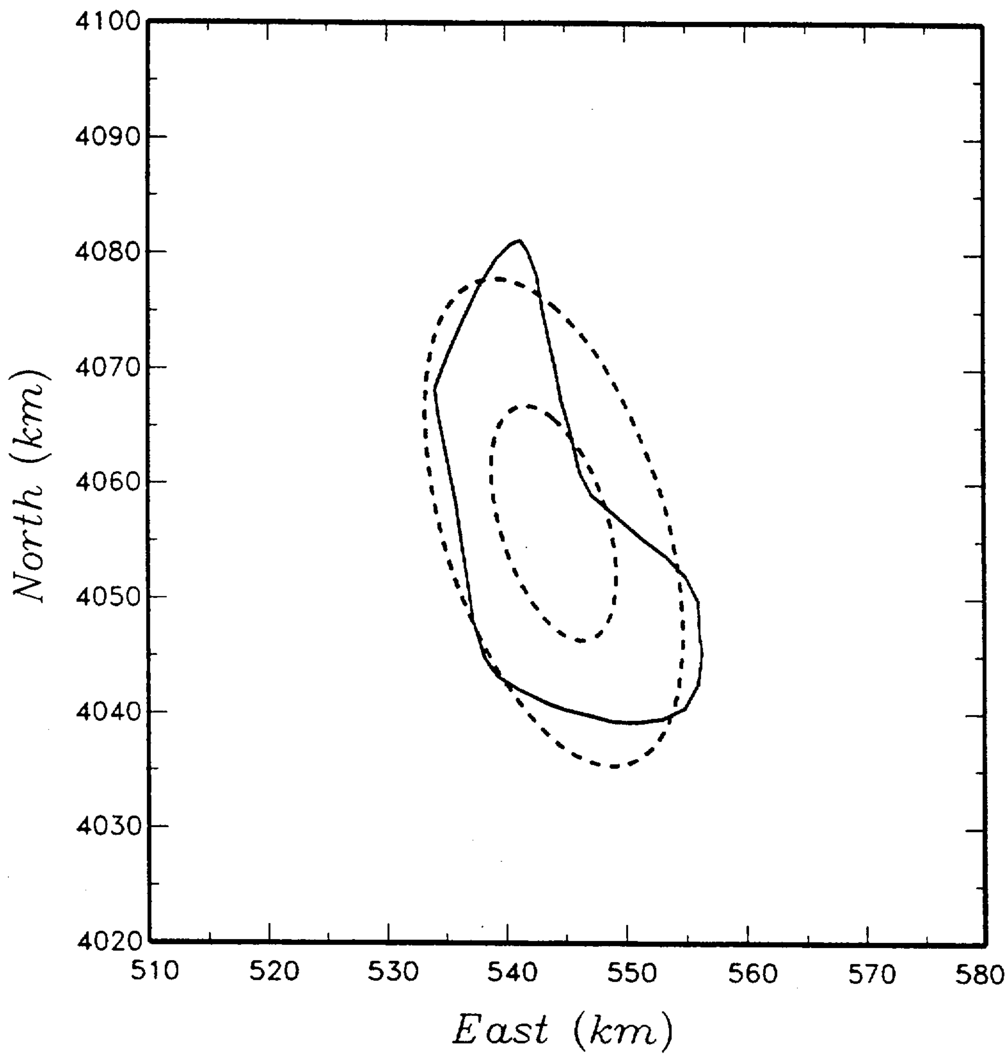


Figure 3-7 Example of fitting a 95-percent density bivariate Gaussian field shape to boundary of a volcanic zone defined by geology. The 50-percent density ellipse is also shown.

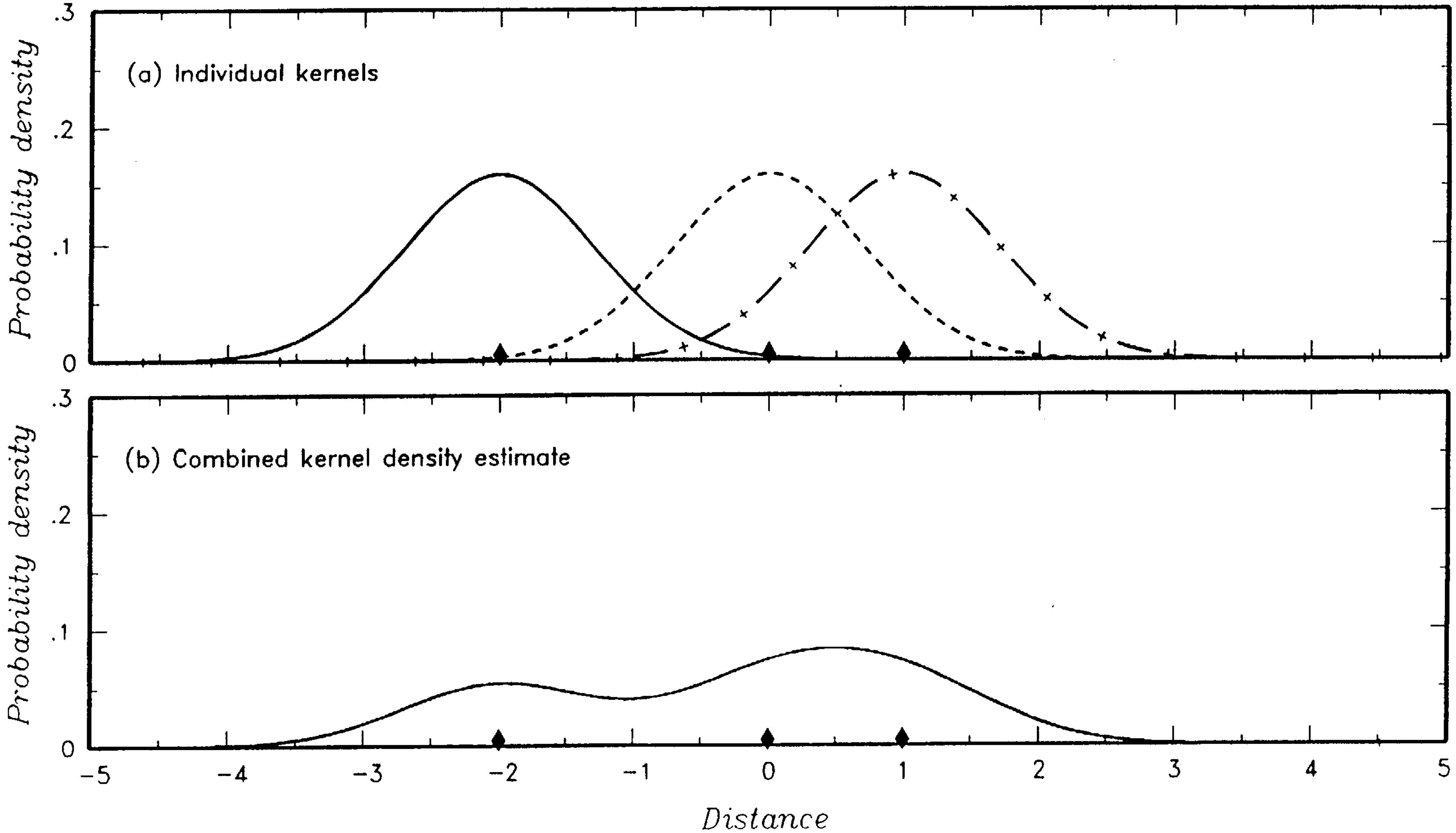


Figure 3-8 **Example of kernel density estimation in one dimension. (a) Individual kernel functions centered on the data points. (b) Summation of individual kernels normalized to unity to produce a composite estimate of the spatial density function.**

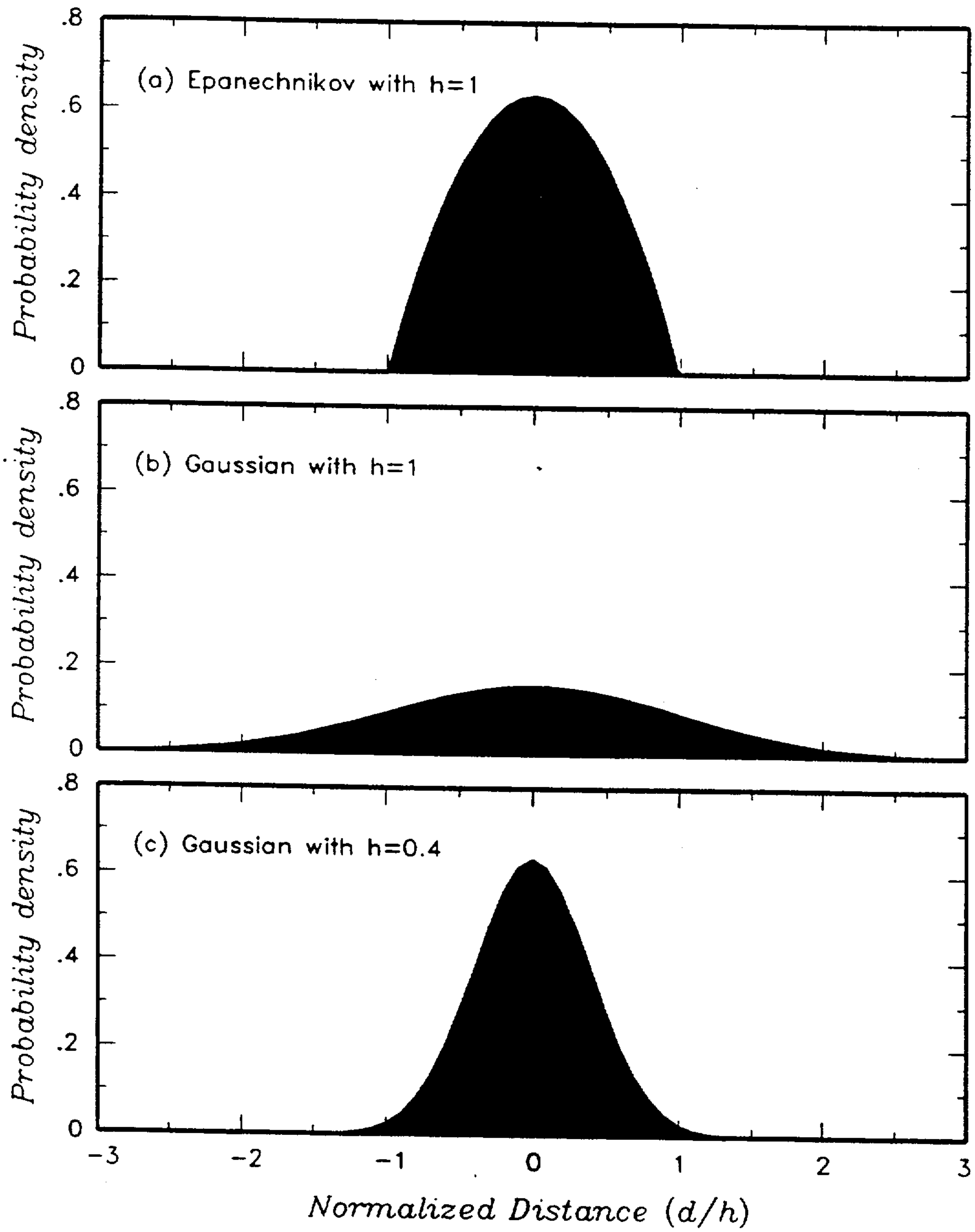


Figure 3-9 Examples of (a) Epanechnikov and (b) Gaussian density kernels with the same value of *h*. In (c) the Gaussian kernel is adjusted to have an *h* 2.5 times smaller than the *h* of the Epanechnikov kernel in (a).

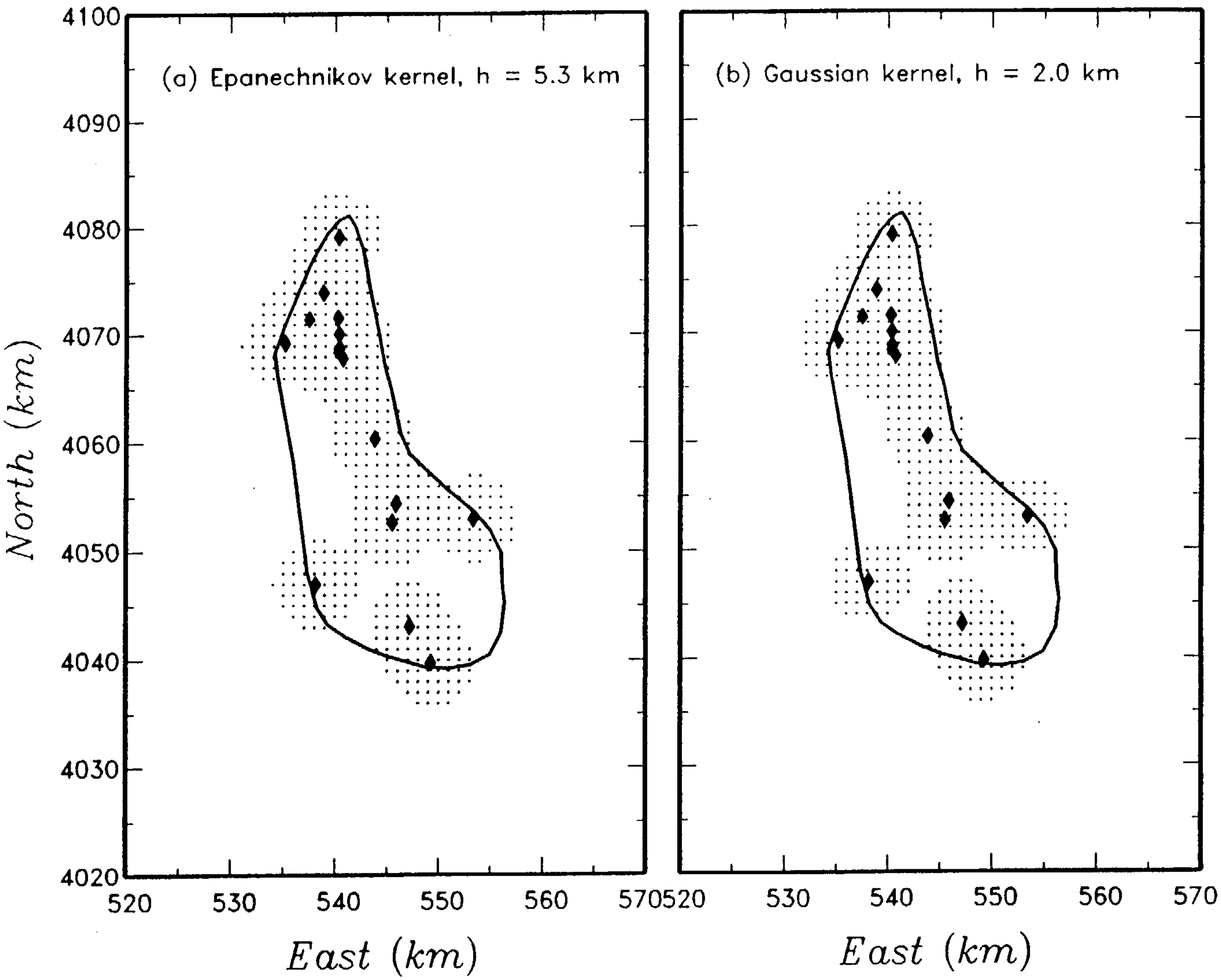


Figure 3-10 Example of fitting kernel density to boundary of a volcanic zone defined by geology. Stippled area defines the 95 percent density contour obtained using (a) a Epanechnikov kernel and (b) a Gaussian kernel.

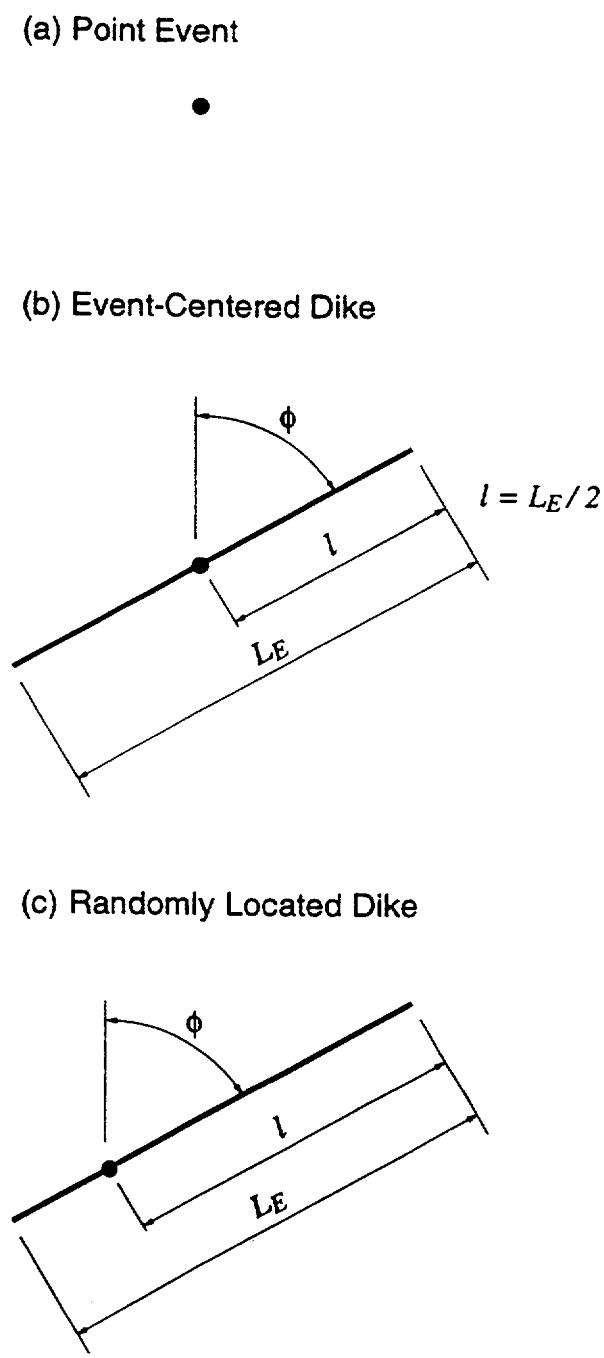


Figure 3-11 Example representations of the locations of volcanic events used in the PVHA. Each event is considered to be either (a) a point, (b) a linear dike centered on the event, or (c) a linear dike randomly located on the event.

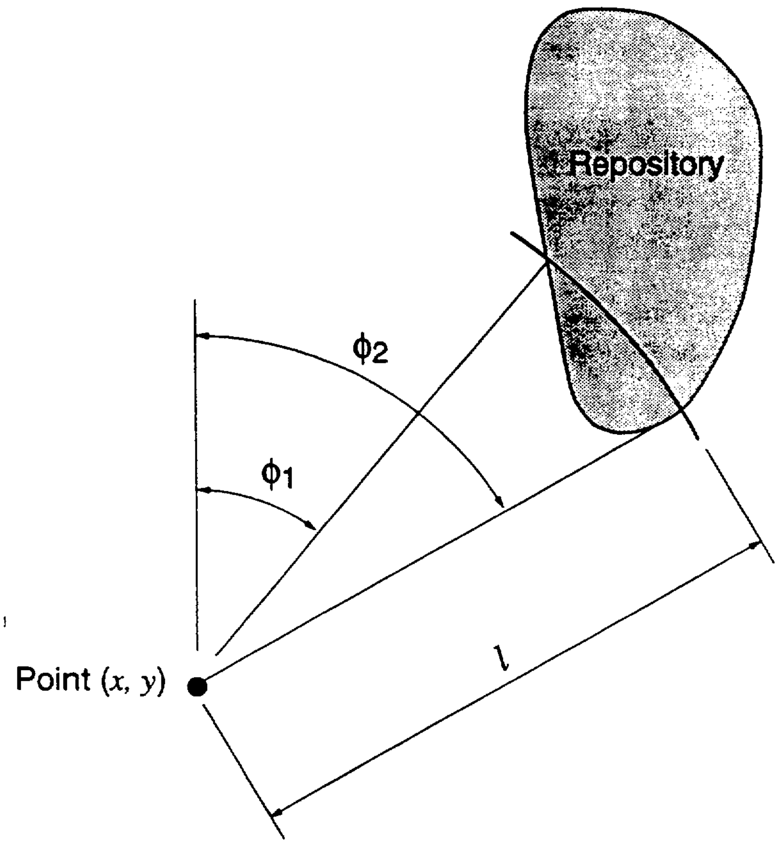


Figure 3-12 Procedure for computing conditional probability of intersection, $P_I(x,y)$.

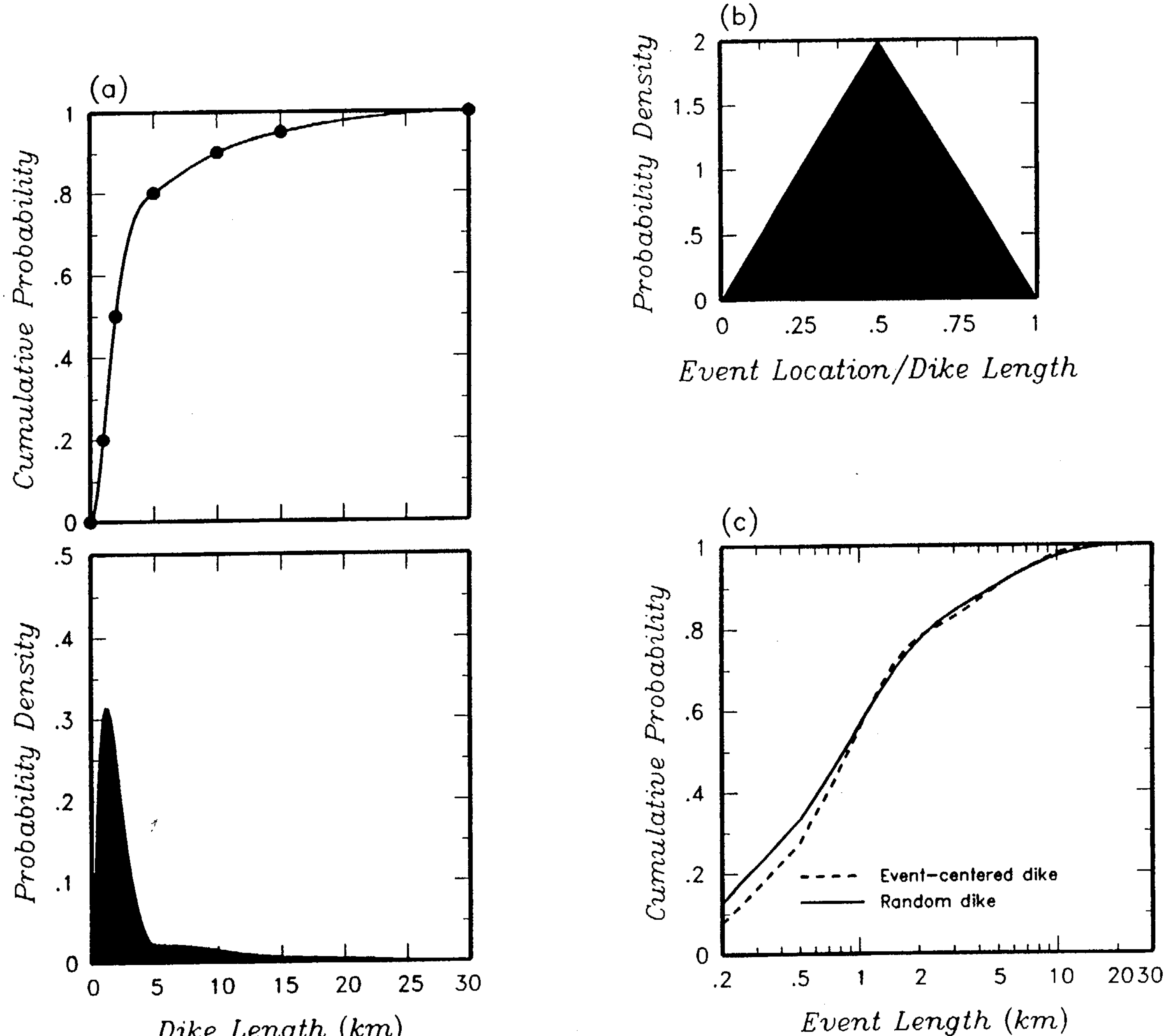


Figure 3-13 Example event length distributions. (a) Expert specified cumulative distribution for total length of an event and the resulting density function. (b) Expert specified distribution for location of an event along the dike. (c) Resulting density functions for distance from the event to the end of the dike for event-centered dikes and randomly placed dikes.

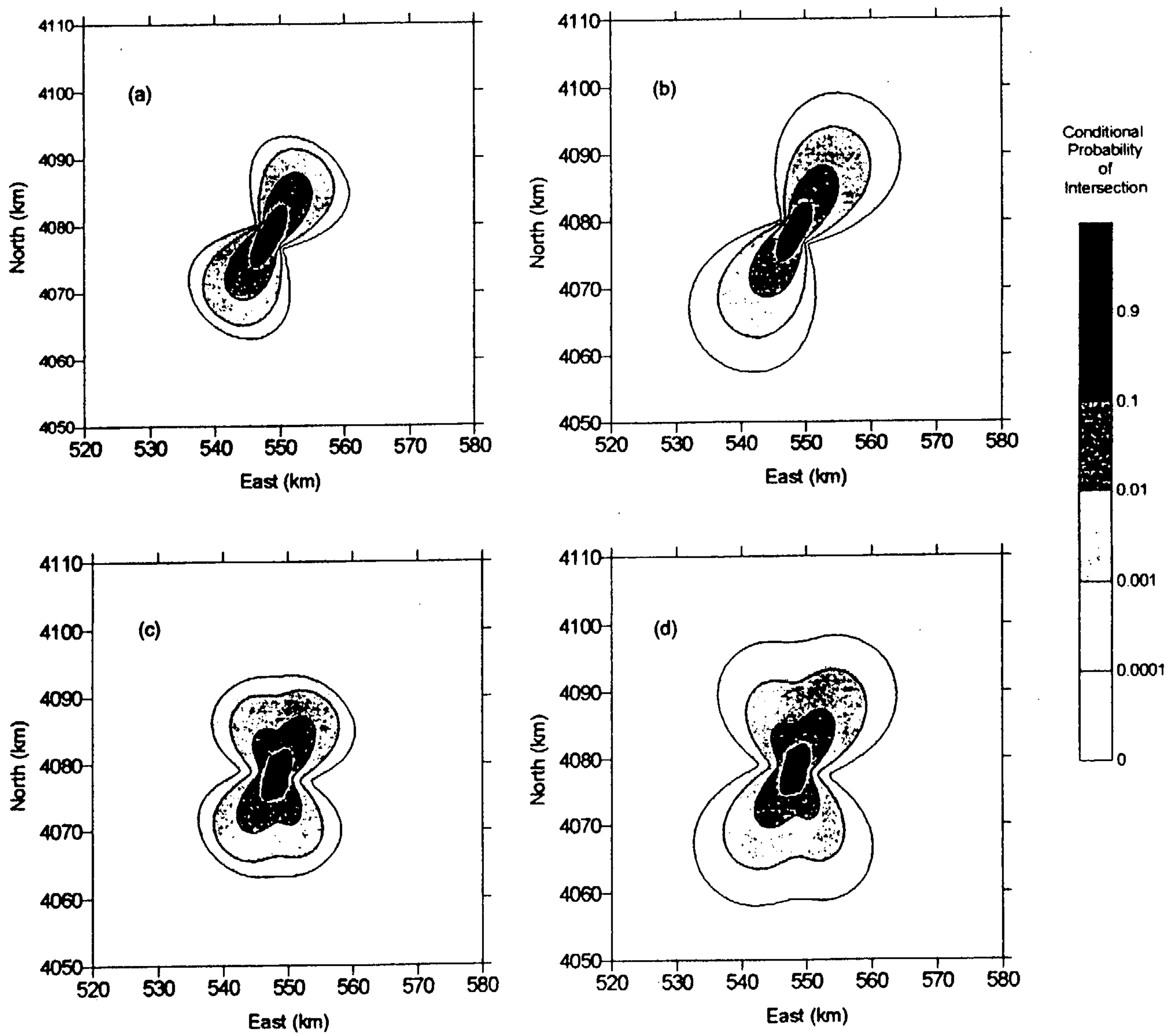


Figure 3-14 Examples of conditional probability of intersection computations. The event length distributions are shown on Figure 3-13(c). (a) Event-centered dikes with bimodal azimuth distribution N30°E ± 15°, (b) Random dikes with azimuth distribution N30°E ± 15°, (c) Event-centered dikes with bimodal azimuth distribution 70-percent frequency N30°E ± 15°, 30-percent frequency N20°W ± 15°, and (d) Random dikes with bimodal azimuth distribution 70-percent frequency N20°W ±15°. 30-percent frequency N20°W± 15°.

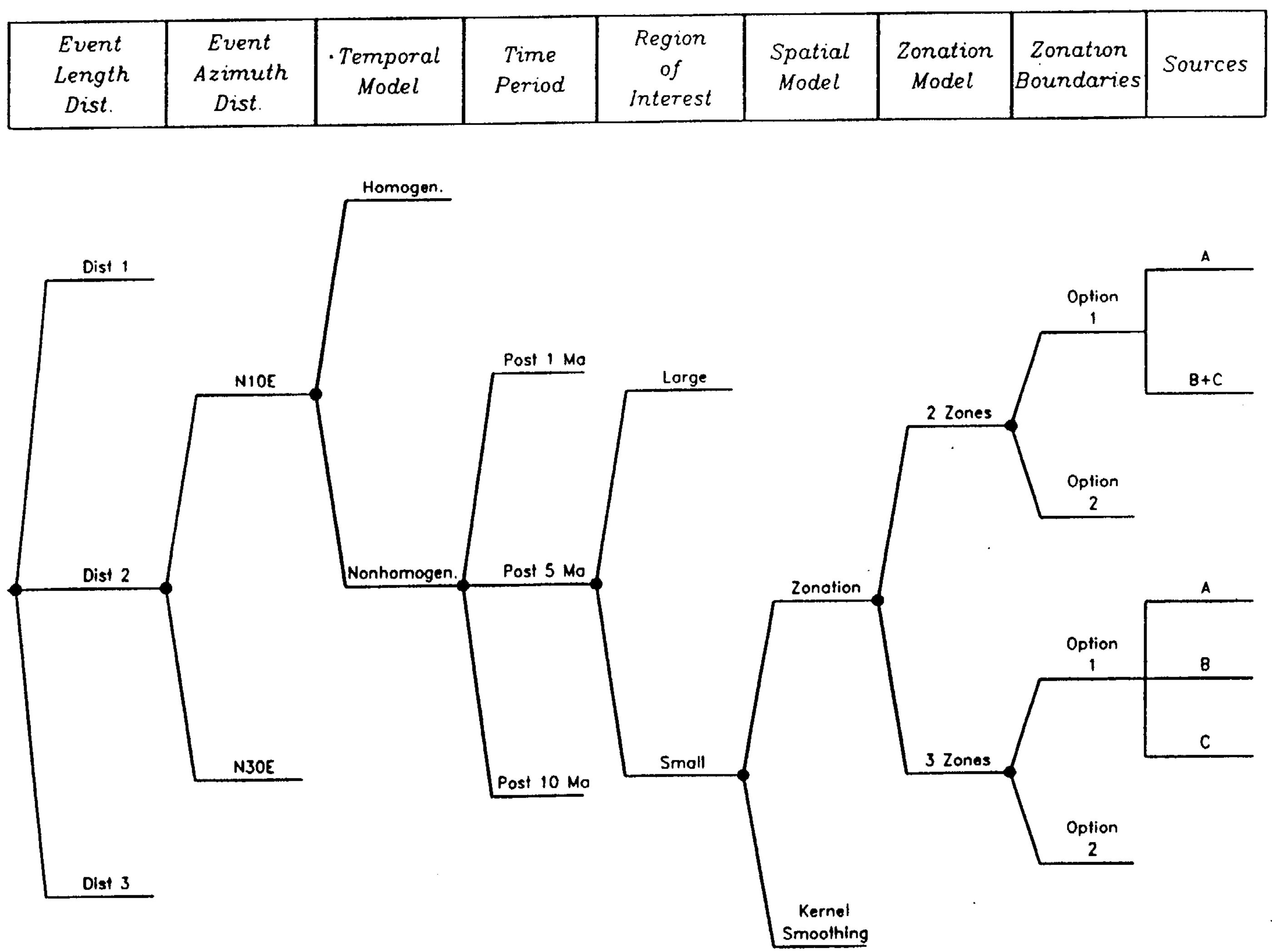


Figure 3-15 General logic tree structure used to construct PVHA computation model.

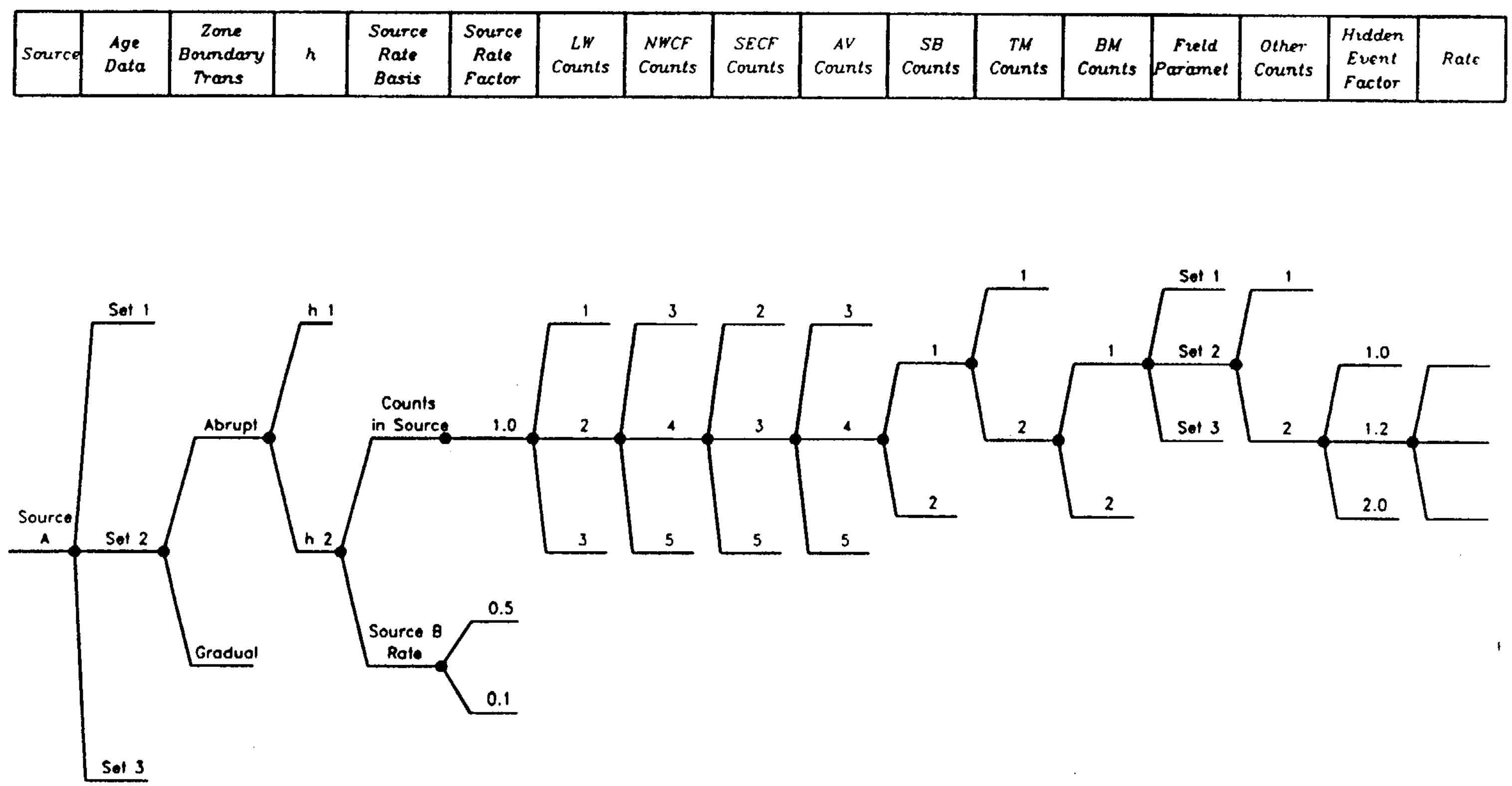


Figure 3-16 Logic tree structure for subtrees addressing the uncertainty in modeling the hazard from specific sources. These subtrees are attached to the overall logic tree shown on Figure 3-15.

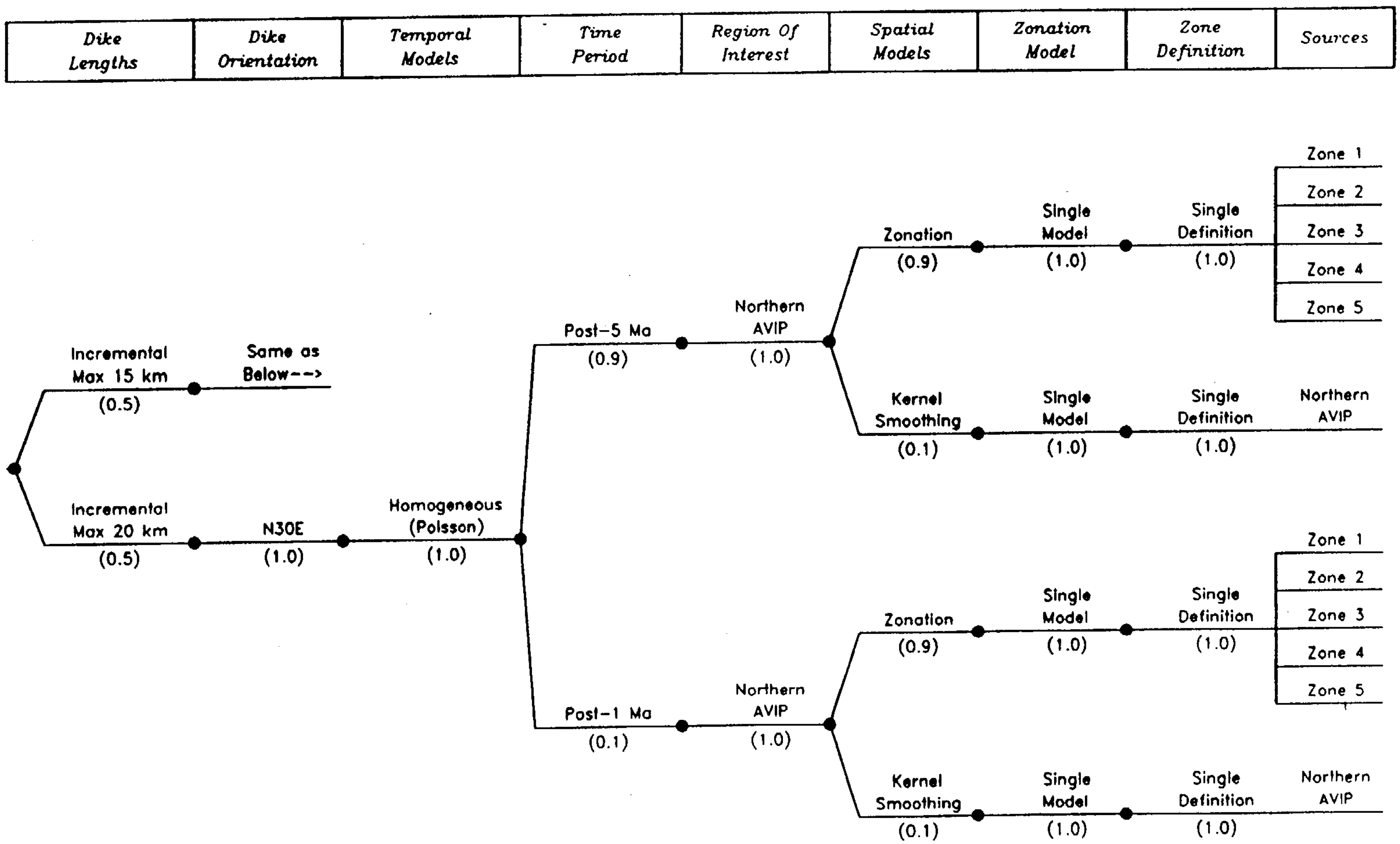


Figure 3-17 Logic tree for the PVHA model developed by Alexander McBirney.

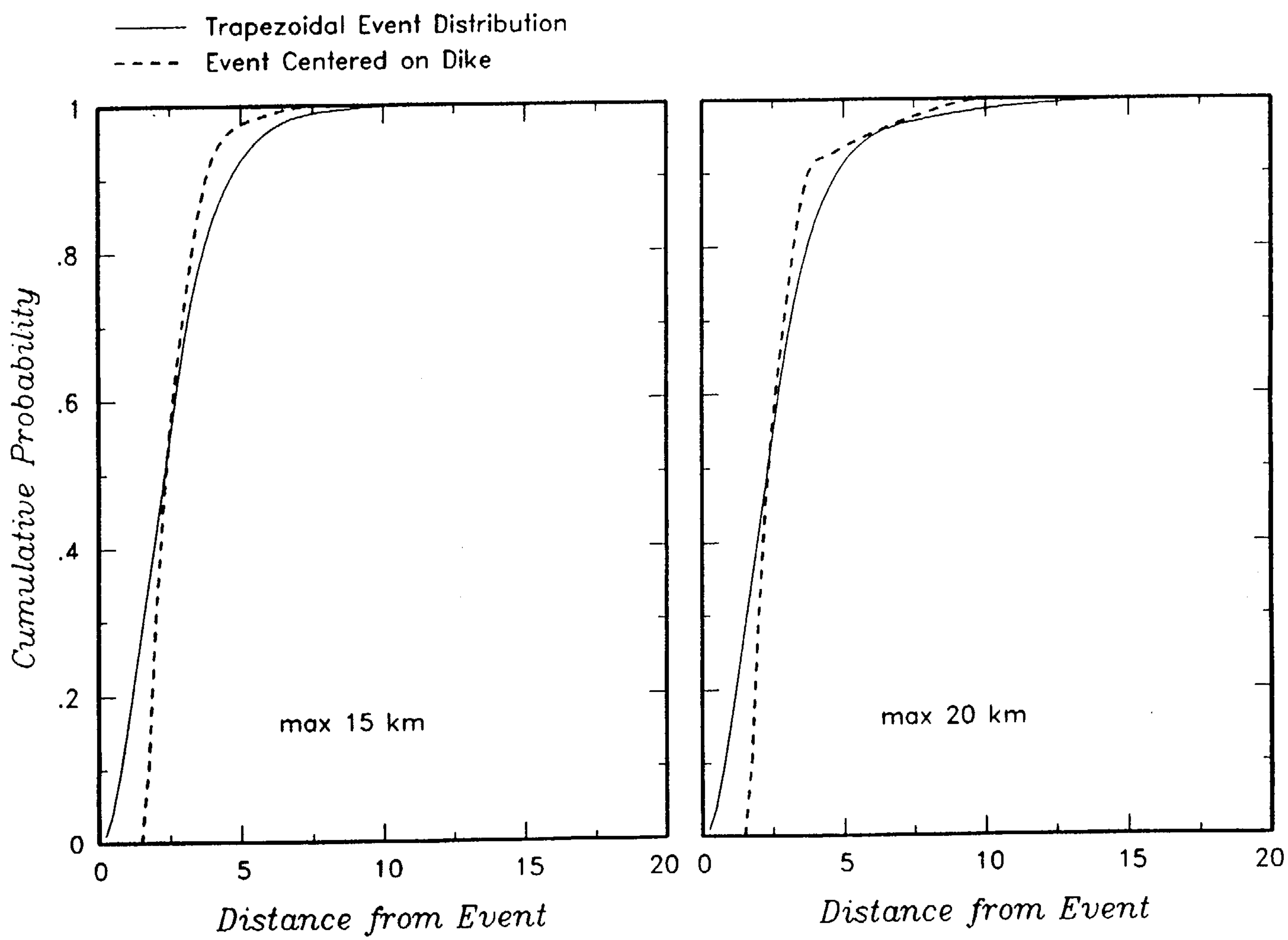


Figure 3-18 Alternative distributions for the length of an event *f(l)* developed from the assessments by Alexander McBirney.

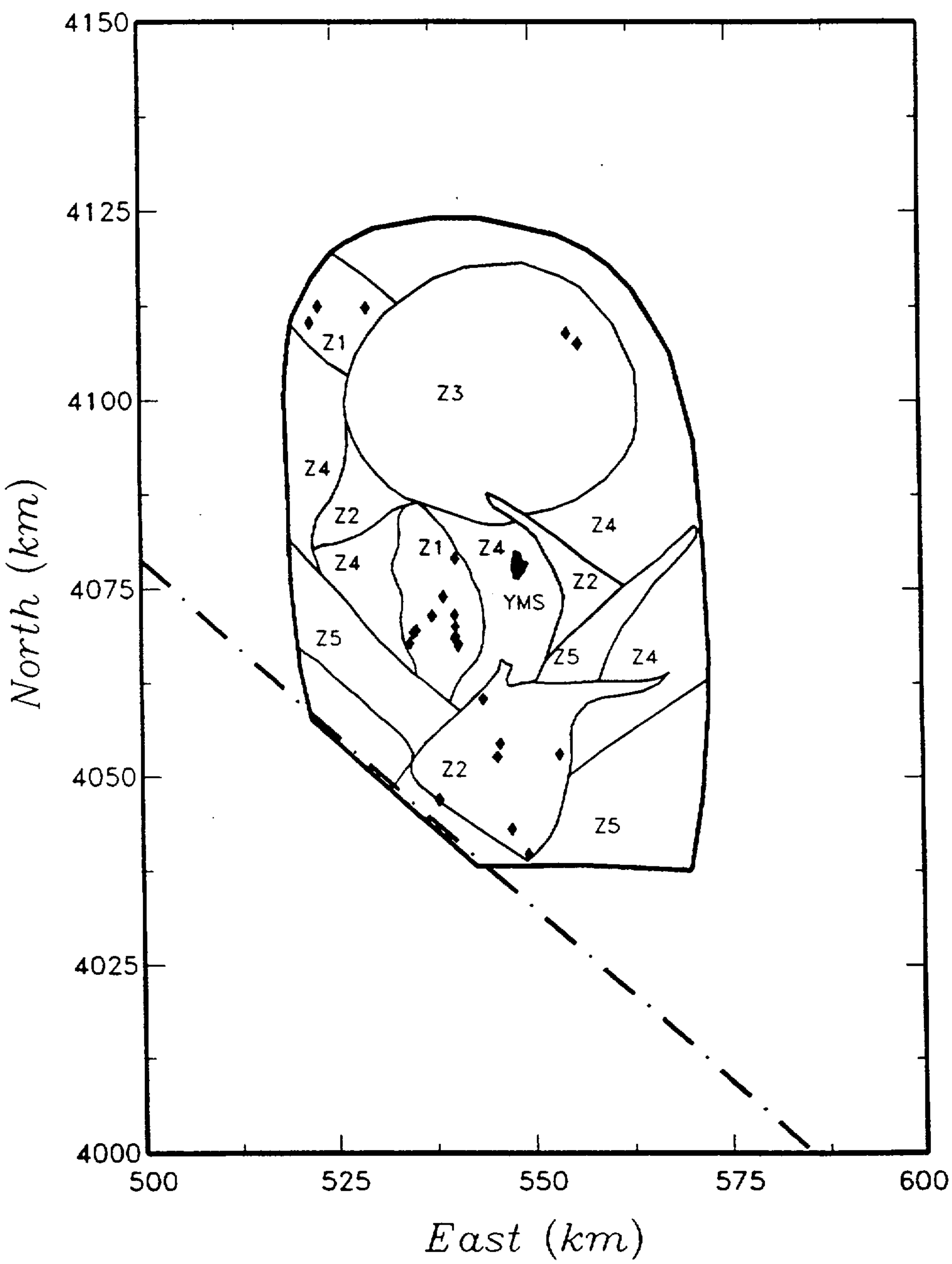


Figure 3-19 Volcanic source zone model developed by Alexander McBirney. Diamonds represent volcanic events for the post-5 Ma time period. YMS refers to the proposed Yucca Mountain repository site and the dash-dot line is the Nevada-California border.

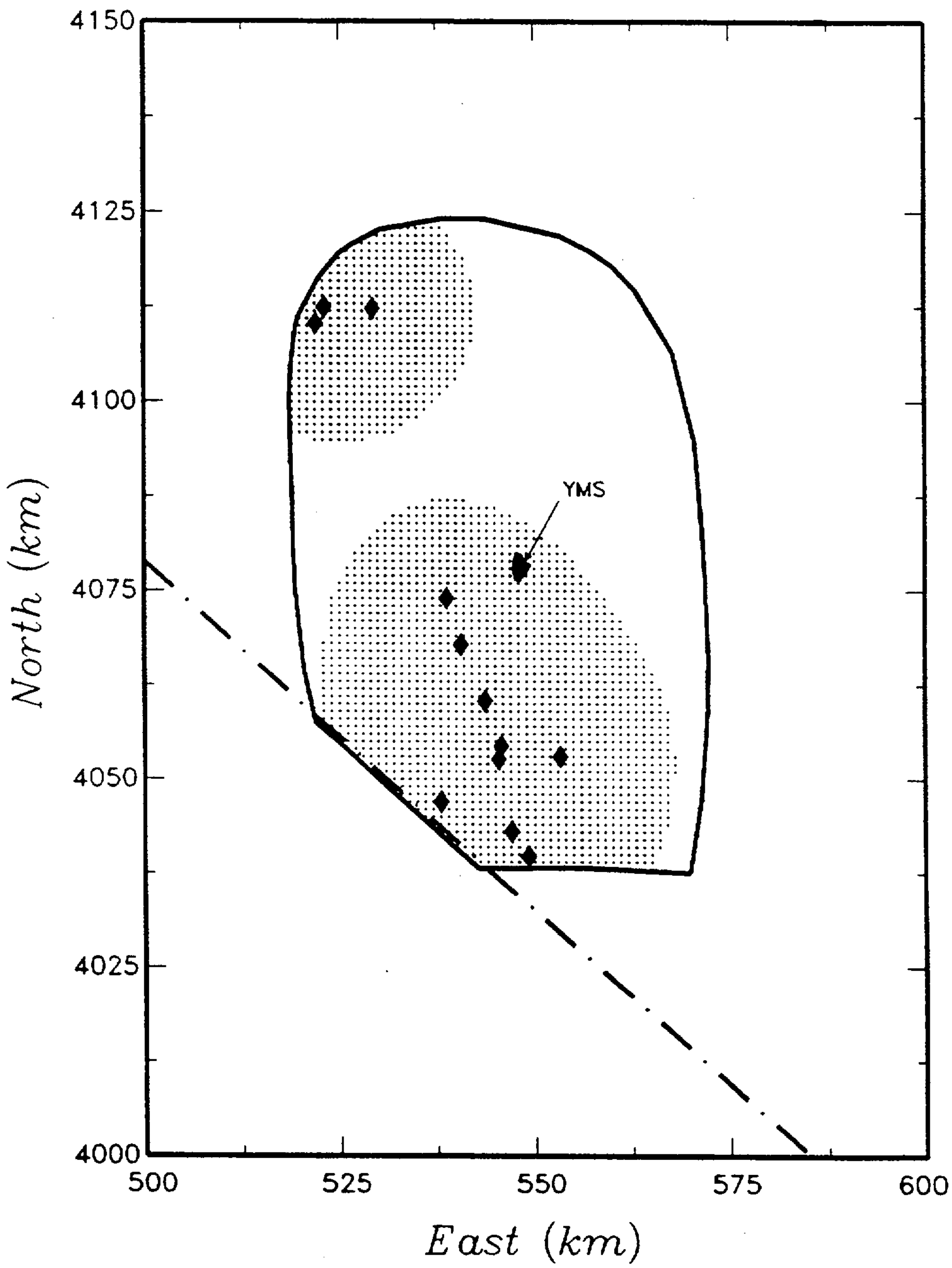


Figure 3-20 Example of a kernel density estimate based on Alexander McBirney's preferred event counts for the post-5 Ma time period and a Gaussian kernel with $h = 9$ km. The stippled area contains 95-percent of the spatial density. YMS refers to the proposed Yucca Mountain repository site and the dash-dot line is the Nevada-California border.

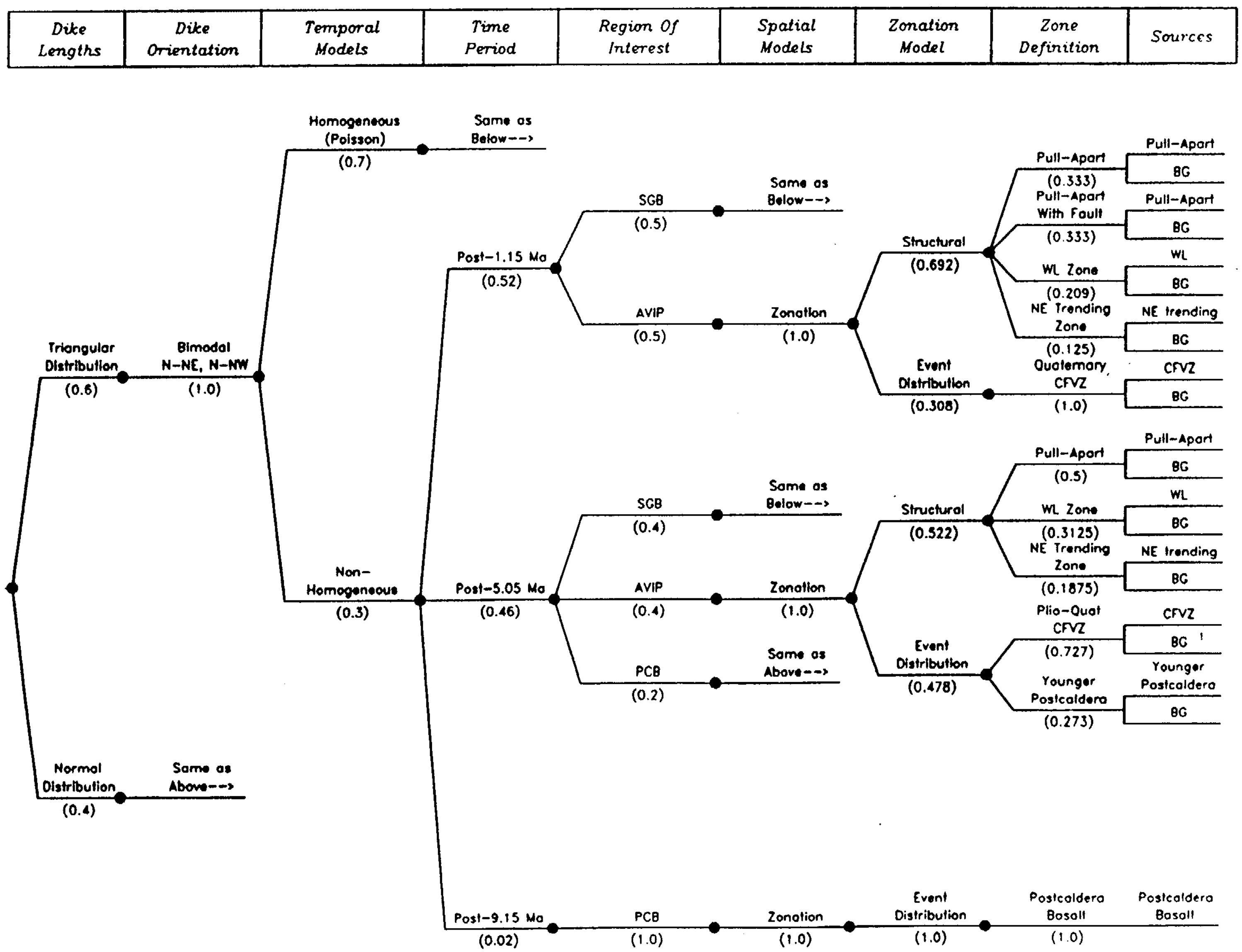


Figure 3-21 Logic tree for the PVHA model developed by Bruce Crowe.

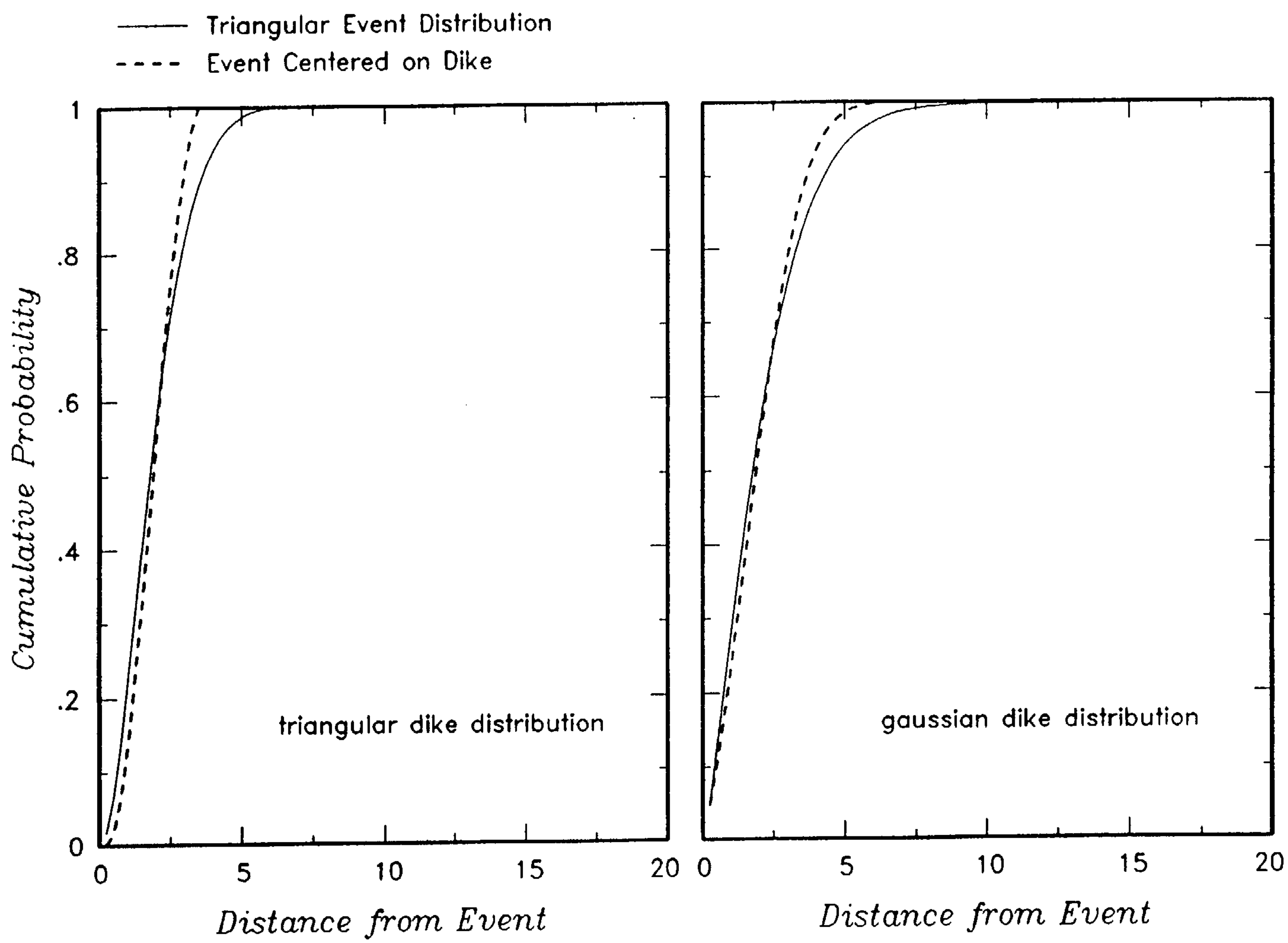


Figure 3-22 Alternative distributions for the length of an event *f(l)* developed from the assessments by Bruce Crowe.

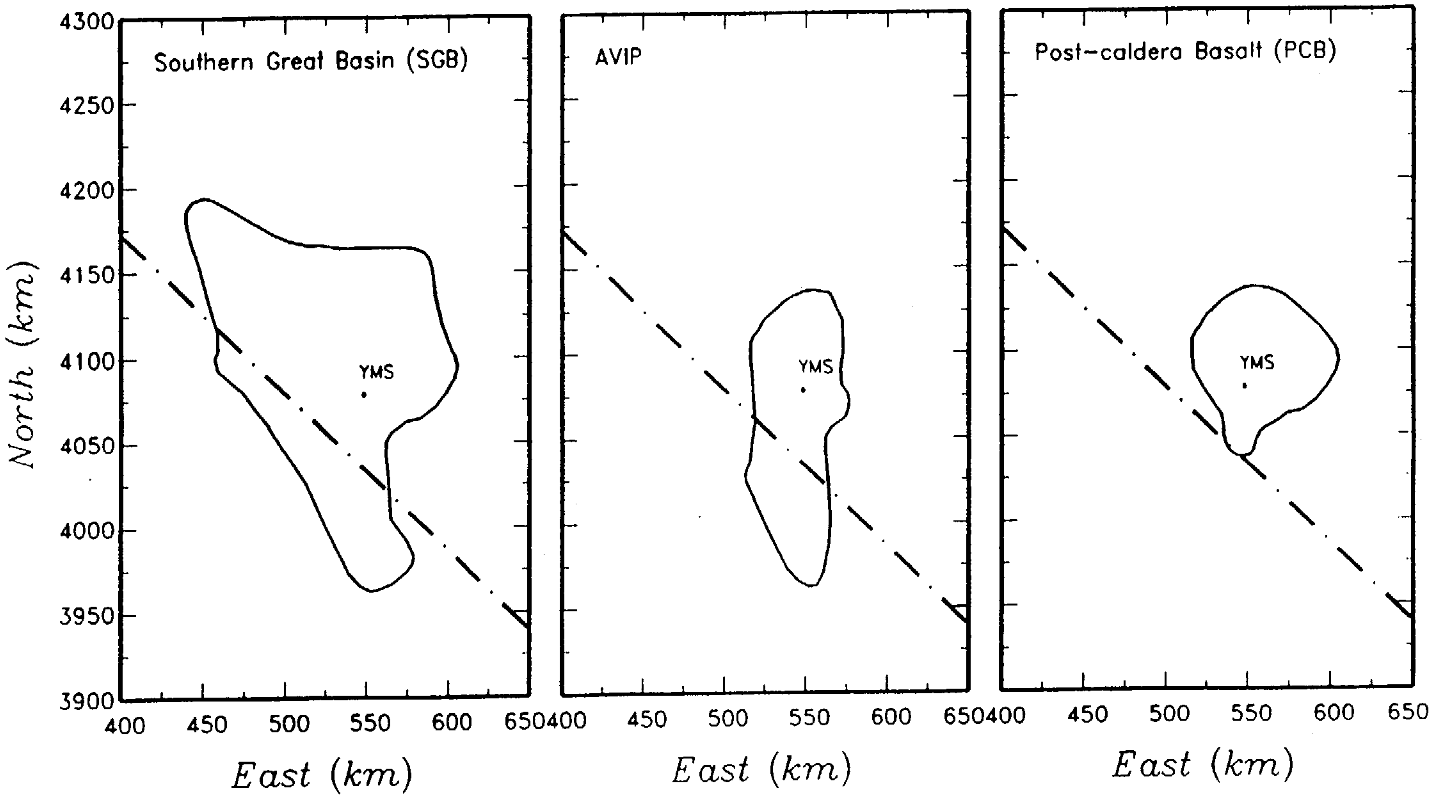


Figure 3-23 Alternative regions of interest used as background source zones in Bruce Crowe's PVHA model. YMS refers to the proposed Yucca Mountain repository site and the dash-dot line is the Nevada-California border.

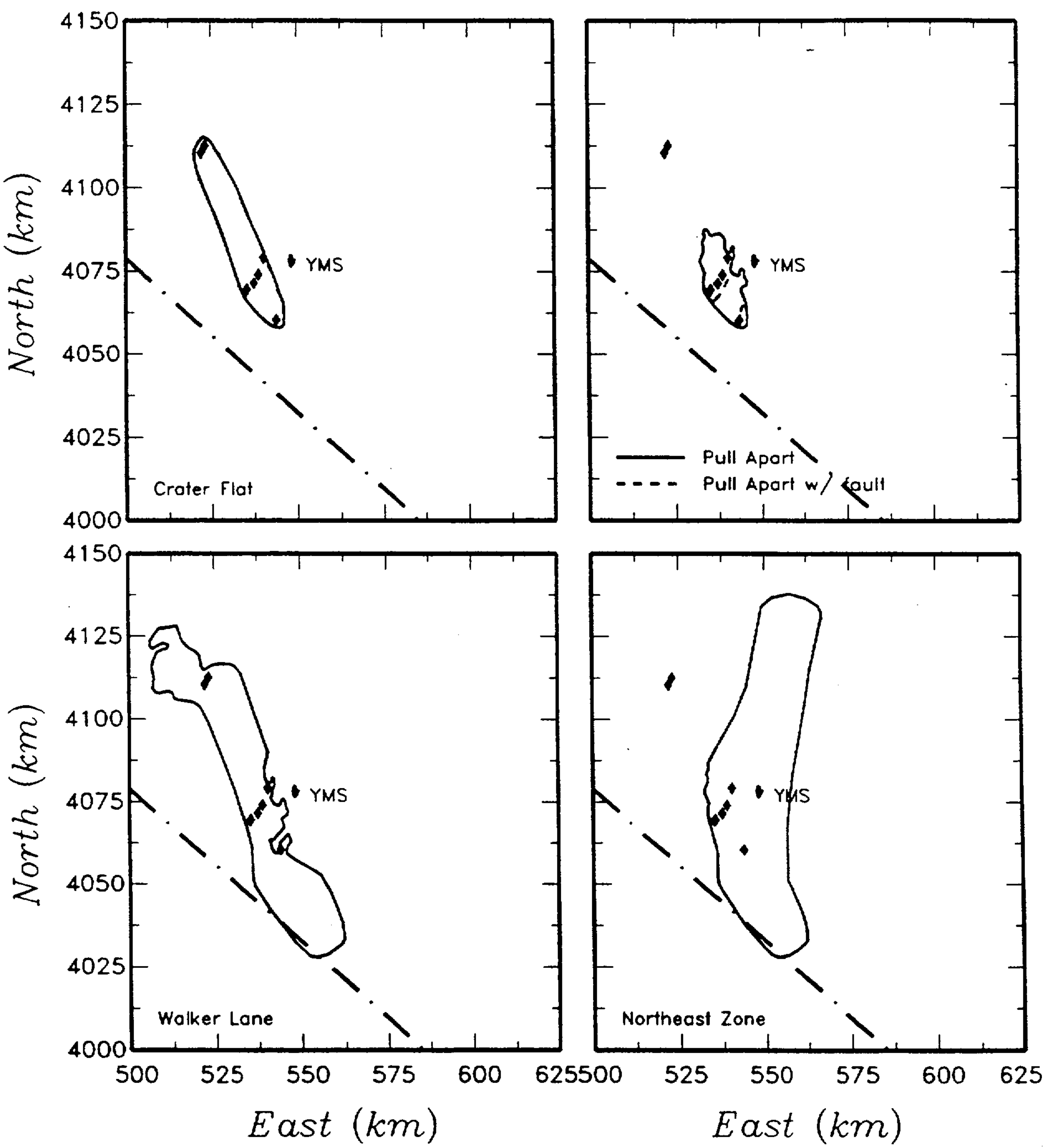


Figure 3-24 Alternative source zones defined by Bruce Crowe for the post-1.15 Ma time period. Diamonds represent volcanic events for the post-1.15 Ma time period. YMS refers to the proposed Yucca Mountain repository site and the dash-dot line is the Nevada-California border.

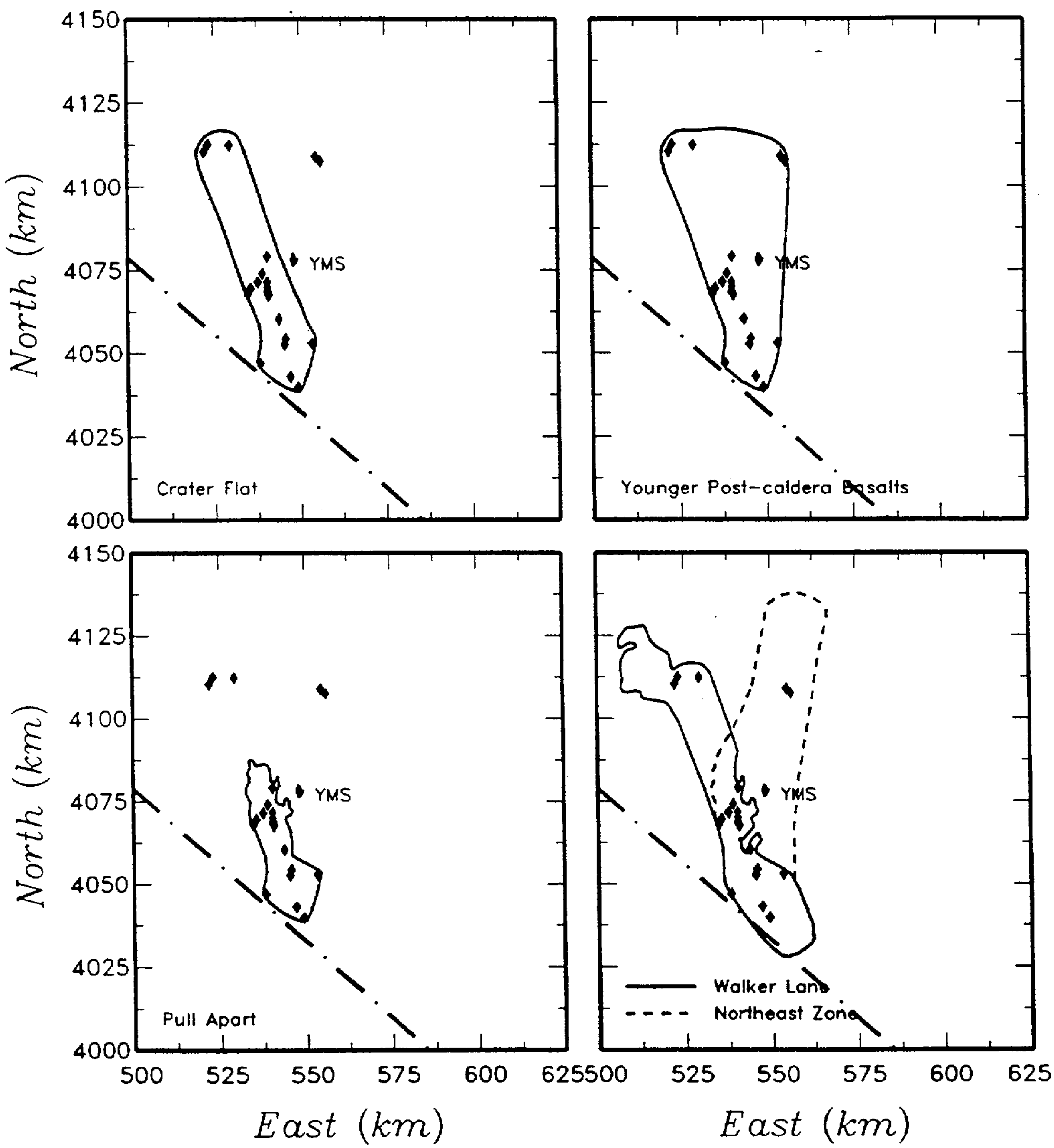
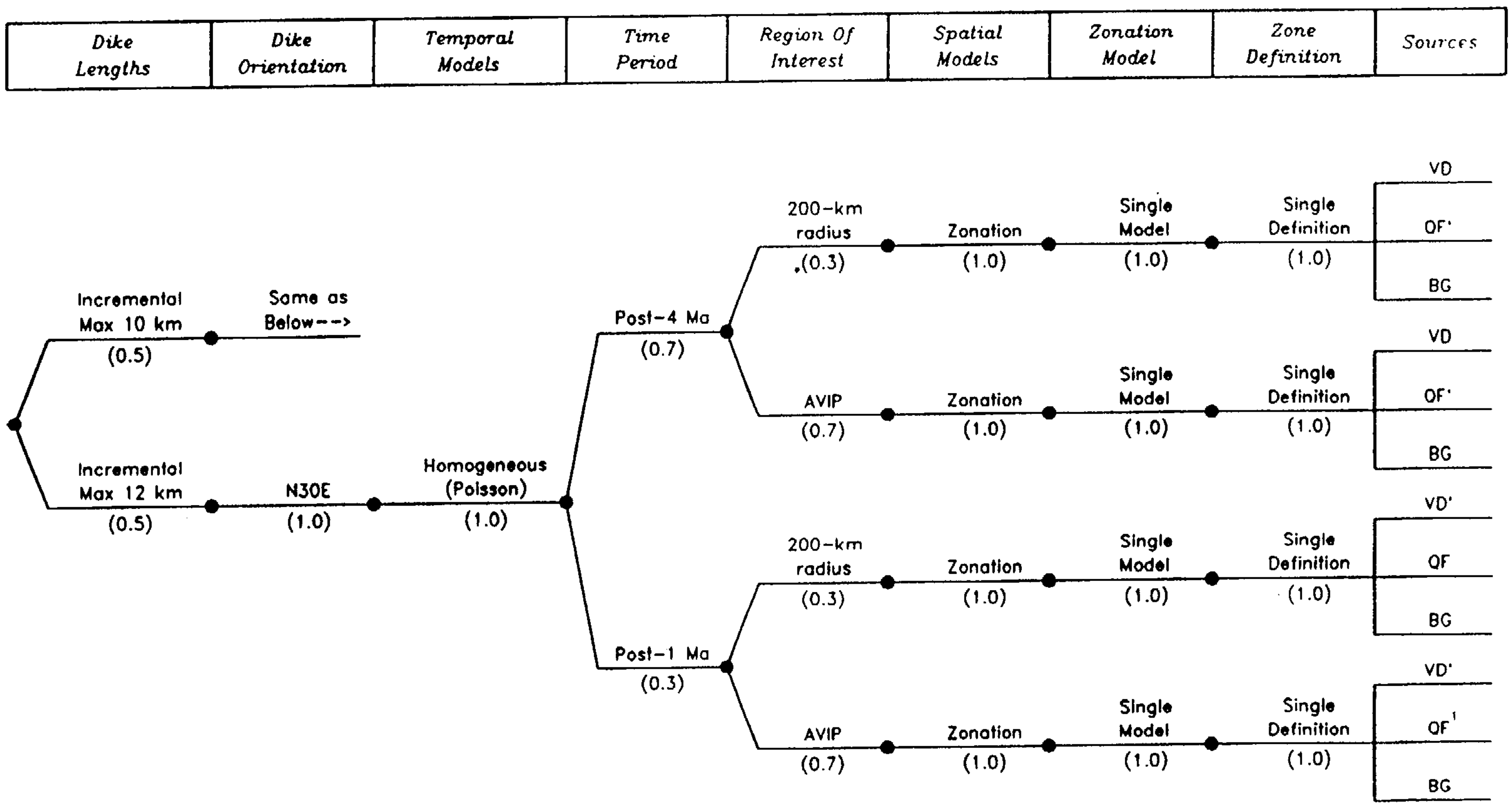


Figure 3-25 Alternative source zones defined by Bruce Crowe for the post-5.05 Ma time period. Diamonds represent volcanic events for the post-5.05 Ma time period. YMS refers to the proposed Yucca Mountain repository site and the dash-dot line is the Nevada-California border.



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 3-26 Logic tree for the PVHA model developed by George Thompson.

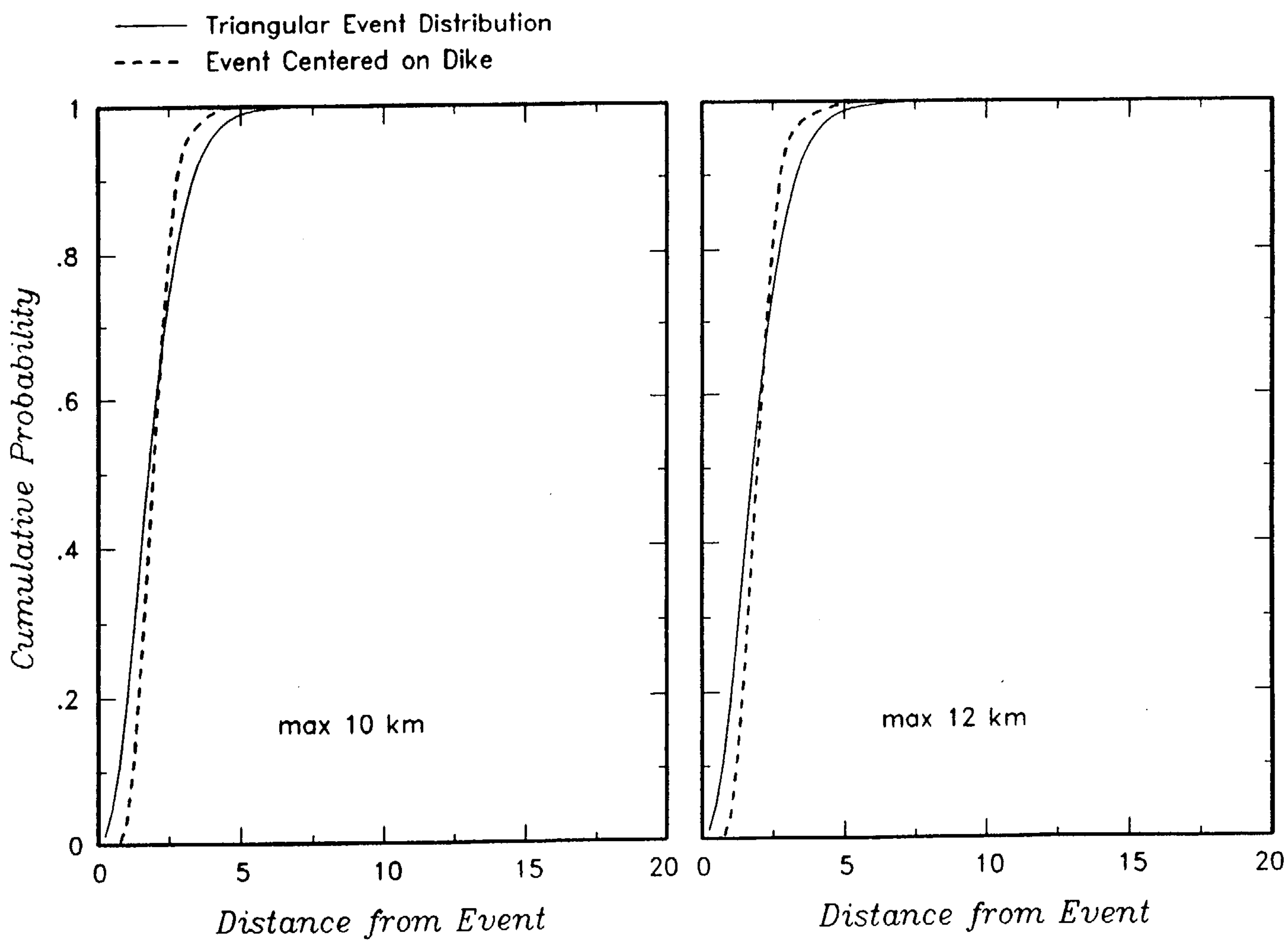


Figure 3-27 Alternative distributions for the length of an event *f(l)* developed from the assessments by George Thompson.

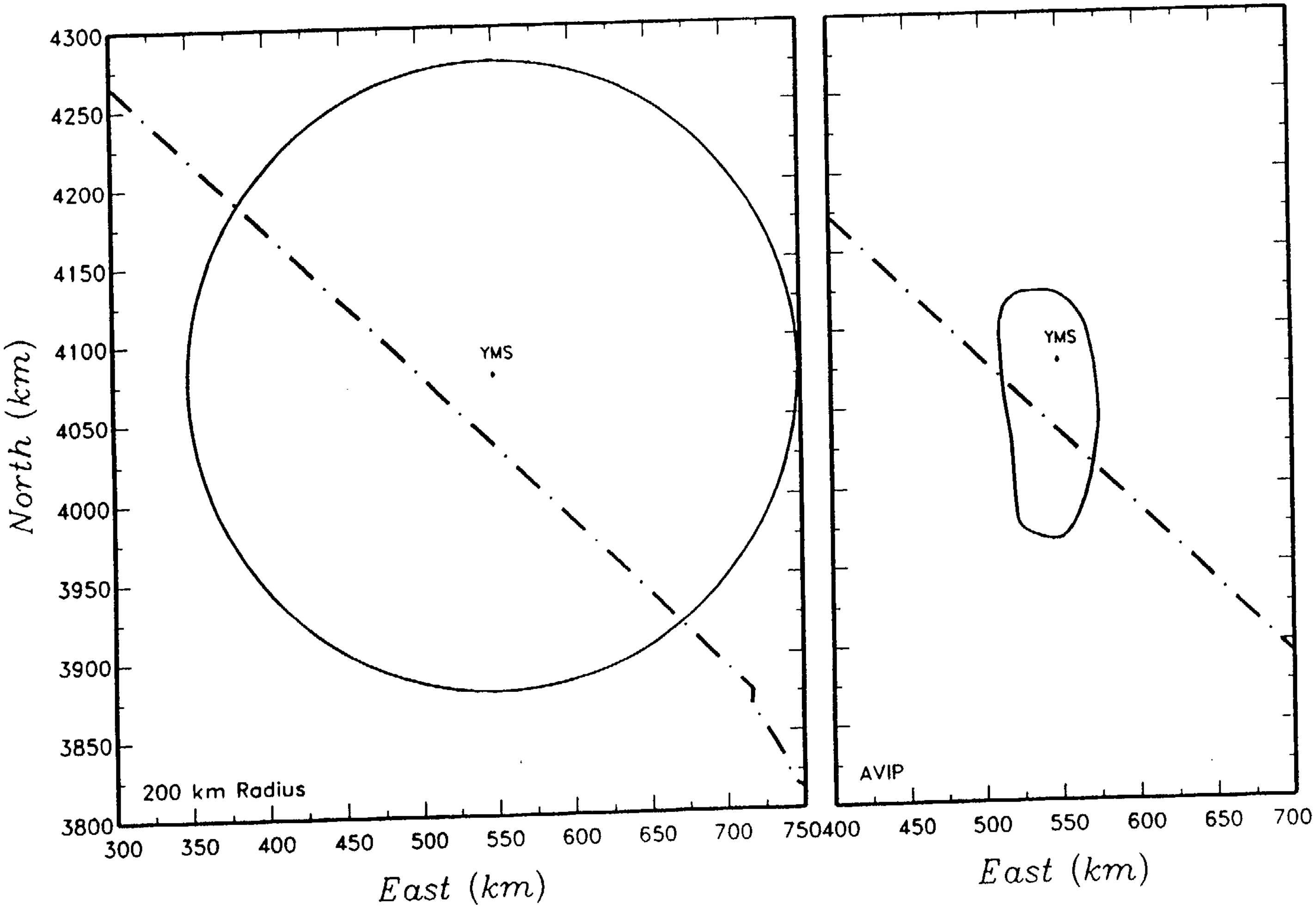


Figure 3-28 Alternative regions of interest used as background source zones in George Thompson's PVHA model. YMS refers to the proposed Yucca Mountain repository site and the dash-dot line is the Nevada-California border.

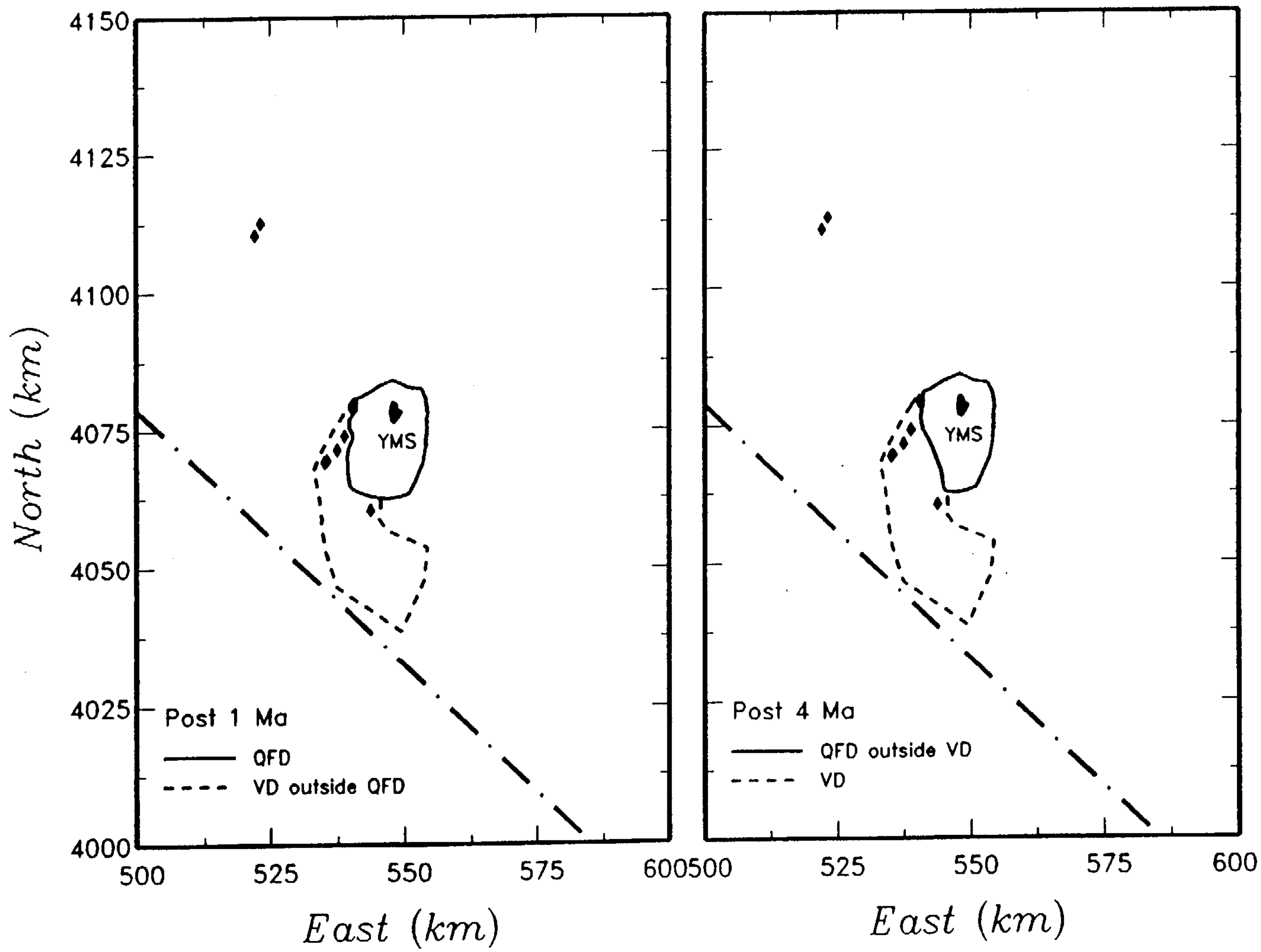


Figure 3-29 Alternative source zones defined by George Thompson. Diamonds represent volcanic events for the post-1 Ma and post-4 Ma time periods. YMS refers to the proposed Yucca Mountain repository site and the dash-dot line is the Nevada-California border.

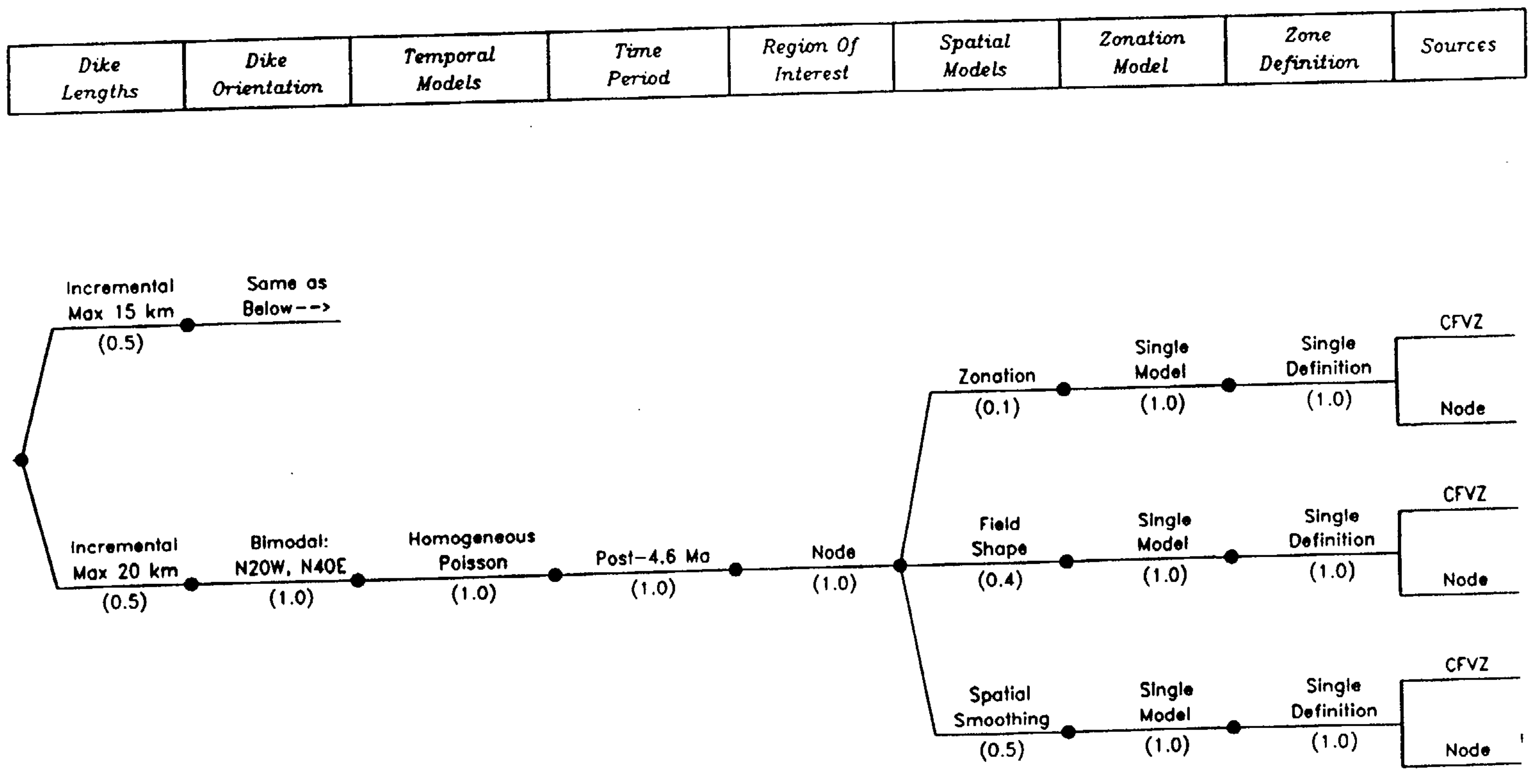


Figure 3-30 Logic tree for the PVHA model developed by George Walker.

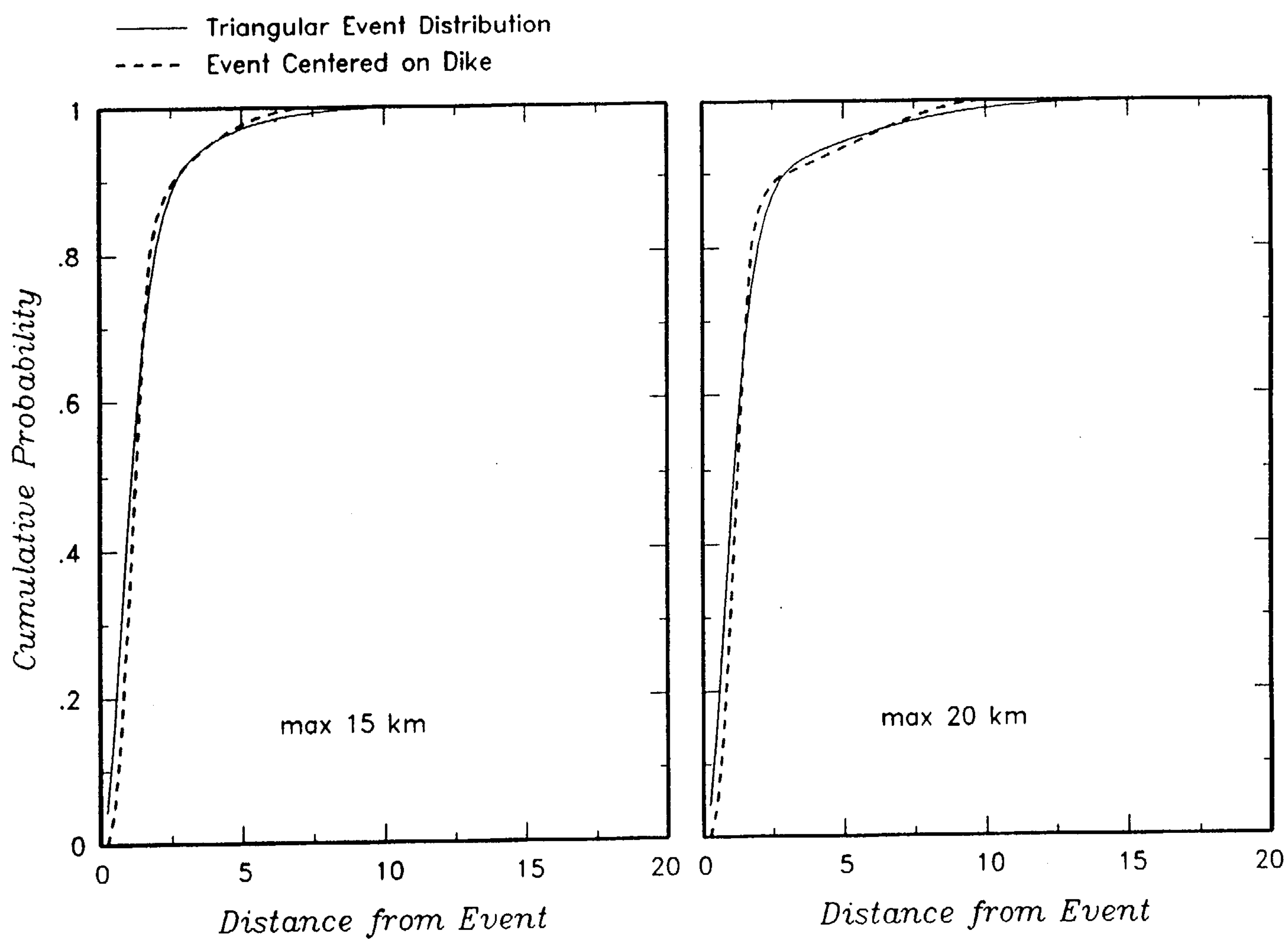


Figure 3-31 Alternative distributions for the length of an event $f(l)$ developed from the assessments by George Walker.

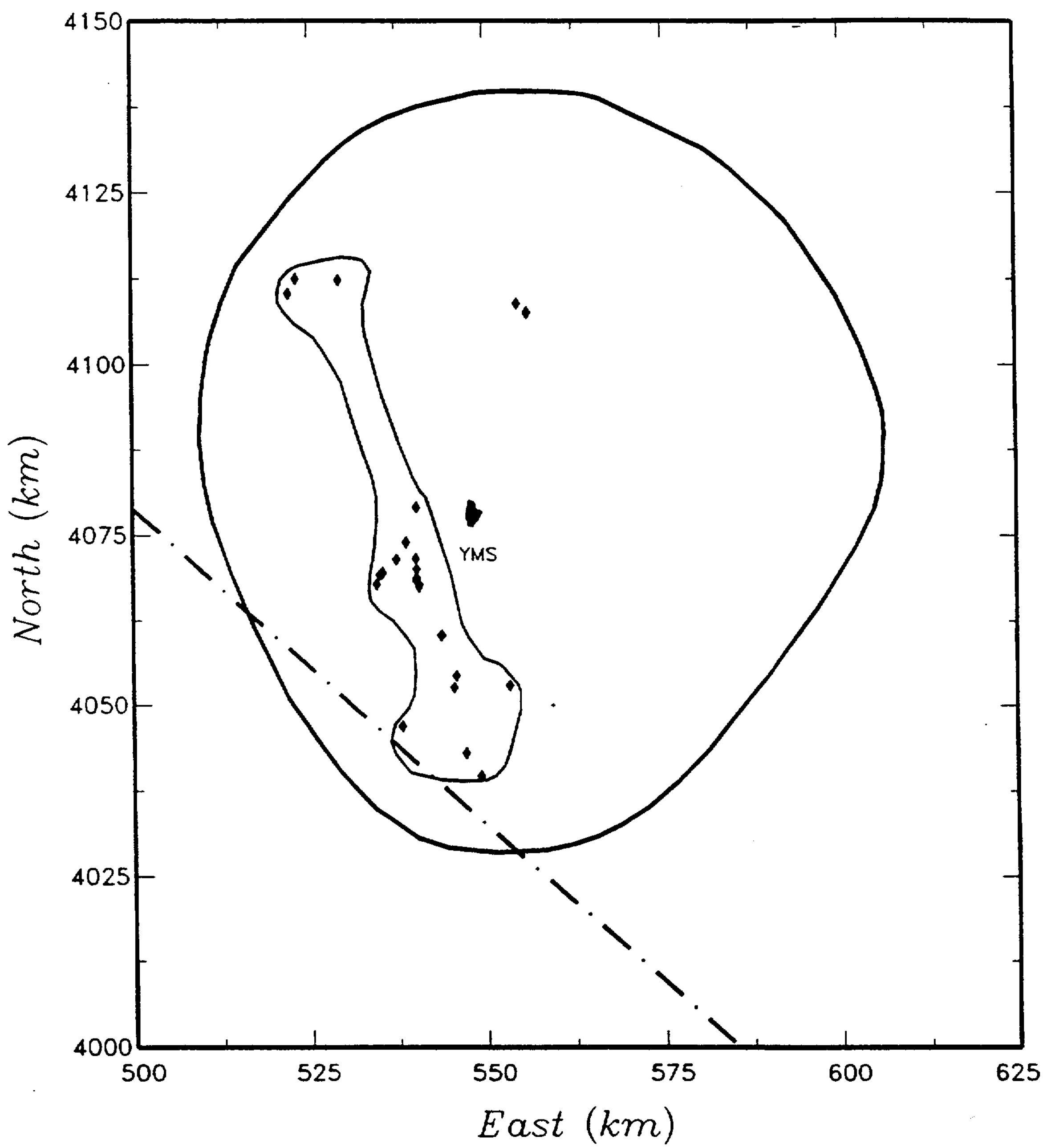


Figure 3-32 Volcanic source zone model developed by George Walker. Diamonds represent volcanic events for the post-5 Ma time period. YMS refers to the proposed Yucca Mountain repository site and the dash-dot line is the Nevada-California border.

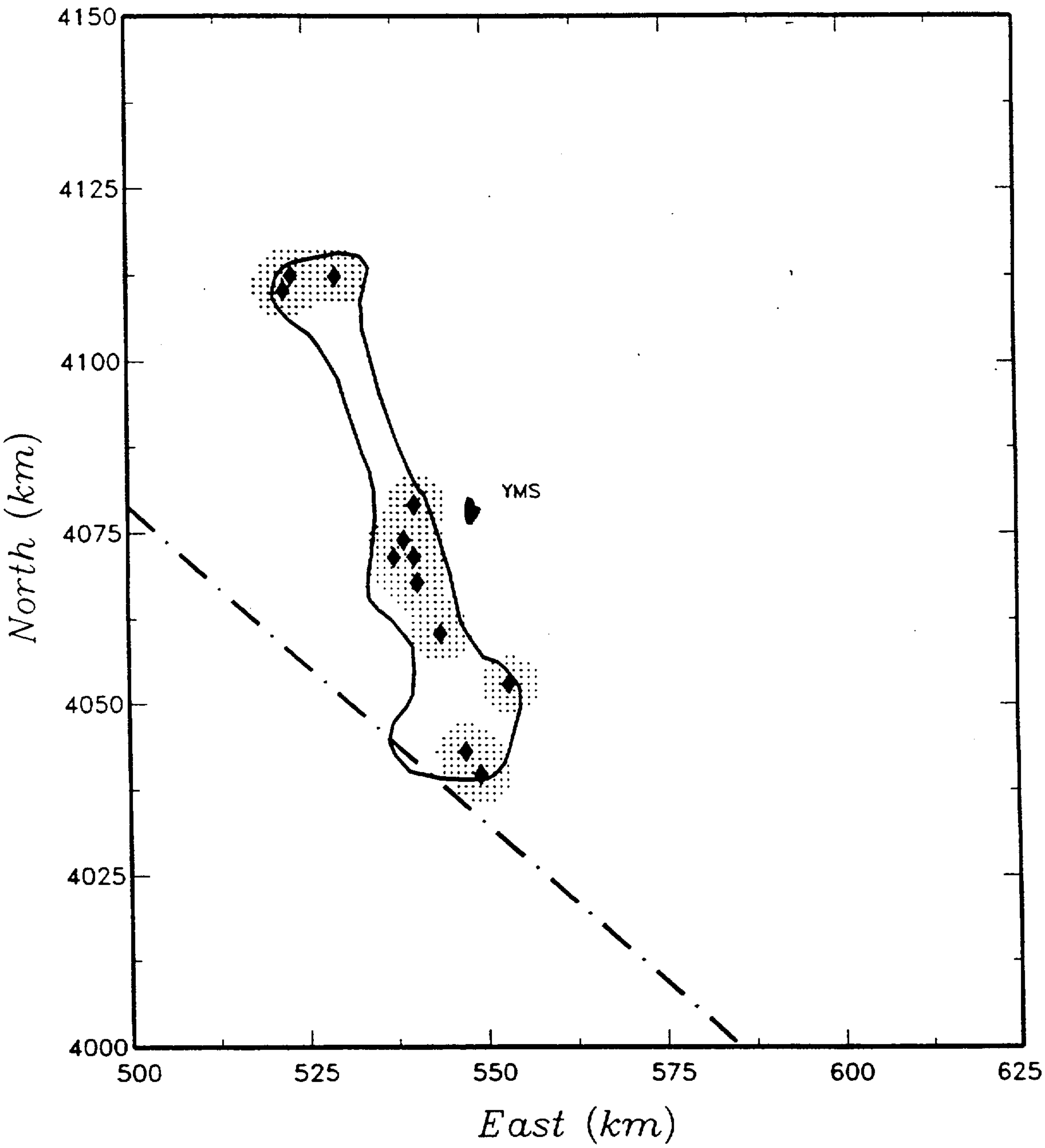


Figure 3-33 Example of a kernel density estimate based on George Walker's preferred event counts for the post-5 Ma time period (shown by diamonds) and the Crater Flat Volcanic Zone representing an approximation of the 90-percent density contour (the stippled area). The resulting Epanechnikov kernel smoothing parameter, *h*, is 5.8 km. YMS refers to the proposed Yucca Mountain repository site and the dash-dot line is the Nevada-California border.

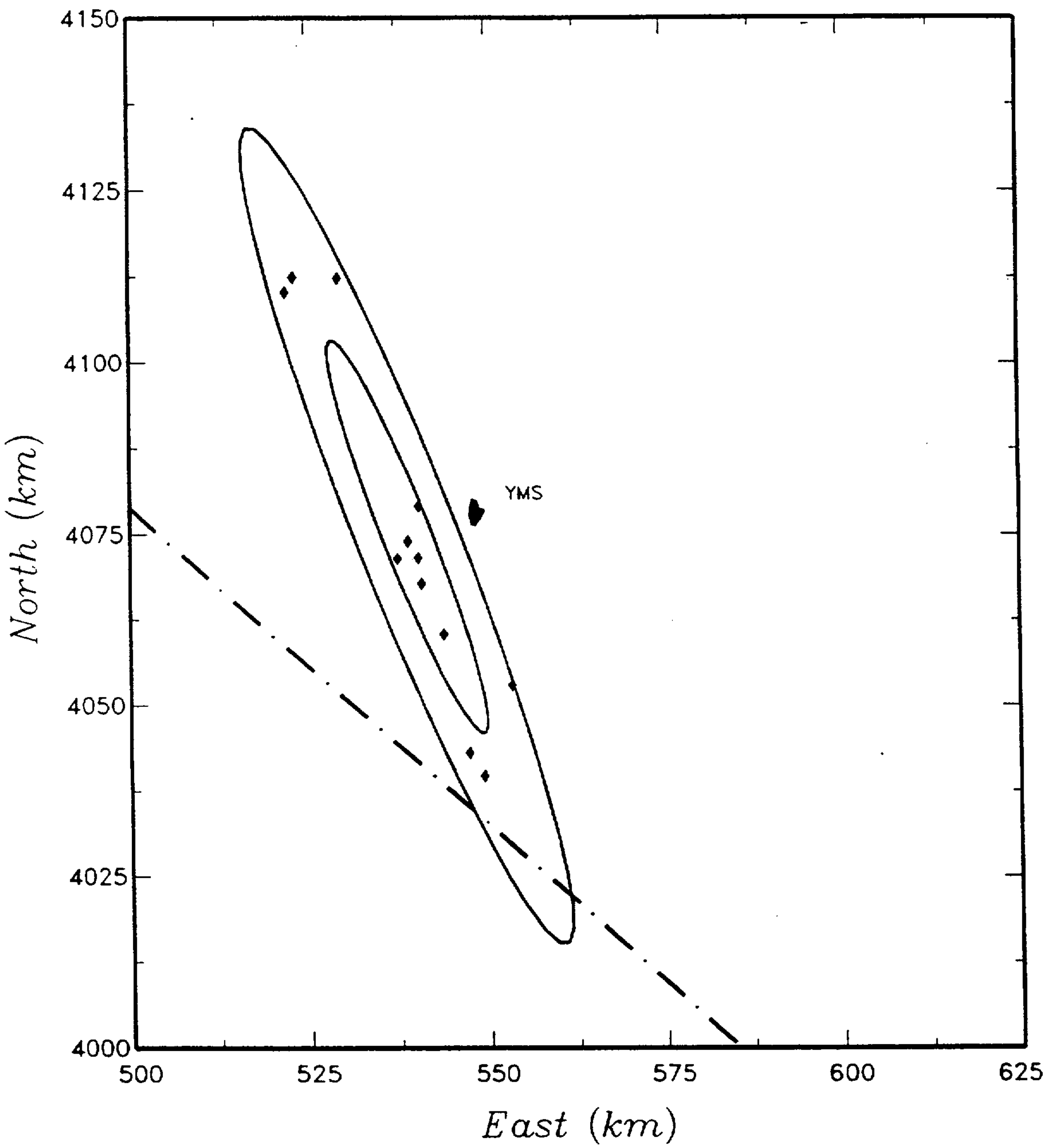


Figure 3-34 Example of the fit of a Gaussian field to George Walker's preferred event counts for the post-5 Ma time period (shown by diamonds) in the Crater Flat Volcanic Zone. The 50th and 95th percentile density contours are shown. YMS refers to the proposed Yucca Mountain repository site and the dash-dot line is the Nevada-California border.

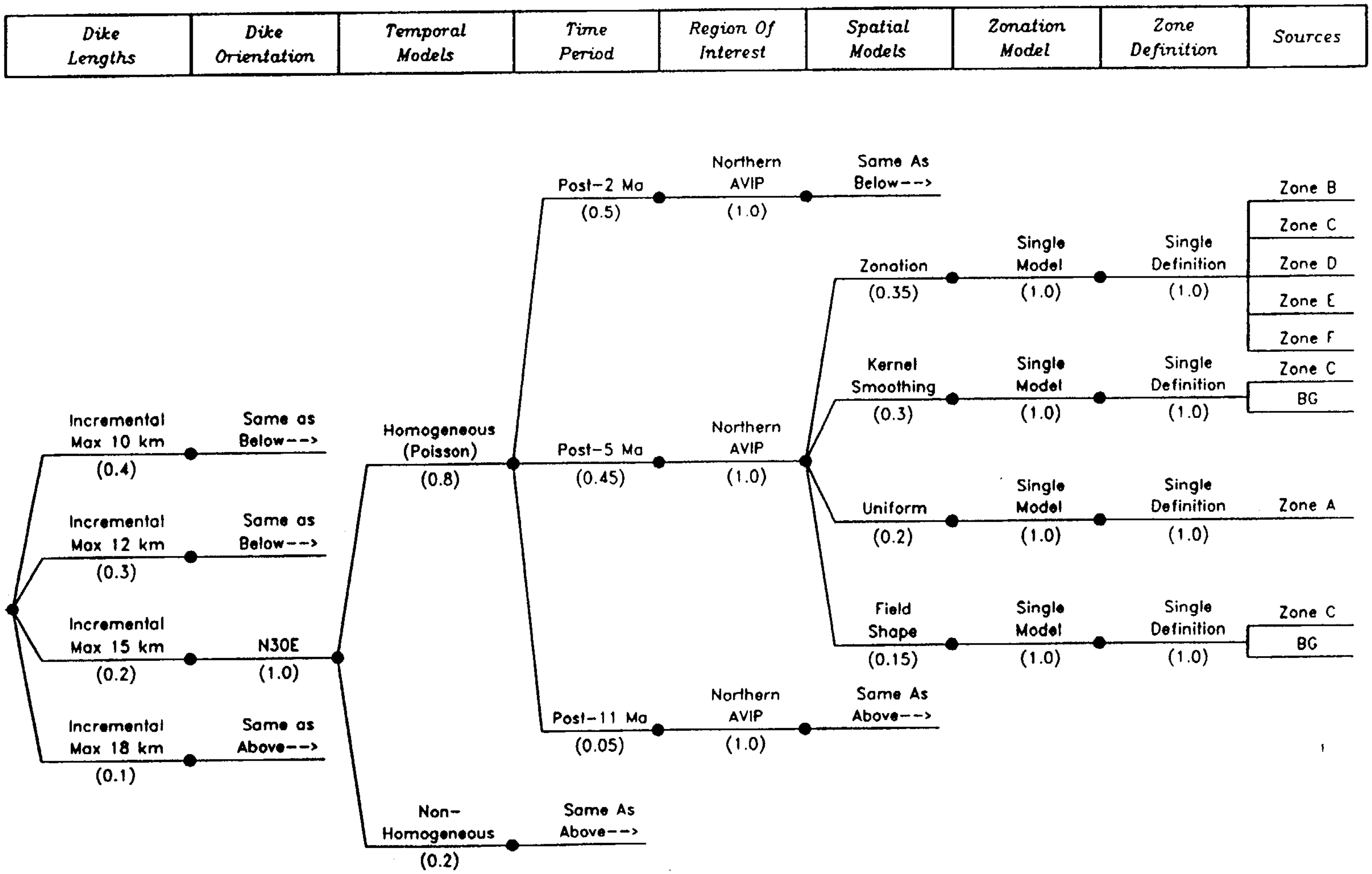


Figure 3-35 Logic tree for the PVHA model developed by Mel Kuntz.

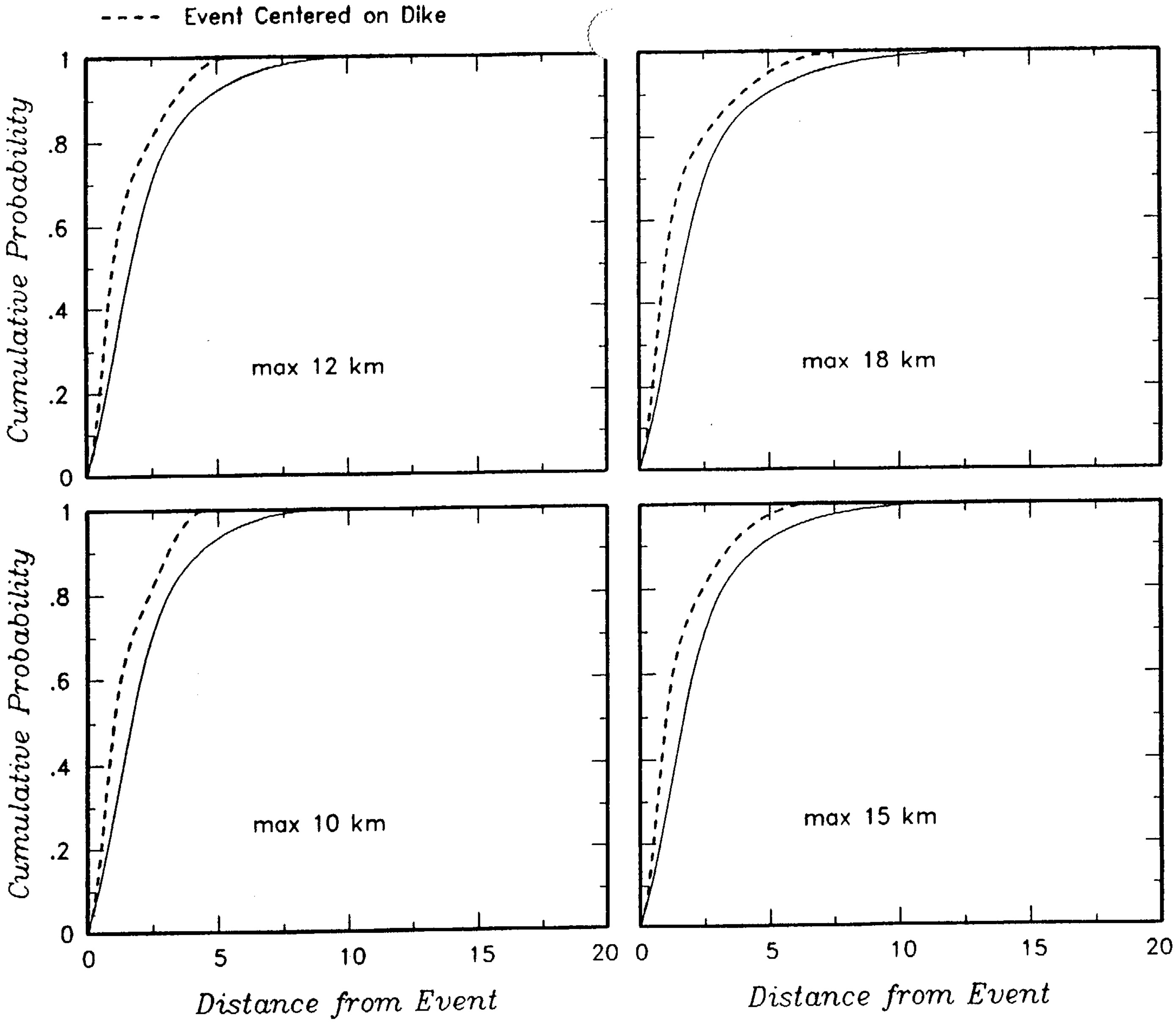


Figure 3-36 Alternative distributions for the length of an event *f(l)* developed from the assessments by Mel Kuntz.

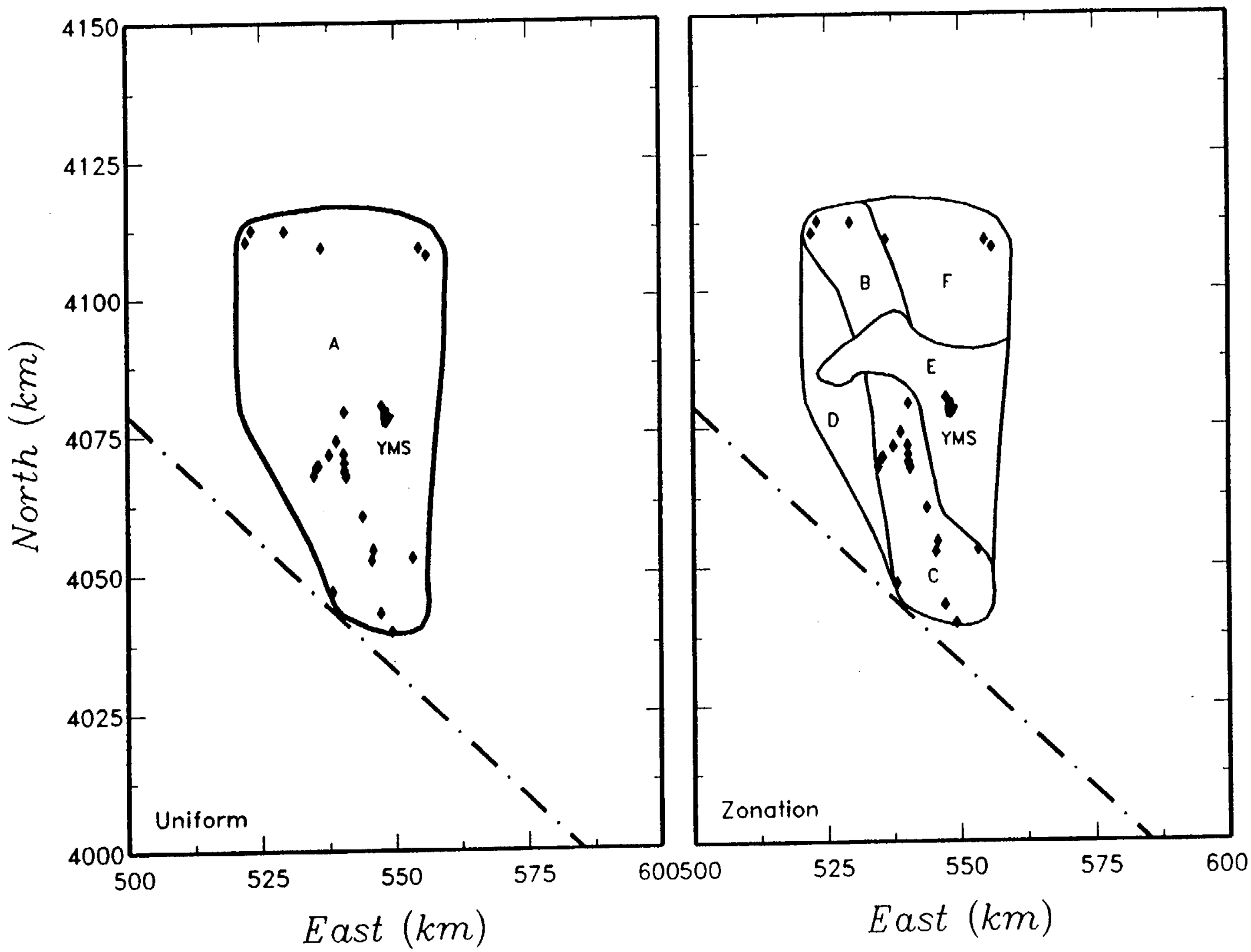


Figure 3-37 Region of interest and volcanic source zone model developed by Mel Kuntz. Diamonds represent volcanic events for the post-11 Ma time period. YMS refers to the proposed Yucca Mountain repository site and the dash-dot line is the Nevada-California border.

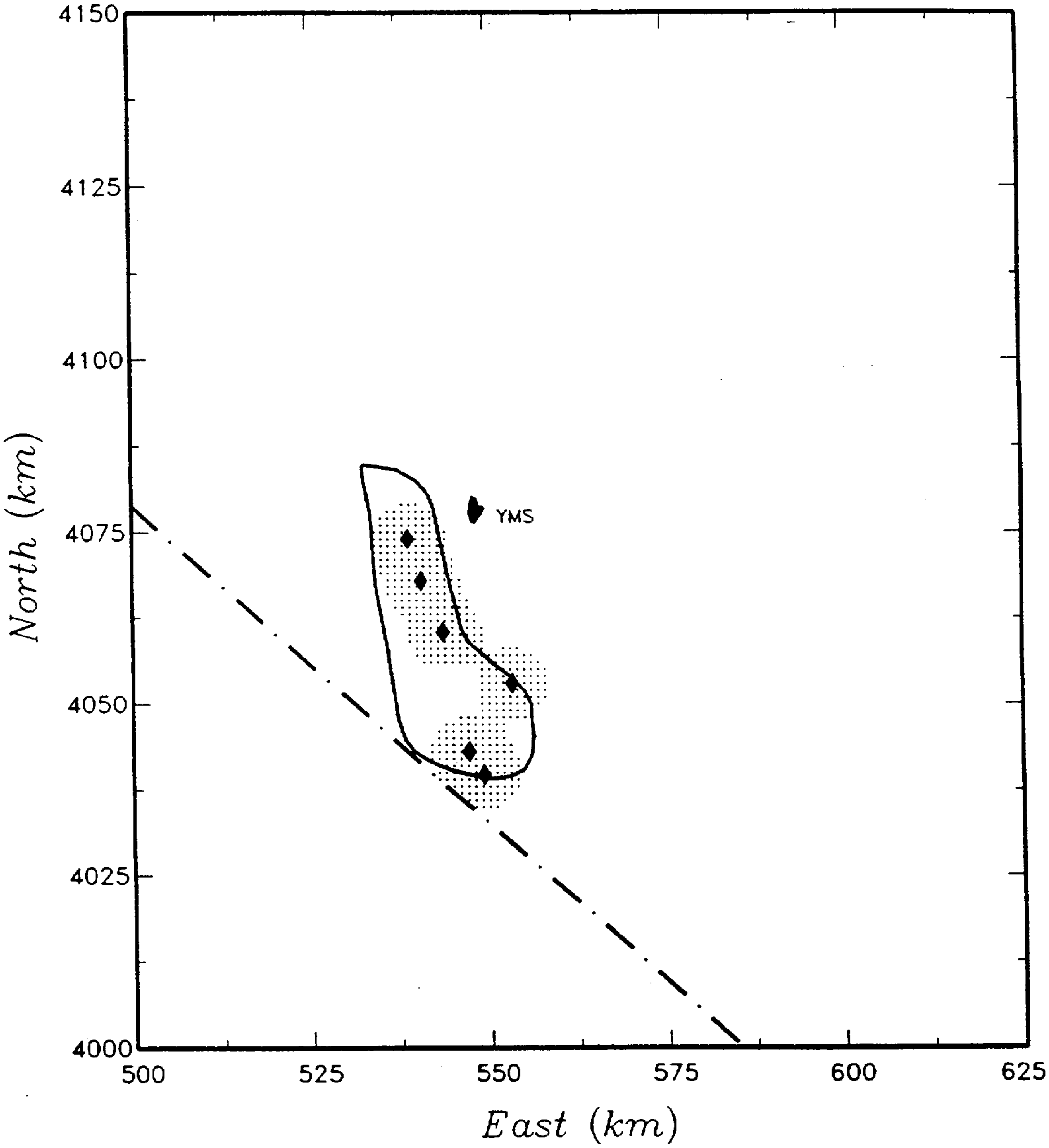


Figure 3-38 Example of a kernel density estimate based on Mel Kuntz's preferred event counts for the post-5 Ma time period (shown by diamonds) and Zone C (Crater Flat) representing an approximation of the 90-percent density contour (the stippled area). The resulting Gaussian kernel smoothing parameter, *h*, is 2.8 km. YMS refers to the proposed Yucca Mountain repository site and the dash-dot line is the Nevada-California border.

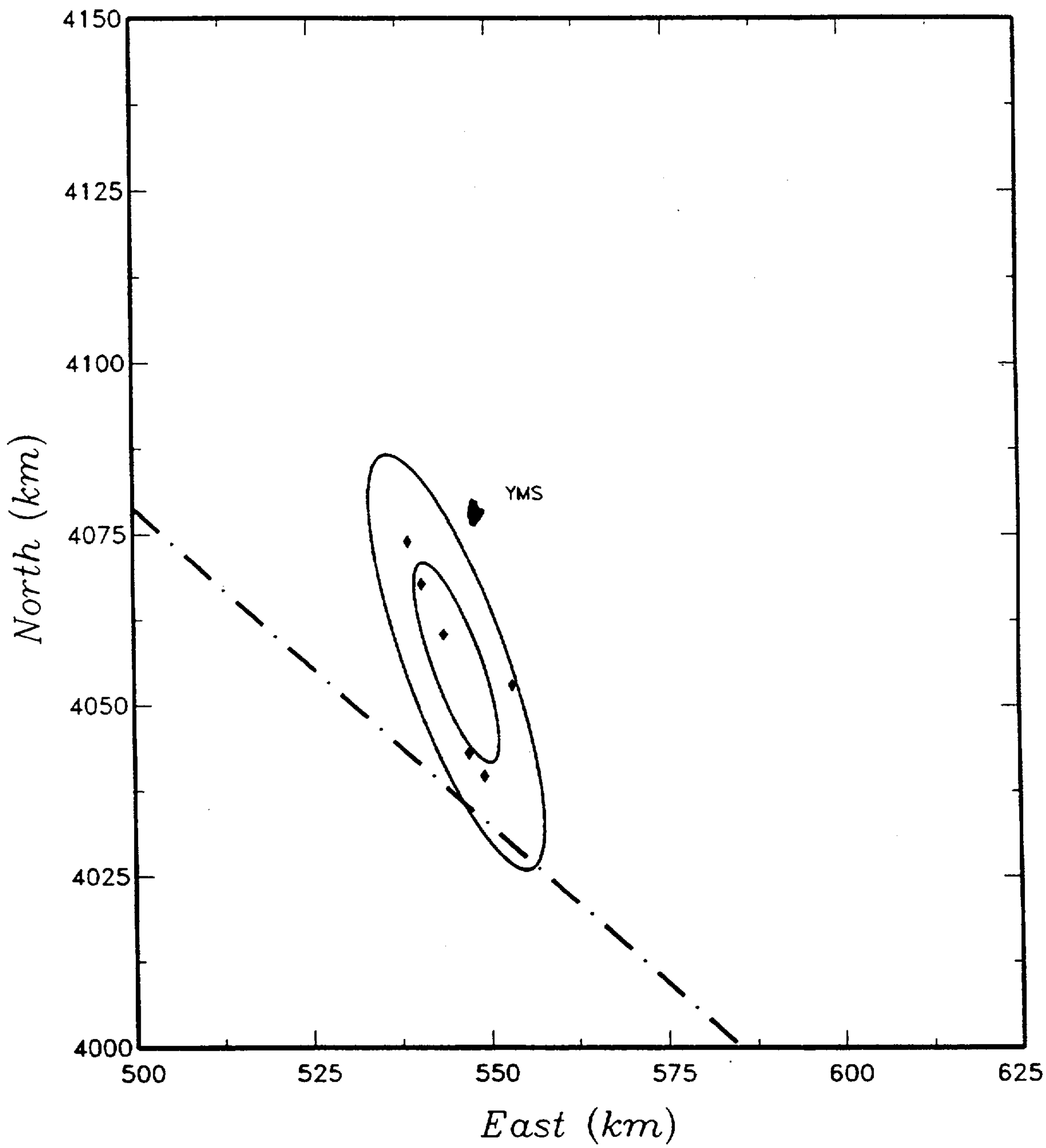


Figure 3-39 Example of the fit of a Gaussian field to Mel Kuntz's preferred event counts for the post-5 Ma time period (shown by diamonds) in Zone C (Crater Flat). The 50th and 95th percentile density contours are shown. YMS refers to the proposed Yucca Mountain repository site and the dash-dot line is the Nevada-California border.

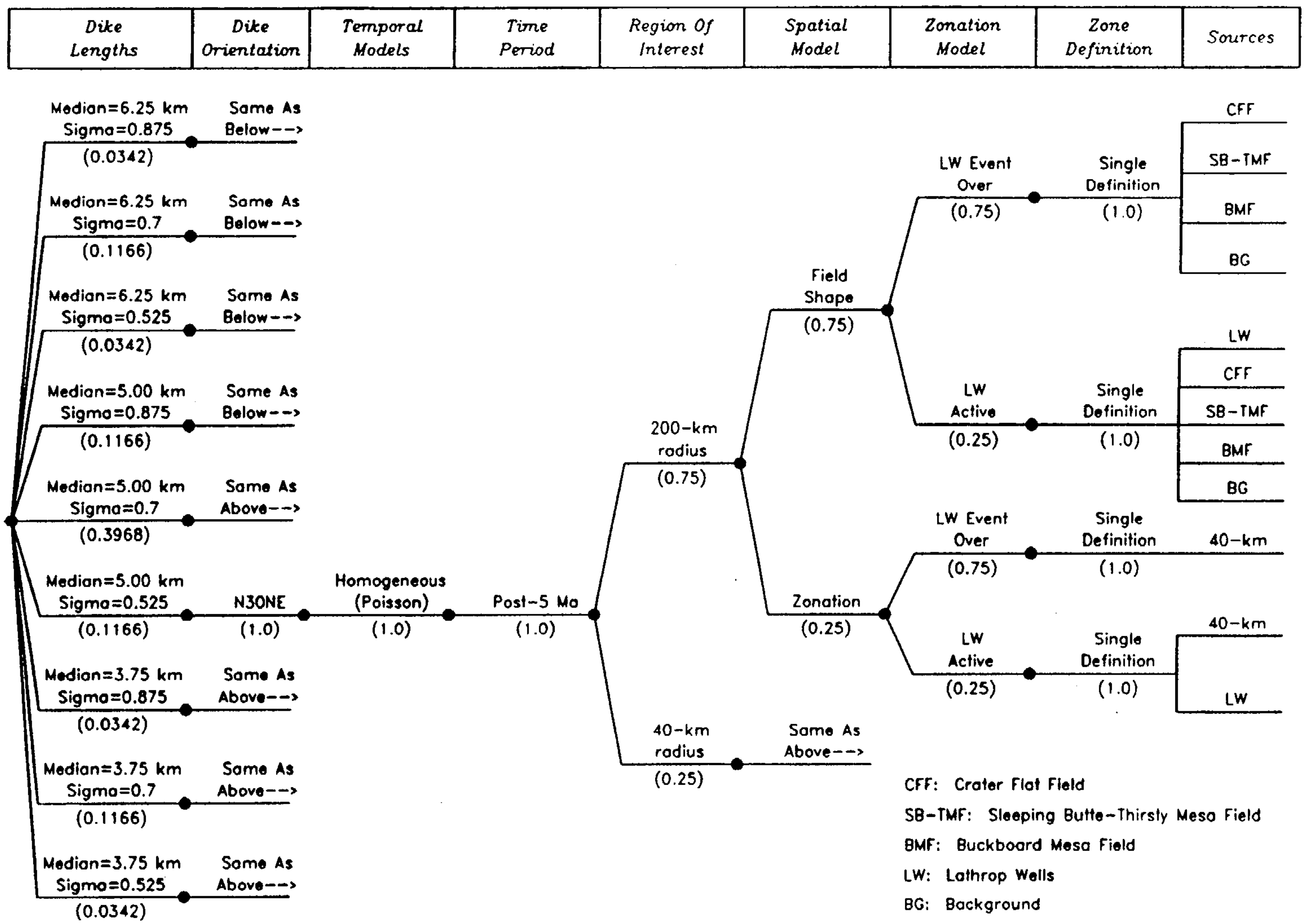


Figure 3-40 Logic tree for the PVHA model developed by Michael Sheridan.

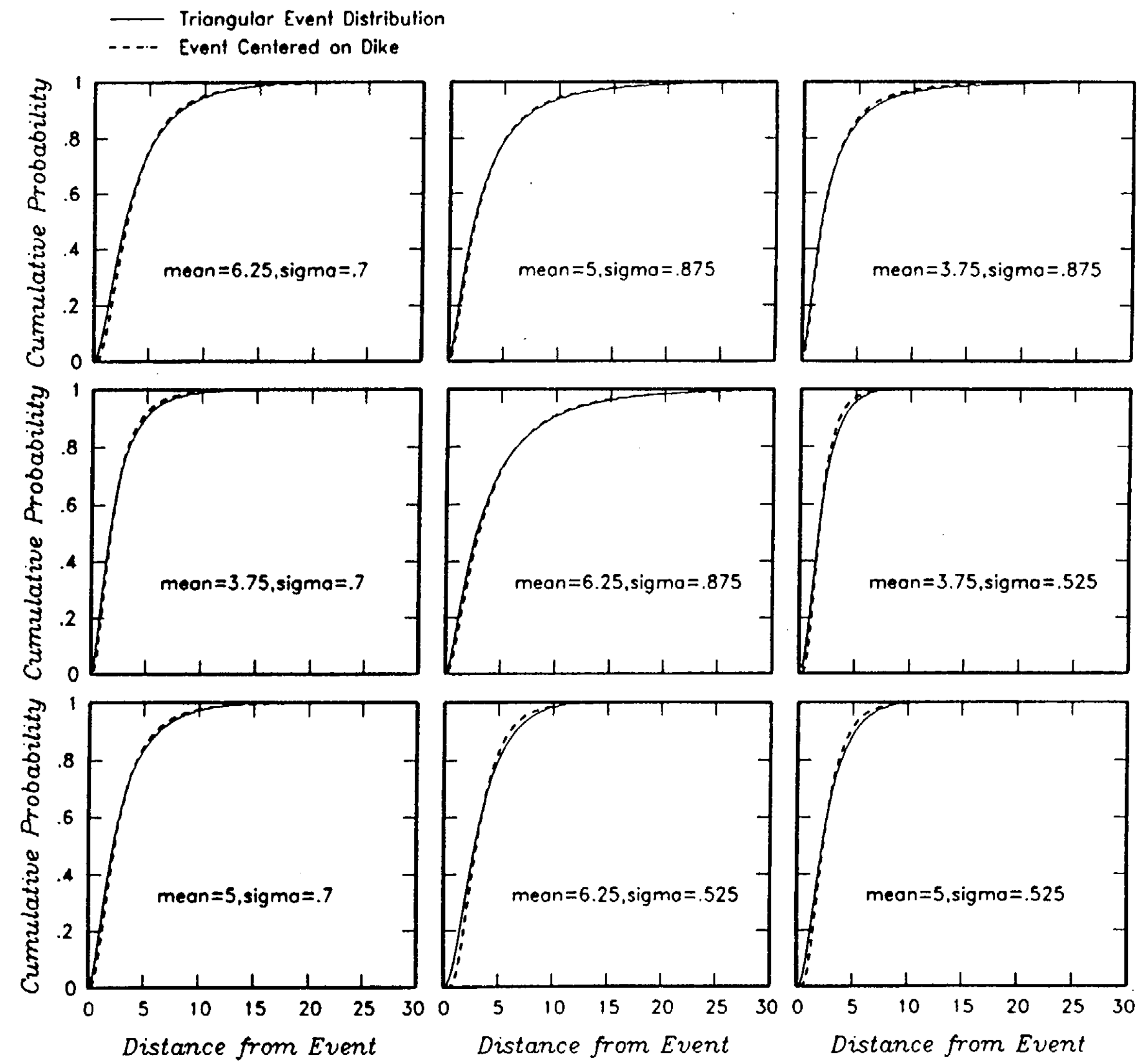


Figure 3-41 Alternative distributions for the length of an event *f(l)* developed from the assessments by Michael Sheridan.

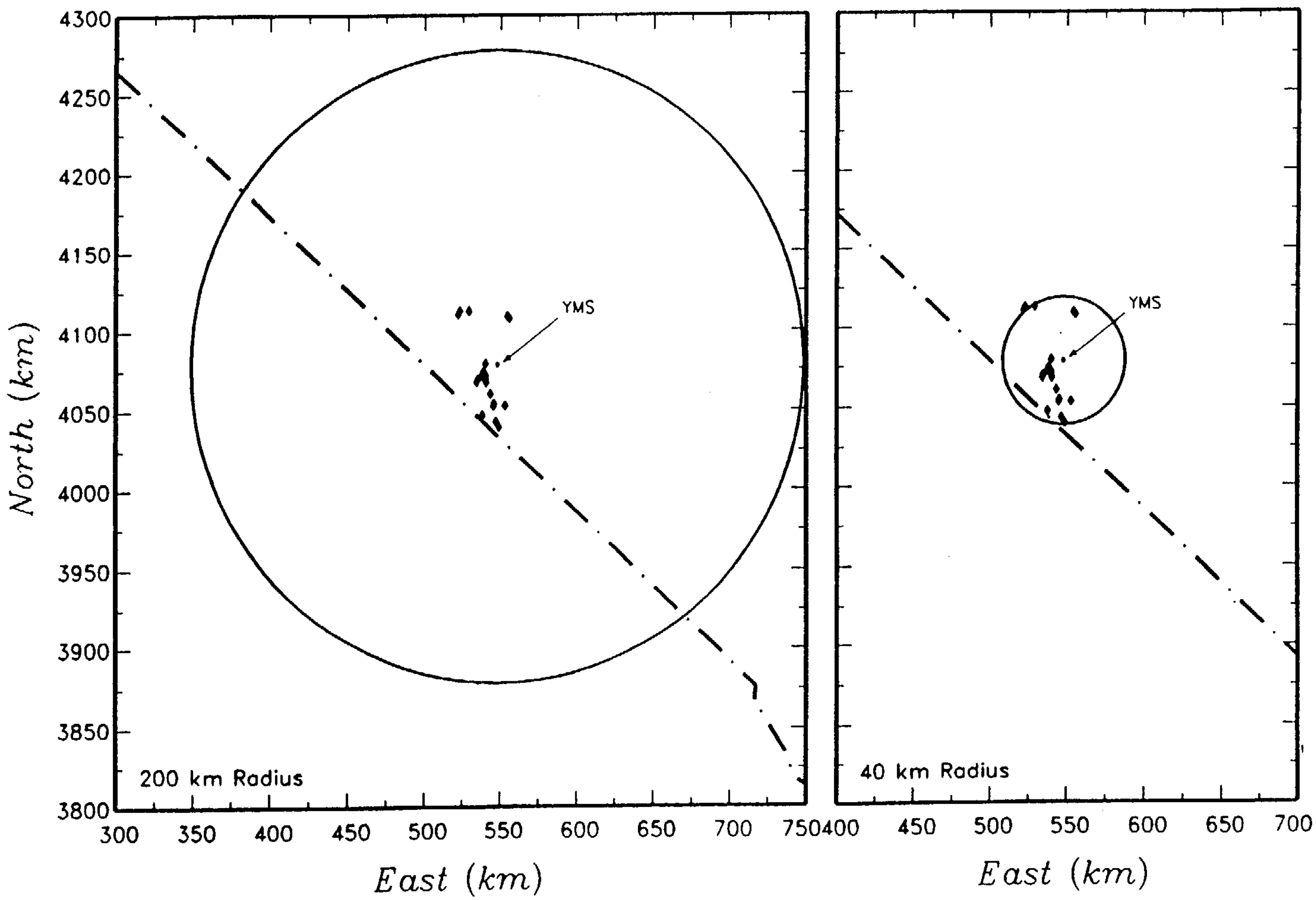


Figure 3-42 Regions of interest specified by Michael Sheridan. Diamonds represent volcanic events for the post-5 Ma time period. YMS refers to the proposed Yucca Mountain repository site and the dash-dot line is the Nevada-California border.

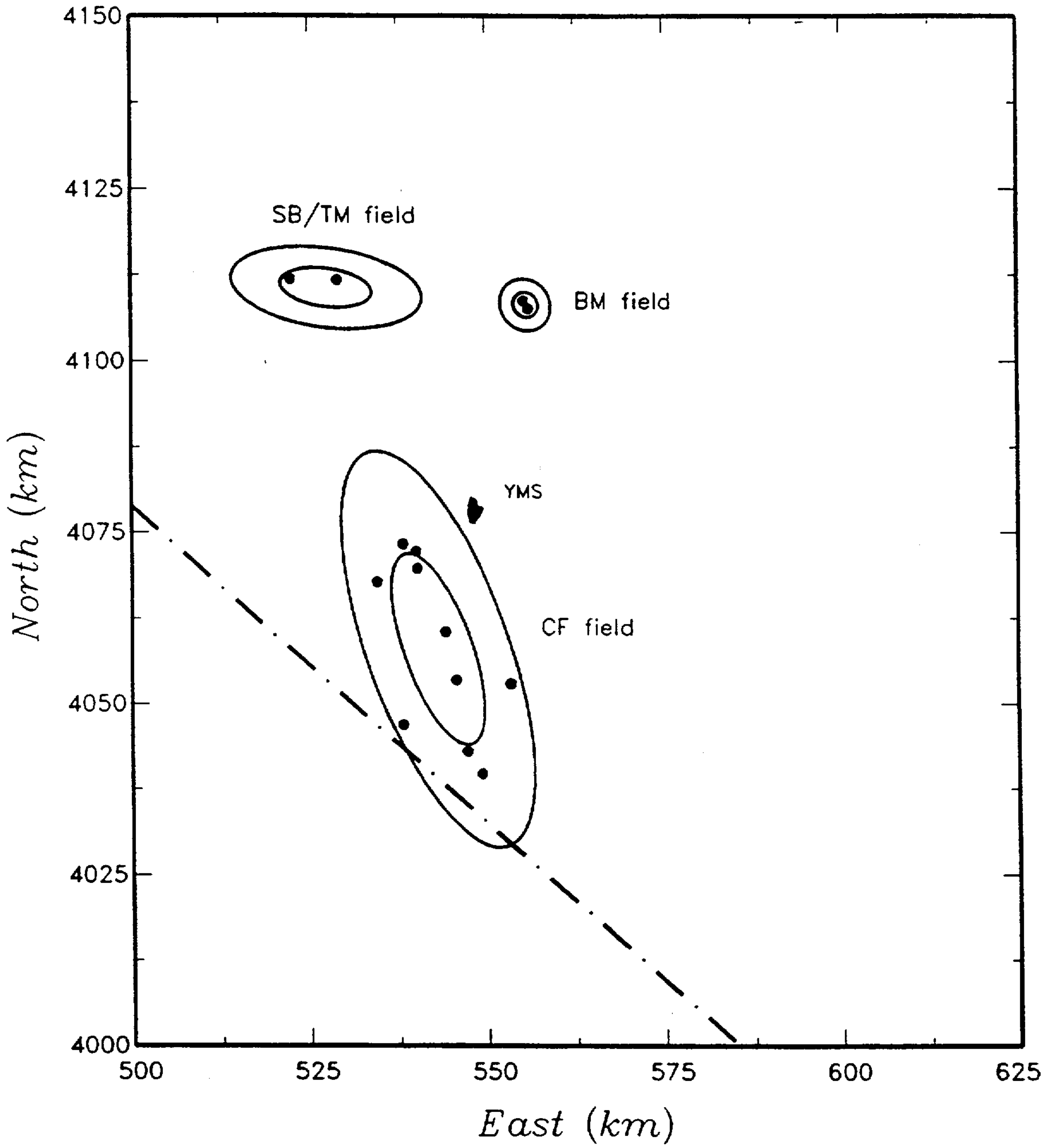


Figure 3-43 Example of the fit of Gaussian fields to Michael Sheridan's preferred event counts for the Crater Flat (CF), Sleeping Butte/Thirsty Mesa (SB/TM), and Buckboard Mesa (BM) fields. The 50[th] and 95[th] percentile contours are shown. YMS refers to the proposed Yucca Mountain repository site and the dash-dot line is the Nevada-California border.

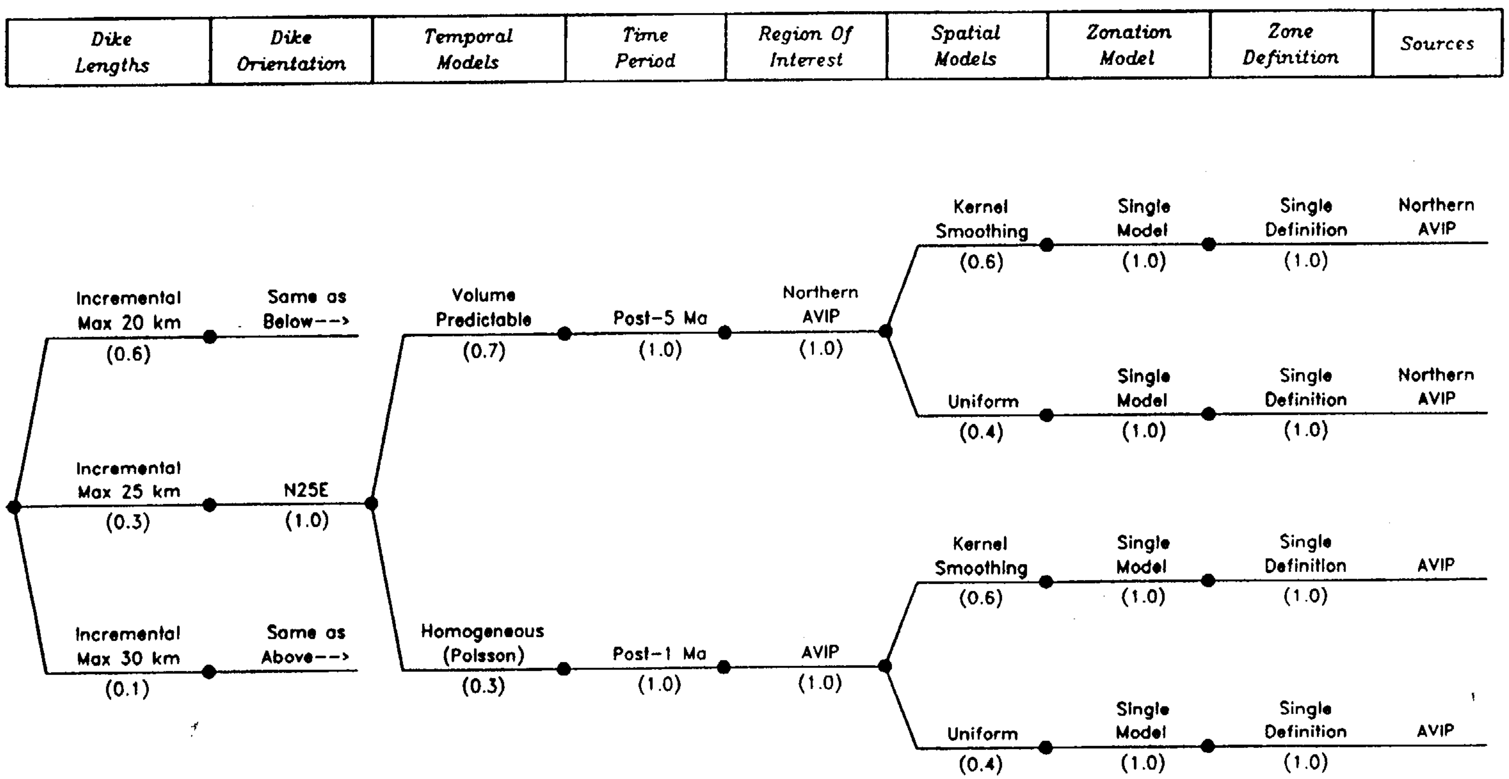


Figure 3-44 Logic tree for the PVHA model developed by Richard Carlson.

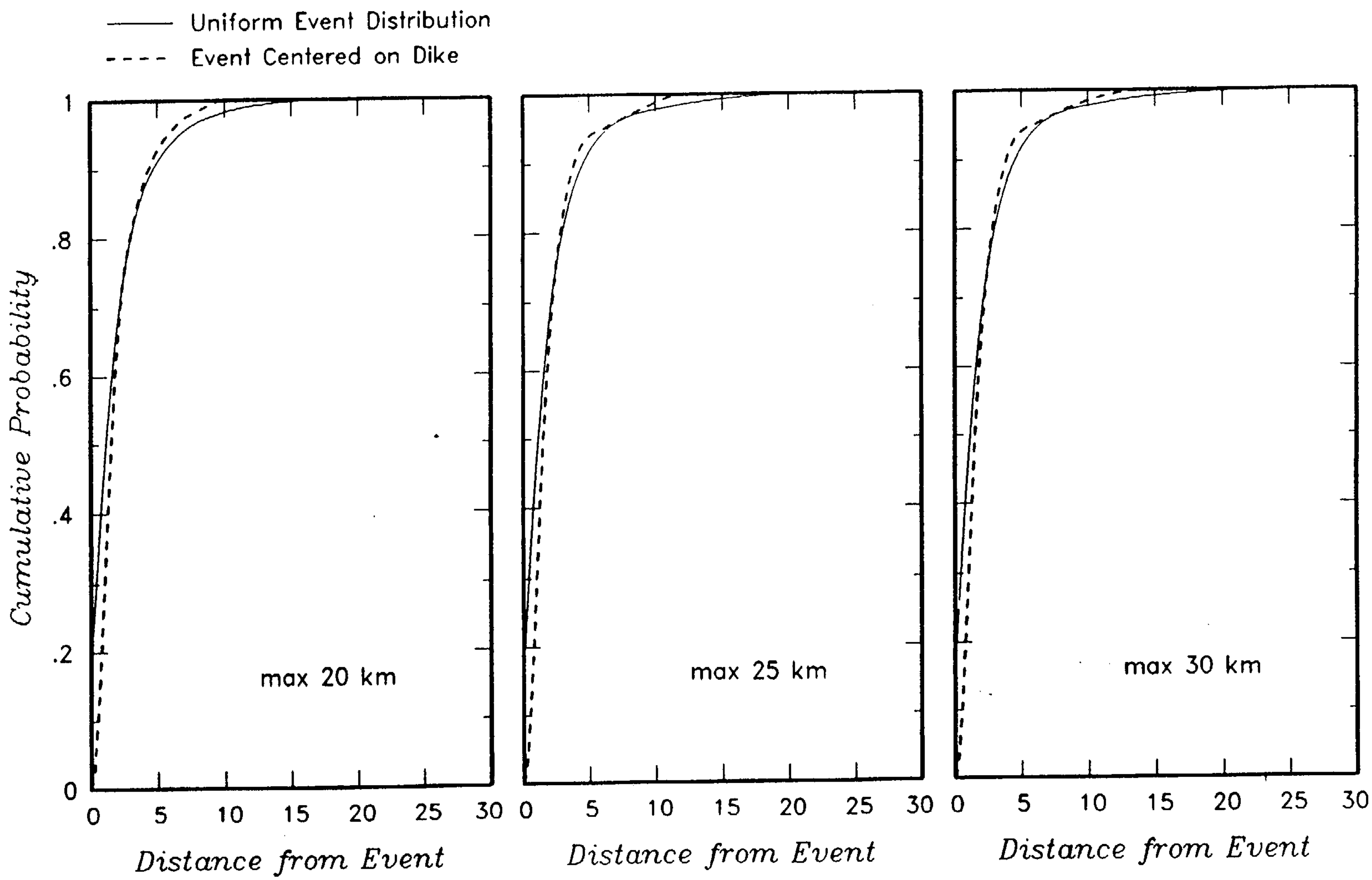


Figure 3-45 Alternative distributions for the length of an event *f(l)* developed from the assessments by Richard Carlson.

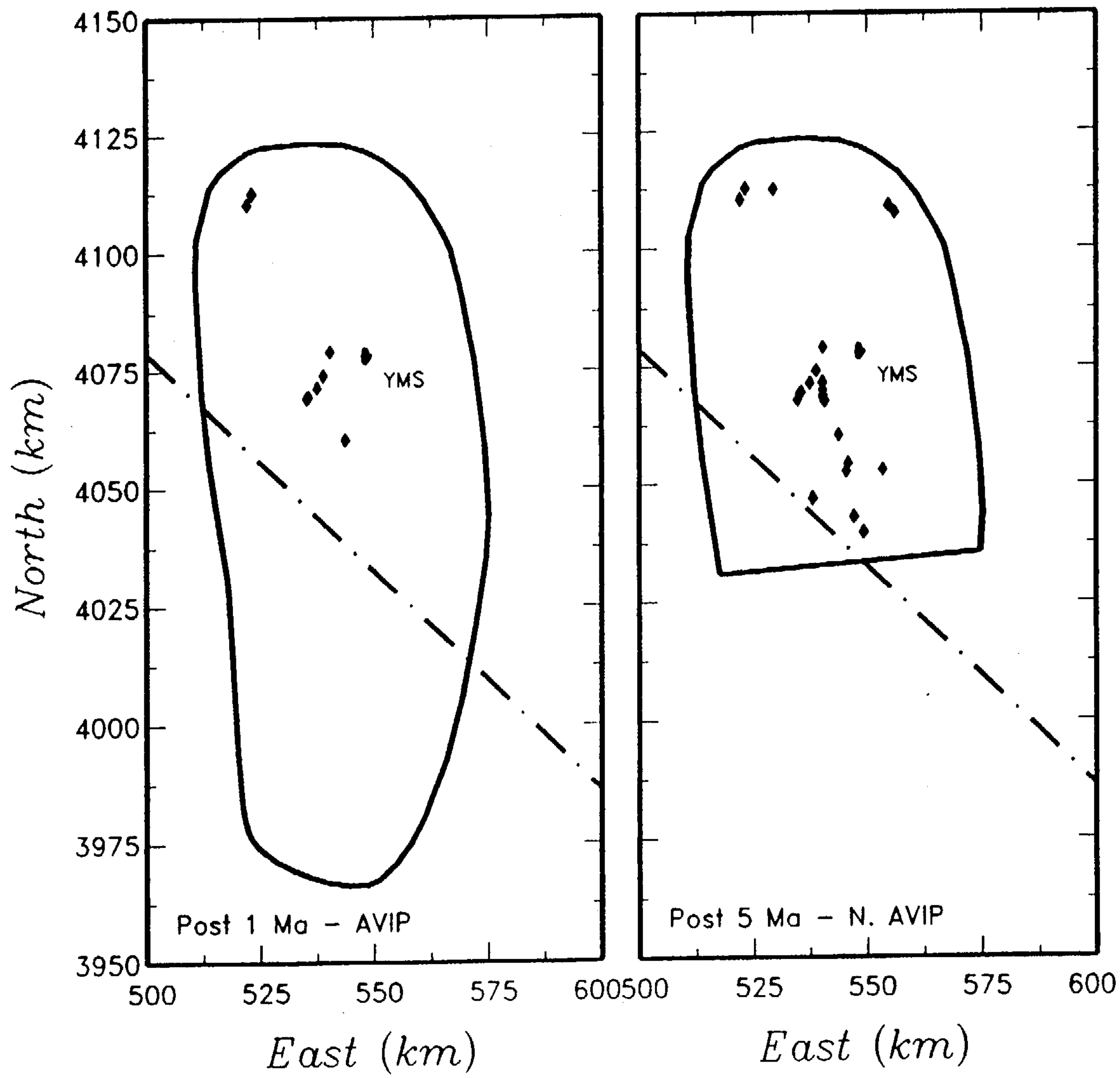


Figure 3-46 Regions of interest specified by Richard Carlson. Diamonds represent volcanic events for the post-1 Ma and the post-5 Ma time periods. YMS refers to the proposed Yucca Mountain repository site and the dash-dot line is the Nevada-California border.

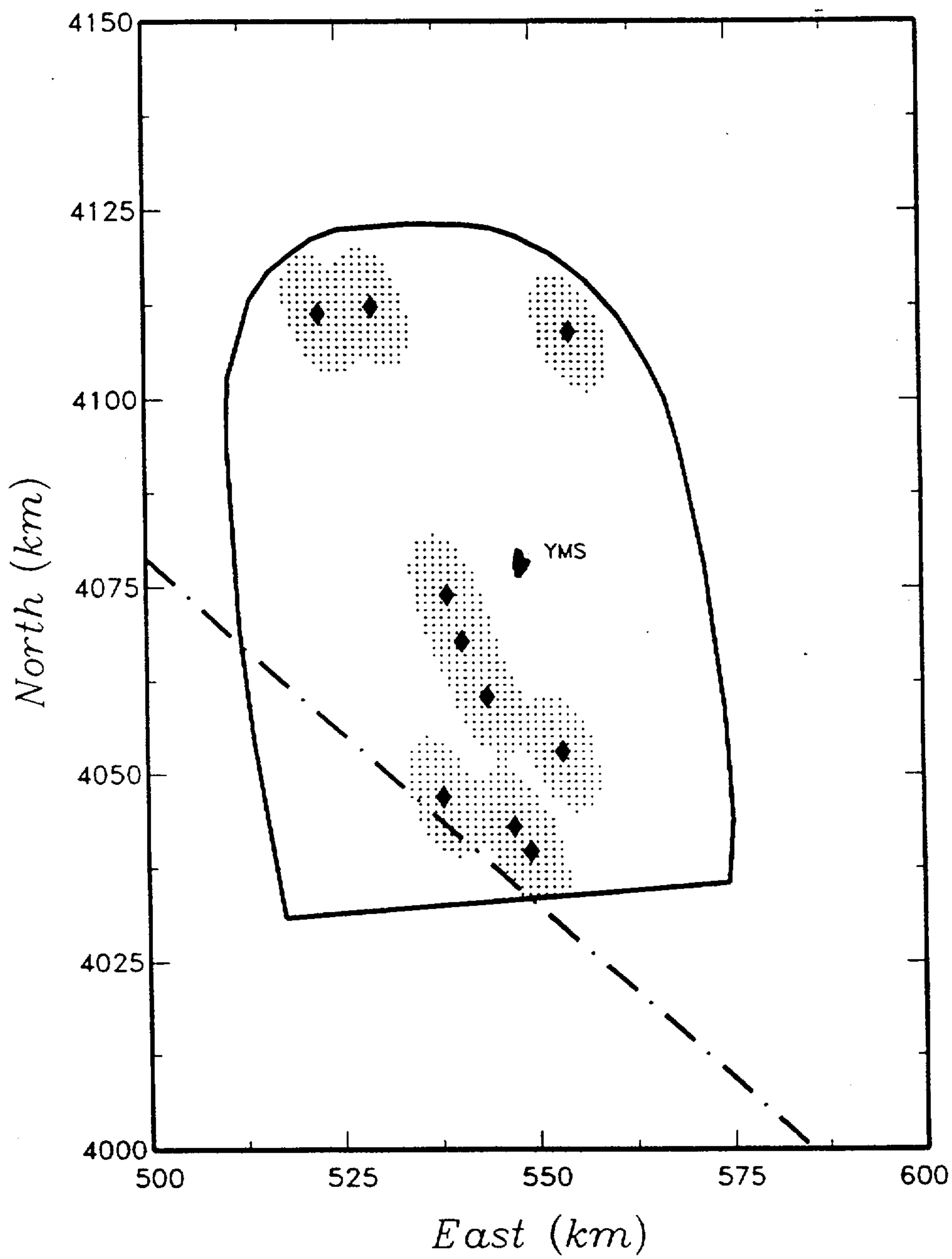


Figure 3-47 Example of the fit of an Epanechnikov kernel with a 2:1 aspect ratio and h for the major axis of 10 km to Richard Carlson's preferred event counts for the northern AVIP region and the post-5 Ma time period. The stippled area outlines the 95[th] percentile density contour. YMS refers to the proposed Yucca Mountain repository site and the dash-dot line is the Nevada-California border.

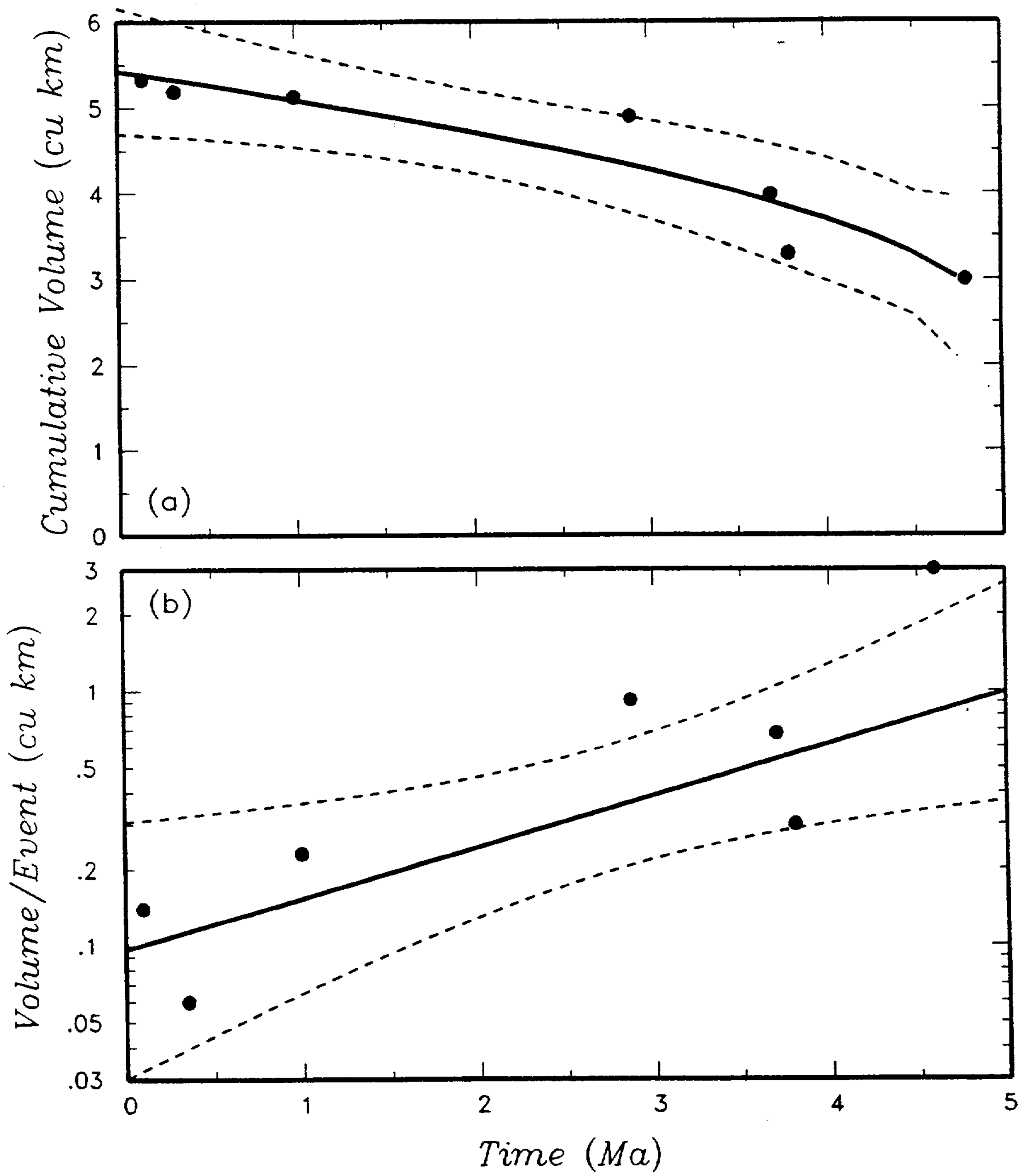


Figure 3-48 Parameters for the volume predictable rate model used by Richard Carlson. (a) Relationship for cumulative volume $V_M(t)$. (b) Example of relationship for volume per event, $V_E(t)$ computed for the most likely event counts in the northern AVIP zone.

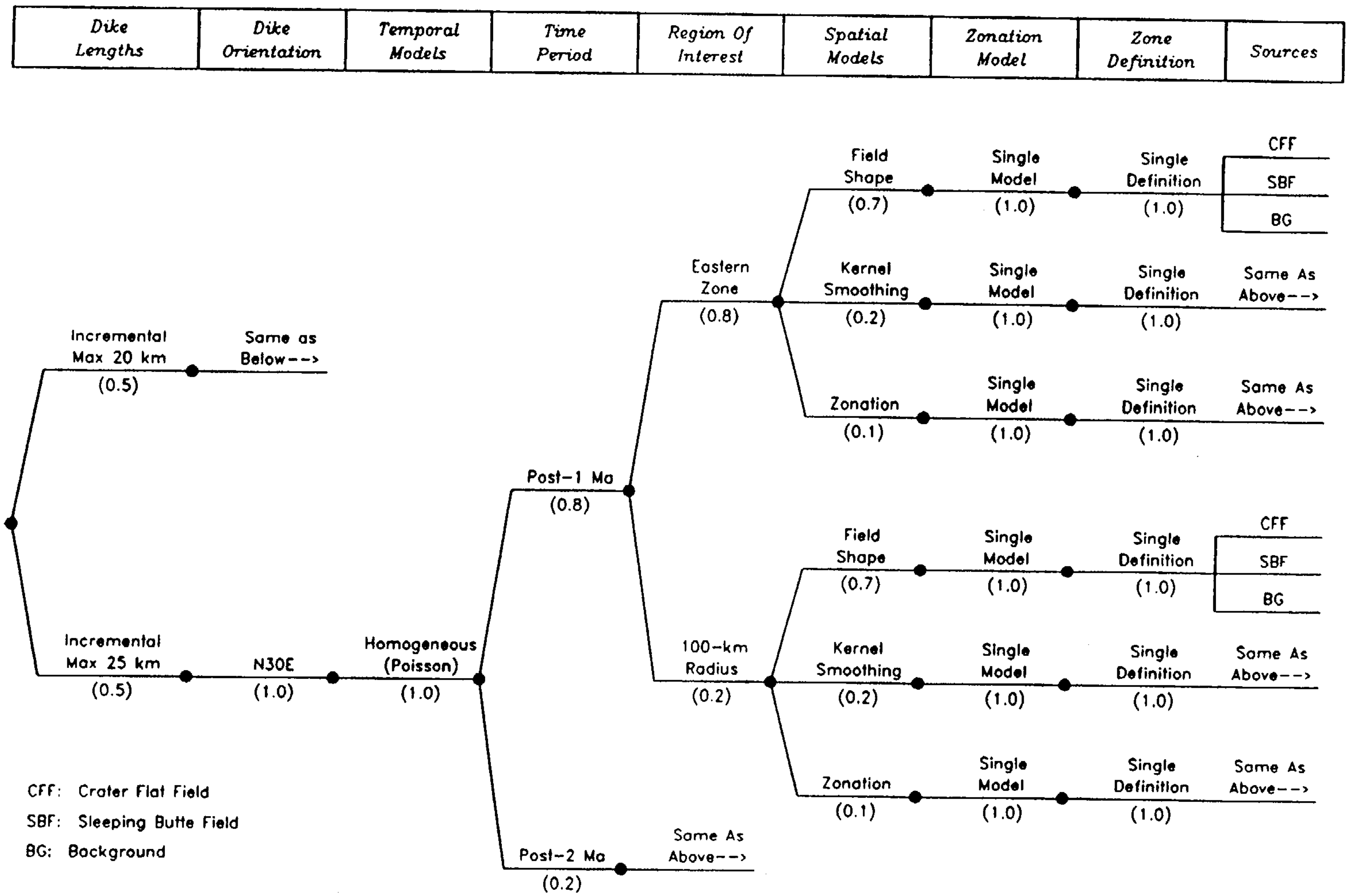


Figure 3-49 Logic tree for the PVHA model developed by Richard Fisher.

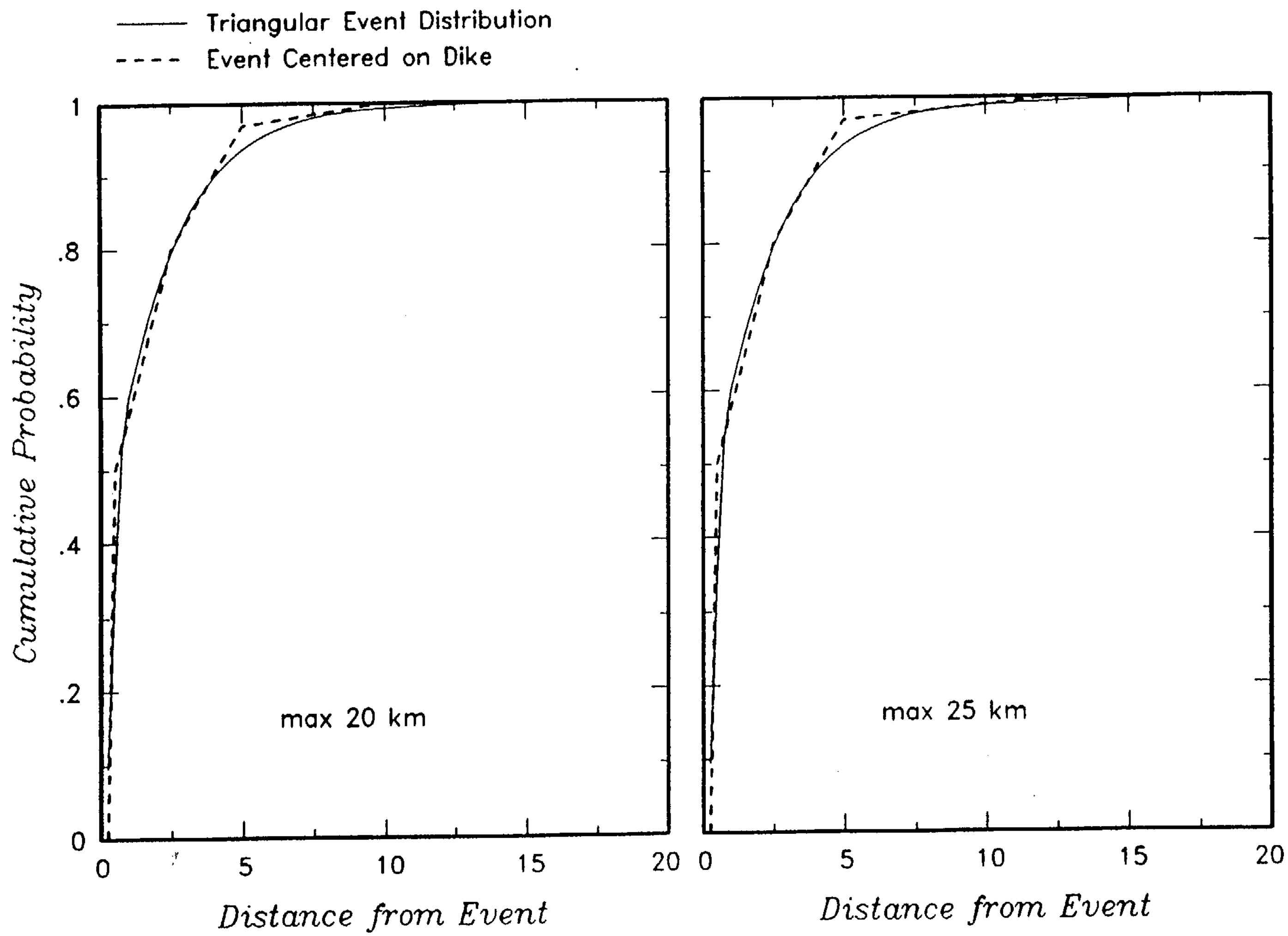


Figure 3-50 Alternative distributions for the length of an event *f(l)* developed from the assessments by Richard Fisher.

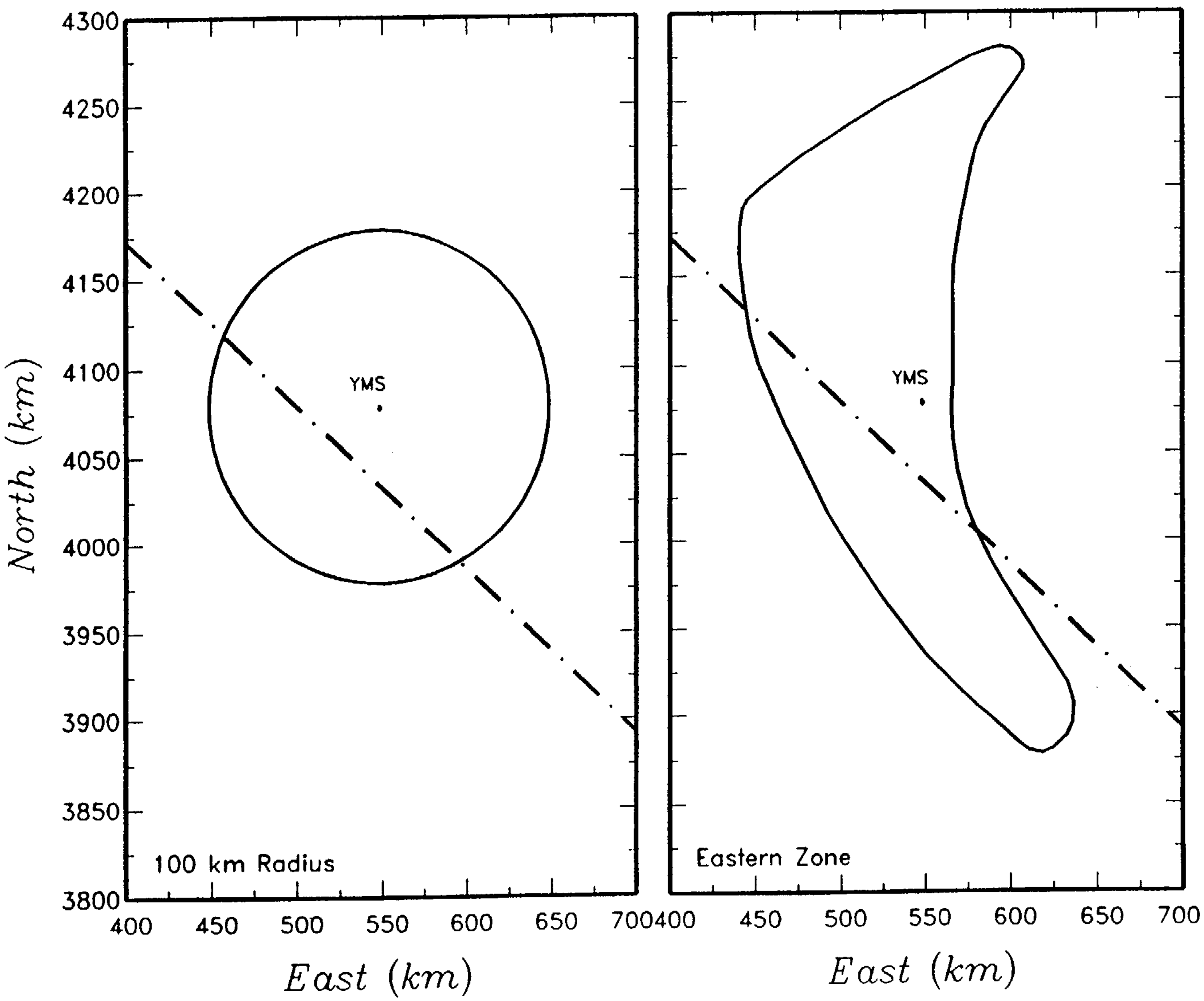


Figure 3-51 Alternative regions of interest considered by Richard Fisher. YMS refers to the proposed Yucca Mountain repository site and the dash-dot line is the Nevada-California border..

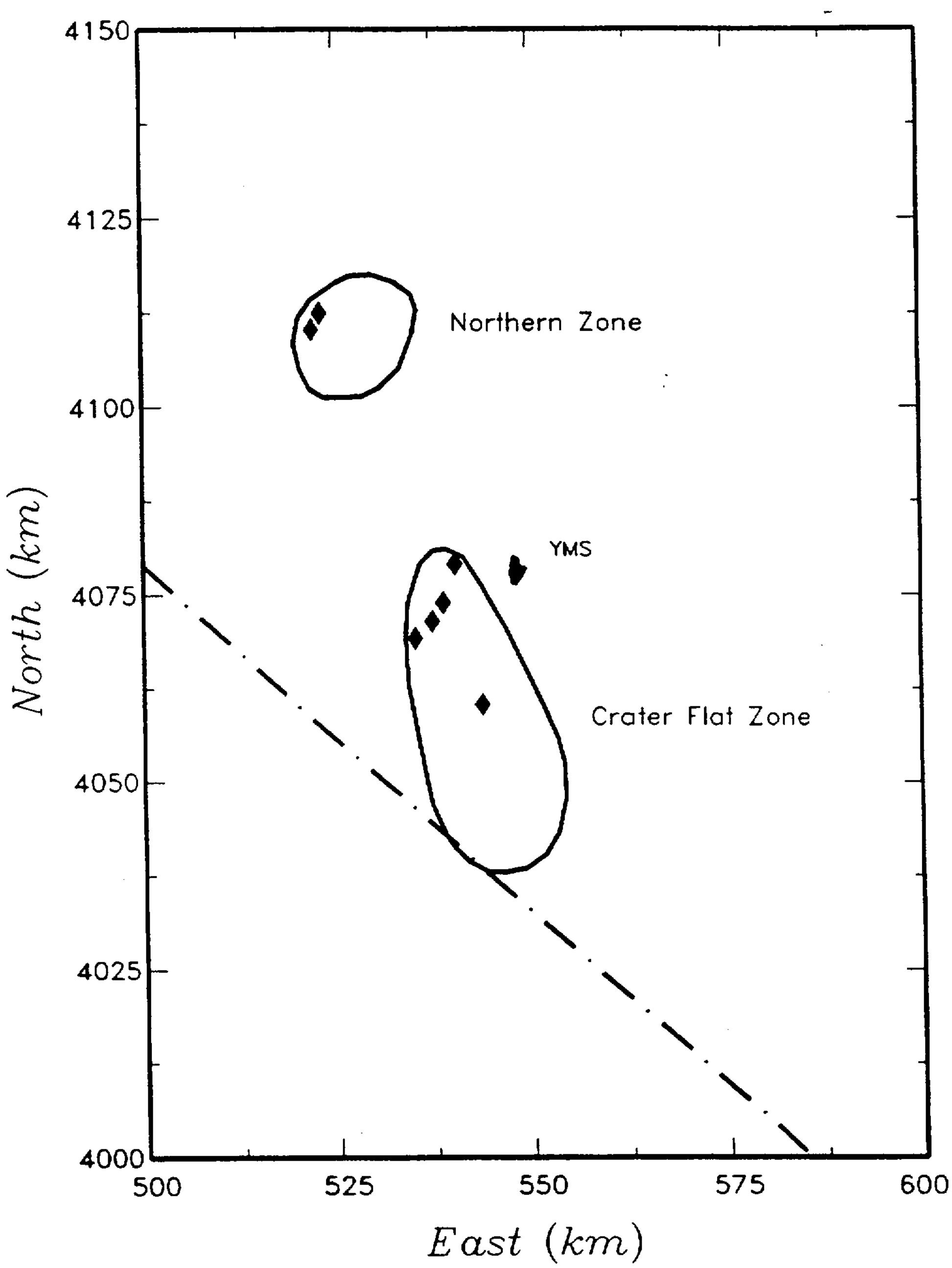


Figure 3-52 Volcanic source zone model developed by Richard Fisher. Diamonds represent volcanic events for the post-2 Ma time period. YMS refers to the proposed Yucca Mountain repository site and the dash-dot line is the Nevada-California border.

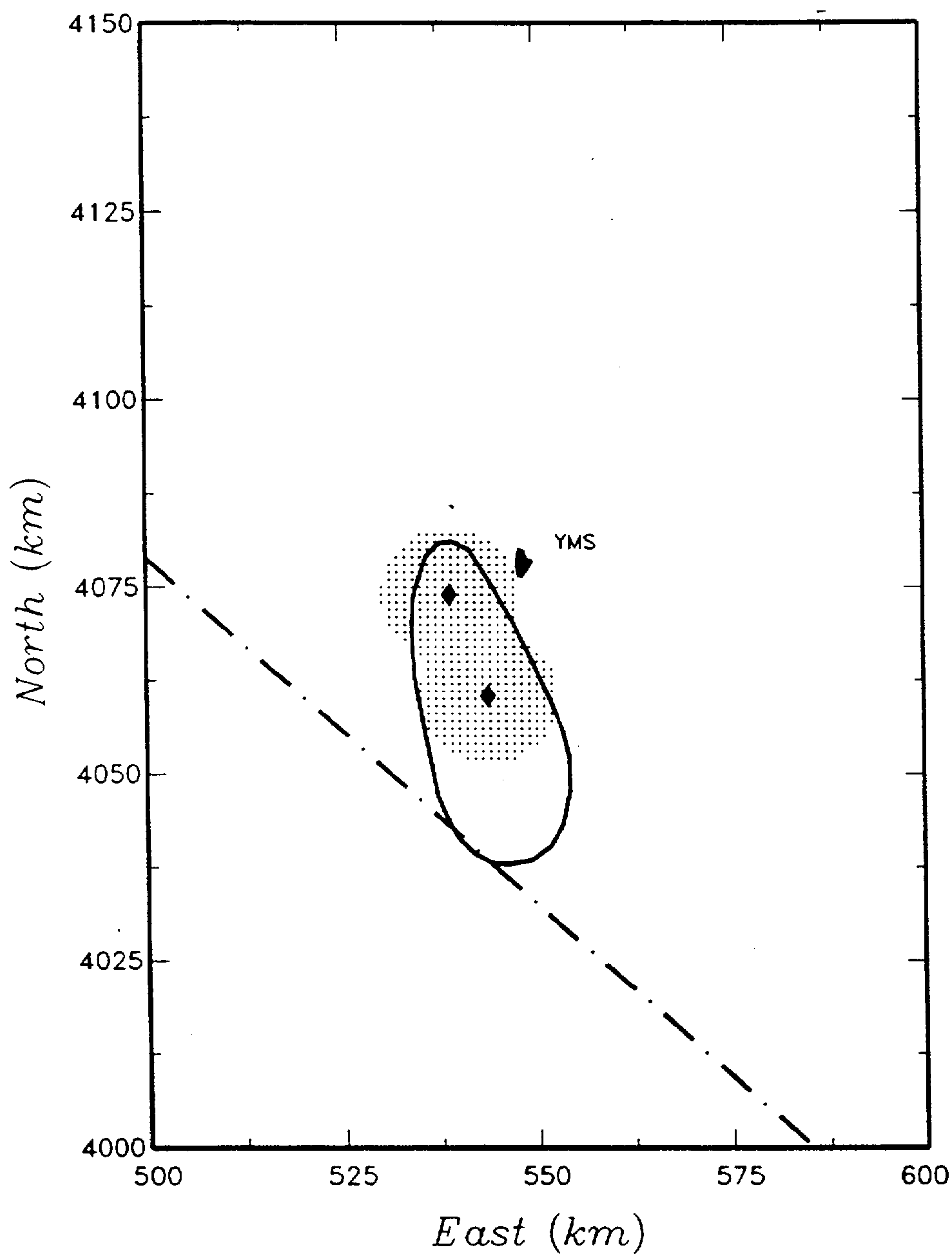


Figure 3-53 Example of a kernel density estimate based on Richard Fisher's preferred event counts for the post-2 Ma time period (shown by diamonds) and the Crater Flat zone representing an approximation of the 90-percent density contour (the stippled area). The resulting Epanechnikov kernel smoothing parameter, *h*, is 10.4 km. YMS refers to the proposed Yucca Mountain repository site and the dash-dot line is the Nevada-California border.

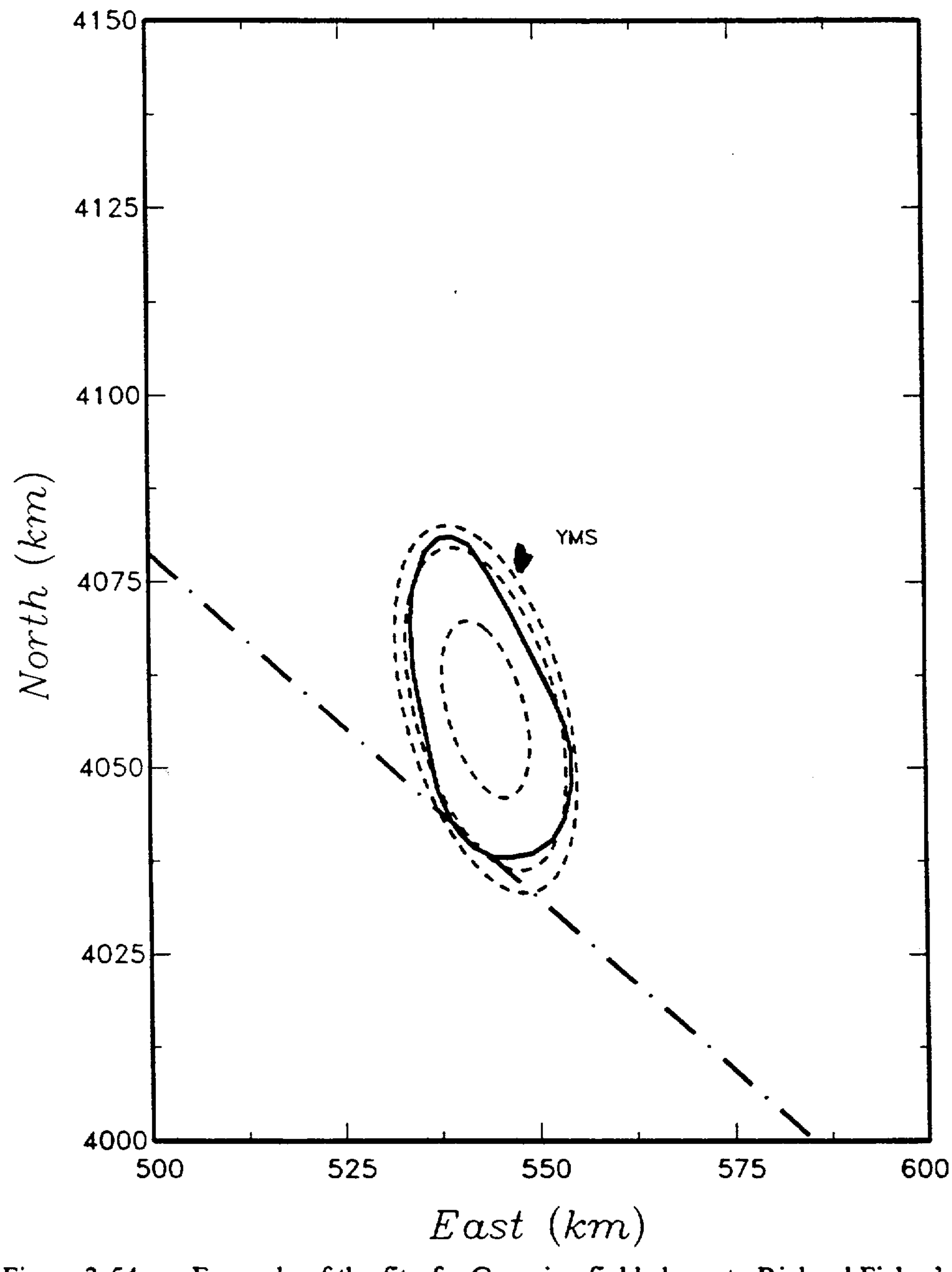
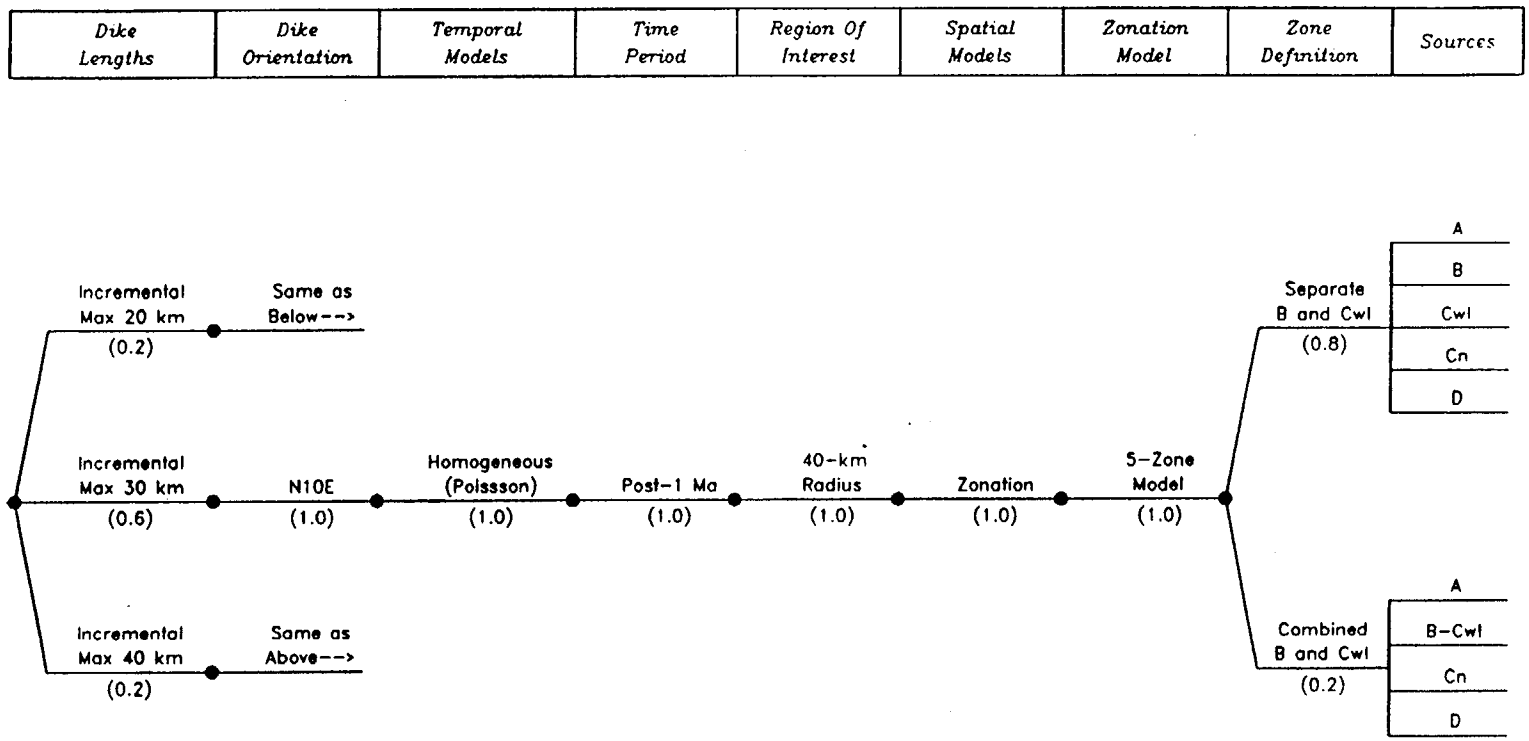


Figure 3-54 Example of the fit of a Gaussian field shape to Richard Fisher's Crater Flat zone boundary assuming it represents a 90-percent density contour. The 50th and 95th percentile density contours are also shown. YMS refers to the proposed Yucca Mountain repository site and the dash-dot line is the Nevada-California border.



A: Subzone A
B: Subzone B
D: Subzone D
Cwl: Subzone C within Walker Lane Belt
Cn: Subzone C outside Walker Lane Belt
B-Cwl: Subzone B and subzone Cwl combined

Figure 3-55 Logic tree for the PVHA model developed by Wendell Duffield.

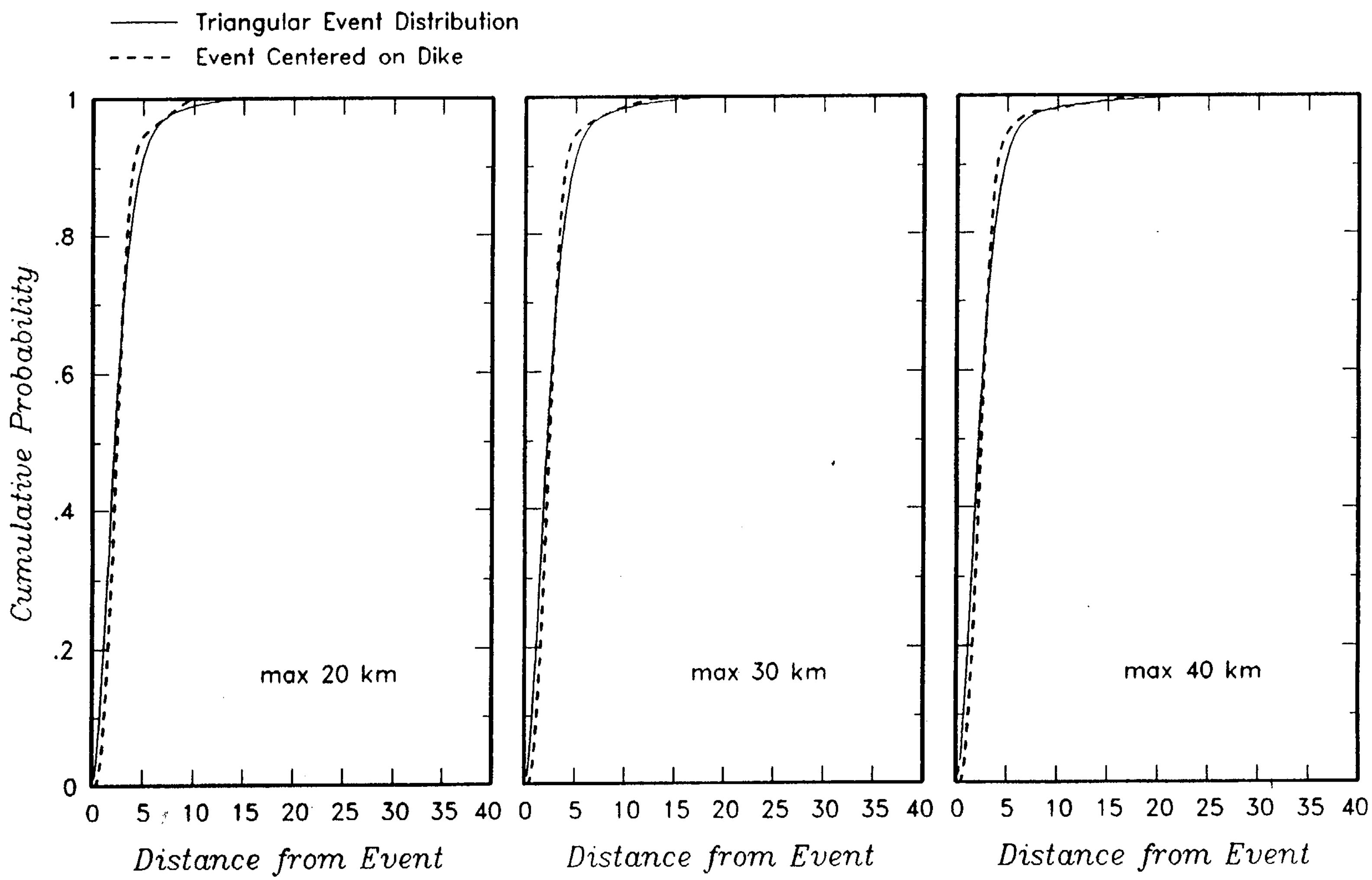


Figure 3-56 Alternative distributions for the length of an event *f(l)* developed from the assessments by Wendell Duffield.

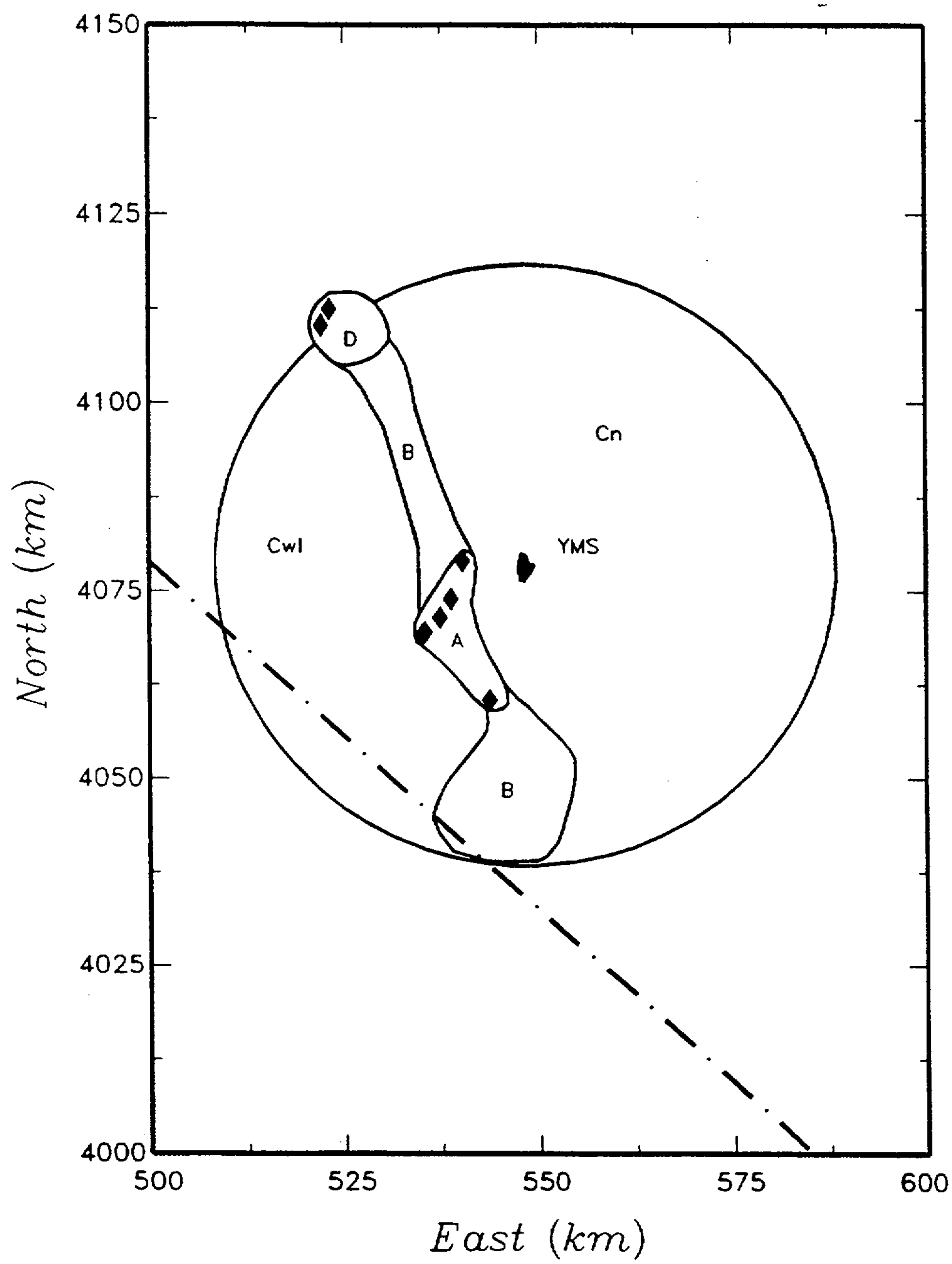


Figure 3-57 Regions of interest and source zones defined by Wendell Duffield. Diamonds represent volcanic events for the post-1 Ma time period. YMS refers to the proposed Yucca Mountain repository site and the dash-dot line is the Nevada-California border.

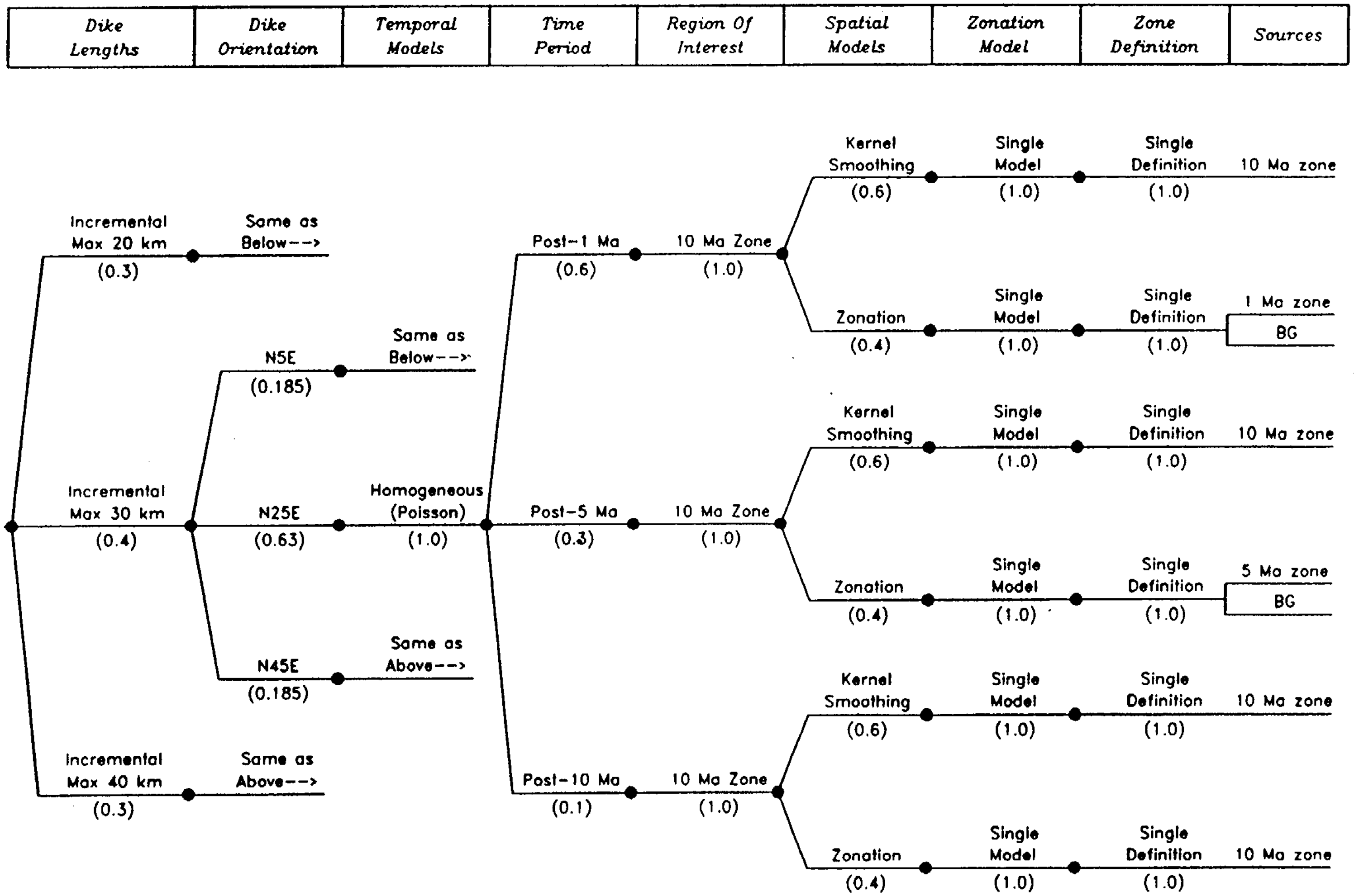


Figure 3-58 Logic tree for the PVHA model developed by William Hackett.

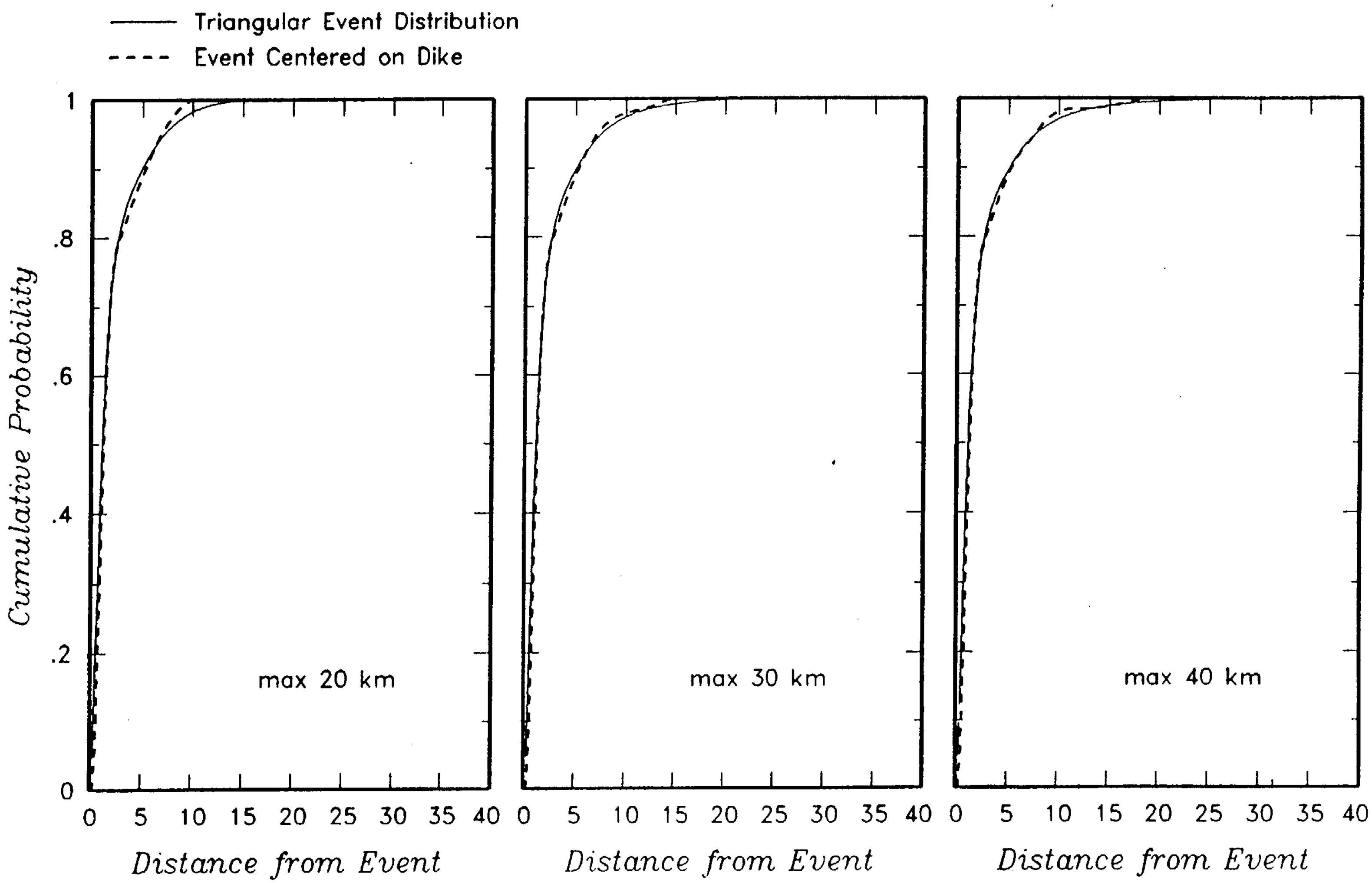


Figure 3-59 Alternative distributions for the length of an event *f(l)* developed from the assessments by William Hackett.

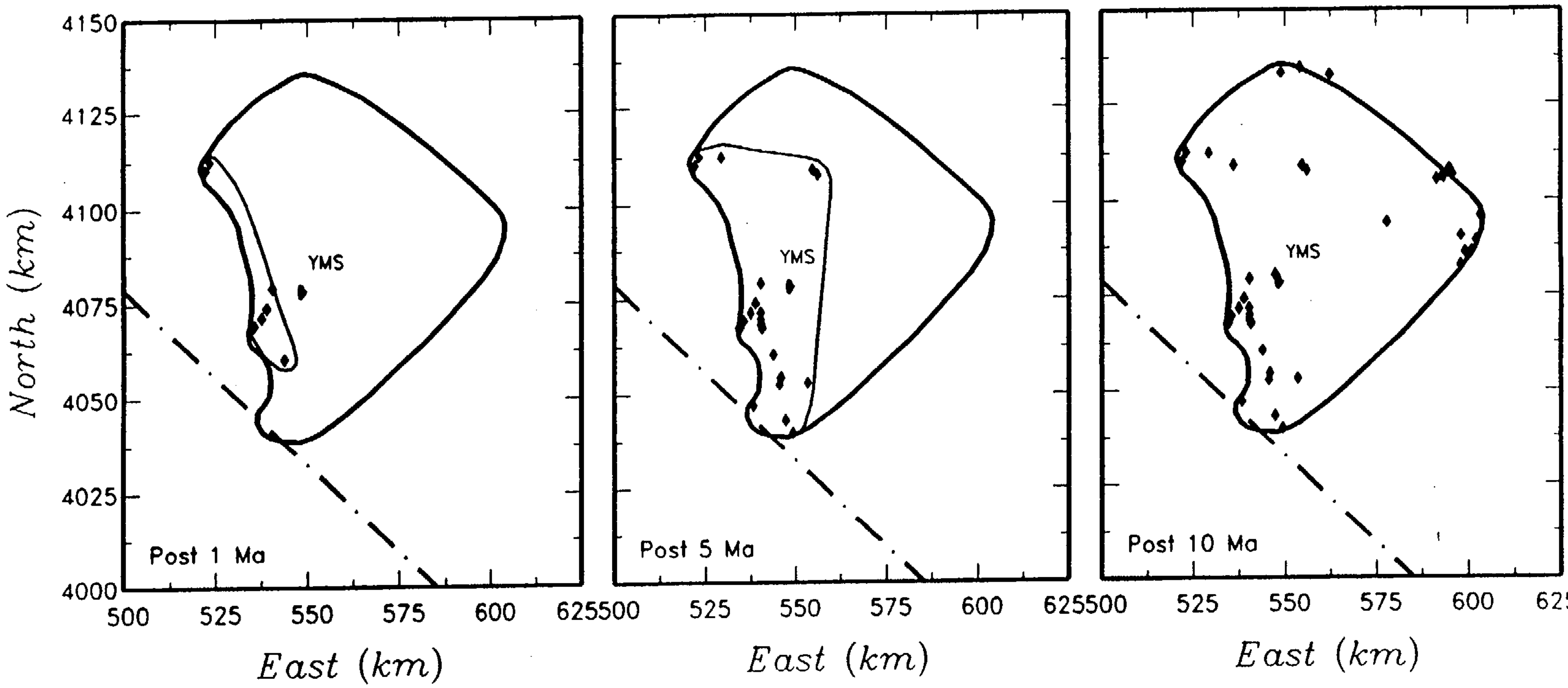


Figure 3-60 Region of interest and source zones defined by William Hackett.. Diamonds represent volcanic events for the indicated time periods. YMS refers to the proposed Yucca Mountain repository site and the dash-dot line is the Nevada-California border.

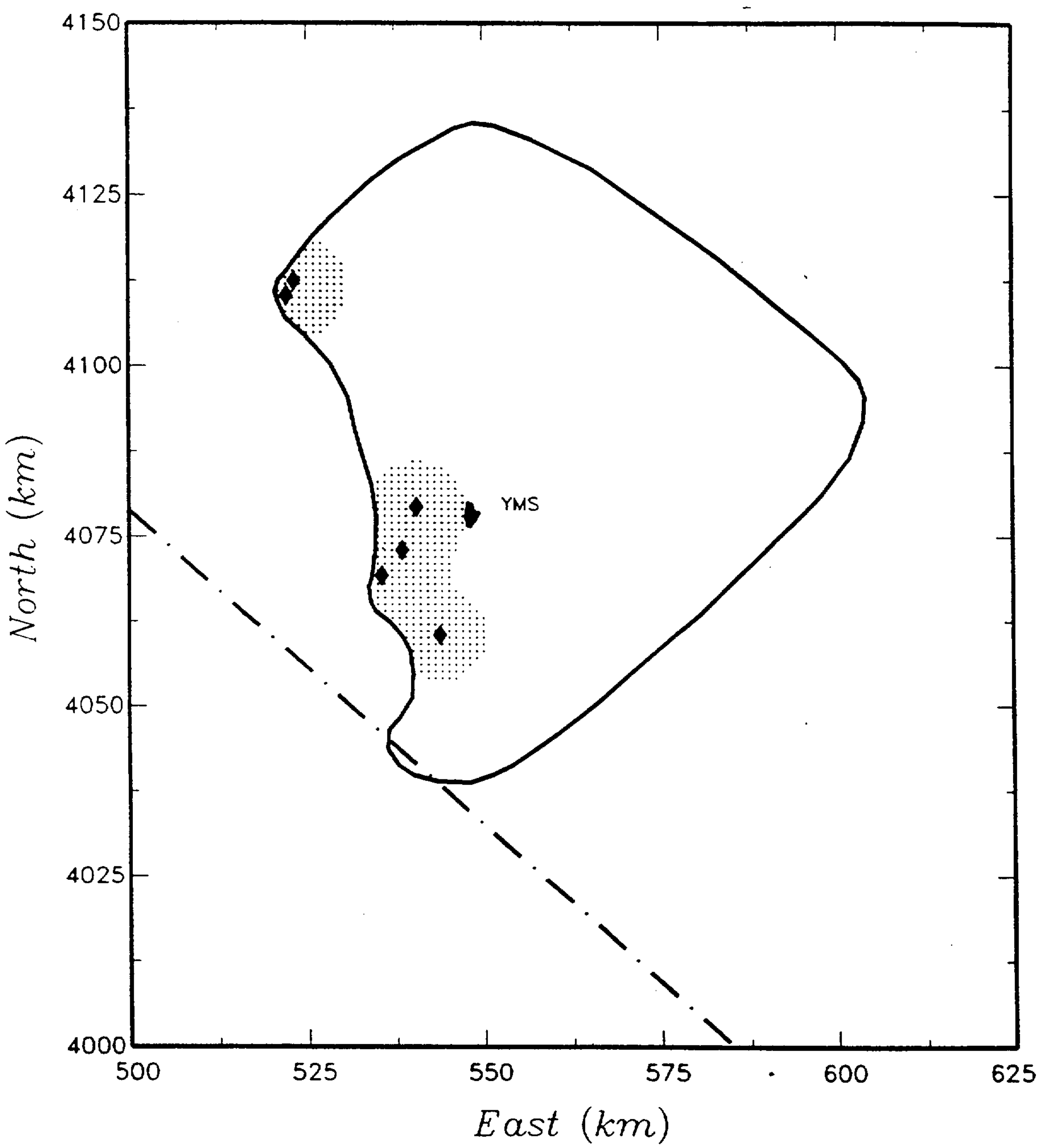


Figure 3-61 Example of the fit of a Gaussian kernel with *h* equal to 3.2 km to William Hackett's preferred event counts for the post-1 Ma time period. The stippled area outlines the 95th percentile density contour. YMS refers to the proposed Yucca Mountain repository site and the dash-dot line is the Nevada-California border.

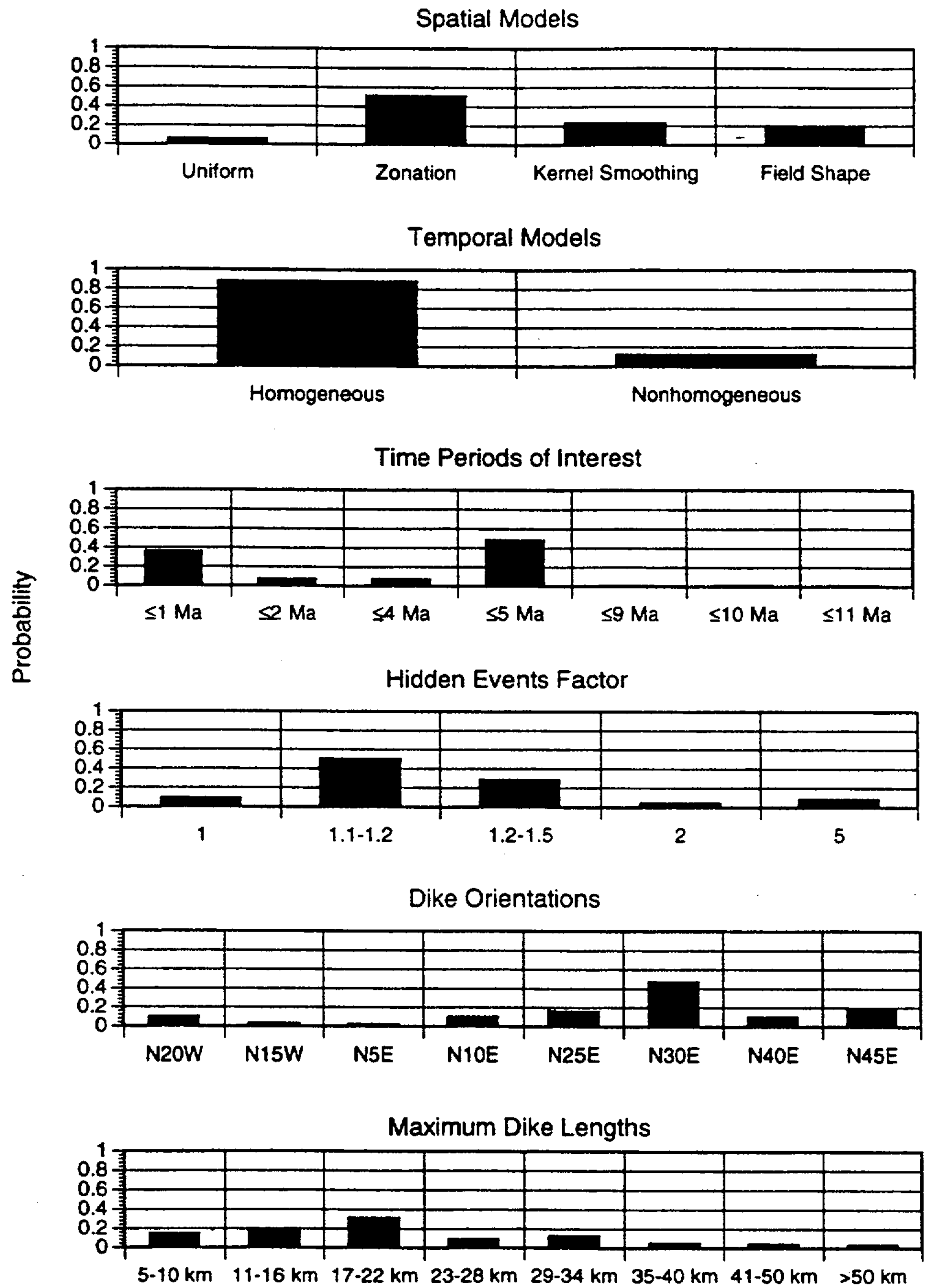


Figure 3-62 Summary of experts' assessments for components of the PVHA model.

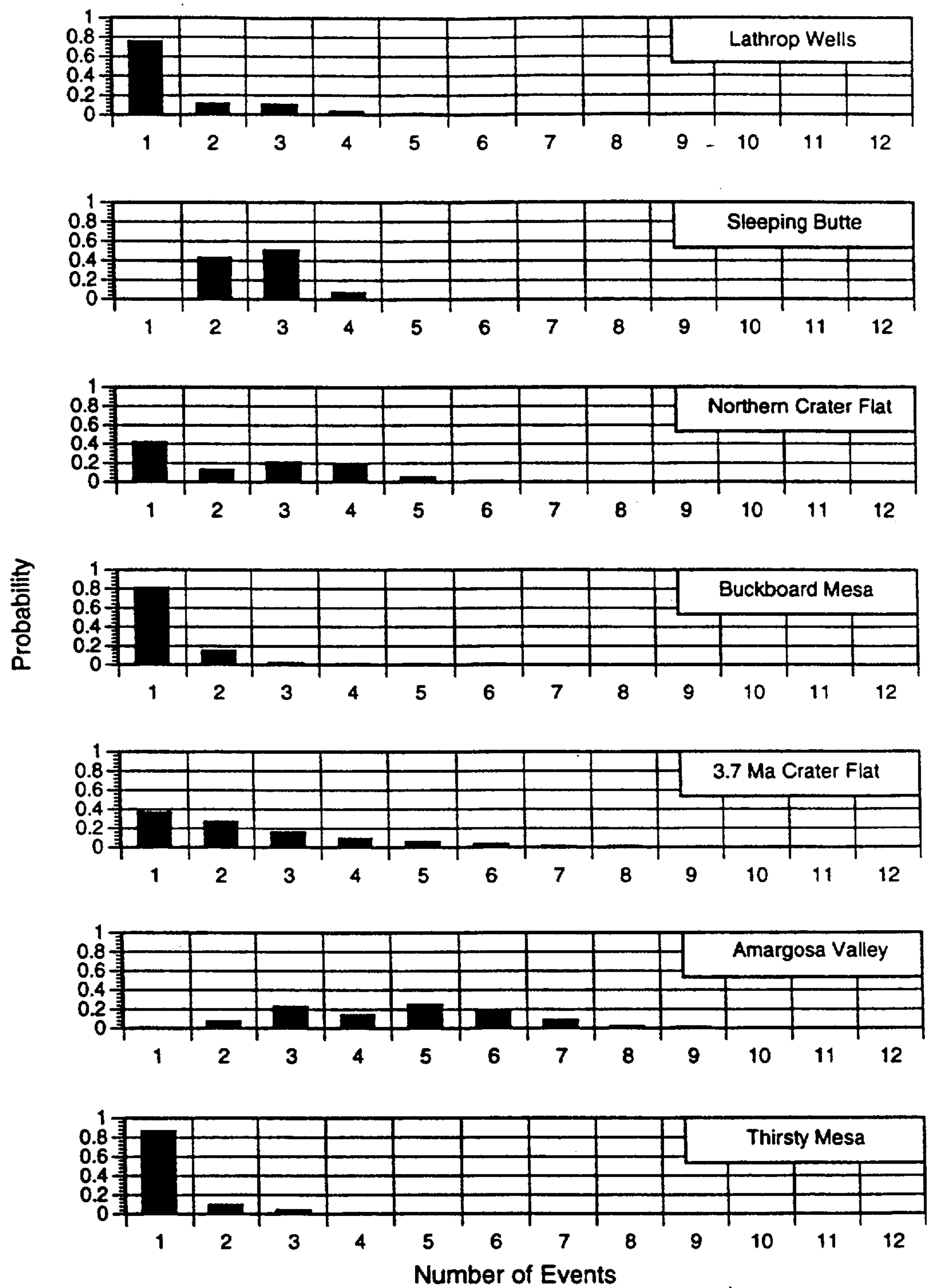


Figure 3-63 Summary of experts' assessments of the number of events at the various volcanic centers.

4.0 PROBABILISTIC VOLCANIC HAZARD ANALYSIS RESULTS

This section presents the results of the probabilistic volcanic hazard analysis (PVHA) performed using the hazard models developed by the 10 experts. The results are presented first for the individual experts in Section 4.1. Section 4.2 presents the aggregated result.

4.1 RESULTS FOR INDIVIDUAL EXPERT PVHA MODELS

Section 3.2 presents the 10 PVHA models developed for this study. Each model is presented in the form of a logic tree (Figures 3-15 and 3-16) that explicitly incorporates the uncertainty in selecting appropriate probabilistic models and model parameters to describe the spatial and temporal occurrence of future volcanic events in the vicinity of the proposed Yucca Mountain repository site and to describe the geometry (length and azimuth) of basaltic dikes associated with these events. Each end branch of these logic trees defines a possible set of models and model parameters that provide an estimate of the annual frequency of intersection of the repository footprint by a volcanic event. The associated probability of the end branch (obtained by multiplying all of the conditional probabilities along the path to the end branch) represents the likelihood that the computed frequency of intersection is the "correct" value for the site volcanic hazard. Thus, the computed results for all of the end branches and their associated probabilities define a probability distribution for the annual frequency of intersection.

The PVHA computation consisted of calculating the rate density of volcanic events on a 1-km by 1-km grid throughout the region defined by the local source zones. Similarly, the conditional probability of intersection was computed for the same grid of points. At each point in the grid the rate density of events was multiplied by the conditional probability of intersection, and the result summed over all points in the grid to yield the annual frequency of intersection.

The computation process was repeated for all possible combinations of event geometries, temporal models, time periods, spatial models, source zone definitions, smoothing parameters, event counts, and statistical distributions in rate estimates defined by the logic tree developed for each expert. The discrete distributions were used to compute the expected frequency of intersection and statistics of the uncertainty in the frequency of intersection. The results for the individual experts are presented below in alphabetical order by first initial.

Alexander McBirney Figure 4-1 presents the results of the hazard computation performed using the PVHA model developed by Alexander McBirney (AM). Part (a) of Figure 4-1 shows a histogram representation of the discrete density distribution for annual frequency of intersection. The histogram uses equal interval widths on a log scale. The mean of the distribution and the 5th-, 50th- (median), and 95th -percentiles of the distribution are indicated on the plot. The mean frequency of intersection is $4.3 \cdot 10^{-9}$ and the 90-percent confidence interval (5th- to 95th-percentile) ranges from $6.9 \cdot 10^{-10}$ to $1.8 \cdot 10^{-8}$. The distribution is skewed to the right, indicating that the preferred models and parameters lead to lower hazard than the mean.

The distribution for frequency of intersection shown on part (a) of Figure 4-1 results from uncertainties in a number of components of the PVHA hazard model. Part (b) of Figure 4-1 presents in summary form the relative contribution of the uncertainty in each of the PVHA components to the total uncertainty in the computed hazard. The plot is in the form of a histogram showing the percent of the total variance in the frequency of intersection that is due to uncertainty in the individual model components specified by Alexander McBirney. The parameters are arranged in the order that they appear in the general PVHA model logic tree (Figures 3-15 and 3-16).

In the PVHA model developed by Alexander McBirney approximately 50 percent of the total variance is due to uncertainty in the spatial model. The next largest contributor to the uncertainty in the hazard is the uncertainty in the rate parameter. As discussed in Section 3.1, the statistical uncertainty in computing the rate of volcanic events from a small data set was included as part of the uncertainty in the PVHA model. The results shown on part (b) of Figure 4-1 indicate that the uncertainty in estimating the rate from a small sample is a significant portion of the total uncertainty. The uncertainty in the hazard resulting from the combined uncertainty in defining the number of events at all of the volcanic centers is the next largest contributor. The impact of uncertainty in the counts at Buckboard Mesa is larger because the events at this center are the basis for the event rates in three source zones, including the one in which the repository is located (Zone-4).

The plot on part (b) of Figure 4-1 list all 24 components of the overall PVHA model defined on Figures 3-15 and 3-16. Many components have no contribution to the variance in the hazard computed by Alexander McBirney's PVHA model because they were not modeled as uncertain. These components are marked by a * on the figure.

Figure 4-2 shows the effect of the choice of maximum dike length and time period on the hazard. These distributions are conditional on the specified parameter. For example, the distribution for a maximum dike length of 15 km was computed by assigning a probability of 1.0 to this maximum dike length in the Alexander McBirney's PVHA model logic tree and probability zero to all other maximum dike lengths. The potential for longer dikes leads to slightly higher hazard estimates. Use of only the post-1 Ma time period leads to higher hazard than computed for the post-5 Ma time period because of the resulting higher frequency for events within the region of interest.

Figure 4-3 shows the effect of the choice of spatial model and the choice of smoothing parameter, *h*, on the computed hazard. Use of the kernel smoothing approach leads to significantly higher hazard because it allows for the relatively higher rate of events in Crater Flat to diffuse outward, and thus increase the rate density of events in the vicinity of the repository. The results for the different values of *h* are presented conditional on the use of the kernel smoothing approach. The increase in *h* from 6 km to 12 km has only a minor effect on the computed hazard. Connor and Hill (1995) also found relatively small differences in the hazard (less than a factor of 2) for comparable changes in *h*.

Bruce Crowe Figure 4-4 presents the results of the hazard computation performed using the PVHA model developed by Bruce Crowe (BC). The mean frequency of intersection is $1.1 \cdot 10^{-8}$ and the 90-percent confidence interval (5^{th}- to 95^{th}-percentile) ranges from $7.4 \cdot 10^{-10}$ to $3.5 \cdot 10^{-8}$. Part (b) of Figure 4-4 presents the relative contribution of the uncertainty in each of the PVHA components to the total uncertainty in the computed hazard. The largest contributor to uncertainty is the choice of time period. The second largest contributor is the uncertainty in zonation. The uncertainty in zonation is conditional on a selected time period and zonation model. For example, it reflects the choice between the alternative zones defined for the Quaternary time period and the structural approach to zonation. The large impact of the uncertainty in zonation on the hazard results arises from alternatives that sometimes place the repository site in zones with high event counts. The next largest contributor to the uncertainty in the hazard is, again, the uncertainty in the rate parameter estimated from a limited data set. Uncertainties in defining the region of interest and in defining the event counts within these regions also have significant contributions to the total uncertainties. Many of the zonation models defined by Bruce Crowe have source zones that do not include the site, and the site hazard is due primarily to the rate density of events in the background zone.

Figure 4-5 shows the effect of the choice of dike length distribution and temporal model on the hazard. The Gaussian dike length distribution has the potential for longer dikes, leading to slightly higher hazard estimates. The homogeneous temporal model results in slightly higher hazard estimates than the nonhomogeneous model because the average β values computed for the Weibull process are less than 1.

Figure 4-6 shows the effect of the choice of time period on the computed hazard. The use of the Plio-Quaternary time period produces significantly higher hazard estimates because the zonation models developed for this time period place higher weight on source zones that include both the site and the events in Crater Flat. The different peaks of the conditional distributions for the Quaternary and Plio-Quaternary time periods produce the bimodal combined distribution shown on part (a) of Figure 4-4. The distribution for the Mio-Plio-Quaternary time period is much narrower than for the other time periods because there are no alternative zonations and the uncertainty in the event rates are smaller because of the larger data sets used to make the estimates.

George Thompson Figure 4-7 presents the results of the hazard computation performed using the PVHA model developed by George Thompson (GT). The mean frequency of intersection is $3.3 \cdot 10^{-8}$ and the 90-percent confidence interval (5^{th}- to 95^{th}-percentile) ranges from $7.2 \cdot 10^{9}$ to $7.4 \cdot 10^{-8}$. Part (b) of Figure 4-7 presents the relative contribution of the uncertainty in each of the PVHA components to the total uncertainty in the computed hazard. The largest contributor to uncertainty is the uncertainty in the rate parameter estimated from a limited data set. Uncertainty in the amount of hidden events (either none or equal to the number of observed events) also is a large contributor to the total uncertainty because it has a significant impact on the overall rate of events.

Figure 4-8 shows the effect of the choice of maximum dike length and time period on the hazard. The alternative maximum dike lengths are similar and produce nearly identical hazard results. Use of the post-1 Ma time period results in higher hazard because of the forecasted higher event frequencies.

George Walker Figure 4-9 presents the results of the hazard computation performed using the PVHA model developed by George Walker (GW). The mean frequency of intersection is $5.8 \cdot 10^{-9}$ and the 90-percent confidence interval (5^{th}- to 95^{th}-percentile) ranges from $9.7 \cdot 10^{-10}$ to $1.5 \cdot 10^{-8}$. Part (b) of Figure 4-9 presents the relative contribution of the uncertainty in each of the PVHA components to the total uncertainty in the computed hazard. The largest contributor to uncertainty is the uncertainty in the rate parameter estimated from a limited data set. Uncertainty in the amount of hidden events (ranging from none to four times the number of observed events) is the second largest contributor because of the large impact on the overall rate of events. The uncertainty in the Gaussian field parameters also has a large contribution to the total uncertainty because they affect the rate density of events near the site associated with the Crater Flat Volcanic Zone.

Figure 4-10 shows the effect of the choice of maximum dike length and spatial model on the hazard. The alternative maximum dike lengths have a significant impact on the hazard because longer dike lengths allow for a greater contribution from events occurring in the Crater Flat Volcanic Zone. The Gaussian field shape and kernel smoothing spatial models produce higher hazard than the zonation model because they allow for the higher rate density of events in Crater Flat to diffuse outward towards the site.

Mel Kuntz. Figure 4-11 presents the results of the hazard computation performed using the PVHA model developed by Mel Kuntz (MK). The mean frequency of intersection is $9.9 \cdot 10^{-9}$ and the 90-percent confidence interval (5^{th}- to 95^{th}-percentile) ranges from $3.2 \cdot 10^{-10}$ to $3.1 \cdot 10^{-8}$. Part (b) of Figure 4-11 presents the relative contribution of the uncertainty in each of the PVHA components to the total uncertainty in the computed hazard. The largest contributor to uncertainty is the uncertainty in the rate parameter estimated from a limited data set. The other major contributor to the uncertainty in the hazard is the uncertainty in the spatial model. Uncertainty in the smoothing parameter, h, the Gaussian field parameters, and the form of the transition across local zone boundaries (abrupt versus gradual) all have minor contributions to the total uncertainty.

Figure 4-12 shows the effect of the choice of maximum dike length on the hazard. The alternative maximum dike lengths have a smaller impact on the hazard than was the case for George Walker's PVHA model because in Mel Kuntz's PVHA model the background source has a rate density closer to that of Crater Flat and, as a result, a larger contribution to the total hazard. The large change in maximum dike length from 10 to 18 km results in only a small change in the distribution for frequency of intersection, primarily in raising the lower tail. Most of the hazard in Mel Kuntz's PVHA model comes from events occurring near the proposed repository site, either in the local source zone, or from the Crater Flat zone when using the kernel smoothing or Gaussian field spatial models because most of the probability density for dike length is placed on short lengths (<5 km). Changes in maximum dike length produce only small changes in the bulk of the dike length distribution, and thus lead to small changes in the conditional probability of intersection.

Figure 4-13 shows the effect of the choice of temporal model and time period on the hazard. The nonhomogeneous temporal model results in slightly higher hazard estimates than the homogeneous model because the average β values computed for the Weibull process using Mel Kuntz's assessments of the appropriate time periods are greater than 1. As was the case for the results of other experts discussed above, the use of the post-2 Ma time period results in higher hazard than that obtained with longer time periods.

Figure 4-14 shows the effect of the choice of spatial model on the hazard. The uniform model produces the highest hazard because it results in the highest event rate density in the repository vicinity. The zonation model produces the lowest event rate density in the site vicinity, and thus the lowest hazard.

Michael Sheridan Figure 4-15 presents the results of the hazard computation performed using the PVHA model developed by Michael Sheridan (MS). The mean frequency of intersection is $1.8 \cdot 10^{-8}$ and the 90-percent confidence interval (5^{th}- to 95^{th}-percentile) ranges from $2.9 \cdot 10^{-9}$ to $4.7 \cdot 10^{-8}$. Part (b) of Figure 4-15 presents the relative contribution of the uncertainty in each of the PVHA components to the total uncertainty in the computed hazard. The largest contributor to uncertainty is the uncertainty in the rate parameter estimated from a limited data set. Other significant contributors to the uncertainty in the hazard are the uncertainty in dike length distribution, spatial model, and Gaussian field parameters. Michael Sheridan's PVHA model includes the possibility that the Lathrop Wells event has not ended and a future eruption associated with this event may occur. The uncertainty whether or not the Lathrop Wells event has ended is represented on part (b) of Figure 4-15 by the uncertainty in zonation model (whether or not to include Lathrop Wells as an additional source zone). This uncertainty also contributes significantly to the total uncertainty.

Figures 4-16 and 4-17 show the effect of the choice of dike length distribution on the hazard. Those distributions that result in longer dike lengths produce higher hazard because they allow for greater contribution from the Crater Flat field and from the Lathrop Wells event (when it is assumed to be still active).

Figure 4-18 shows the effect of the choice of spatial model and the uncertainty in the termination of the Lathrop Wells event on the hazard. The uniform model produces higher hazard than the Gaussian field model because it results in higher event rate density in the repository vicinity. The potential for continuation of the Lathrop Wells event results in higher hazard because of the associated high frequency of an additional dike emplacement (10^{-5} per year).

Richard Carlson Figure 4-19 presents the results of the hazard computation performed using the PVHA model developed by Richard Carlson (RC). The mean frequency of intersection is $1.4 \cdot 10^{-8}$ and the 90-percent confidence interval (5th- to 95th-percentile) ranges from $1.0 \cdot 10^{-9}$ to $4.5 \cdot 10^{-8}$. Part (b) of Figure 4-19 presents the relative contribution of the uncertainty in each of the PVHA components to the total uncertainty in the computed hazard. The largest contributor to uncertainty is the uncertainty in the rate parameter estimated from a limited data set. The other significant contributors to the uncertainty in the hazard are the uncertainty in the spatial model, uncertainty in the smoothing parameter, h, and uncertainty in the counts at northwestern Crater Flat (NWCF). Uncertainty in event counts affects the spatial distribution of events used to perform the kernel smoothing as well as the overall rate of events. In particular, the spatial extent of the events at northwestern Crater Flat impacts the computation of the spatial density in the site vicinity.

Figure 4-20 shows the effect of the choice of maximum dike length on the hazard for the random. The alternative maximum dike lengths have a small impact on the hazard.

Figure 4-21 shows the effect of the choice of temporal and spatial models on the hazard. The nonhomogeneous temporal model results in slightly lower hazard estimates than the homogeneous model because, although it predicts a higher overall rate of events, the events are more spatially diffuse, resulting in a lower predicted spatial density in the repository vicinity. The uniform model produces higher hazard than the kernel smoothing model because it results in higher event rate density in the repository vicinity.

Richard Fisher Figure 4-22 presents the results of the hazard computation performed using the PVHA model developed by Richard Fisher (RF). The mean frequency of intersection is $1.8 \cdot 10^{-8}$ and the 90-percent confidence interval (5th- to 95th-percentile) ranges from $3.4 \cdot 10^{-9}$ to $4.1 \cdot 10^{-8}$. Part (b) of Figure 4-22 presents the relative contribution of the uncertainty in each of the PVHA components to the total uncertainty in the computed hazard. The largest contributor to uncertainty is the uncertainty in the rate parameter estimated from a limited data set. The next largest contributor is the uncertainty in the event counts within the regions of interest (other zone event counts). Other significant contributors to the uncertainty in the hazard are the uncertainty in the time period, region of interest, spatial model, and the event counts for northwestern Crater Flat.

Figure 4-23 shows the effect of the choice of maximum dike length and time period on the hazard. The alternative maximum dike lengths have a small impact on the hazard. The alternative time periods of post-1 Ma and post-2 Ma produce estimates of the hazard that are different by approximately a factor of two because there is little difference in the event counts within these two time periods.

Figure 4-24 shows the effect of the choice of region of interest and spatial model on the hazard. The use of the eastern zone as the region of interest produces higher hazard because it includes two additional areas with large event counts (Lunar Crater and Cima), resulting in a higher rate density within the background zone. The zonation model produces the lowest hazard and the kernel smoothing model produces the highest hazard because of the relative difference in the spatial density in the site vicinity. The Gaussian field model produce similar estimates of the hazard to that obtained from the zonation model because Richard Fisher restricted the field parameters and the kernel smoothing parameter to produce the same spatial density contours at the boundary of the Crater Flat zone.

Wendell Duffield. Figure 4-25 presents the results of the hazard computation performed using the PVHA model developed by Wendell Duffield (WD). The mean frequency of intersection is $1.6 \cdot 10^{-9}$ and the 90-percent confidence interval (5^{th}- to 95^{th}-percentile) ranges from $8.7 \cdot 10^{-11}$ to $4.3 \cdot 10^{-9}$. Part (b) of Figure 4-25 presents the relative contribution of the uncertainty in each of the PVHA components to the total uncertainty in the computed hazard. The largest contributor to uncertainty is the uncertainty in the rate parameter estimated from a limited data set. The other significant contributors to the uncertainty in the hazard are the uncertainty in the maximum dike length and the uncertainty in the potential for a hidden event in the background zone, which is included as uncertainty in other event counts.

Figure 4-26 shows the effect of the choice of maximum dike length and zonation model on the hazard. Consideration of longer maximum dike lengths leads to significantly higher hazard estimates. Wendell Duffield's spatial model is a source zone encompassing Crater Flat and a background zone in the vicinity of the site with a substantially lower rate density of volcanic events. Thus, most of the hazard is associated with events in the Crater Flat zone and increasing the maximum dike length leads to a higher likelihood that events occurring in the Crater Flat source zone will intersect the repository. Use of the alternative representations for Zone B and C_{WL} leads to the same hazard because it does not impact the event rate density in the site vicinity.

William Hackett Figure 4-27 presents the results of the hazard computation performed using the PVHA model developed by William Hackett (WH). The mean frequency of intersection is $3.0 \cdot 10^{-8}$ and the 90-percent confidence interval (5^{th}- to 95^{th}-percentile) ranges from $5.6 \cdot 10^{-9}$ to $7.8 \cdot 10^{-8}$. Part (b) of Figure 4-27 presents the relative contribution of the uncertainty in each of the PVHA components to the total uncertainty in the computed hazard. The largest contributor to uncertainty is the uncertainty in the spatial model. Uncertainty in the rate parameter and uncertainty in the smoothing parameter, *h*, result in similar levels of uncertainty in the hazard.

Figure 4-28 shows the effect of the choice of maximum dike length on the hazard. The alternative maximum dike lengths produce only small differences in the hazard because most of the hazard results from near by events.

Figure 4-29 shows the effect of the uncertainty in mean dike azimuth on the computed hazard. There is a gradual increase in the hazard as the mean azimuth changes from N05°E to N45°E. This increase results from a greater number of dikes associated with potential future events being oriented towards the repository site in the post-1 Ma source zone.

Figure 4-30 shows the effect of the choice of time period and spatial model on the hazard. The highest hazard results from use of the post-5 Ma time period. The post-1 Ma and post-5 Ma time periods have similar estimates of the rate of events in the region of interest, but the repository site lies within the source zone for the post-5 Ma time period. The zonation model produces lower hazard than the kernel smoothing model because the favored zonation (the post-1 Ma zone) does not include the site in the zone with the highest event rate.

4.2 AGGREGATE HAZARD

Figure 4-31 compares the hazard results obtained for the 10 PVHA models developed by the volcanic experts. The relative smoothness of the distributions reflects the number of discrete end branches of the logic trees defined by each expert. However, all of the distributions span a large range in the estimates of the frequency of intersection, indicating that each expert considered that there are significant uncertainties in estimating the hazard.

Computing the aggregate distribution for the frequency of intersection requires specification of the weight to be assigned to each expert's distribution. As stated in Section 2.2.11, the objective from the beginning of the study was to be able to apply equal weights to the experts' assessments of the volcanic hazard. For the reasons given in Section 2.2.11, it is our judgment that this objective has been achieved and equal weights are appropriate.

Figure 4-32 shows the aggregate hazard results. Part (a) shows the aggregate of the 10 distributions shown on Figure 4-31. The mean frequency of intersection is $1.5 \cdot 10^{-8}$ and the 90-percent confidence interval (5^{th}- to 95^{th}-percentile) ranges from $5.4 \cdot 10^{-10}$ to $4.9 \cdot 10^{-8}$. Also shown on the plot are the mean and median values for the 10 individual experts' distributions. The individual means and medians span about one and one-half orders of magnitude and all lie within the 90-percent confidence interval of the aggregate distribution. The aggregate distribution is skewed somewhat to the left (in log space), with a concentration of mass near the mean frequency of intersection. The distributions of the individual medians and means mirror this general shape.

Part (b) of Figure 4-32 compares the 90-percent confidence intervals computed for the 10 individual experts' distributions to the 90-percent confidence interval for the aggregate distribution. The medians and means from part (a) are also shown. Nearly all of the individual confidence intervals overlap each other and all but one of the individual confidence intervals contain the aggregate median and mean. The lowest hazard estimates result from Wendell Duffield's model in which very strong preference is placed on the most recent past for predicting the future and on restricting events to Crater Flat. The median and mean values computed from his PVHA model lie within most of the individual 90-percent confidence intervals.

Figure 4-33 presents the relative contribution of the uncertainty in each of the PVHA components to the total uncertainty in the aggregate hazard. Part (a) shows the total variance split into inter-expert (expert to expert differences) and intra-expert (individual expert uncertainty) components. The expert-to-expert differences represent about one-third of the total variance in the frequency of intersection. The majority of the uncertainty in the hazard results from the uncertainties specified by the individual experts (intra-expert uncertainty).

Part (b) of Figure 4-33 shows the breakdown of the intra-expert variance among the various components of the PVHA model logic tree. This plot shows the relative contribution to the total intra-expert variance averaged over all experts. The largest component of the intra-expert uncertainty results from the statistical uncertainty in estimating the event rates. This component (approximately 40 percent of the intra-expert variance) is significantly larger than the combined contributions of uncertainties in evaluating the event counts at the various volcanic centers (approximately 11 percent of the intra-expert variance). The second largest component of the intra-expert uncertainty in the hazard results from uncertainty in the appropriate spatial model (approximately 14 percent of the intra-expert variance). Uncertainty in defining the parameters of the various spatial models together contribute a comparable level of uncertainty (approximately 13 percent of the intra-expert variance). The modeled uncertainty in the temporal models and appropriate time period have a smaller contribution to the total uncertainty, as does uncertainty in the dike length distributions.

Figures 4-34 through 4-37 show various sensitivity analysis results. Figure 4-34 shows the effect of the choice of maximum dike length and temporal model on the aggregate hazard distribution for frequency of intersection. Conditional distributions were computed using only each experts minimum value for maximum dike length and each experts maximum value for maximum dike length. The range in maximum dike lengths produces only a small change in the hazard (approximately 30 percent difference in the mean frequency of intersection). This small effect is because the experts placed most of the probability mass on short lengths in their dike length distributions. Thus, the effect of alternative maximum dike lengths was to change the conditional probability of intersection function (e.g Figure 3-14) only in the area where the conditional probability is very low. At the same time, nearly all of the experts' assessments contained spatial models that produced event densities in the vicinity of the proposed repository site that are a significant fraction of those estimated for Crater Flat. As a result, the majority of the hazard results from the potential occurrence of events near the repository and is relatively insensitive to the assigned maximum dike length.

Use of the homogeneous and nonhomogeneous temporal models produces very similar estimates of the volcanic hazard. (Note that only three of the experts, BC, MK, and RC, included nonhomogeneous temporal models in their assessments and the results shown on Figure 4-34 for the nonhomogeneous model are the aggregate of these three conditional distributions.)

Figure 4-35 shows the effect of the choice of time period on the aggregate hazard distribution. Conditional results are shown for the Quaternary period (post 1 or 2 Ma), the Plio-Quaternary period (post ~5 Ma), and the Mio-Plio-Quaternary period (post ~10 Ma). (Again note that the results are the aggregate of the conditional distributions for those experts that included the particular time period as an alternative in their PVHA model.) Use of the Quaternary and Plio-

Quaternary time period produces similar hazard estimates and the results for the post-10 Ma time period are slightly lower. The conditional distribution for the Quaternary time period is broader in part because the event occurrence rates are estimated from fewer numbers of events and are thus more uncertain.

Figure 4-36 shows the effect of the choice of spatial model on the aggregate hazard distribution. Use of the uniform model produces the highest hazard because the site always lies in this source zone. The zonation models produce the lowest hazard because they typically restrict the highest rate density of events to Crater Flat. The zonation models also produce the broadest conditional distribution because the alternative source zones result in substantial changes in the event rate density estimates in the site vicinity. However, all of the conditional mean estimates of the frequency of intersection for the four spatial models are within a factor of two of each other.

All of the hazard estimates presented above were computed using the randomly placed dike representation of volcanic events [part (c) of Figure 3-11]. As a sensitivity analysis, the frequency of intersection was also computed using the two other event representations discussed in Section 3, point events and dikes centered on the event (see Figure 3-11). Point events were considered to have intersected the repository if they occurred within 0.25 km of the repository boundary. Figure 4-37 compares the resulting aggregate distributions for frequency of intersection. The mean values for frequency of intersection are $5.7 \cdot 10^{-9}$, $1.4 \cdot 10^{-8}$, and $1.5 \cdot 10^{-8}$ for point events, event-centered dikes, and random dikes, respectively. Note that the distribution computed for the point representation of events has significant probability mass at annual frequencies lower than 10^{-12} and the 5^{th}-percentile is plotted at 10^{-12} on the figure. The event-centered dike and the random dike representations of events produce very similar estimates of hazard for the same reason that the aggregate results are relatively insensitive to the assessment of the maximum dike length.

Finally, we examined the sensitivity of the results to expert selection. The results shown on Figure 4-32 are the aggregate assessments of 10 individuals selected from the available population of experts on basaltic volcanism. One may ask what would have been the result if a different group of equally qualified experts had been selected and subjected to the same process. Also, one may ask what is the sensitivity of the answer to the size of the panel selected. Two analyses were performed to examine this issues.

First, it is possible to examine the range of results for subsets of the expert panel. For example, there are 10 possible subsets of 9 experts, 252 possible subsets of 5 experts, and 10 possible subsets of 1 expert. For each subset, an aggregate distribution for the frequency of intersection can be computed, and the resulting mean hazard and percentiles of the hazard distribution obtained. The range in the various statistics is a possible indication of the range one might obtain from other expert panels of smaller size.

Figure 4-38 presents the results of this type of analysis. All possible subsets of from 1 to 10 experts were defined and an aggregate distribution for frequency of intersection computed for each subset. The resulting range in mean values and the 5th and 95th percentiles of the combined distributions are plotted as continuous curves on the figure versus the number of experts in the subsets. The results indicate that for subsets of greater than five experts, the range in mean hazard and in the 95th percentile hazard are relatively small. The 5th percentile of the hazard distribution shows more variability among the experts than the other two measures. This is because the lower hazard estimates are more sensitive to the details of the hazard models (placement of zone boundaries, dike length distributions) than are the mean and 95th percentile hazard estimates. The results for the 95th percentile hazard are somewhat limited by the maximum event frequencies one can estimate from the observed data, and thus do to vary greatly among the experts.

A second approach to evaluating the variability in the hazard estimates is to use the bootstrapping technique. Assuming that the selected panel is representative of the population of qualified experts, then one can simulate a new panel of 10 experts by randomly selecting experts from the existing panel. The selection is done with replacement (i.e an expert can be selected more than once) because it is assumed that each expert is equally likely to represent a member of the population of qualified experts. The aggregate distribution computed from the simulated expert panel represents one possible result that might be obtained if the entire study were repeated, including selecting a new panel (which very likely might contain some members of the existing panel). By repeating the simulation multiple times, a bootstrap distribution for the statistical measures of the hazard can be obtained.

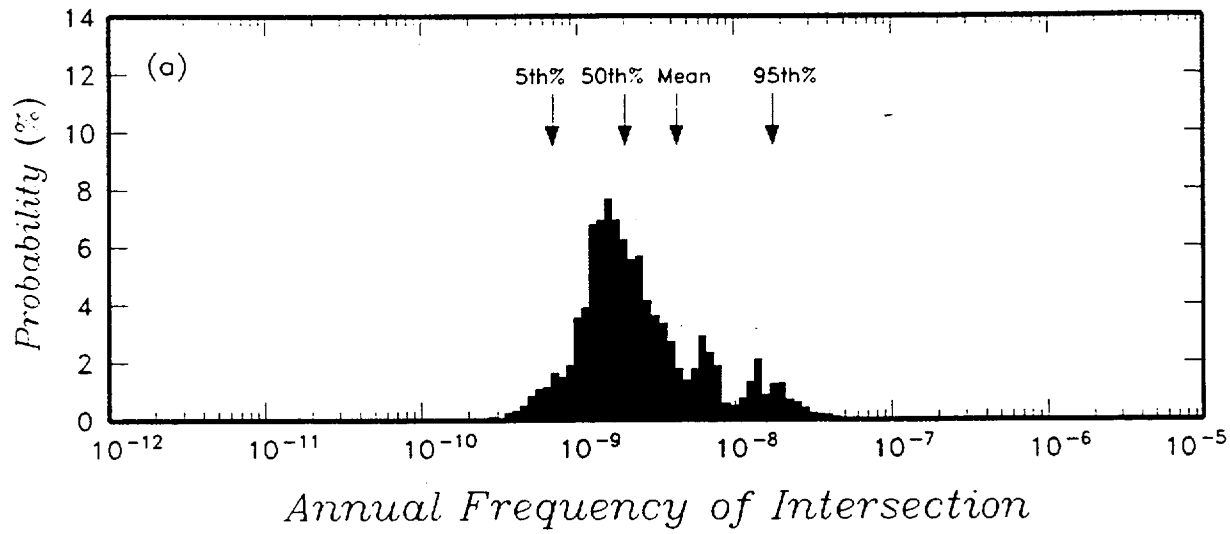
The bootstrap approach was applied to the development of the aggregate hazard distribution. One thousand simulations of aggregate distributions were computed by randomly sampling, with replacement, 10 experts from the panel. For each simulation, the mean and the 5th and 95th percentiles of the aggregate hazard distribution were computed. The resulting 1,000 estimates of the hazard statistics were then ordered to form confidence intervals for the three hazard statistics.

These are plotted on Figure 4-38 as horizontal error bars representing the 90-percent bounds of the simulated distributions (5^{th} to 95^{th} percentiles) for the hazard statistics. The dots are plotted at the medians. The resulting 90-percent intervals show similar characteristics to those obtained from the subset analysis and indicate stability of the results.

The conclusion that can be drawn is that we would not expect to obtain a significantly different result upon repeating the entire process. This results from the fact that most of the uncertainty in the estimated hazard arises from the uncertainty that an individual expert has in interpreting the available data rather than from differences between the interpretations of the experts.

4.3 SUMMARY

The results of the PVHA analysis are that the aggregate expected annual frequency of intersection of the repository footprint by a volcanic event is $1.5 \cdot 10^{-8}$, with a 90-percent confidence interval of $5.4 \cdot 10^{-10}$ to $4.9 \cdot 10^{-8}$. The major contributions to the uncertainty in the frequency of intersection are the statistical uncertainty in estimating the rate of volcanic events from small data sets and the uncertainty in modeling the spatial distribution of future events. Although there are significant differences between the interpretations of the 10 experts, most of the uncertainty in the computed frequency of intersection is due to the average uncertainty that an individual expert expressed in developing the appropriate PVHA model.



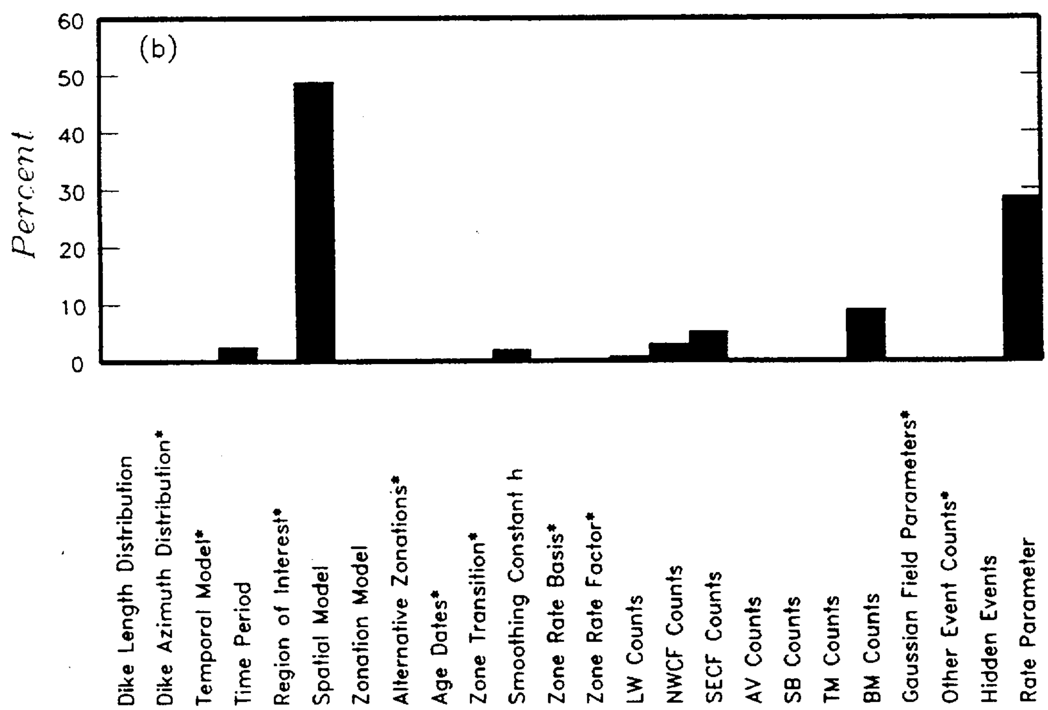


Figure 4-1 PVHA results obtained using Alexander McBirney's PVHA model. (a) Distribution for annual frequency of exceedance. (b) Relative contribution of uncertainty in various components of the PVHA model to the total variance in annual frequency of intersection. Components marked with a * were not treated as uncertain.

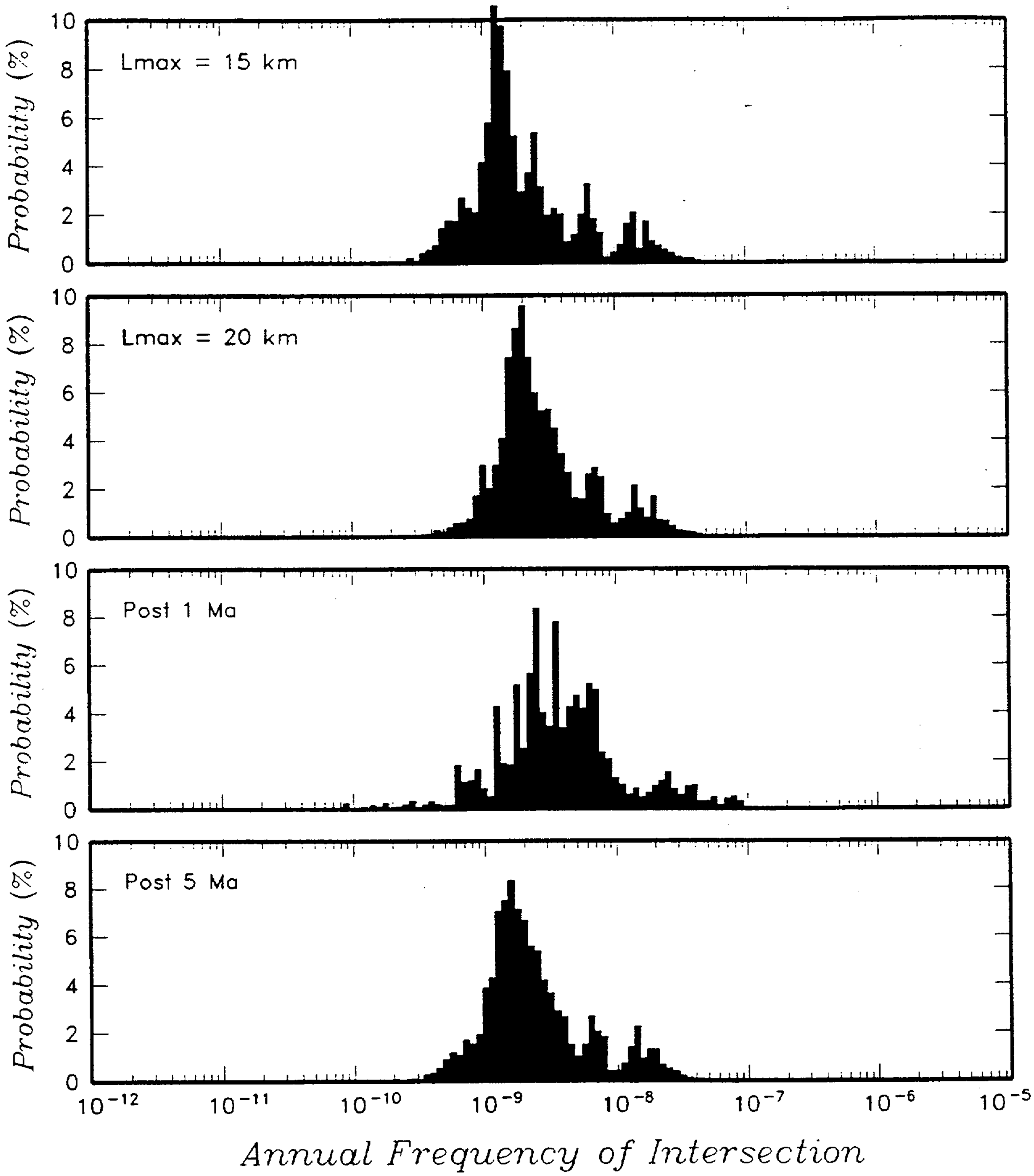


Figure 4-2 Effect of choice of maximum dike length and time period of interest on computed hazard distribution for Alexander McBirney's PVHA model.

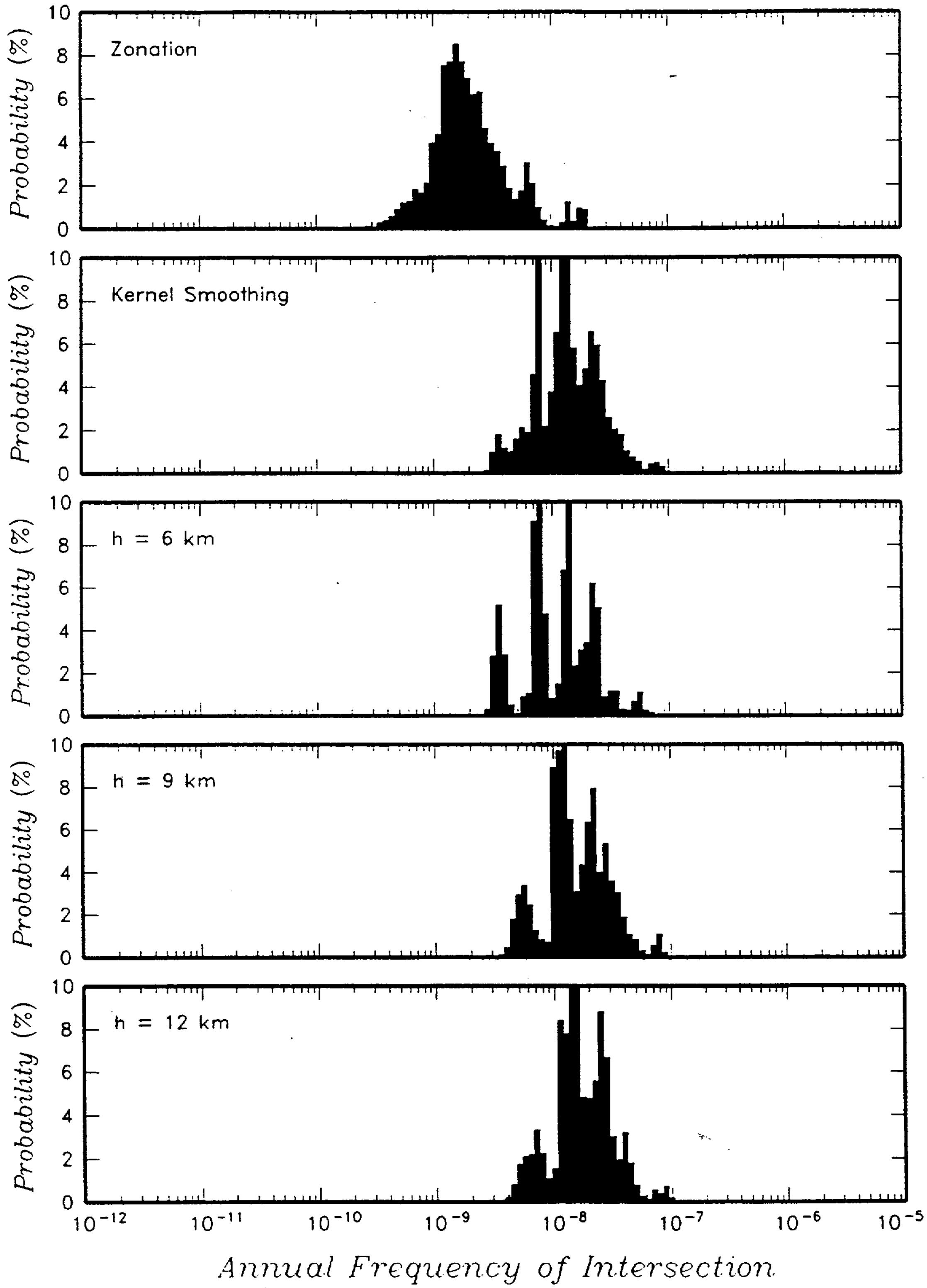


Figure 4-3 Effect of choice of spatial model and smoothing parameter, *h*, on computed hazard distribution for Alexander McBirney's PVHA model.

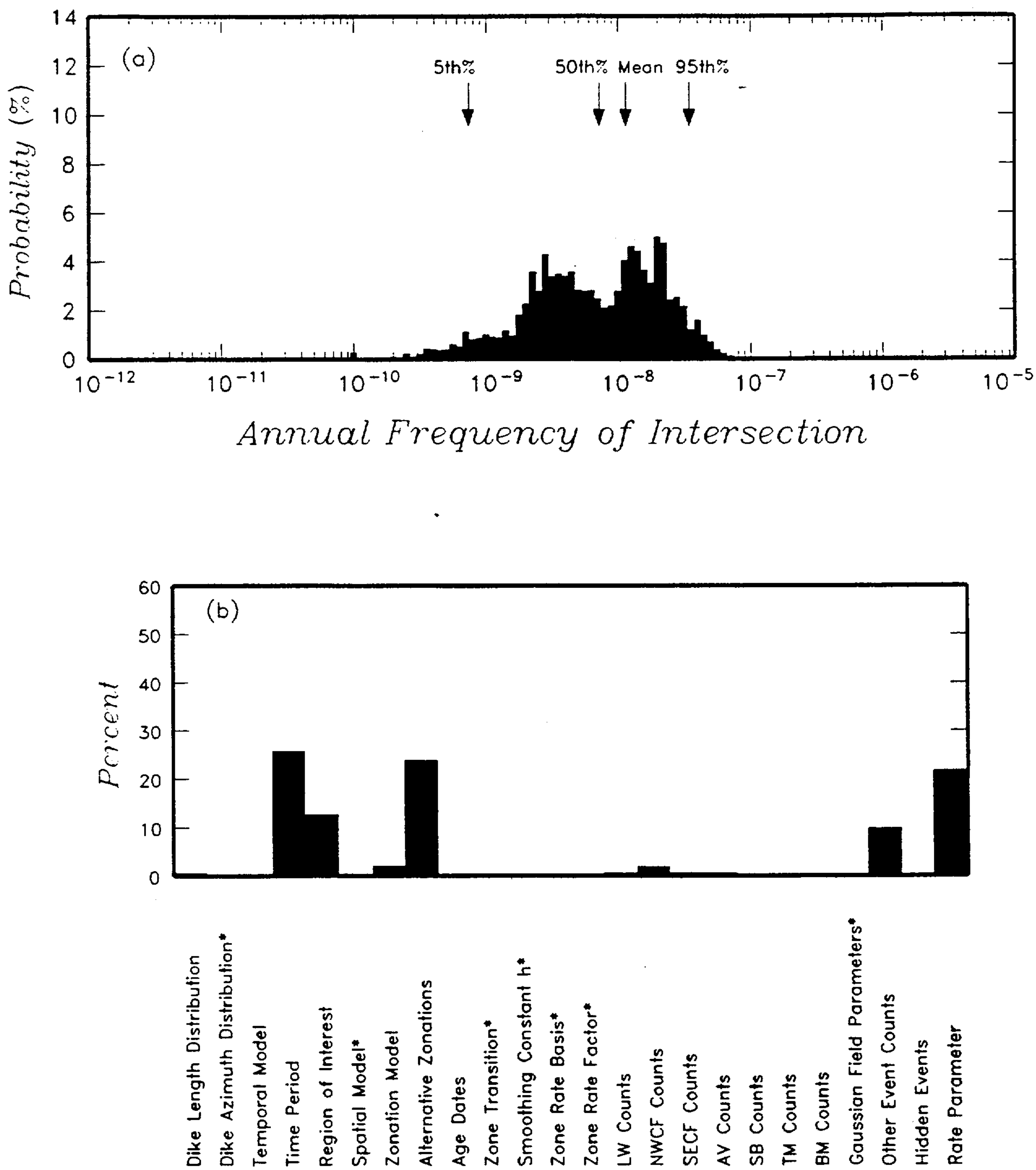


Figure 4-4 PVHA results obtained using Alexander McBirney's PVHA model. (a) Distribution for annual frequency of exceedance. (b) Relative contribution of uncertainty in various components of the PVHA model to the total variance in annual frequency of intersection. Components marked with a * were not treated as uncertain.

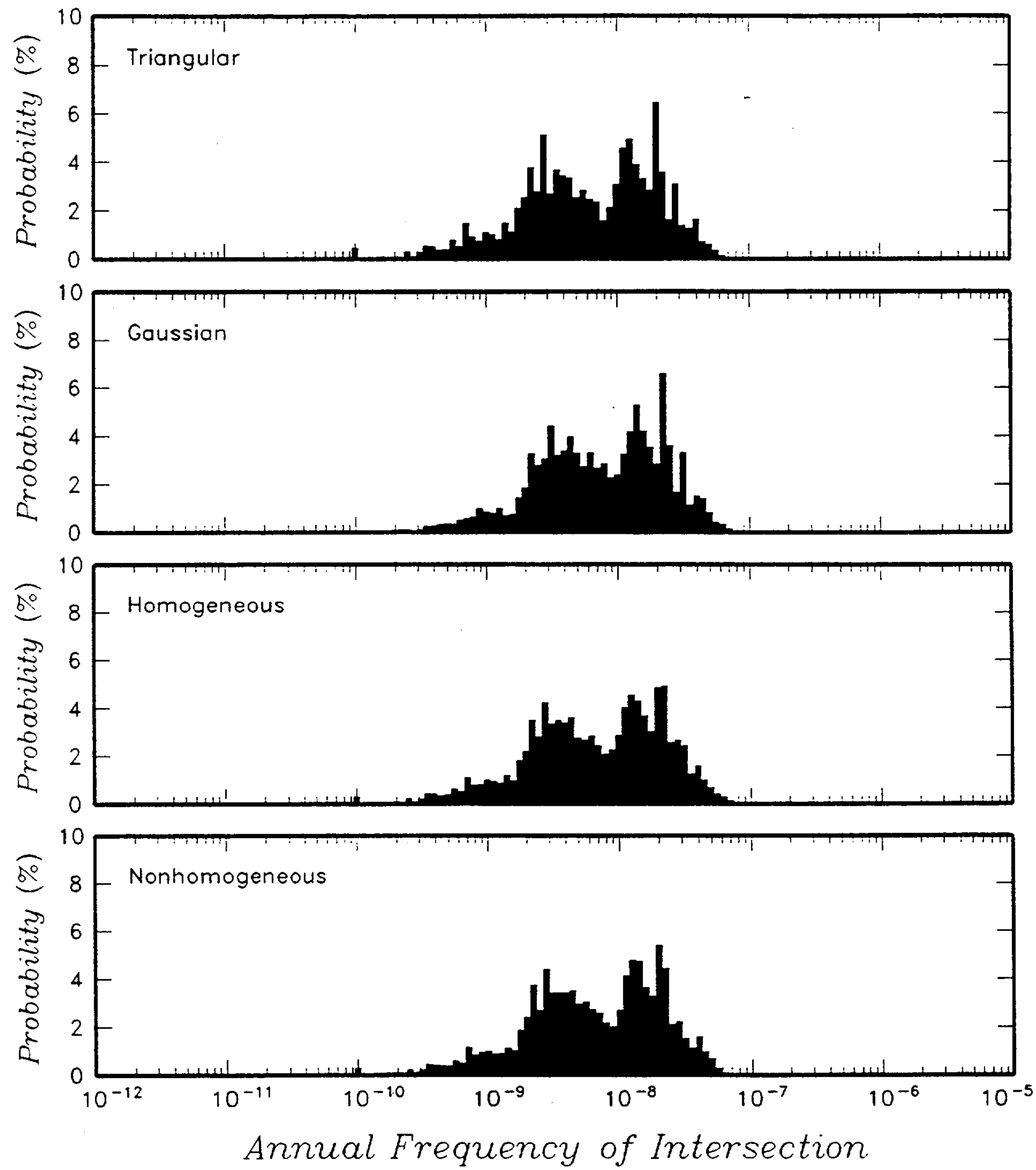


Figure 4-5 Effect of choice of dike length distribution and temporal model on computed hazard distribution for Bruce Crowe's PVHA model.

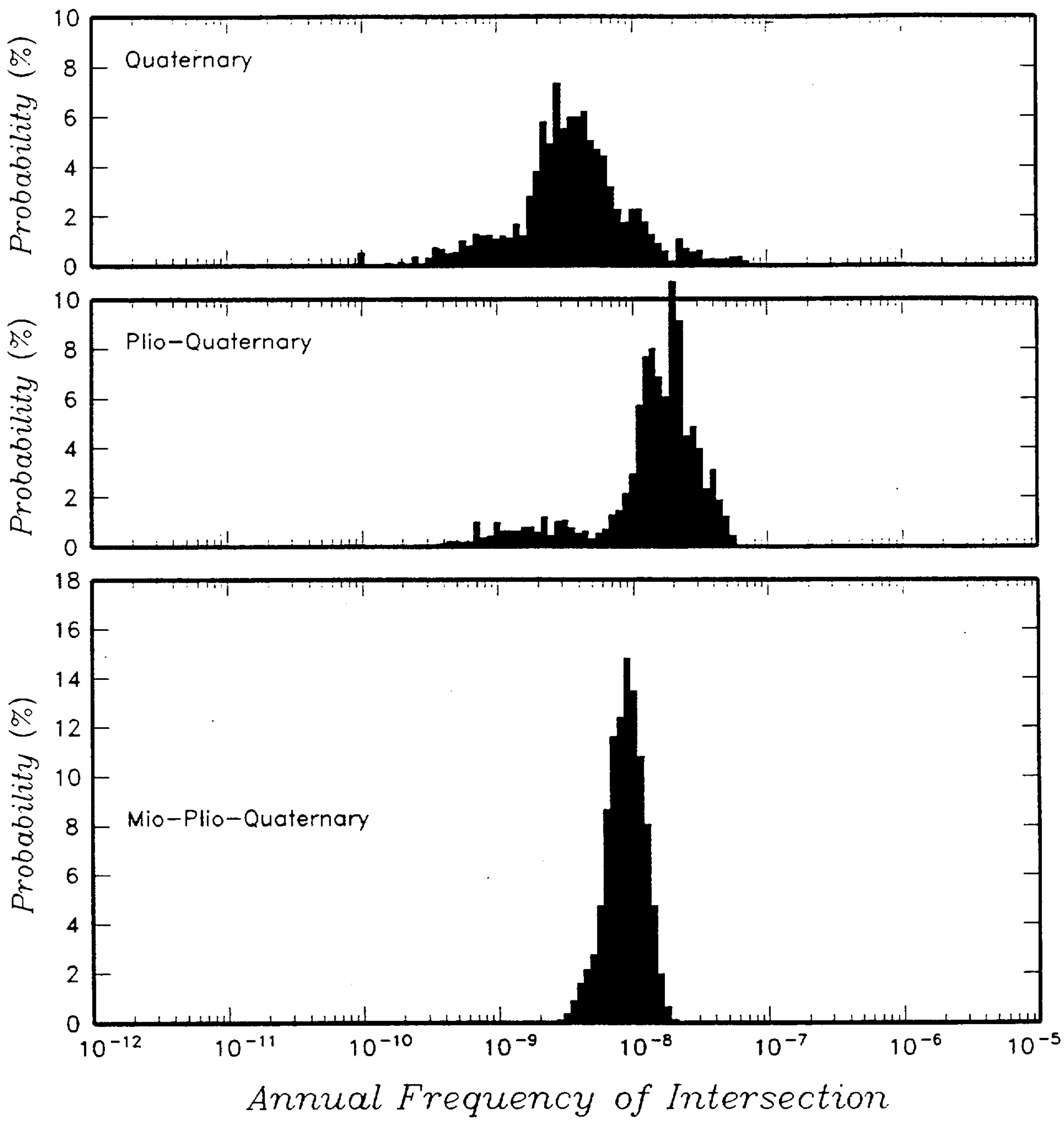
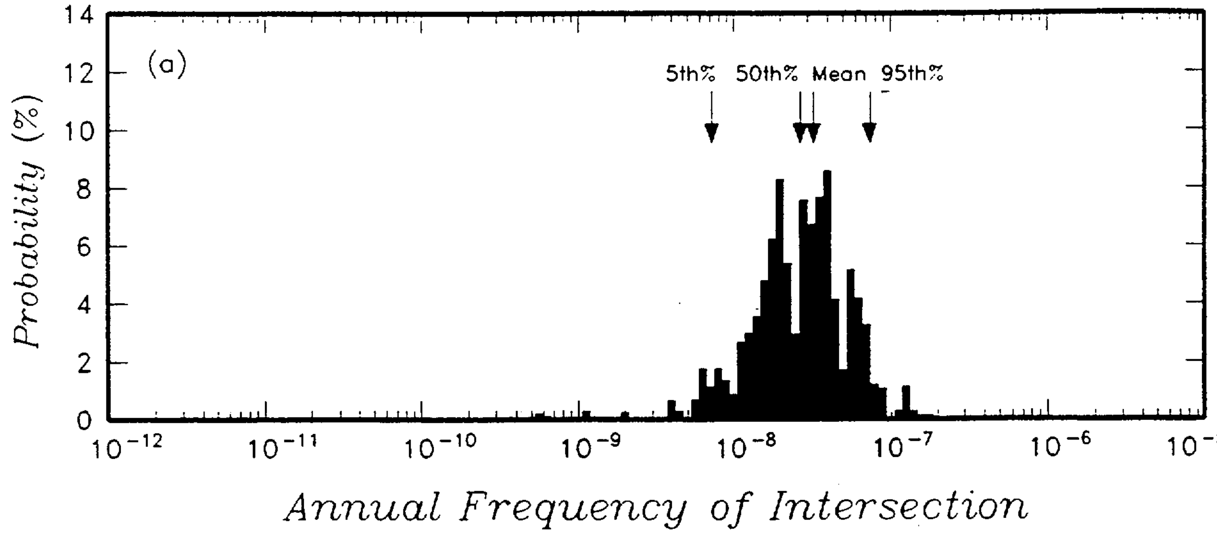


Figure 4-6 Effect of choice of time period on computed hazard distribution for Bruce Crowe's PVHA model.



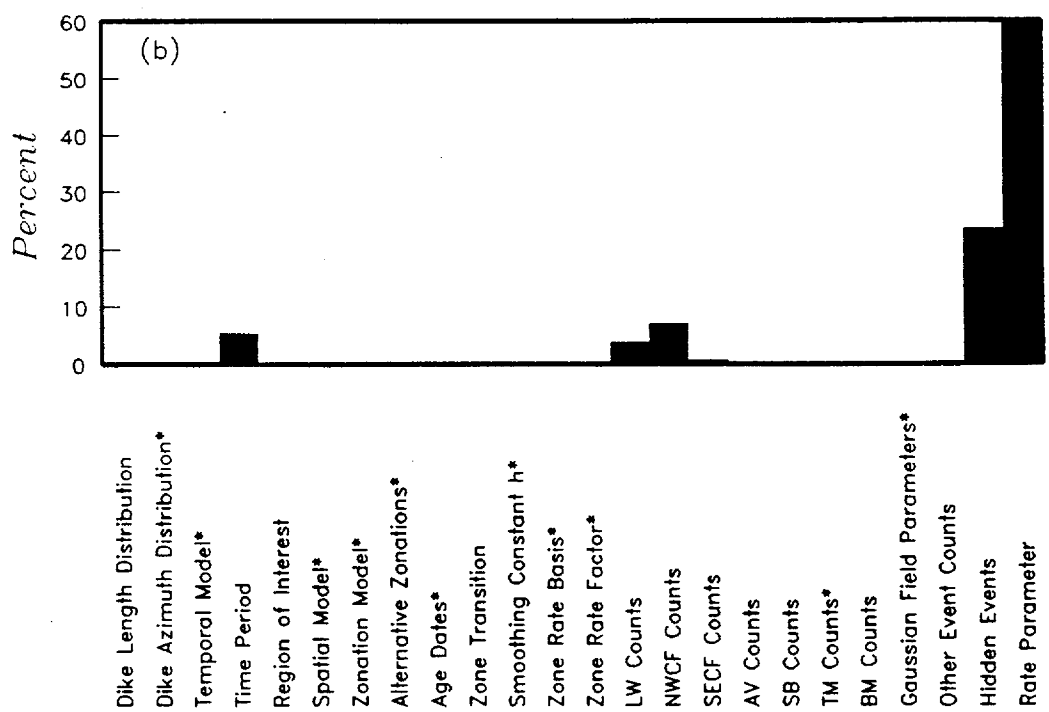


Figure 4-7 PVHA results obtained using George Thompson's PVHA model. (a) Distribution for annual frequency of exceedance. (b) Relative contribution of uncertainty in various components of the PVHA model to the total variance in annual frequency of intersection. Components marked with a * were not treated as uncertain.

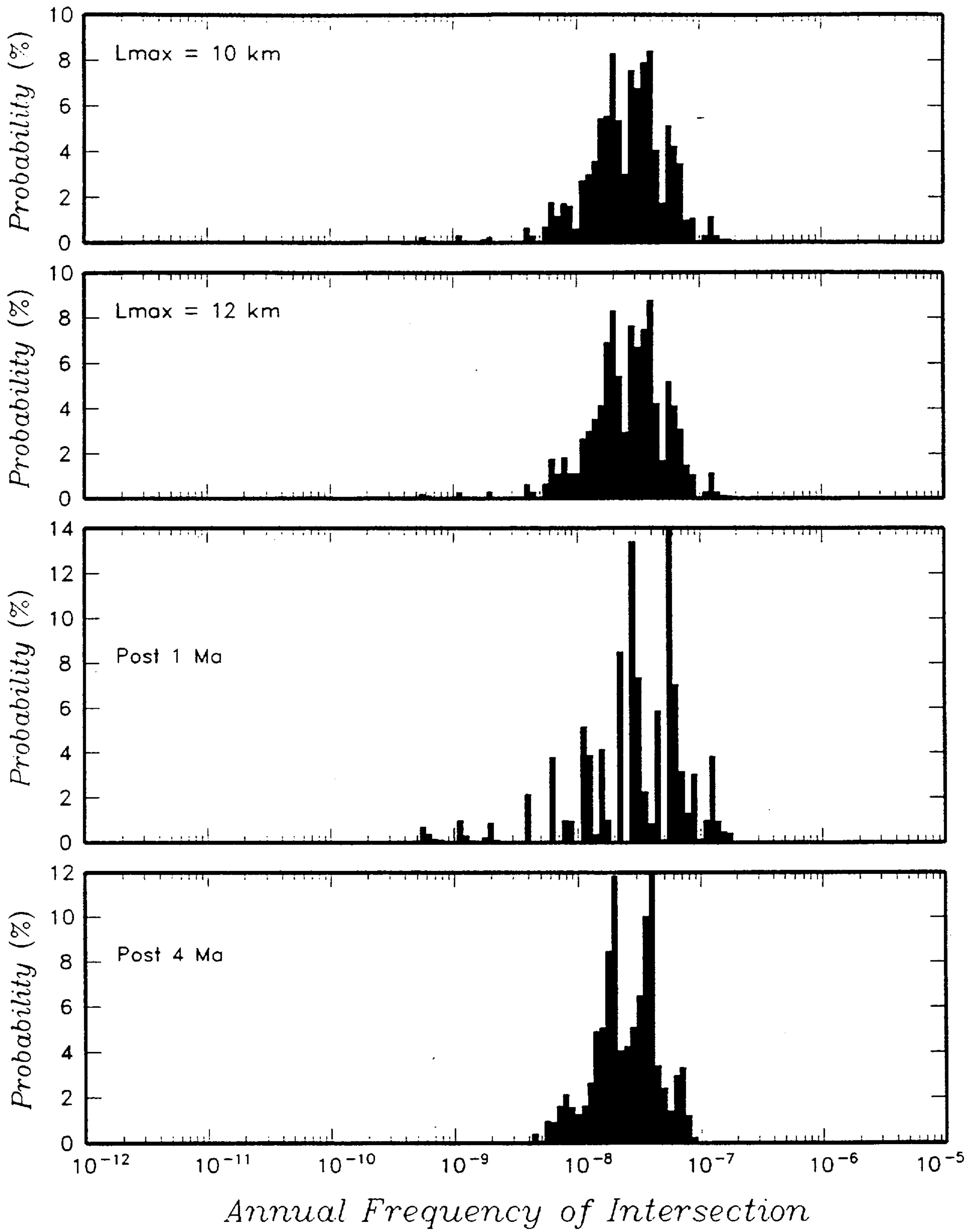
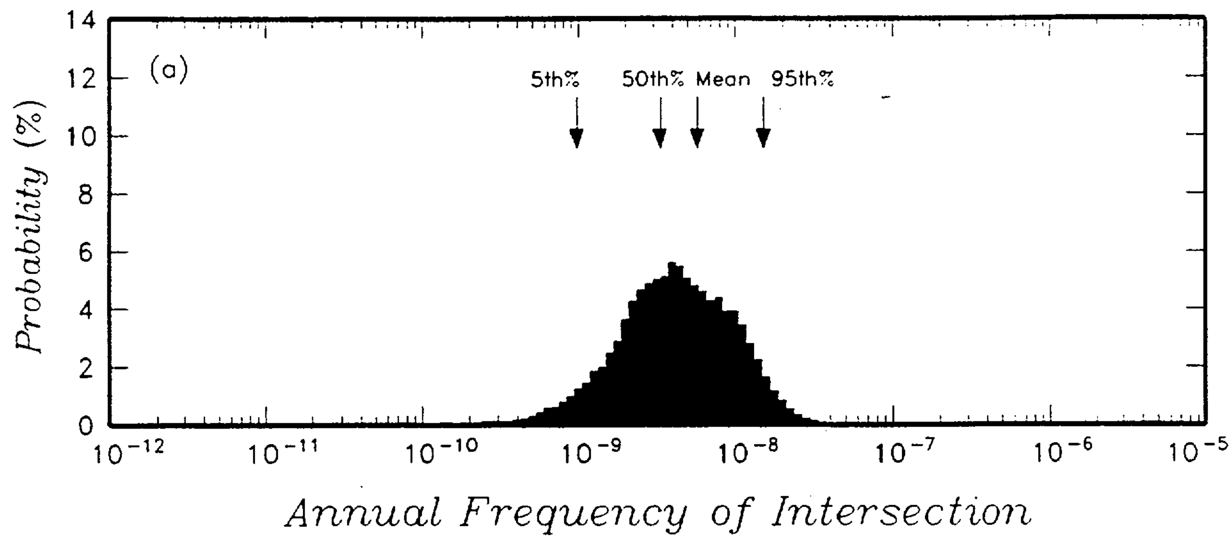


Figure 4-8 Effect of choice of maximum dike length and time period of interest on computed hazard distribution for George Thompson's PVHA model.



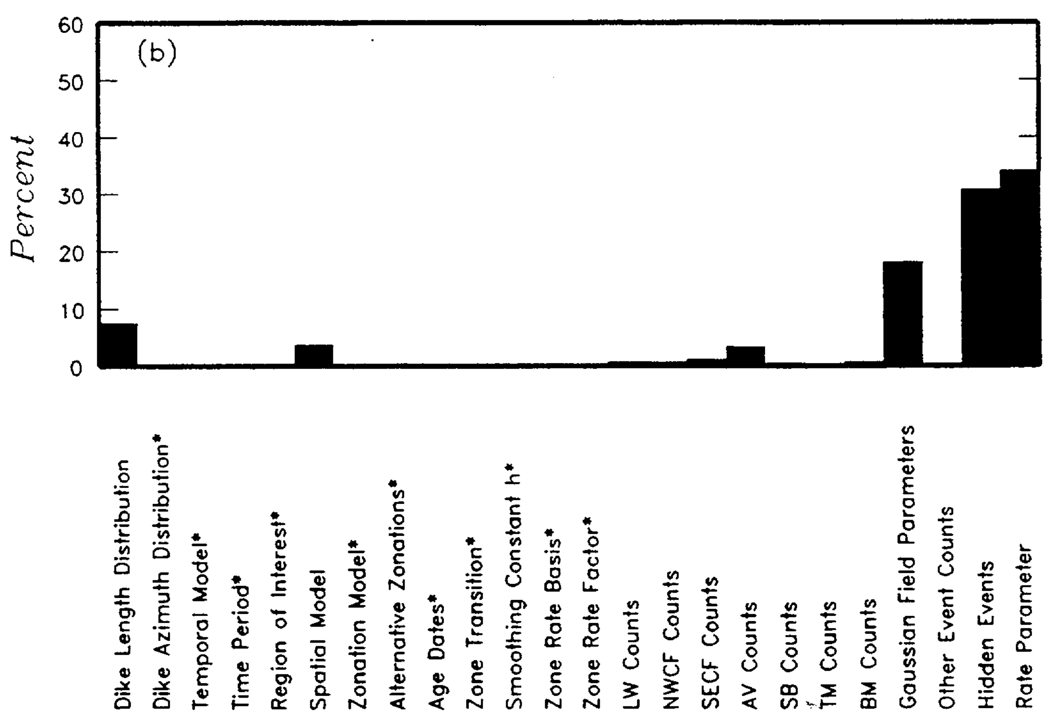


Figure 4-9 PVHA results obtained using George Walker's PVHA model. (a) Distribution for annual frequency of exceedance. (b) Relative contribution of uncertainty in various components of the PVHA model to the total variance in annual frequency of intersection. Components marked with a * were not treated as uncertain.

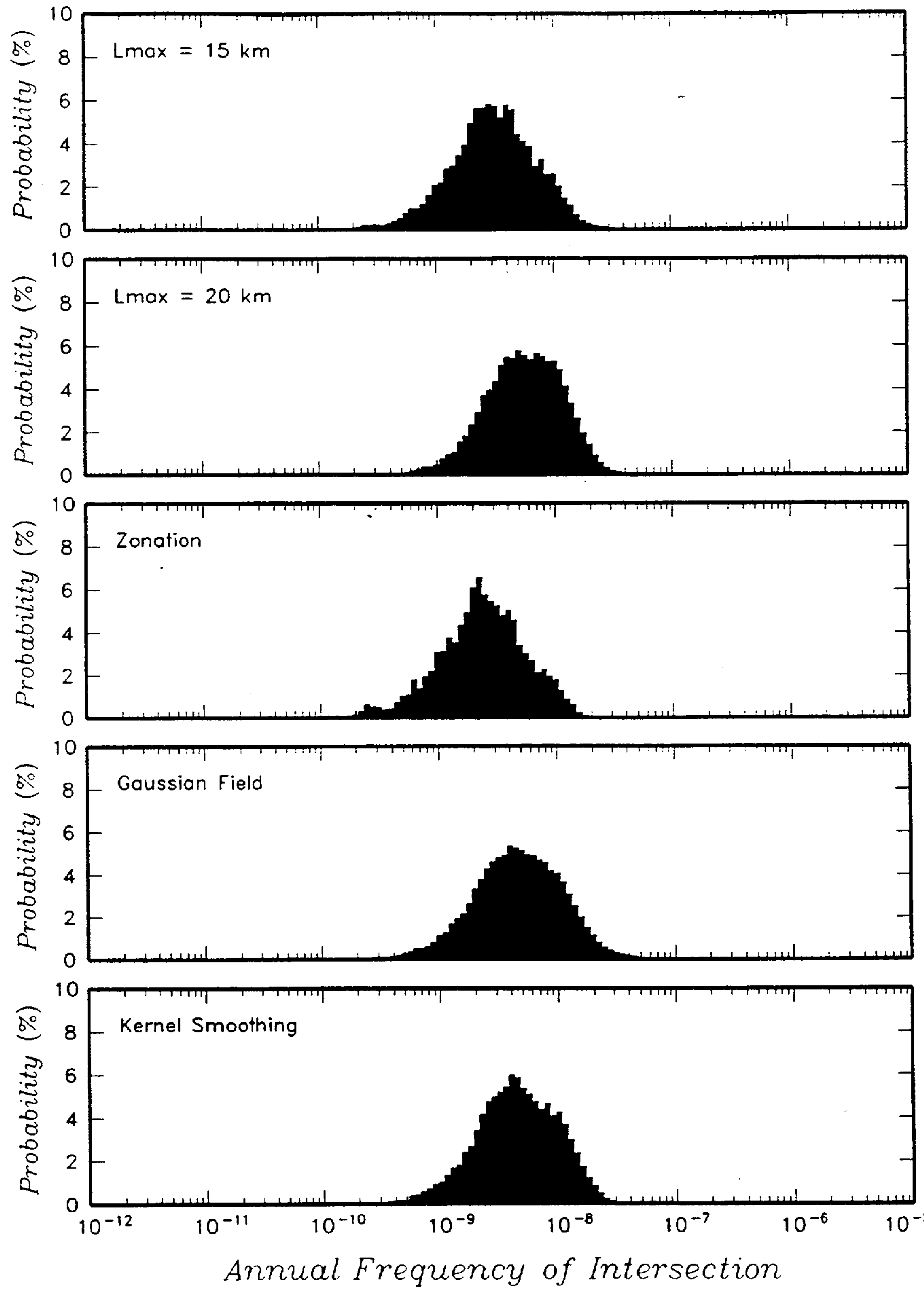


Figure 4-10 Effect of choice of maximum dike length and spatial model on computed hazard distribution for George Walker's PVHA model.

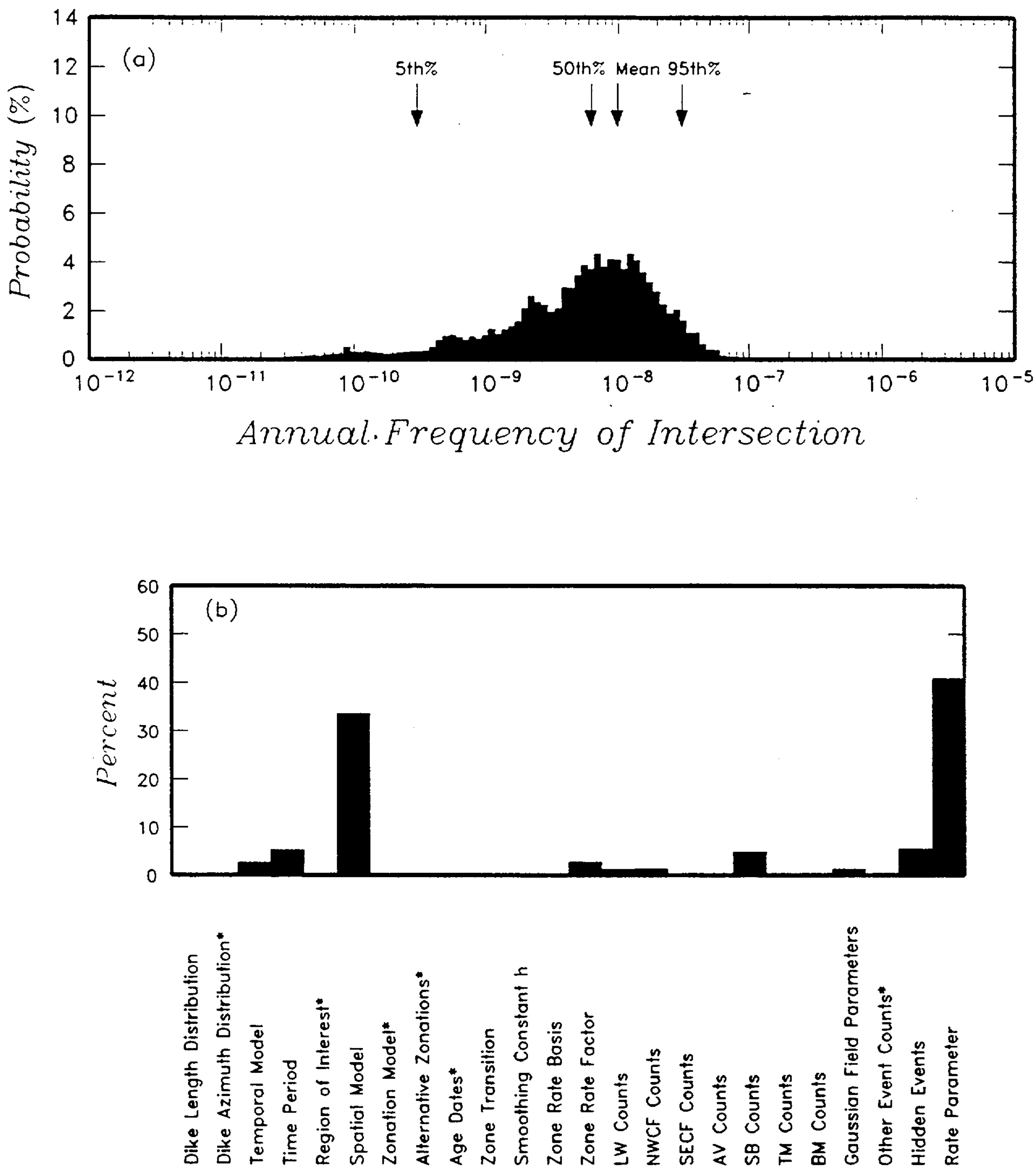


Figure 4-11 PVHA results obtained using Mel Kuntz's PVHA model. (a) Distribution for annual frequency of exceedance. (b) Relative contribution of uncertainty in various components of the PVHA model to the total variance in annual frequency of intersection. Components marked with a * were not treated as uncertain.

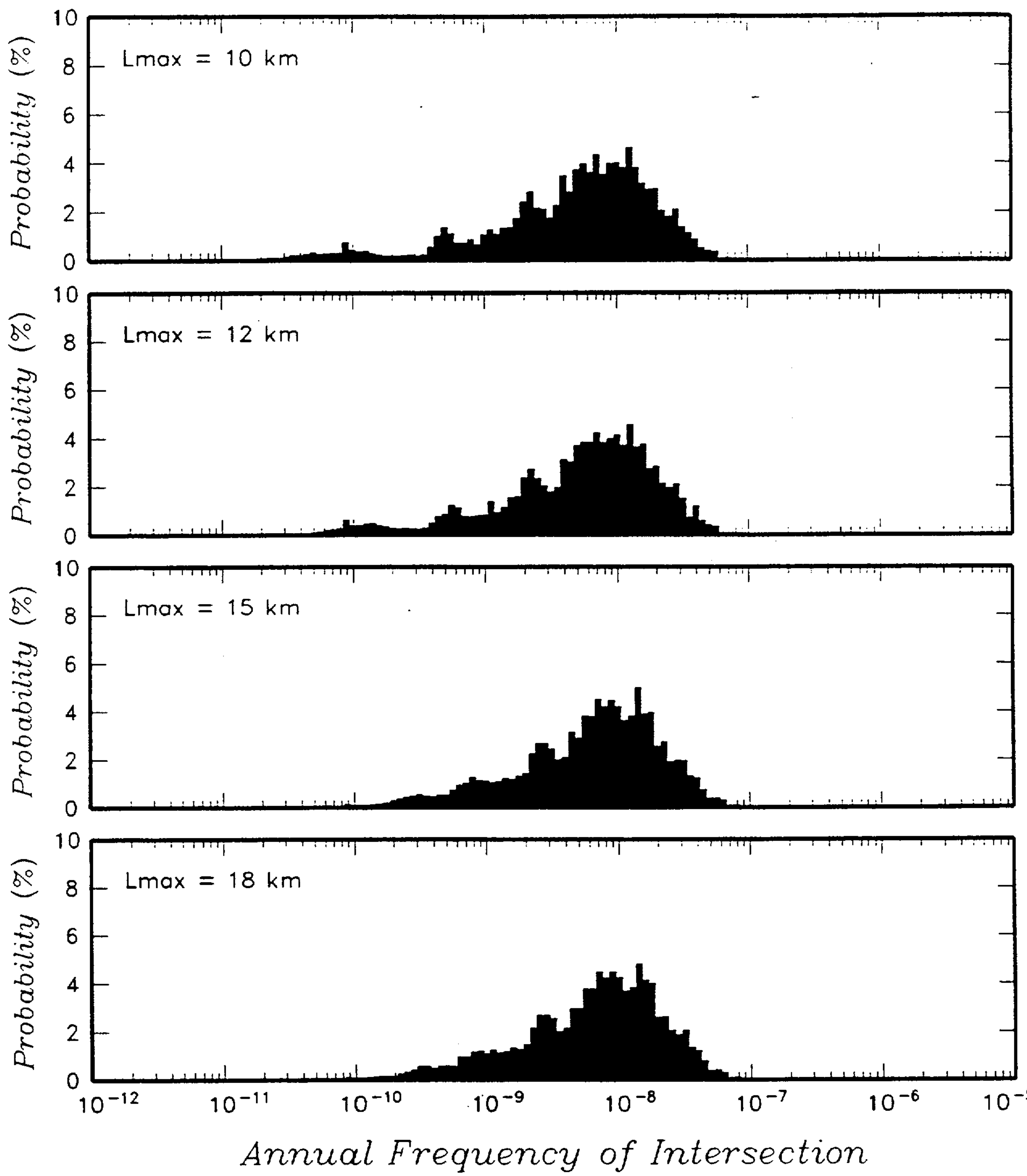


Figure 4-12 Effect of choice of maximum dike length on computed hazard distribution for Mel Kuntz's PVHA model.

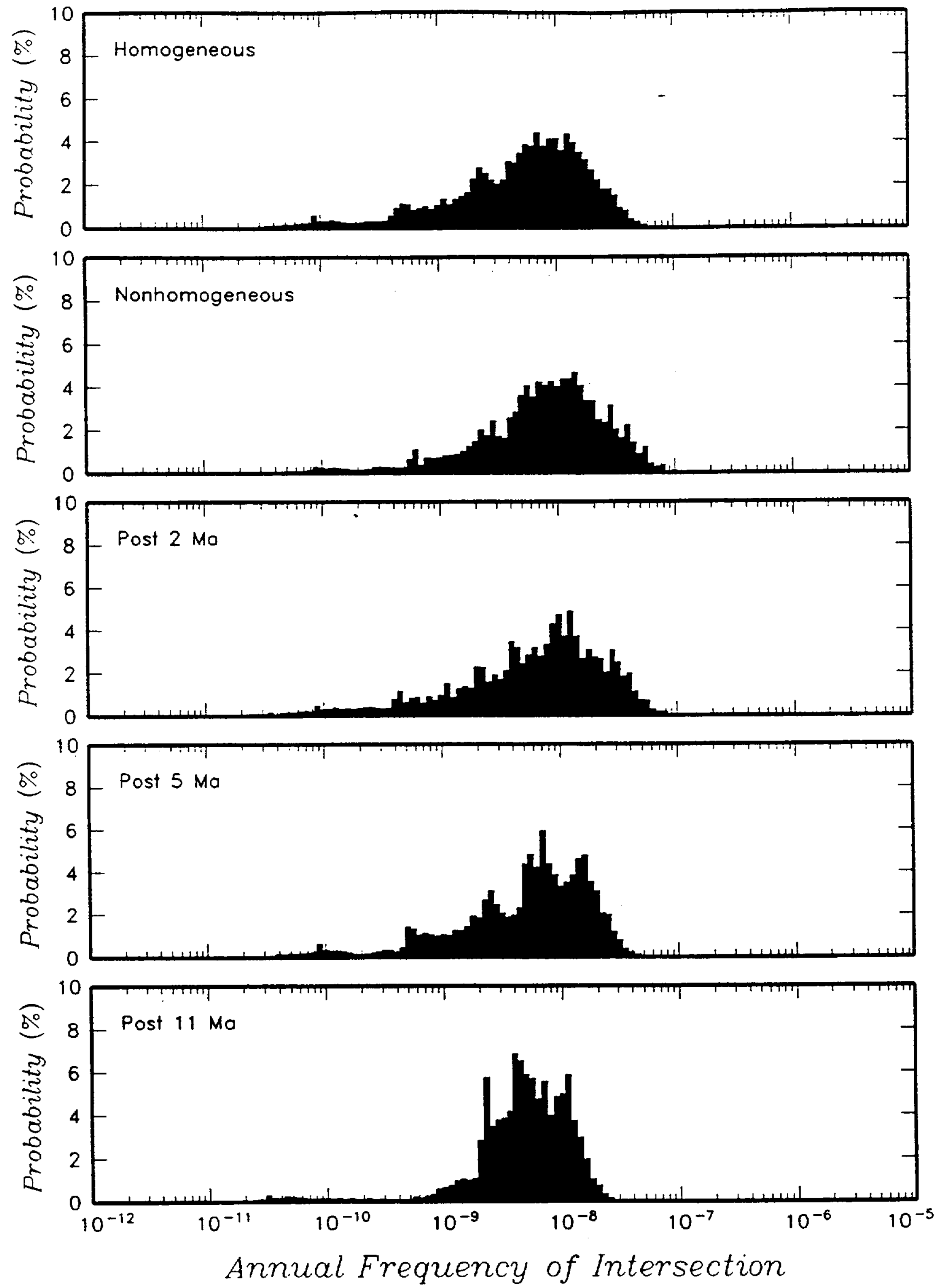


Figure 4-13 Effect of choice of temporal model and time period of interest on computed hazard distribution for Mel Kuntz's PVHA model.

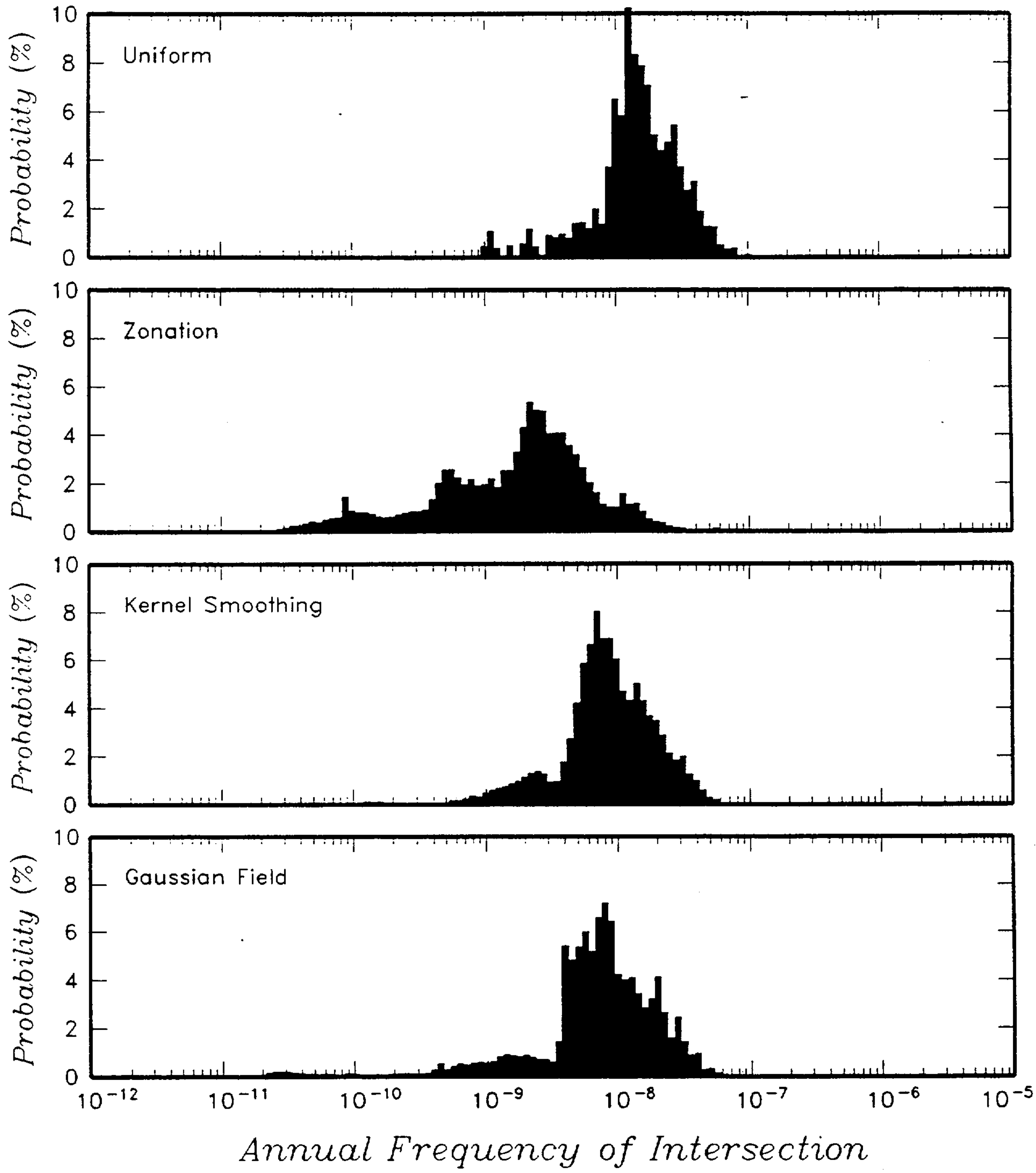


Figure 4-14 Effect of choice of spatial model on computed hazard distribution for Mel Kuntz's PVHA model.

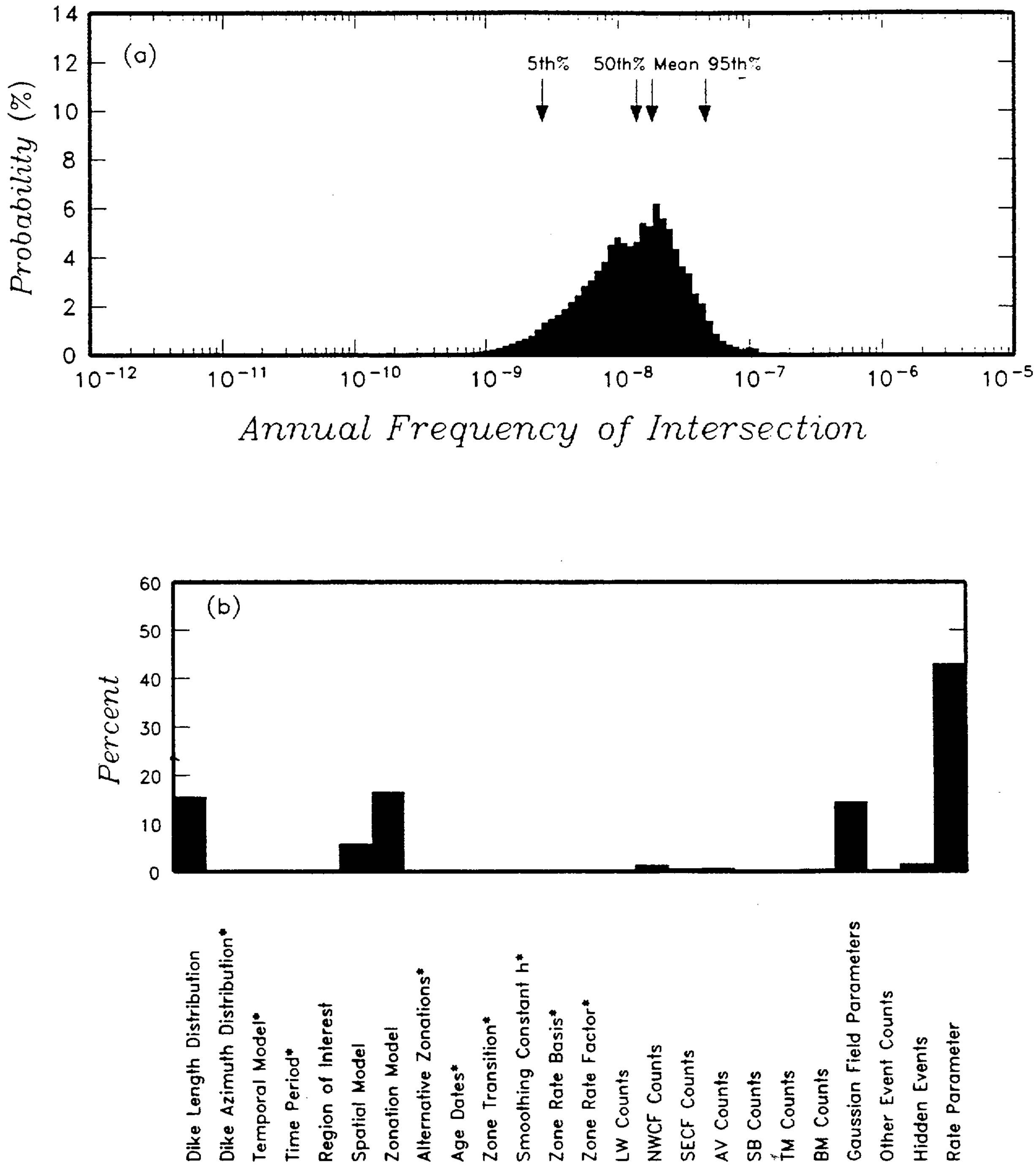


Figure 4-15 PVHA results obtained using Michael Sheridan's PVHA model. (a) Distribution for annual frequency of exceedance. (b) Relative contribution of uncertainty in various components of the PVHA model to the total variance in annual frequency of intersection. Components marked with a * were not treated as uncertain.

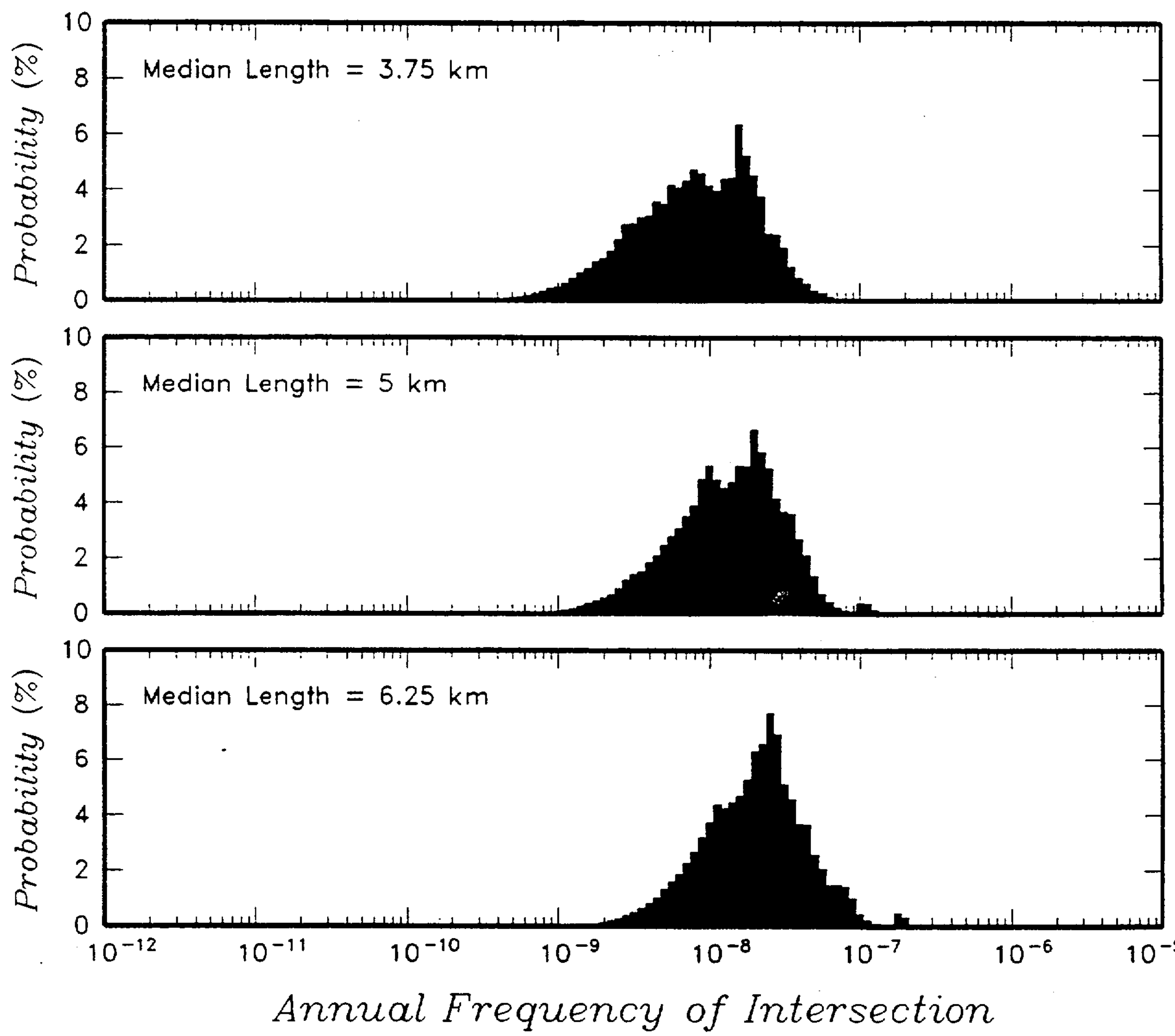


Figure 4-16 Effect of choice of median dike length on computed hazard distribution for Michael Sheridan's PVHA model.

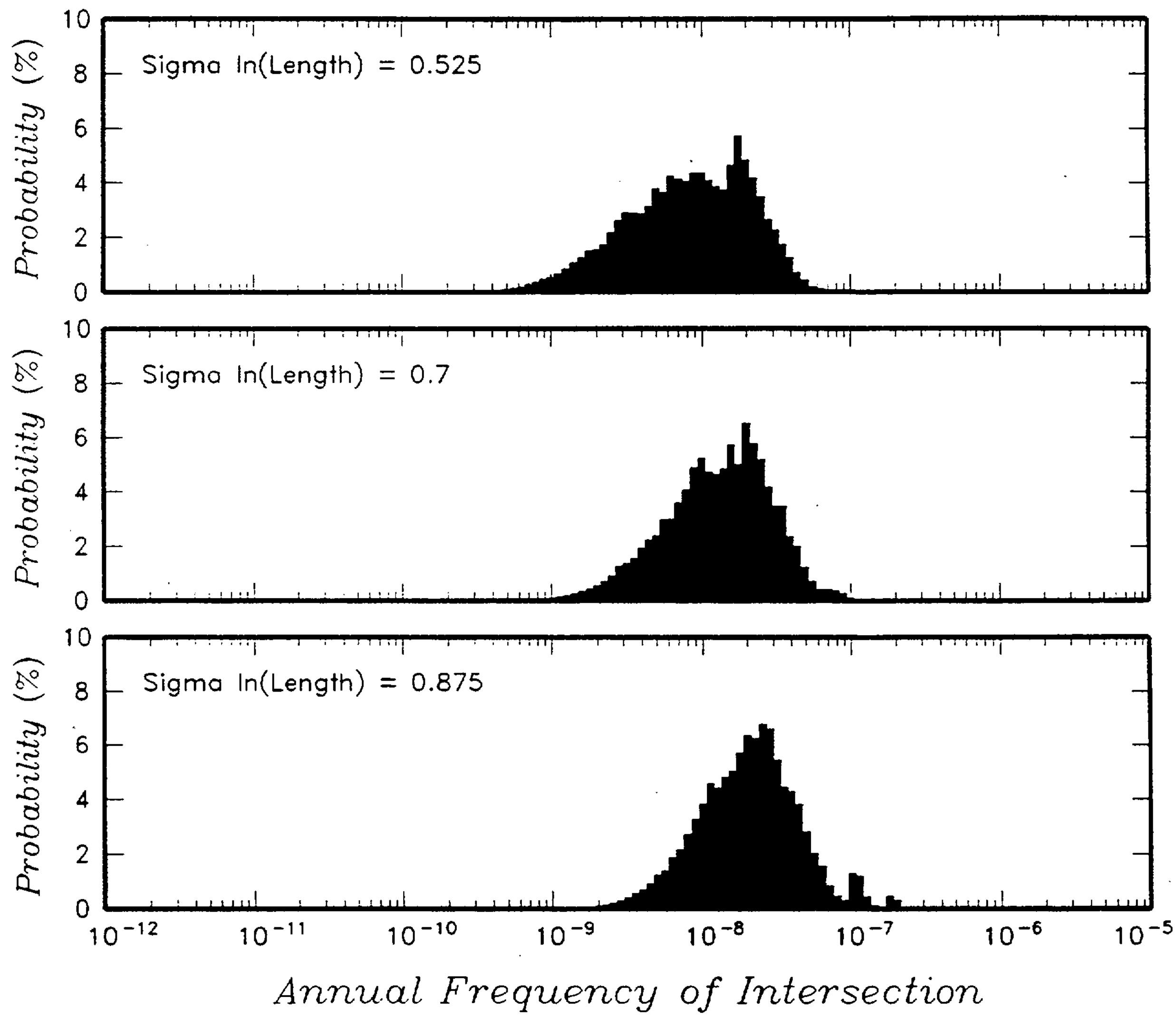


Figure 4-17 Effect of choice of standard error on ln(dike length) on computed hazard distribution for Michael Sheridan's PVHA model.

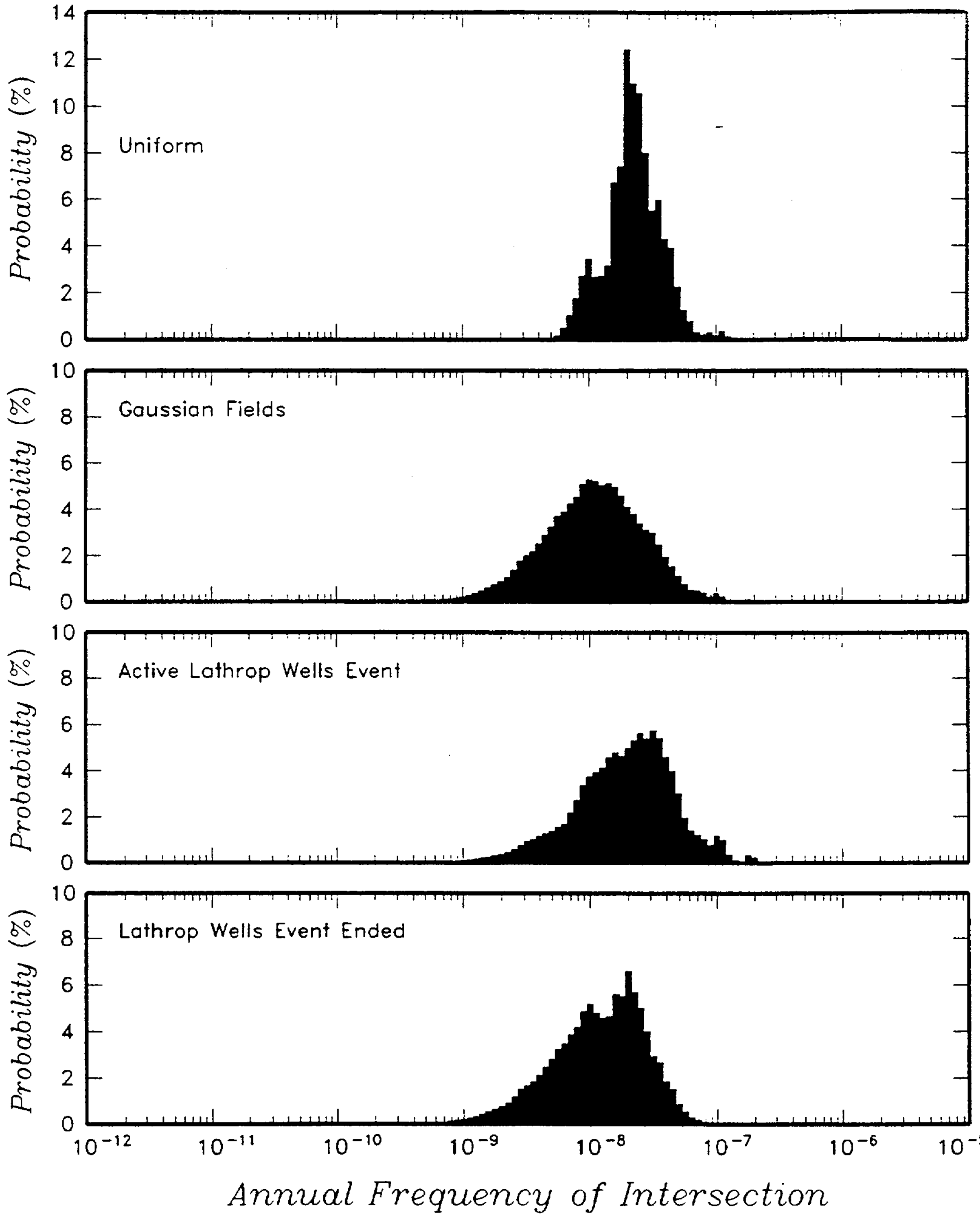


Figure 4-18 Effect of choice of spatial model and activity of Lathrop Wells event on computed hazard distribution for Michael Sheridan's PVHA model.

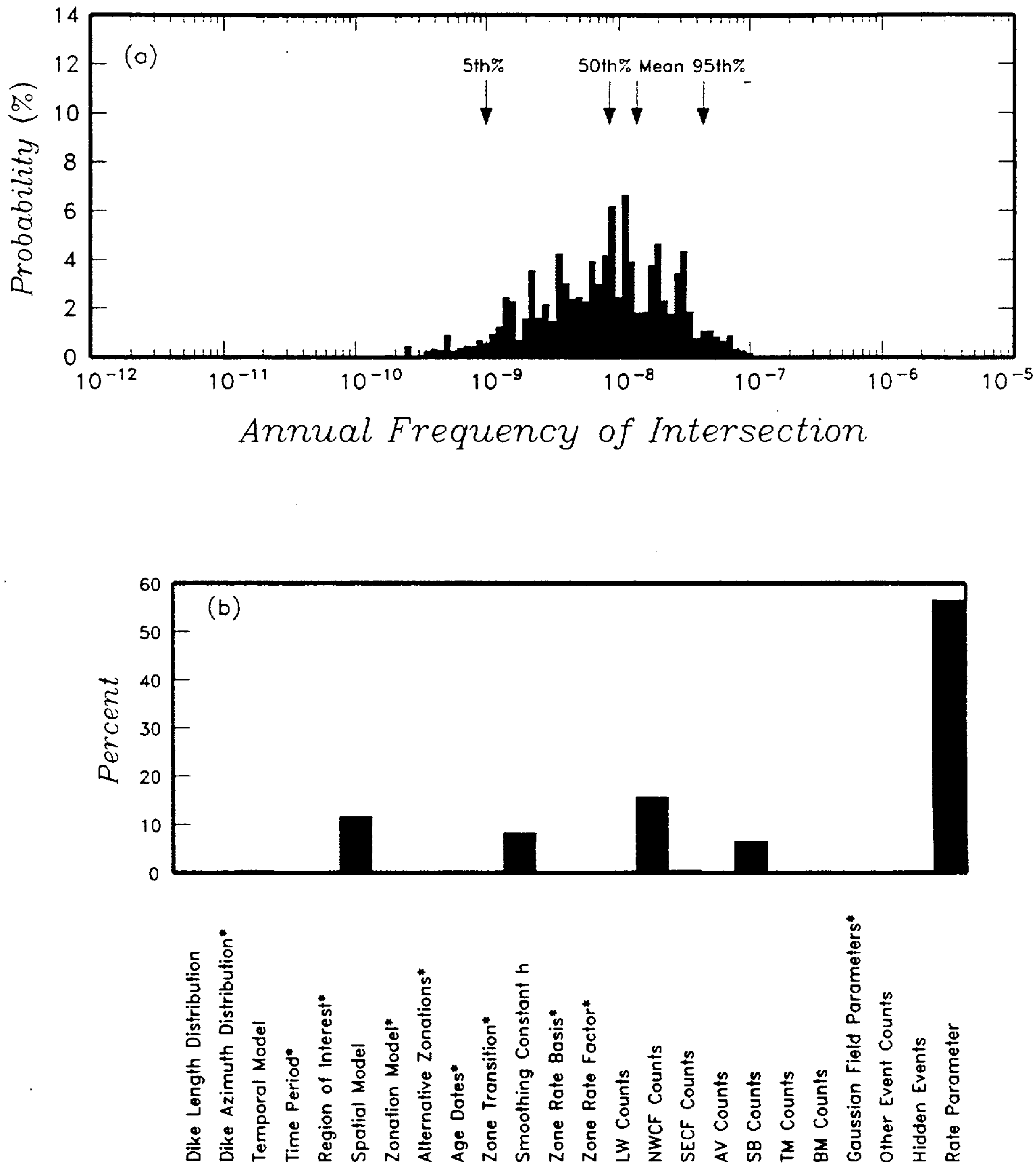


Figure 4-19 PVHA results obtained using Richard Carlson's PVHA model. (a) Distribution for annual frequency of exceedance. (b) Relative contribution of uncertainty in various components of the PVHA model to the total variance in annual frequency of intersection. Components marked with a * were not treated as uncertain.

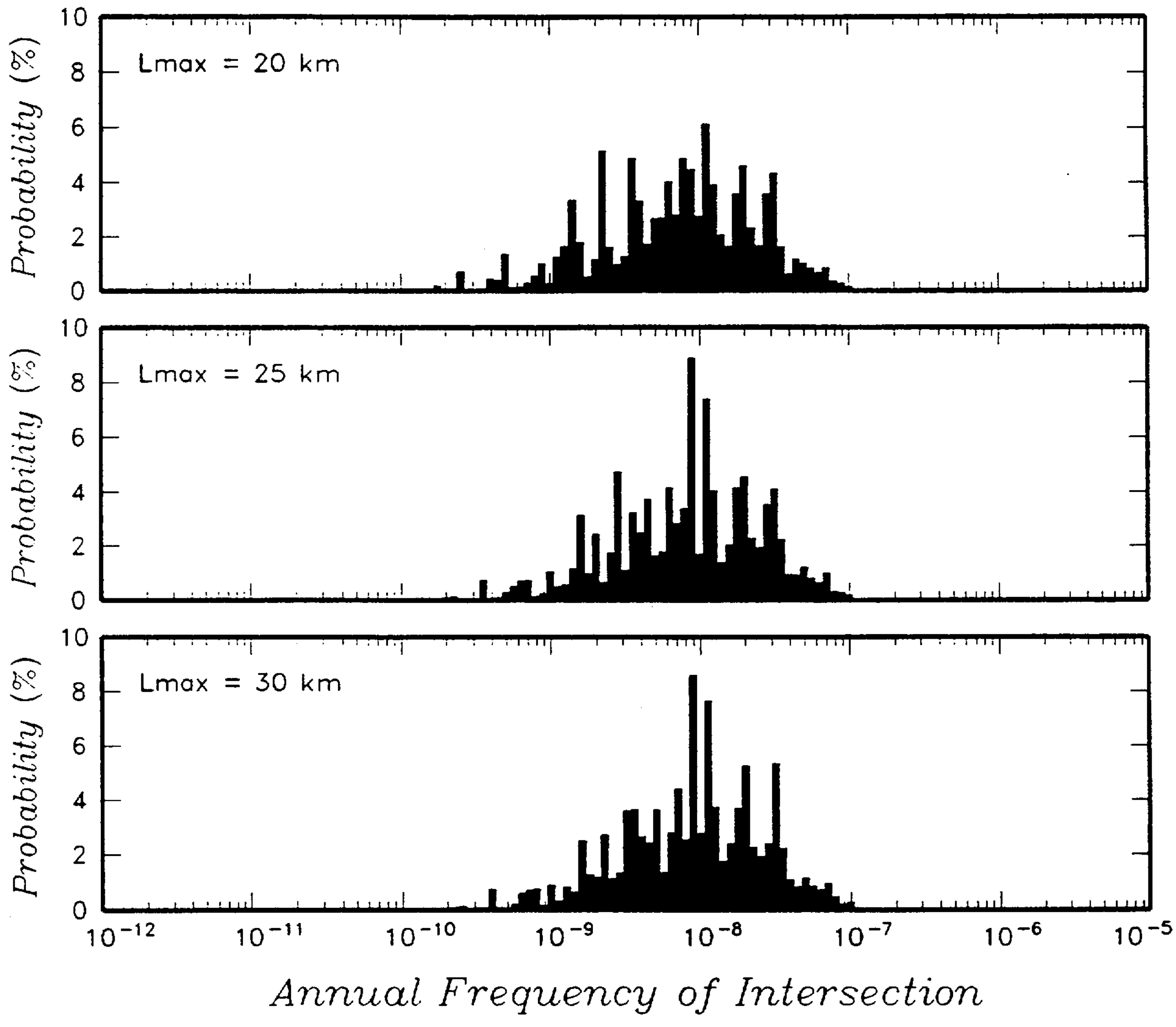


Figure 4-20 Effect of choice of maximum dike length on computed hazard distribution for Richard Carlson's PVHA model.

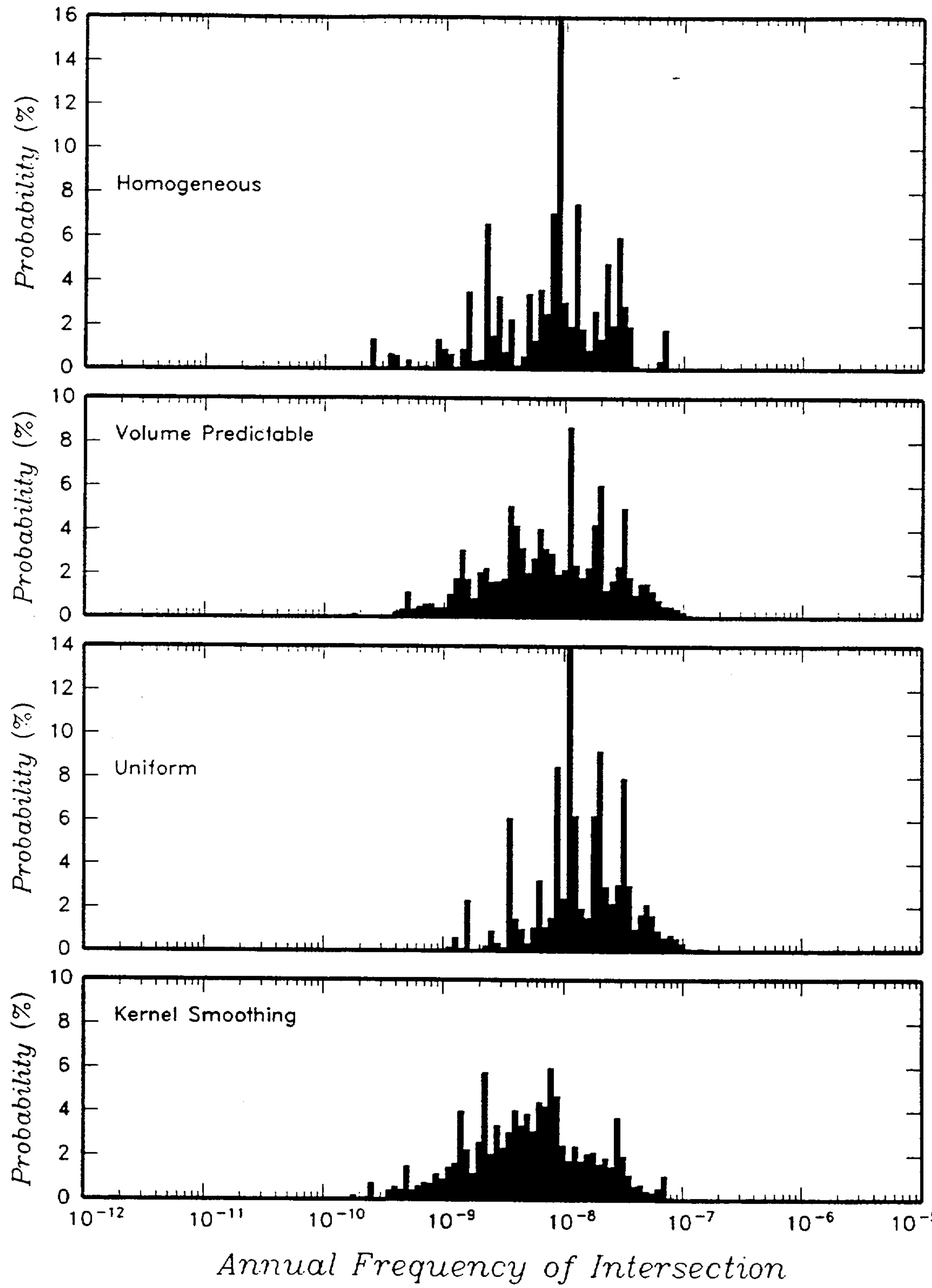


Figure 4-21 Effect of choice of temporal and spatial models on computed hazard distribution for Richard Carlson's PVHA model.

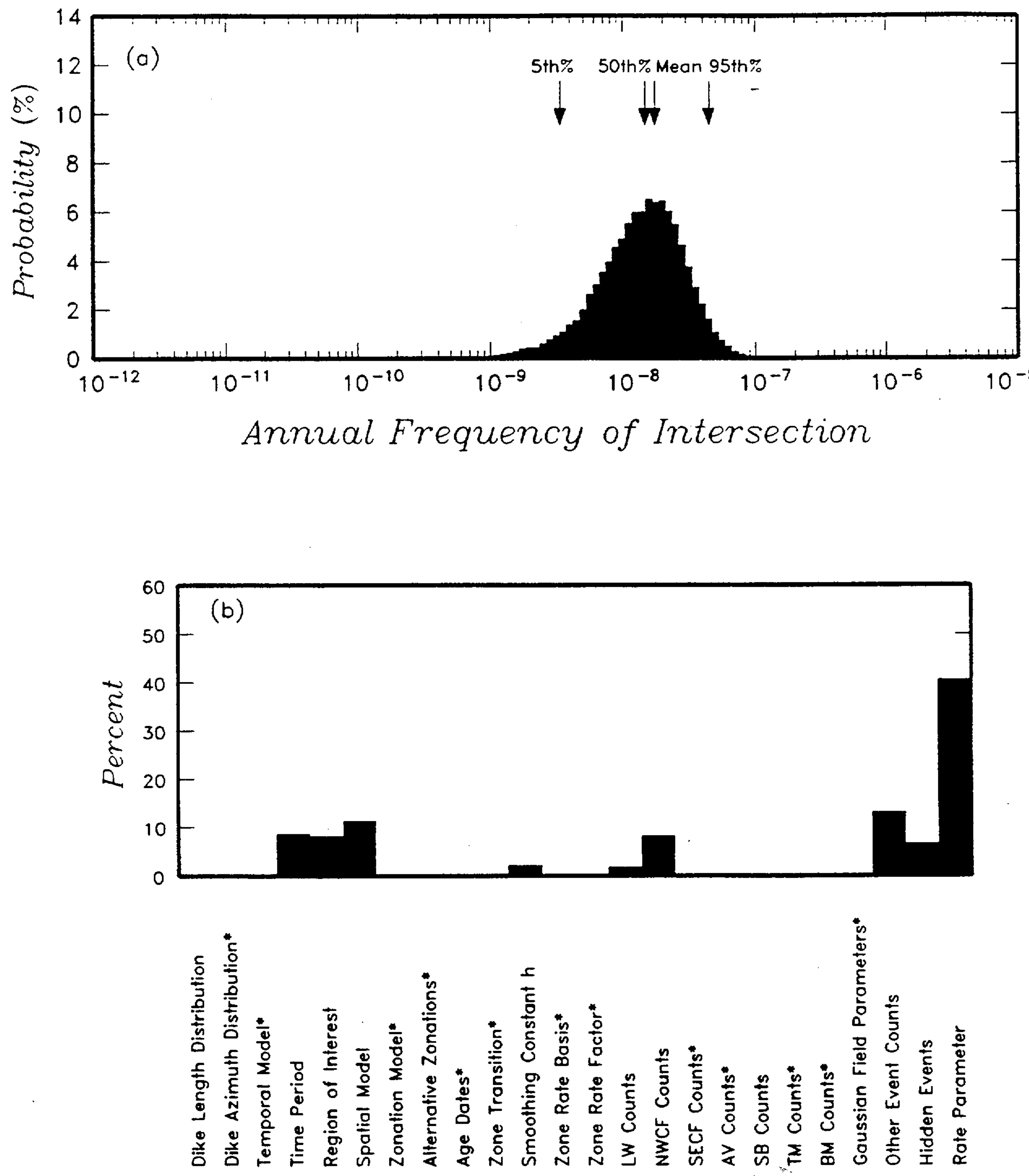


Figure 4-22 PVHA results obtained using Richard Fisher's PVHA model. (a) Distribution for annual frequency of exceedance. (b) Relative contribution of uncertainty in various components of the PVHA model to the total variance in annual frequency of intersection. Components marked with a * were not treated as uncertain.

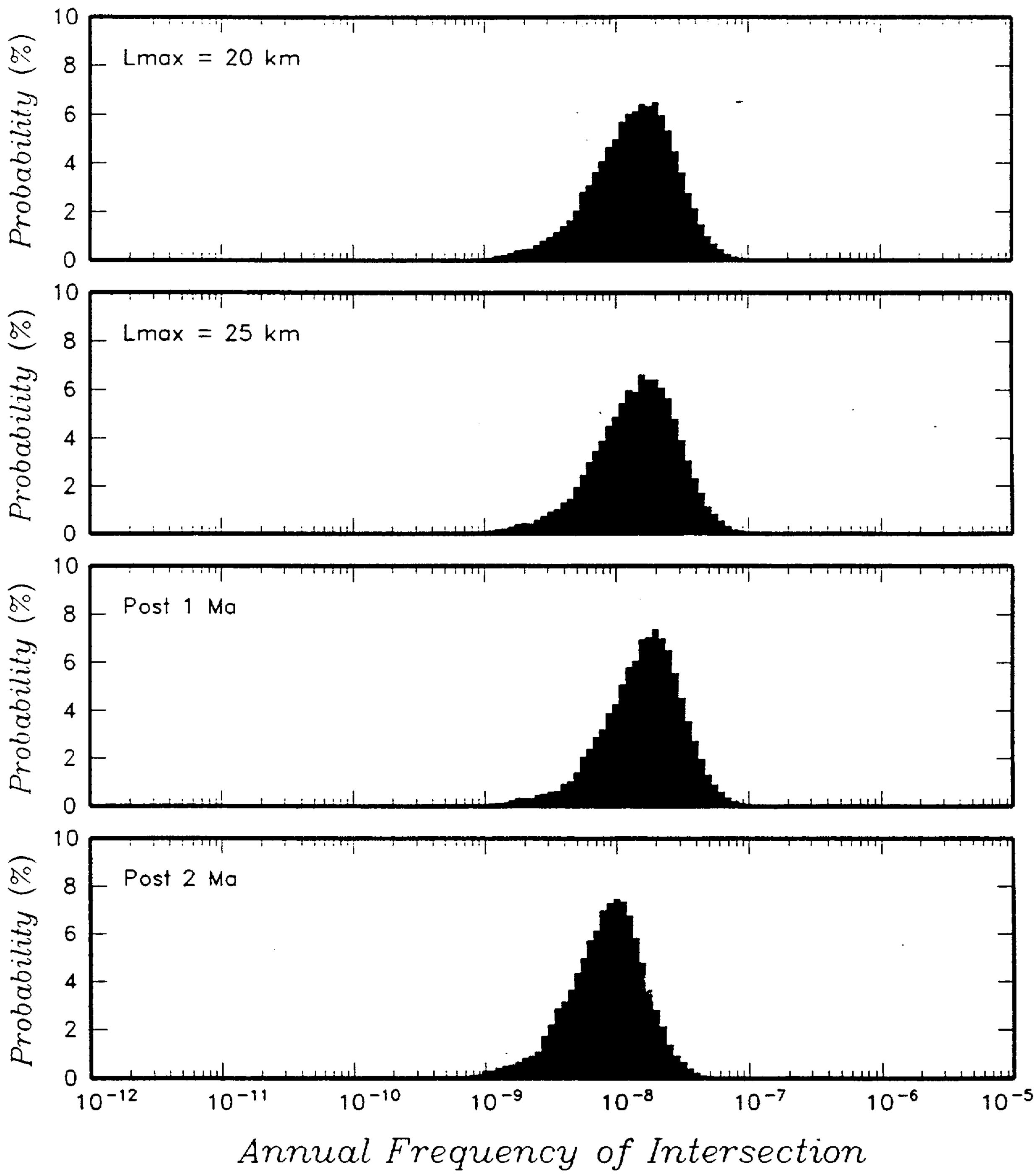


Figure 4-23 Effect of choice of maximum dike length and time period of interest on computed hazard distribution for Richard Fisher's PVHA model.

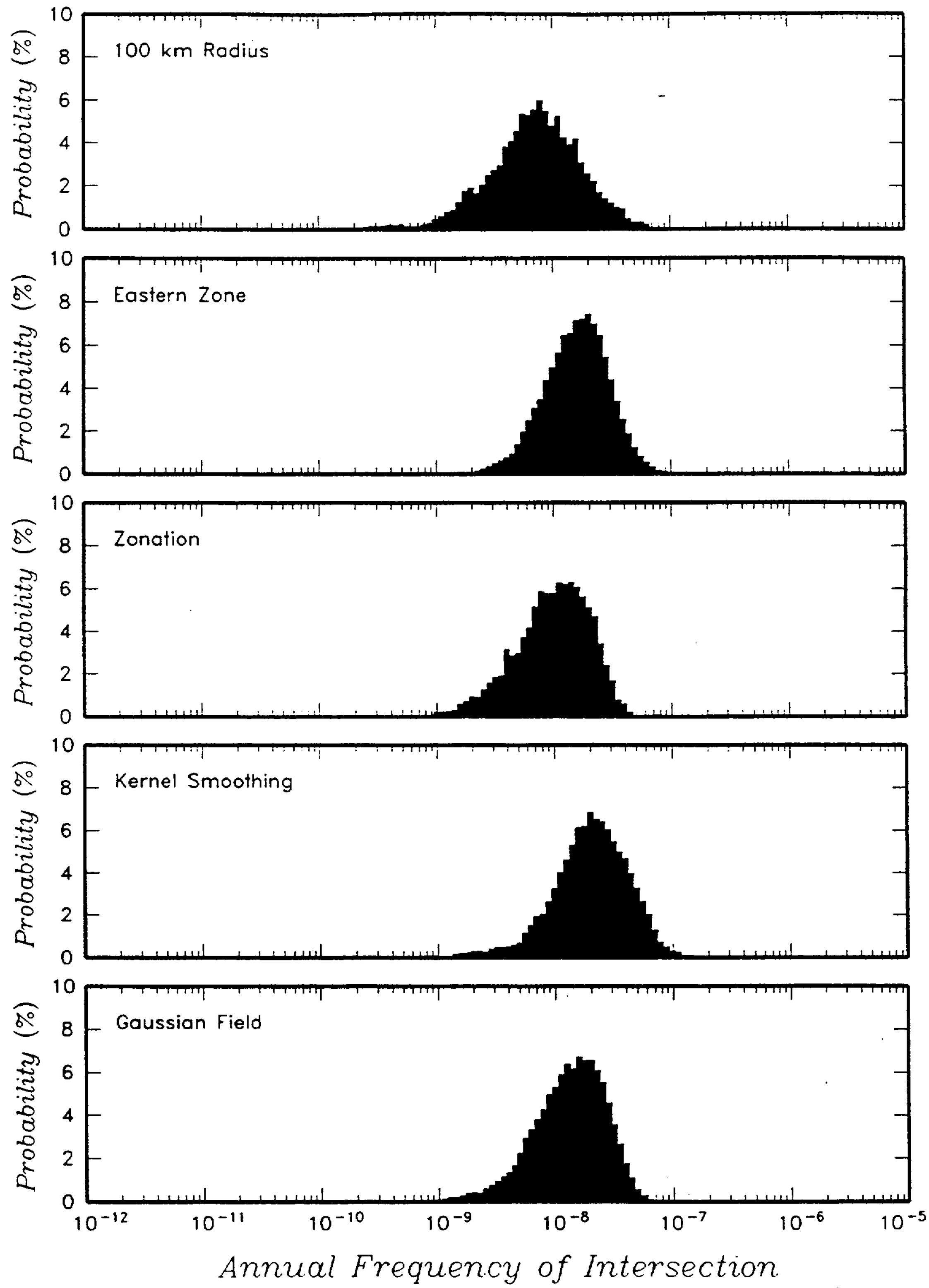
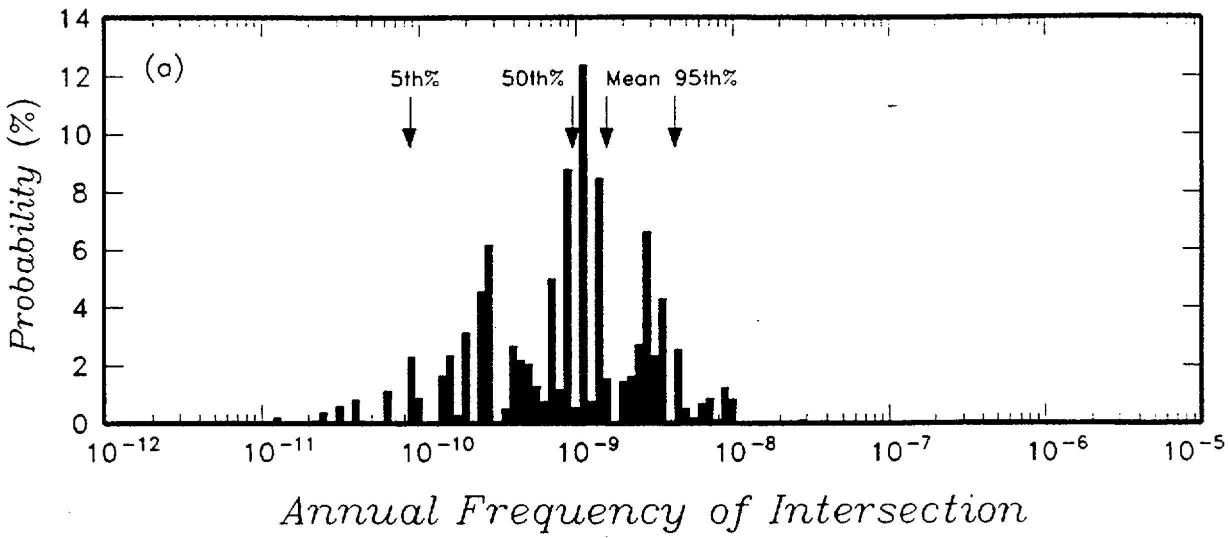


Figure 4-24 Effect of choice of region of interest and spatial model on computed hazard distribution for Richard Fisher's PVHA model.



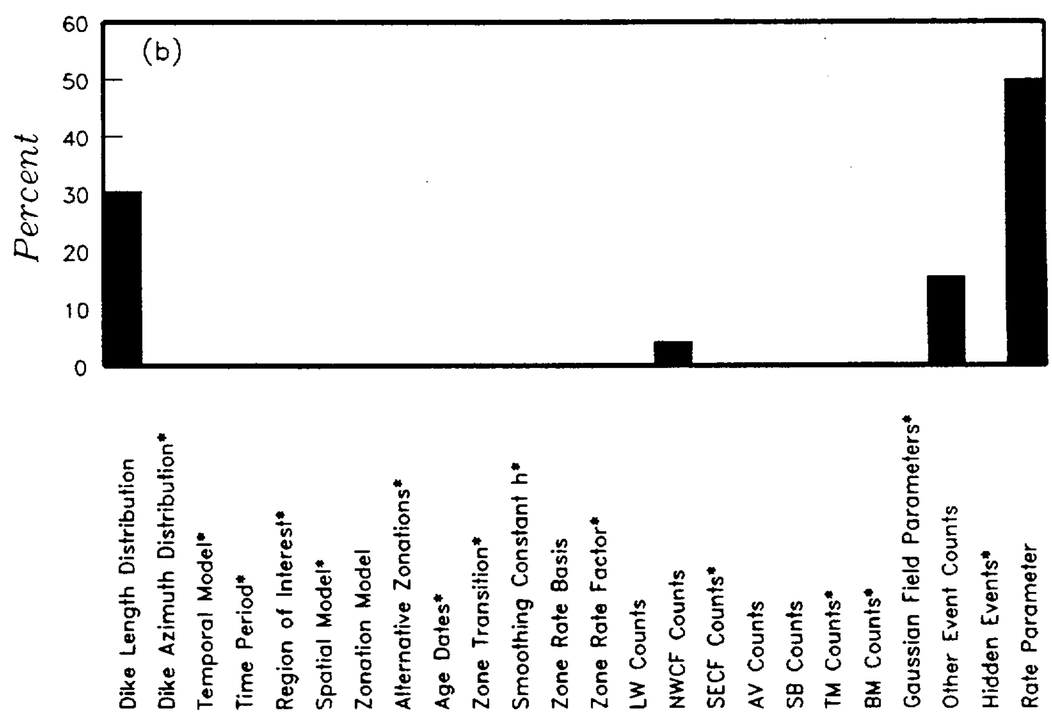


Figure 4-25 PVHA results obtained using Wendell Duffield's PVHA model. (a) Distribution for annual frequency of exceedance. (b) Relative contribution of uncertainty in various components of the PVHA model to the total variance in annual frequency of intersection. Components marked with a * were not treated as uncertain.

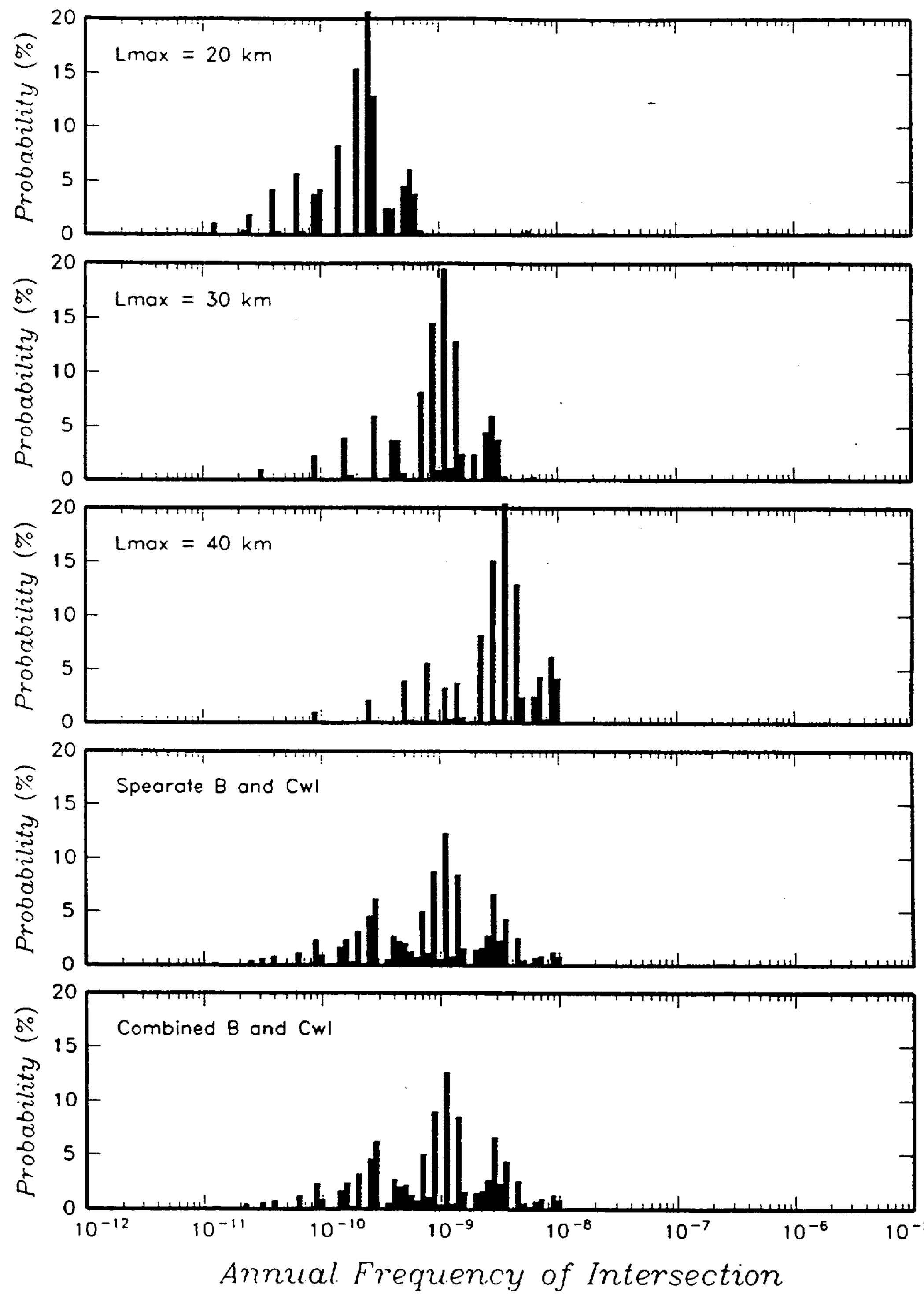


Figure 4-26 Effect of choice of maximum dike length and zonation model on computed hazard distribution for Wendell Duffield's PVHA model.

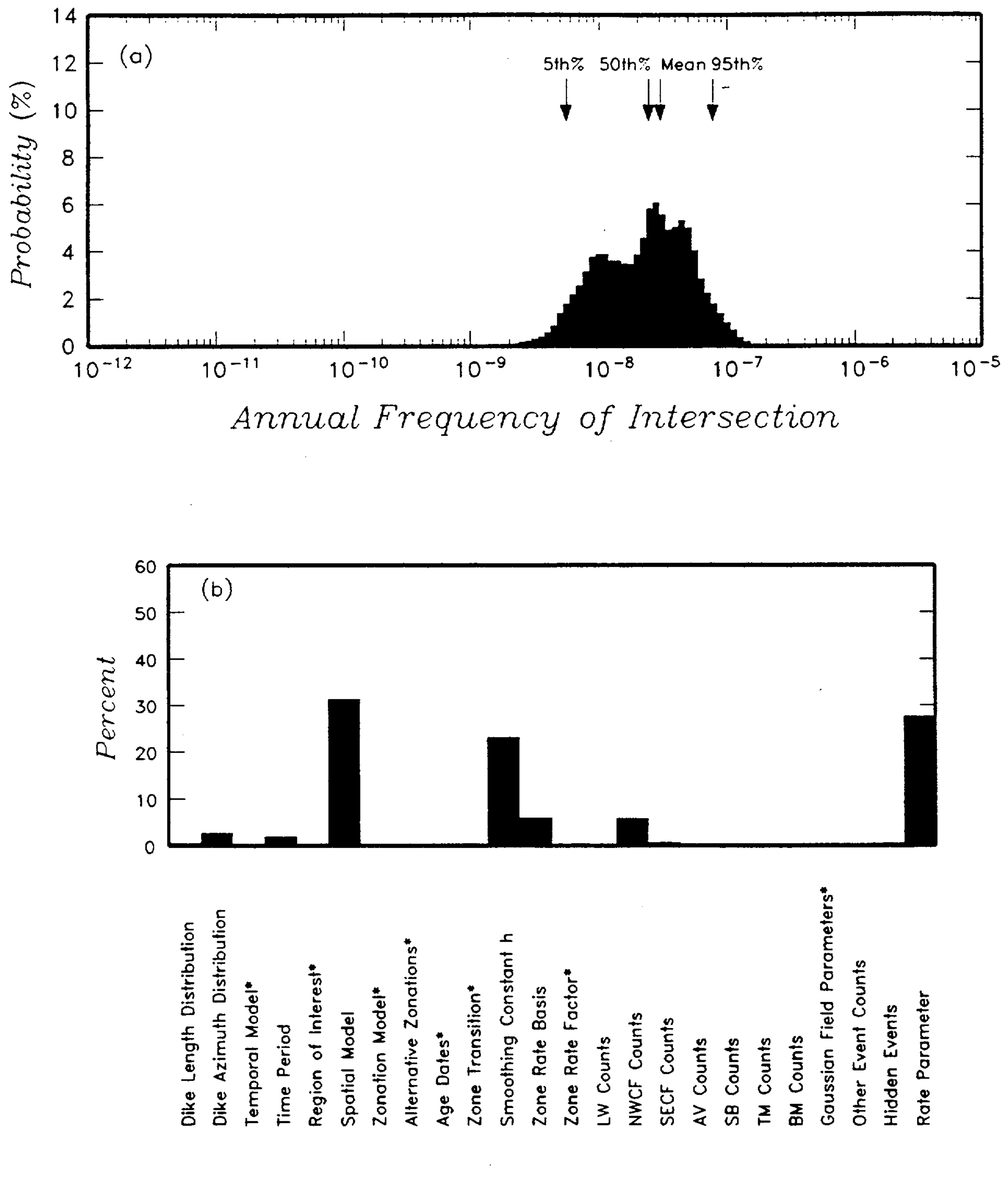


Figure 4-27 PVHA results obtained using William Hackett's PVHA model. (a) Distribution for annual frequency of exceedance. (b) Relative contribution of uncertainty in various components of the PVHA model to the total variance in annual frequency of intersection. Components marked with a * were not treated as uncertain.

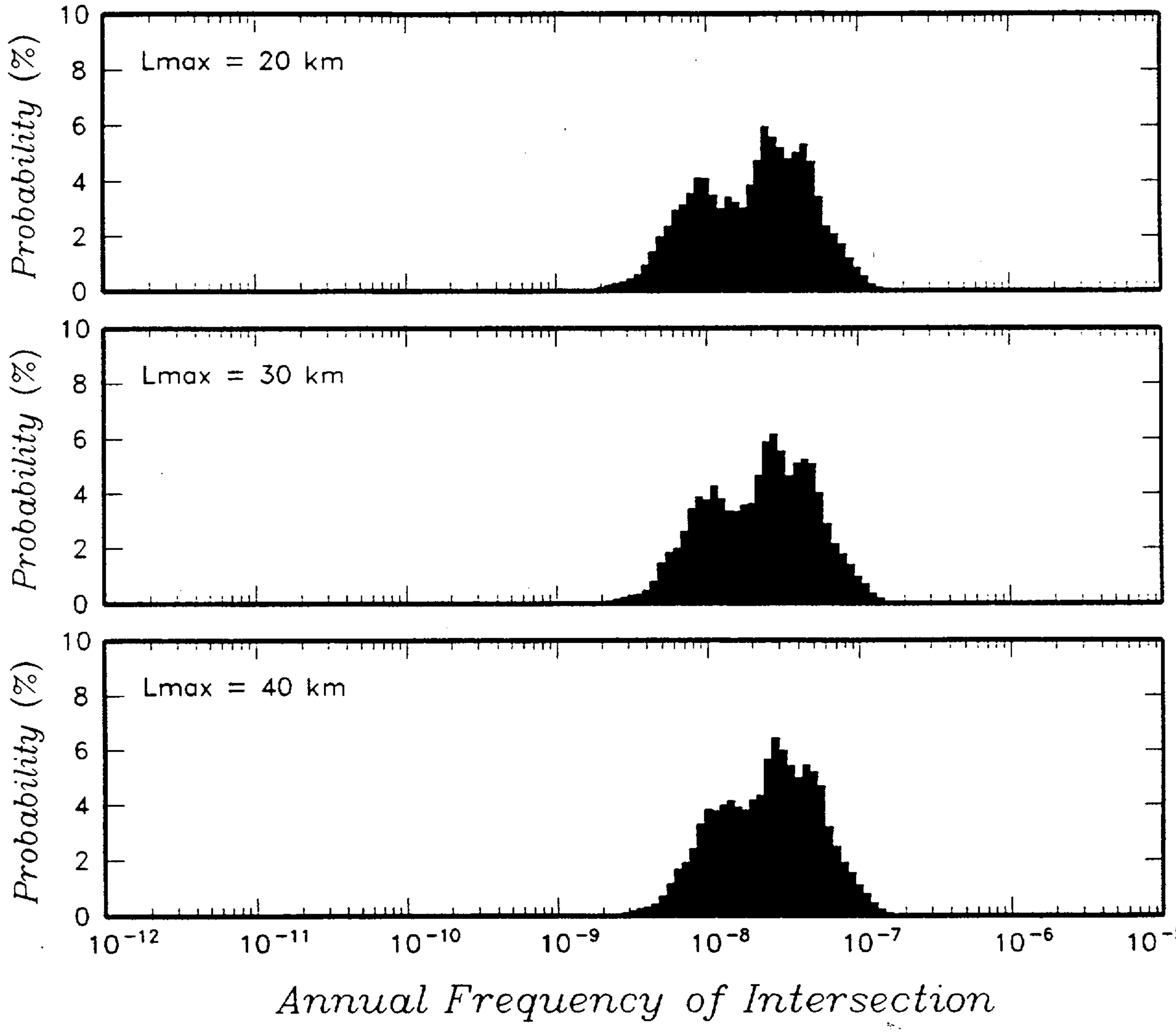


Figure 4-28 Effect of choice of maximum dike length on computed hazard distribution for William Hackett's PVHA model.

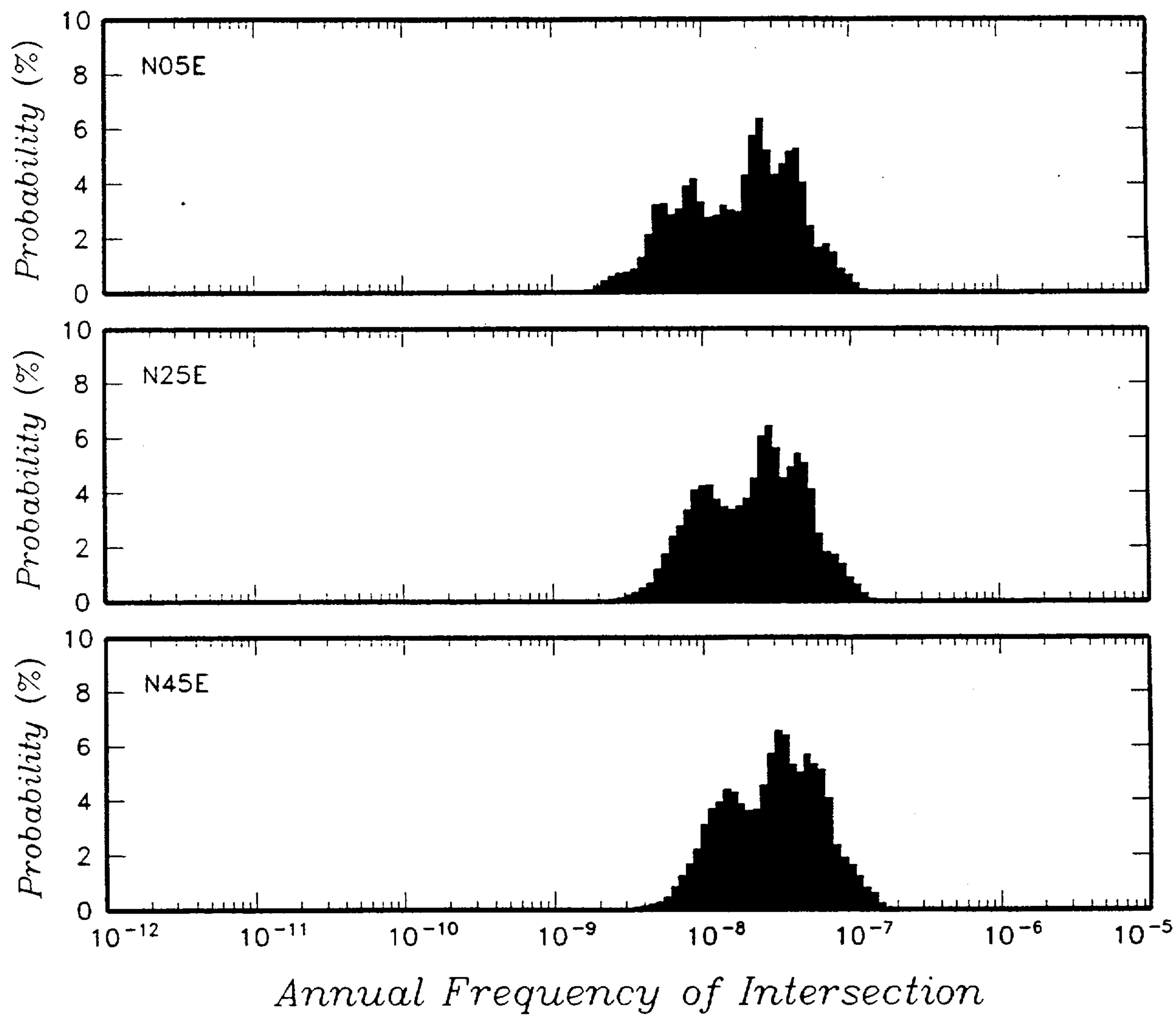


Figure 4-29 Effect of choice of mean dike azimuth on computed hazard distribution for William Hackett's PVHA model.

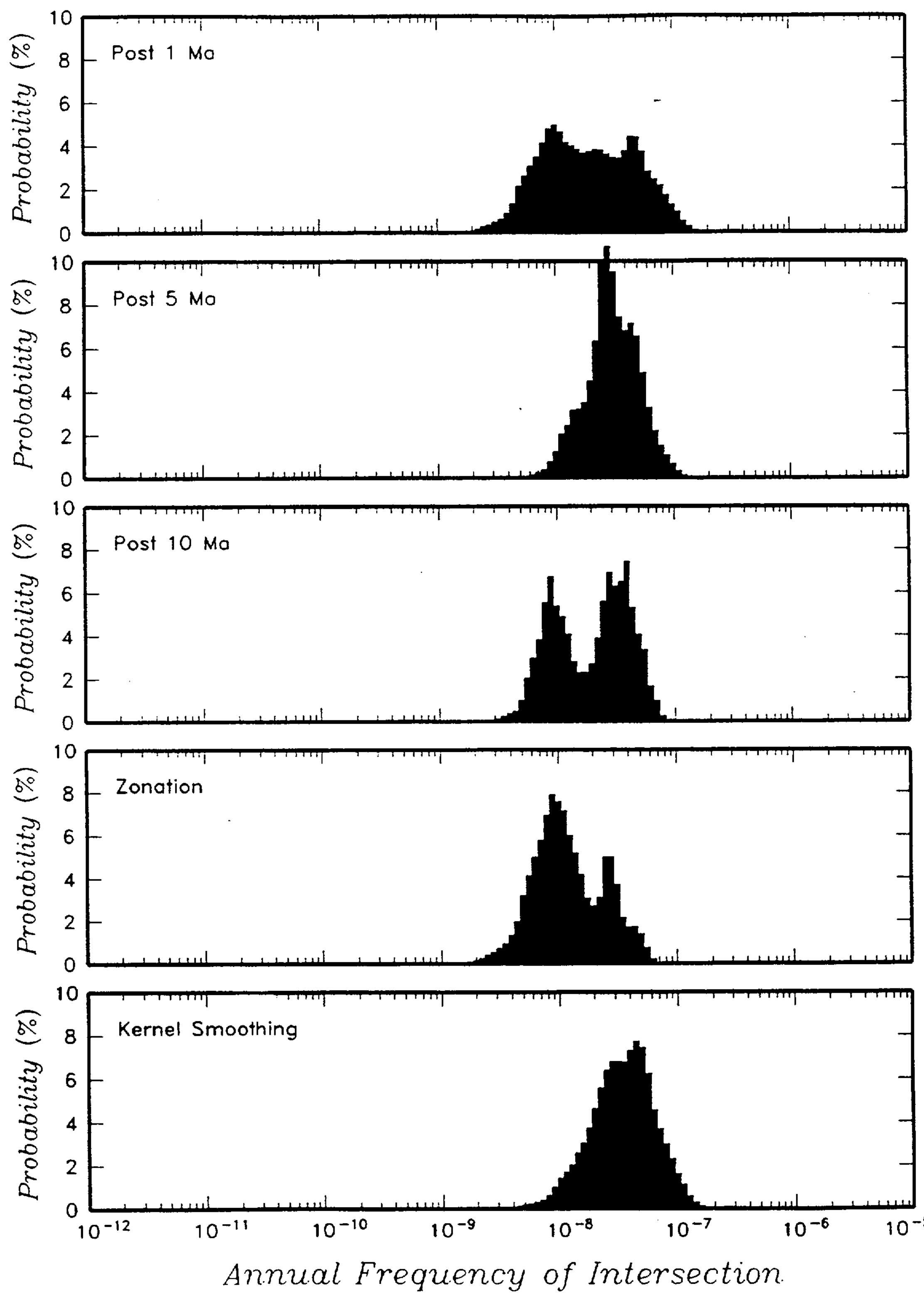


Figure 4-30 Effect of choice of and time period of interest and spatial model on computed hazard distribution for William Hackett's PVHA model.

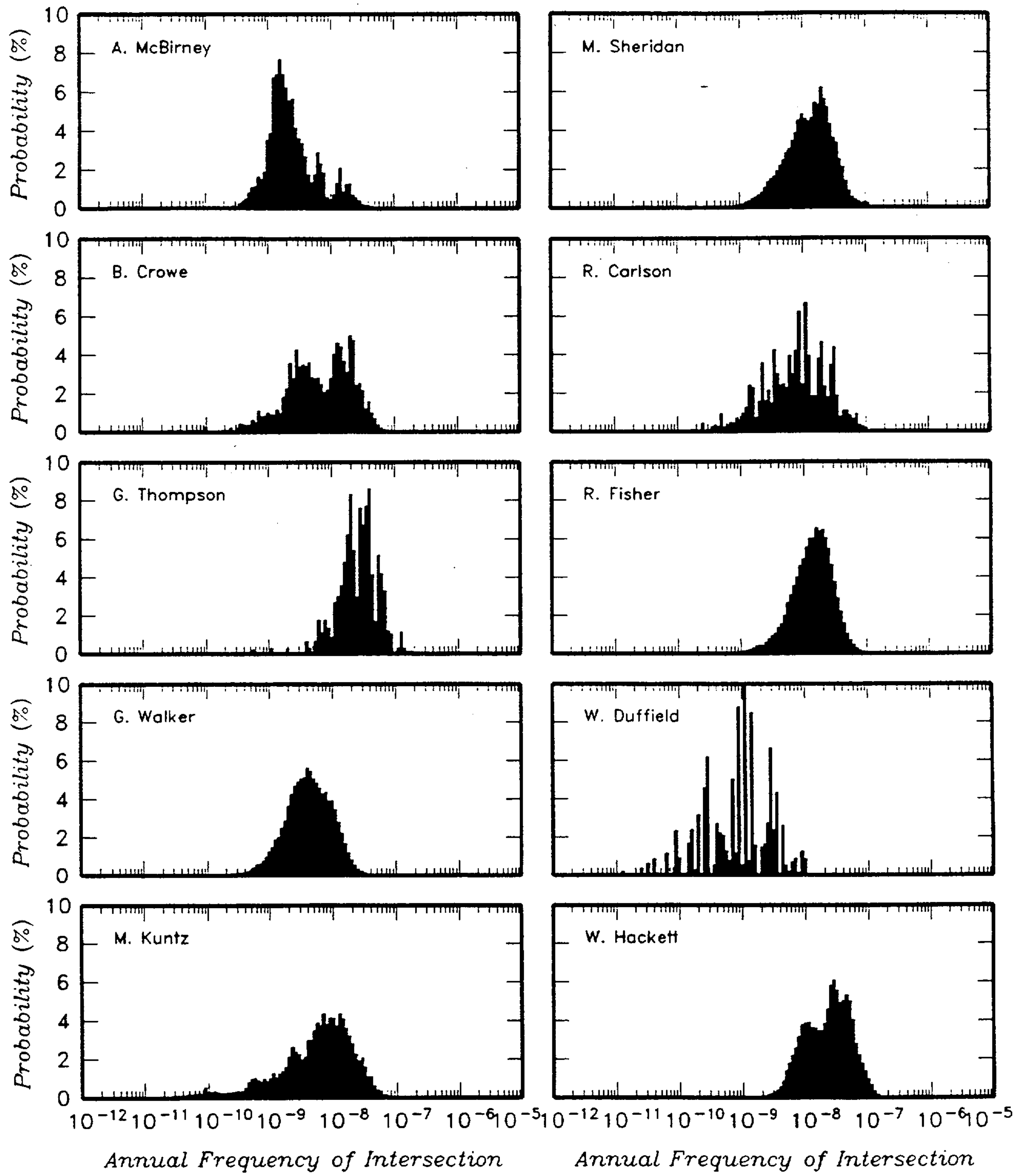


Figure 4-31 Comparison of individual expert distributions for frequency of intersection.

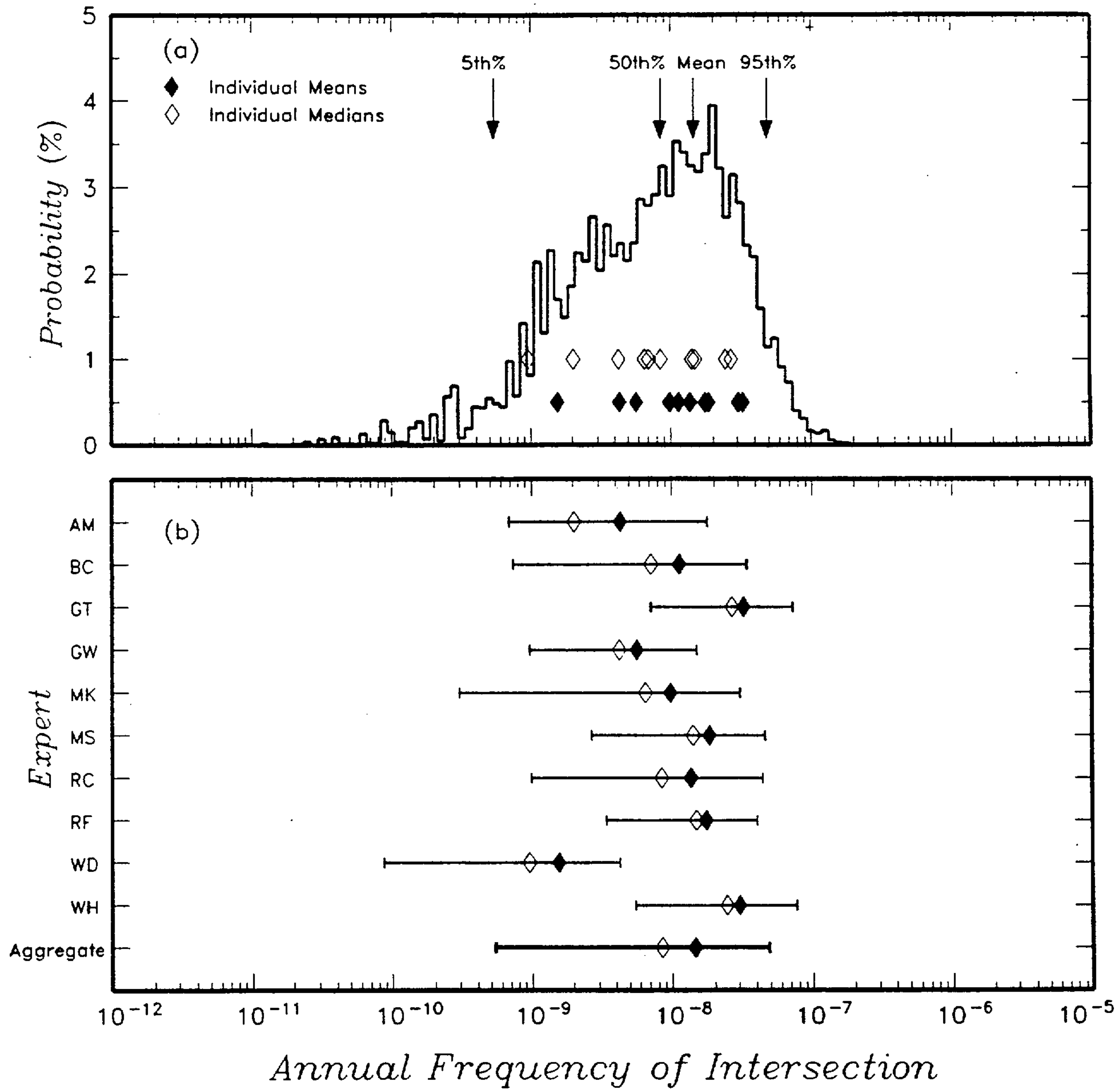


Figure 4-32 Aggregate results for frequency of intersecting the Yucca Mountain repository foot print by a volcanic event. (a) Aggregate distribution for frequency of intersection. (b) Individual and aggregate means, medians, and 90-percent confidence intervals (horizontal bars).

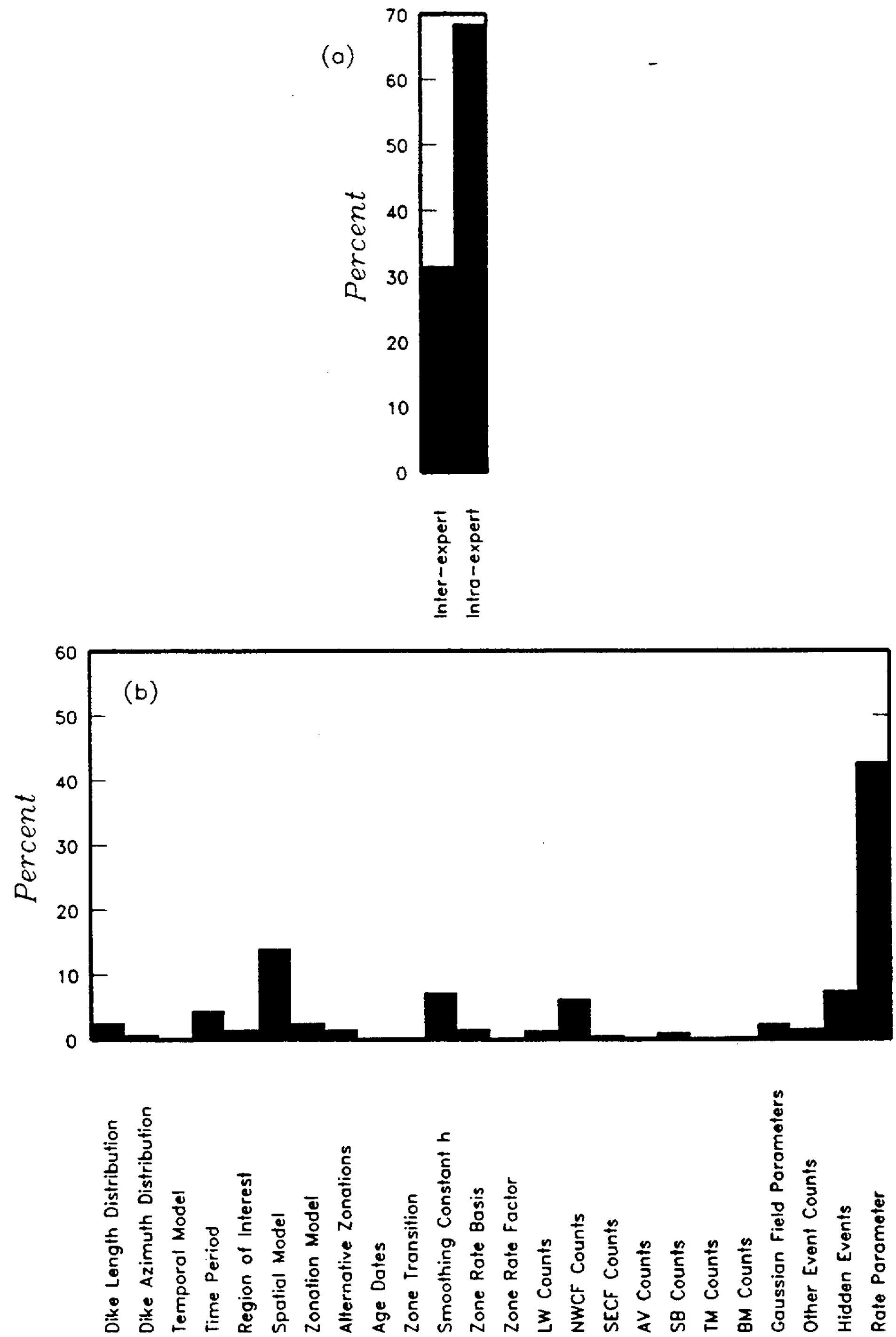


Figure 4-33 Relative contribution of uncertainty in various components of the aggregate PVHA model to the total variance in annual frequency of intersection. (a) Comparison of inter-expert and intra-expert components. (b) Breakdown of intra-expert component of variance.

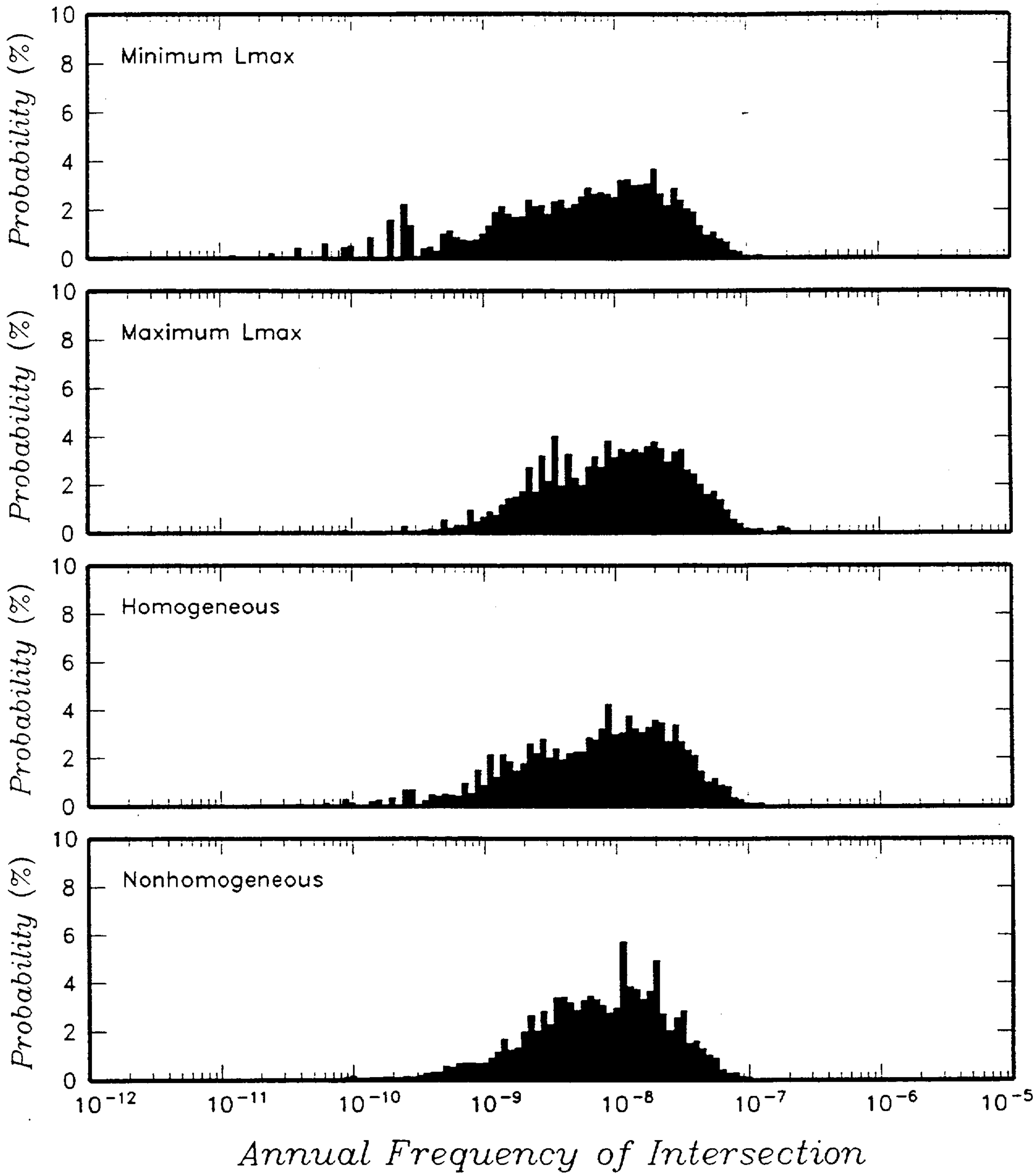


Figure 4-34 Effect of maximum dike length and temporal model on aggregate hazard distribution.

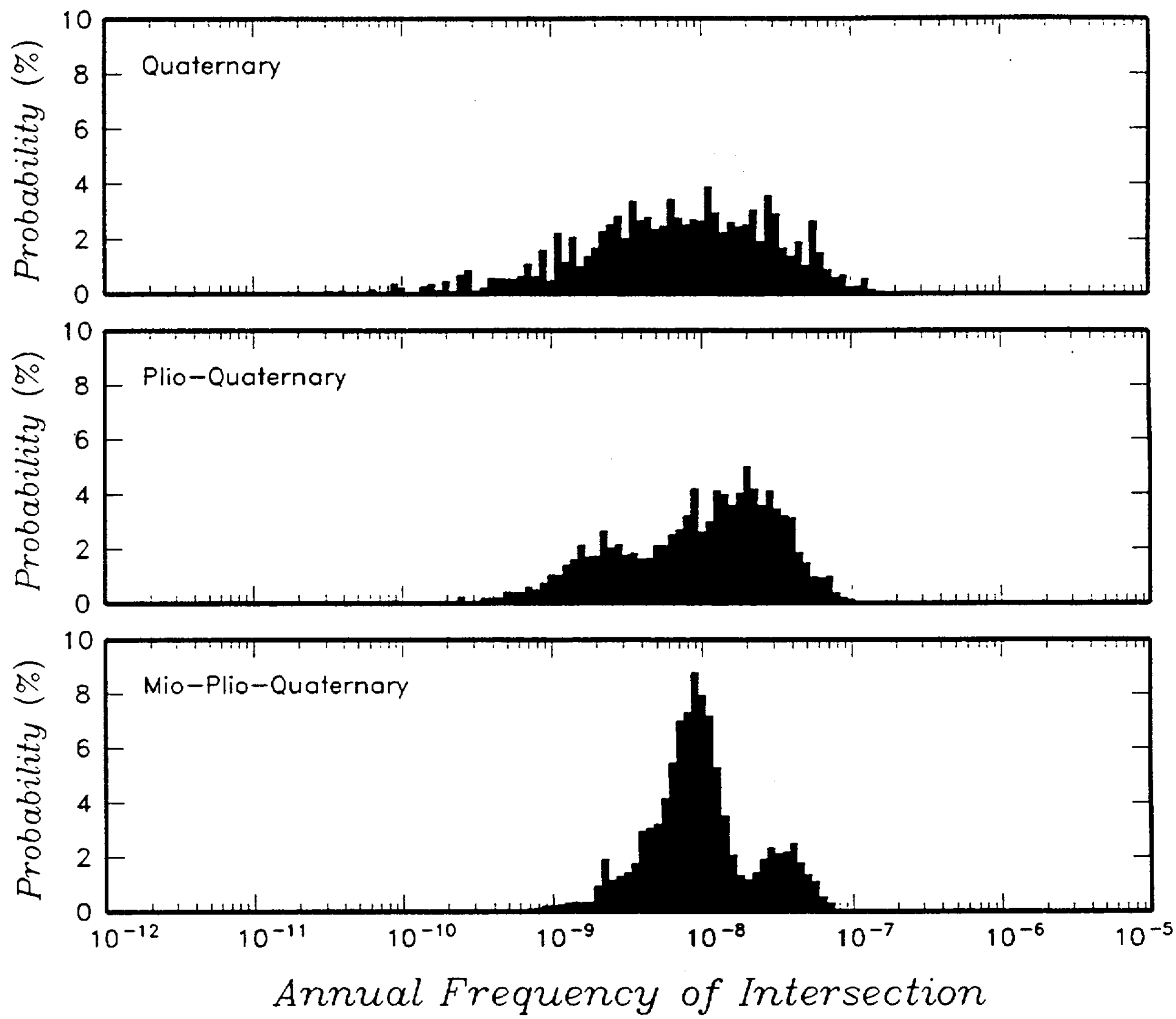


Figure 4-35 Effect of choice of time period on aggregate hazard distribution. Time periods are Quaternary (post 1 to 2 Ma), Plio-Quaternary (post ~5 Ma), and Mio-Plio-Quaternary (post ~10 Ma).

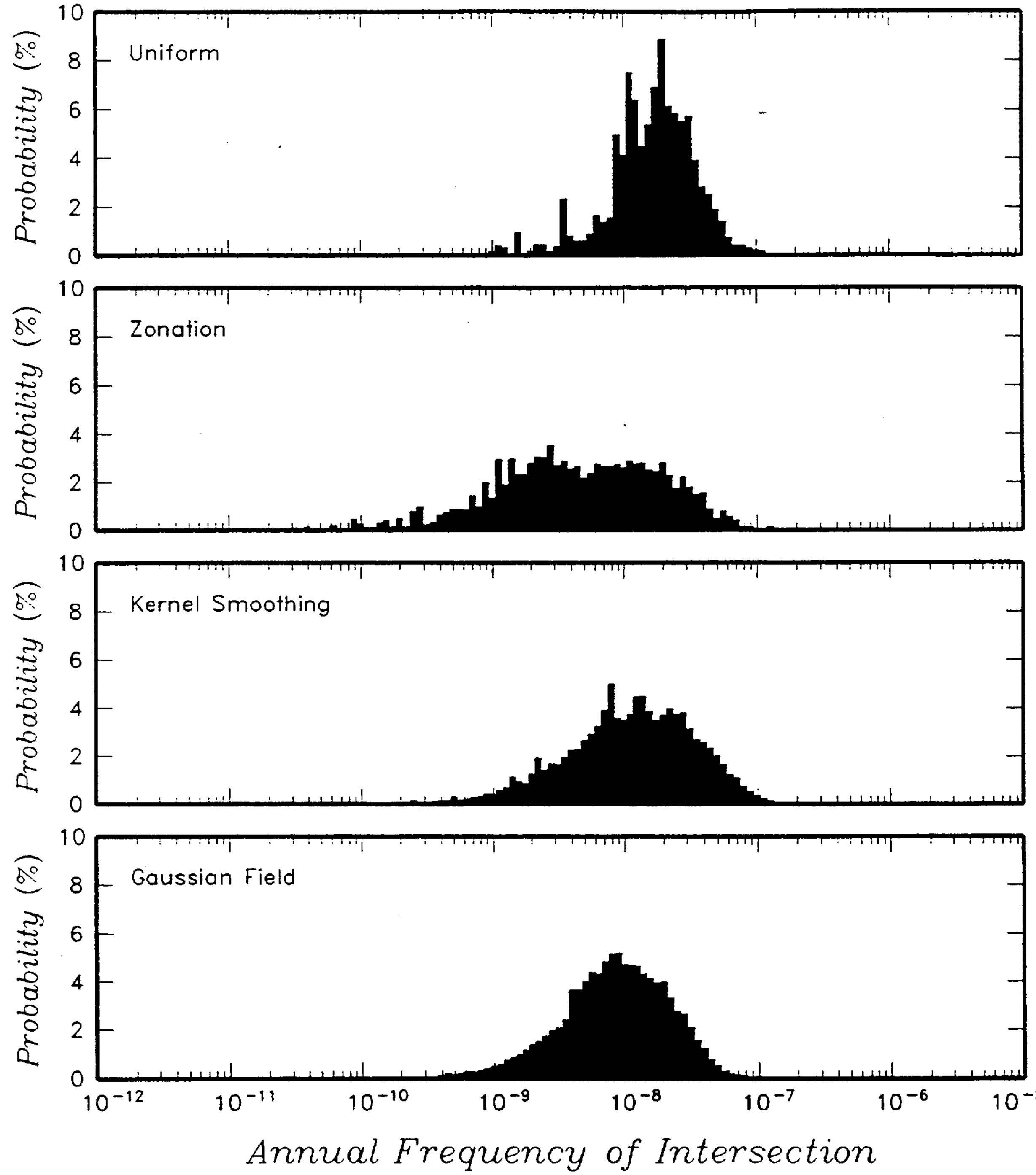


Figure 4-36 Effect of choice of spatial model on aggregate hazard distribution.

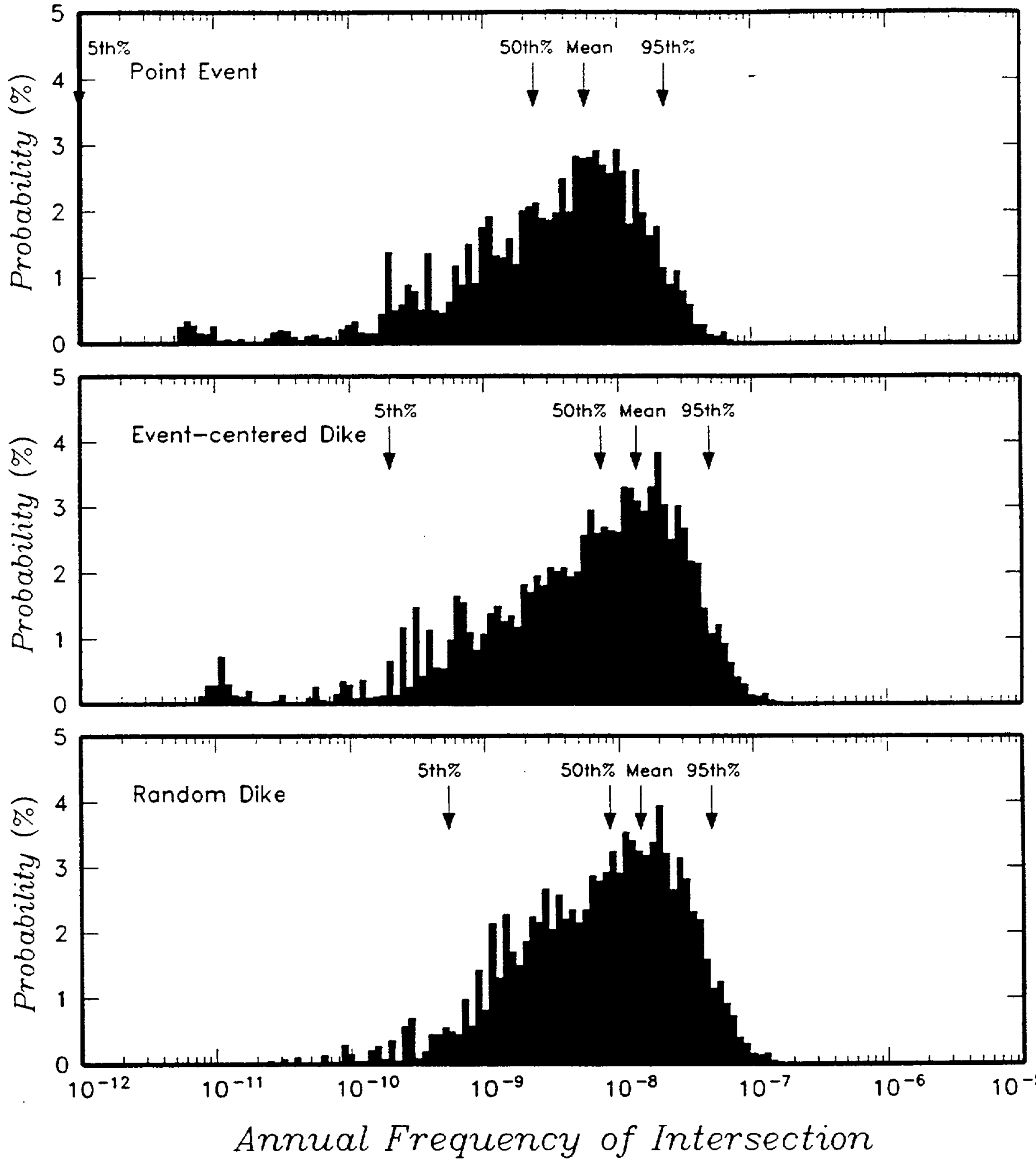


Figure 4-37 Comparison of aggregate distributions for frequency of intersection computed using the three event representations shown on Figure 3-11.

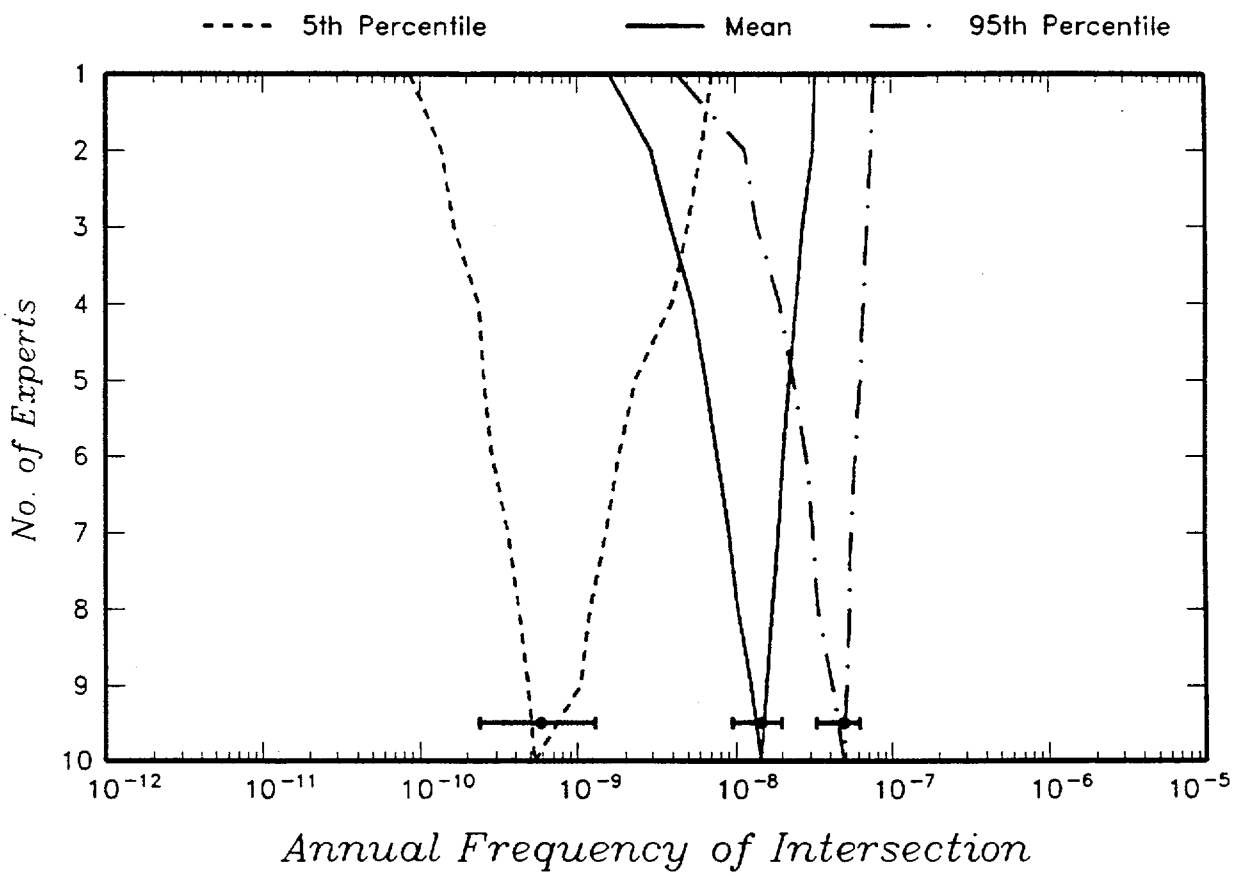


Figure 4-38 Evaluation of the variability in the estimates of the mean and 5th and 95th percentiles of the aggregate hazard distribution. The dashed, solid and dash-dot curves show the limits of the associated statistics considering all possible subsets of varying numbers of experts. The horizontal error bars show the 90-percent confidence intervals and the dots the median values for 1,000 bootstrap simulations of the aggregate distribution.

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APPENDIX A

BIOGRAPHIES
MEMBERS OF THE EXPERT PANEL
PROBABILISTIC VOLCANIC HAZARD ANALYSIS PROJECT

BIOGRAPHIES
MEMBERS OF THE EXPERT PANEL
PROBABILISTIC VOLCANIC HAZARD ANALYSIS PROJECT

Dr. Richard W. Carlson has been a staff scientist at the Department of Terrestrial Magnetism, Carnegie Institution of Washington, for the past 15 years. His research has focused on geochemical and geochronological investigations relating to the origin of large volume volcanism and the continental lithosphere as well as the formation chronology of the lunar crust. Specific study areas have included the Columbia River flood basalts, basaltic volcanism in the northern Basin and Range, the Cenozoic basalts of China and Indochina, and the relation of granitoid and ultramafic magmatism in the early formation of the Kaapvaal Craton of southern Africa. Recently, Dr. Carlson has been involved in development of the Re-Os isotope system and its application to understanding the formation of the continental lithospheric mantle and the role this mantle plays in continent formation and stabilization. This work has included analyses of volcanic rocks from the northwestern United States and mantle xenoliths from Montana, Siberia, and southern Africa. Dr. Carlson has served on numerous evaluation panels including proposal review for the National Science Foundation (NSF), National Research Council panels on Explosive Volcanism and on Earth Science Research, the Continental Dynamics program of the NSF, and the proposal evaluation panels for the International Science Foundation. Currently, Dr. Carlson is the program representative for the International Association of Volcanology and Chemistry of the Earth's Interior to the International Union of Geodesy and Geophysics. Dr. Carlson obtained his B.A. degree in Chemistry from the University of California, San Diego (1976) and his Ph.D. in Earth Science from the Scripps Institution of Oceanography (1980).

Dr. Bruce M. Crowe has been with Los Alamos National Laboratory for 20 years. He initiated volcanic hazard studies of basaltic volcanism in the Yucca Mountain region in 1979 as a joint project with the U.S. Geological Survey. He developed and applied the approach used in probabilistic volcanic hazard assessment for the Yucca Mountain region in the early 1980s and directed the volcanism project for the Department of Energy from the early 1980s until 1994 (the volcanism project is now directed by Dr. Frank Perry, Los Alamos National Laboratory). Dr. Crowe has conducted research on the volcanic geology of the southern Basin and Range province, the California borderland, the central Cascade range, the Jemez volcanic field, and the southwest Nevada volcanic field. He participated in and directed volcanic monitoring teams studying volcanic activity in the Caribbean, Mt. St. Helens, and Hawaii and worked on joint volcanologic and atmospheric studies of trace-element compositions of volcanic gases from multiple eruptive phases of Kilauea volcano during the middle 1980s. Dr. Crowe has been Group Leader of the Applied Geosciences and the Isotope Geochemistry groups at Los Alamos Group and served as the Deputy Technical Project Officer, the Technical Project Officer, and the Geochemistry Coordinator for the programs conducted by the Los Alamos National Laboratory for the Yucca Mountain Site Characterization Project (YMP). Dr. Crowe currently is the Principal Investigator of the probabilistic volcanic hazard assessment aspects of the Los Alamos volcanism program and is involved in studies applying decision analysis, risk assessments, and simulation modeling to volcanism studies and other programmatic applications. Dr. Crowe has a B.A. from Fresno State University (1969) and M.A. (1972) and Ph.D. (1974) degree from the University of California at Santa Barbara.

Dr. Wendell A. Duffield has studied volcanoes for most of his 29-year career as a geologist with the U.S. Geological Survey. He was introduced to volcanoes through a three-year tour of duty at the Survey's Hawaiian Volcano Observatory. While in Hawaii, he contributed to the understanding of the high degree of mobility of the south flank of Kilauea Volcano, and documented a lava-lake analog of global plate tectonics. He subsequently worked on a succession of USGS projects related to Cenozoic volcanic rocks in the western United States, most notably in the Warner Range of northeastern California, the Coso Range of east central California, and the Black Mountains of New Mexico. His principal emphasis has been on physical aspects of volcanology, supplemented by chemical characteristics of the rocks and, for some projects, assessment of geothermal-energy potential. Geologic mapping has been a primary tool, which has served as the basis for gathering fundamental information such as the volume-space-time-composition relations with volcanic fields. Dr. Duffield managed the USGS Program of Geothermal Research from 1979 through 1982. He was an invited volcano/geothermal research geologist with the BRGM in Orleans, France, from 1977 to 1978, and with the Icelandic Energy Authority during the summer of 1984. He was a member of teams that responded to eruption crises for El Chichon in 1982 and Pinatubo in 1991. Other areas of field study include Alaska, Azores, Chile, Costa Rica, Honduras, Jordan, and La Reunion. Dr. Duffield has a B.A. degree in Geology from Carleton College, Minnesota (1963) and M.S. and Ph.D. degrees in Geology from Stanford University (1965 and 1967, respectively).

Dr. Richard V. Fisher, currently Professor Emeritus in Residence at the University of California, Santa Barbara (UCSB), began teaching at UCSB in 1955 and retired in 1993. He began research on volcaniclastic rocks in 1953 in the Cascade Mountains, Washington. Guiding research interests throughout his research career have been the identification and characterization of epiclastic and pyroclastic rocks, including ash fall, pyroclastic flows, pyroclastic surges, lahars, and hyperconcentrated flood flows, with emphasis on determining flow and emplacement mechanisms. He was first to use fluid dynamic principles to explain the flow and emplacement of ignimbrite, and in 1966 introduced the idea of column fallback to produce pyroclastic flows, the concept of "flow transformation" in sediment gravity flows, and the concept of separate transport and depositional systems for pyroclastic flows. Dr. Fisher has pioneered works on the sedimentology and bedforms of tephra deposits and emplacement processes of high flow regime base surges and was instrumental in founding the interdisciplinary field of volcaniclastic geology, coining the word "volcaniclastic." In 1980 he was awarded a U.S. Senior Scientist Award by the Alexander von Humboldt Foundation in West Germany. In 1984 he co-authored the book *Pyroclastic Rocks*. In 1985 he received the N.L. Bowen award from the American Geophysical Union, honoring his research on flow mechanisms of pyroclastic flows, and in 1994 he received a Special Award for Pioneering Research in Volcaniclastic Rocks jointly from the International Association of Sedimentologists and the Vesuvius Volcanological Observatory of Italy. Dr. Fisher received his B.A. degree in Geology from Occidental College near Los Angeles, California (1952) and a Ph.D. degree from the University of Washington (1957).

Dr. William R. Hackett has more than 20 years' experience as a geoscientist, with expertise in igneous processes, physical volcanology, volcanic petrology, and the probabilistic assessment of volcanic and seismic hazards. He has research experience in New Zealand, Japan, Hawaii, and western North America. Dr. Hackett was a tenured faculty member of Idaho State University from 1982 to 1990, where he remains an Adjunct Professor and supervises graduate students. From 1990 to 1994, he was a staff scientist with the Idaho National Engineering Laboratory and worked in the areas of regional tectonics, environmental geoscience, performance assessment of waste-storage facilities, development of comprehensive geologic and geophysical data for safety analysis of critical INEL facilities, and the potential impacts of volcanism upon the energy infrastructure of the western U.S. After consulting "on the side" for more than ten years, in 1994 Dr. Hackett established an independent practice, WRH Associates. He is a Registered Professional Geologist in the state of Idaho. Dr. Hackett is the sole or co-author of more than 25 refereed journal articles, five encyclopedia articles, a book chapter on the paleoseismology of volcano-extensional environments, a book chapter on Snake River Plain regional geology, and is the editor of two geoscience books. He is active in several professional geoscience societies and committees. He serves on the Board of Directors and is Chair of the Research Committee for the Henrys Fork Foundation, Inc., and is a co-facilitator for the Henrys Fork Watershed Council. Dr. Hackett earned a B.A. in Geology from Franklin and Marshall College (1974), a M.S. in Earth Science from Case Western Reserve University (1977), and a Ph.D. in Geology from Victoria University of Wellington, New Zealand (1985).

Dr. Mel A. Kuntz is a Research Geologist in the Branch of Central Regional Geology, U.S. Geological Survey, Denver, Colorado. His specialties are volcanology and the petrology of plutonic igneous rocks. Dr. Kuntz has spent the major part of his 20-year professional career studying the basaltic volcanic rocks of the eastern Snake River Plain, Idaho. These studies include field mapping, petrographic and petrochemical studies, radiometric studies, evaluation of volcanic hazards at the Idaho National Engineering Laboratory (INEL), and theoretical analysis of basalt-magma generation and eruption mechanisms. He is currently a co-investigator with hydrologists, geologists, and isotope geochemists of the USGS in the study of the three-dimensional subsurface stratigraphy of basaltic lava flows of the INEL. Dr. Kuntz is the author or co-author of about 50 publications relating to the geology of the eastern Snake River Plain and the INEL, including the geologic map of the INEL, and numerous other reports and geologic maps of parts of the INEL and the eastern Snake River Plain. He was involved in field studies of pyroclastic-flow and related deposits of the 1980 eruptions of Mount St. Helens and, with two USGS colleagues, published geologic maps and journal papers relating to those deposits. In addition to his 20-year volcanologic studies, he has also studied the plutonic rocks of the western margin of the Idaho batholith near McCall, Idaho, since 1982. Dr. Kuntz has a B.A. from Carleton College (1961) in Geology and American History, a M.S. in Geology from Northwestern University (1964), and a Ph.D. from Stanford University (1968) in Geology and Geochemistry.

Dr. Alexander R. McBirney is Professor Emeritus at the University of Oregon in Eugene and has more than 35 years of experience in the field of volcanology. Dr. McBirney has carried out extensive research projects in the volcanic provinces of Central America, the Cascades, the Galapagos Islands, and East Greenland. At the University of Oregon, Dr. McBirney served as Associate Professor and Director of the Center for Volcanology from 1965 to 1968, and as Professor and Chairman for the Department of Geology from 1968 to 1971. He was a Visiting Professor at the California Institute of Technology in 1978, and at the University of Paris, Orsay, from 1985 to 1986. The founding editor of the Journal of Volcanology and Geothermal Research, he served as editor-in-chief from 1976 to 1989. His publications include the widely-used book, *Volcanology*, which he co-authored with the late Howel Williams, and numerous papers on volcanic hazards. Dr. McBirney has been a consultant on the safety of nuclear power plants in the United States, the Philippines, and Indonesia, and is currently a panel member of the International Atomic Energy Agency, which is responsible for preparing a safety guide for volcanic hazards. In 1990 he received the N.L. Bowen Award from the American Geophysical Union. Dr. McBirney received his bachelors degree from the United States Military Academy at West Point (1946) and his doctorate from the University of California at Berkeley (1961).

Dr. Michael F. Sheridan is Professor of Geology at the State University of New York (SUNY) at Buffalo and has been Chairman of the Geology Department since 1990. Prior to his appointment to SUNY, he was Professor of Geology at Arizona State University. His research was based on a balance of field work, laboratory experiments, and computer models related to phenomena and products of explosive volcanism. The objective of this work was to understand the generation and dispersal of volcanic materials using data from the size and shape of fragments, the textures of deposits, and the geometry of dispersal of major units. A large fraction of this work was devoted to understanding hydro volcanism, the explosive interaction of magma with external water. His current academic interest is in evaluation of volcanic hazards and development of methods for mitigation of risks. Dr. Sheridan was a Fulbright Scholar in Iceland and a visiting scientist at several universities in Italy and Mexico, where he taught courses on volcanology. He organized international workshops on explosive volcanism in Italy in 1982 and Mount St. Helens in 1984. He has studied the products of some of the major explosive eruptions of historical times and has published volcanic risk evaluations and/or volcanic hazard maps of Vesuvius and Colima Volcanoes. In January 1995, he was invited by the Mexican Government to help prepare a volcanic hazard map of Popocatepetl Volcano using 3-D computer flow simulations that he developed. He has been co-chairman of both regional and national Geological Society of America meetings. Dr. Sheridan earned his A.B. degree from Amherst College (1962) and his M.S. (1964) and Ph.D. (1965) degree from Stanford University.

Dr. George A. Thompson is Professor of Geophysics at Stanford University. He participated in the founding of the Geophysics Department about 40 years ago. Prior to joining the Stanford faculty, he was a geologist and geophysicist with the U.S. Geological Survey, where he worked on mineral deposits and on Basin and Range/Sierra Nevada tectonics. While at Stanford he helped design and interpret the Lunar gravity experiment on Apollo 17. In recent years, his research with students has focused on deep seismic exploration of the crust and on the interplay between magmatism and earthquakes. He served as Chair of the Stanford Geophysics Department (1967 to 1986), concurrently as Chair of the Geology Department (1979 to 1982), and as Dean of the School of Earth Sciences (1987 to 1989). His numerous professional activities include: consultant to the Advisory Committee on Reactor Safeguards and the Advisory Committee on Nuclear Waste of the U.S. Nuclear Regulatory Commission; member of the Senior External Events Review Group, Lawrence Livermore National Laboratory; vice-chairman of the National Research Council Panel on Coupled Processes at Yucca Mountain; and chairman of the National Research Council Committee on the proposed Ward Valley, California, low-level nuclear waste site. He is a member of the National Academy of Sciences. Dr. Thompson holds a B.S. degree in Geology from Penn State (1941), a M.S. in Geology from M.I.T. (1942), and a Ph.D. in Geology from

from Penn State (1941), a M.S. in Geology from M.I.T. (1942), and a Ph.D. in Geology from Stanford (1949).

Dr. George P.L. Walker has been Professor of Volcanology at the University of Hawaii in Honolulu since 1980; he plans to retire from this position at the end of 1995 to pursue research and write. At the University of Hawaii, he taught about 50 courses in geology and volcanology, was heavily involved with graduate-student advising, and did volcanology research on a wide variety of topics in the Azores, Caroline Islands, Ecuador, Hawaii, Iceland, Italy, Indonesia, Japan, Madeira, Mexico, New Zealand, Papua New Guinea, the Philippines, Samoa, and Scotland. He also published about 70 scientific papers. His activities included U.N.-sponsored volcanic-hazards studies in Ecuador and Colombia, following closely on the disaster of Ruiz in 1985, and advising the State of California on volcanic hazards from a possible eruption in Long Valley. Prior to coming to Hawaii he spent three years on a research fellowship in New Zealand. Based at the University of Auckland, he did research on three great explosive eruptions of the rhyolitic volcanoes of the Taupo Zone. This interval in New Zealand followed about 25 years as a faculty member at Imperial College, University of London, giving courses in mineralogy, geology, and volcanology and doing research. He was supervisor for about 10 graduate students, all of whom subsequently pursued successful careers in geology. Dr. Walker's research included mapping projects in Uganda and the Belgian Congo, a mineralogic study on pegmatites in Mozambique, and a ten-year mapping project in the Miocene basalt plateaus of eastern Iceland. In the field of volcanology he conducted basic research on lava flows, pyroclastic flows, and pyroclastic falls. During this 25-year period he published about 70 scientific papers, including some of the first on volcanic hazards. Dr. Walker graduated with a B.S. and a M.S. in Geology from the Queen's University, Belfast, in 1948 and 1949 respectively, and gained his Ph.D. from the University of Leeds in 1956.

BIOGRAPHIES
MEMBERS OF THE METHODOLOGY DEVELOPMENT TEAM
PROBABILISTIC VOLCANIC HAZARD ANALYSIS PROJECT

Dr. Kevin J. Coppersmith, the PVHA Project Manager at Geomatrix Consultants, has 17 years of consulting experience, with primary emphasis in hazard analysis. Dr. Coppersmith has pioneered approaches to characterizing earth sciences data, and their associated uncertainties, into probabilistic hazard analyses. His background and experience lie in the use of geologic data to characterize the location, magnitude, and rate of occurrence of natural hazards. He has conducted regional studies for spatially-distributed systems and site-specific studies for power plants, highway bridges, and other critical facilities. Dr. Coppersmith has a B.S. in Geology from Washington and Lee University (1974), and a Ph.D. in Geology from the University of California, Santa Cruz (1979).

Dr. Roseanne C. Perman, the PVHA Assistant Project Manager at Geomatrix Consultants, has more than 15 years experience in consulting geology. Since 1990 Dr. Perman has participated in a variety of geologic studies for the proposed high-level nuclear waste repository at Yucca Mountain, Nevada. These studies include a probabilistic seismic hazard analysis, sponsored by the Electric Power Research Institute, to demonstrate methods for the elicitation of expert judgment; development of the Seismic Hazard Analysis Methodology topical report; and geologic studies for the area surrounding the proposed surface-handling facilities in Midway Valley adjacent to the proposed repository. Dr. Perman has participated in and managed a variety of multidisciplinary studies to evaluate potential earthquake hazards to critical facilities and to assess public policies regarding seismic safety. Dr. Perman also has a strong background in sedimentary stratigraphy and has conducted assessments of paleontological resources on lands throughout the western United States. Dr. Perman has B.A. degrees in Geography and Earth Sciences (1976 and 1981) and M.A. and Ph.D. degrees in Paleontology (1985 and 1988) from the University of California at Berkeley.

Dr. Robert R. Youngs, associated with Geomatrix Consultants, is responsible for probabilistic modelling and calculations for the PVHA project. Dr. Youngs has had a major role in the development of probabilistic hazard methodologies that incorporate geologic information and account explicitly for the uncertainties in earth sciences data. He has been involved in a broad range of studies whose application is risk analysis for decision-making regarding the design of new facilities, prioritization of site characterization activities, and retrofit of existing facilities.

His role in these studies has been to translate the descriptions of hazards developed by earth scientists into quantitative assessments of hazard. He has developed a number of computer applications to evaluate ground shaking, soil liquefaction, and fault rupture hazards for both site-specific and regional mapping studies. An important aspect of these assessments has been the explicit incorporation of uncertainty assessments. Dr Youngs has extensive experience in developing logic structures to represent the uncertainties in earth science assessments and in presenting the results of such assessments in a regulatory environment. Dr. Youngs has M.S. and Ph.D. degrees in Geotechnical Engineering from the University of California, Berkeley (1973 and 1982) and a B.S. in Civil Engineering from California State Polytechnical University (1969).

Dr. Peter A. Morris, the lead normative expert for the PVHA project, is the Chief Executive Officer at Applied Decision Analysis, Inc. Dr. Morris has over 20 years experience in the research, teaching, and application of decision analysis and quantitative modeling. His areas of expertise include decision and risk analysis, combining expert judgments, probability analysis, and mathematical modeling. He specializes in problem structuring, and eliciting and aggregating expert judgments in large, technically complex and uncertain decision problems. Dr. Morris originated the Bayesian approach to combining expert judgments, which has provided the foundation for a significant portion of current expert-aggregation research and practical applications. Prior to joining Applied Decision Analysis, he was with Xerox Corporation for five years where he developed and applied quantitative modeling tools to a wide range of Xerox problems. Before that, he worked with the U.S. Department of Defense where he was the founding director of the Modeling and Analysis Office and a systems analyst in the Office of Systems Analysis. Since 1971, Dr. Morris has held a part-time appointment as a professor in the Department of Engineering-Economic Systems at Stanford University where he teaches mathematical modeling and probabilistic analysis. He has been active in the academic and professional communities and was the president of the Decision Analysis Group of the Institute for Management Sciences. Dr. Morris has a B.S. in Electrical Engineering, from the University of California at Berkeley (1968) and M.S. and Ph.D. degrees in Engineering-Economic Systems from Stanford University (1970 and 1971).

Dr. C. Allin Cornell is a civil engineer with a widely recognized expertise in probability, statistics, and decision analysis. After two decades (1964-1983) in a traditional professorial position at the Massachusetts Institute of Technology, Professor Cornell changed to a half-time (research) Professor at Stanford University supervising graduate student research, and a half-time independent engineering consultant. This arrangement allows him to combine practicing the application of advanced probabilistic methods and conducting the research stimulated by the needs indentified through that practice. His early research led to the development of now "classic" probabilistic seismic hazard analysis (PSHA) and the basis for the first probability-based Load and Resistance Factor Design (LRFD) structural building codes. His later work and practice has included advancements in theory and application of PSHA and analyses of offshore structures, including nonlinear probabilistic structural system reliability under wave and seismic loading. His consulting activities range over a variety of fields for a variety of industries and federal organizations. He is a past president of the Seismological Society of America and an elected member of the National Academy of Engineering (1981). Professor Cornell attended Stanford University where he has an A.B. degree in Architecture, and M.S. and Ph.D. degrees (1960-1964) in Civil Engineering.

Dr. J. Carl Stepp, currently associated with Woodward-Clyde Federal Services, has more than 30 years experience in earthquake hazards assessment. He has conducted research, developed industrial applications, and developed and applied seismic regulations. He was a research scientist and research team leader with the U. S. Coast and Geodetic Survey for eleven years, where he developed probabilistic seismic hazard assessment methodology. For six years, he was involved with regulatory development and application as Chief of the Geosciences Branch at the U. S. Nuclear Regulatory Commission, including: (1) implementation of the federal nuclear plant seismic and geologic regulation, Appendix A to 10 CFR Part 100; (2) participation as a member of the International Atomic Energy Agency's Seismic Safety Guide 50-SG-S1 Working Group; and (3) regulatory review of seismic evaluations for more than sixty applications for nuclear plant licenses; (4) development of the initial draft of the Nuclear Regulatory Commission's high level waste regulation, 10 CFR Part 60. For ten years he was Manager of the Seismic Center at the Electric Power Research Institute, conducting a broad research program on earthquake hazard assessment methodology development, earthquake strong ground motion evaluation procedures, methodology to evaluate nuclear plants to determine their vulnerability to seismically initiated severe accidents, and seismic regulation development including the current revision of the Nuclear Regulatory Commission's seismic and geologic regulations for nuclear plants. Since 1993 Dr. Stepp has been a private consultant and is associated with the Geotechnical Engineering Center, Department of Civil Engineering, University of Texas at Austin, as a Research Scientist. Dr. Stepp has a B.S. in Geology from Oklahoma State University (1959), a M.S. in Geophysics from the University of Utah (1961), and a Ph.D. in Geophysics from Pennsylvania State University (1971).

Dr. Richard P. Smith provides technical advice on volcanic hazards assessment to the PVHA project. Dr. Smith has been associated with the Idaho National Engineering Laboratory since

1986. He has conducted both volcanic and seismic hazard assessments for the eastern Snake River Plain. This work has required detailed knowledge of the regional geologic and geophysical setting, regional neotectonics, in-situ crustal stress and crustal heat flow, paleoseismology, and site-specific geotechnical investigations. Dr. Smith has extensive experience in magmatic processes, particularly dike injection, and its relationship to extensional tectonism in the regions of the Basin and Range of Idaho, the eastern Snake River Plain, and the Rio Grande Rift of Colorado and New Mexico. Between 1973 and 1986 Dr. Smith conducted research and participated in mining geology work in volcanic and subvolcanic terrain of Colorado for Climax Molybdenum Company. This work included studies of regional geology and geophysics, caldera-related dike swarms, igneous petrology, hydrothermal activity, and ore deposit genesis. Dr. Smith is an adjunct faculty member at Idaho State University. He received a B.S. in 1965 from Marshall University in West Virginia and M.S. and Ph.D. degrees in Geology from the University of Colorado at Boulder in 1968 and 1975.

Dr. Stephen T. Nelson has worked with Woodward-Clyde Federal Services since March, 1993, as a support contractor for the U.S. Department of Energy Yucca Mountain Project. His primary responsibilities have included technical management, planning, and integration support of the geochemistry and volcanism portions of the Project; and technical support for the issue resolution process with the U.S. Nuclear Regulatory Commission for both geochemistry and volcanism. Dr. Nelson has an academic background that is within the general areas of petrology, isotope geochemistry, geochronology and tectonomagmatic history of the Cordillera, especially the western United States and Southern Volcanic Zone of the Chilean Andes. He has worked extensively with the Rb-Sr, Sm-Nd, U-Pb and O isotope systematics of igneous rocks in order to elucidate processes involved in magma genesis and evolution. He also has extensive experience in the $^{40}Ar/^{39}Ar$ system, and has applied this technique to determine the thermal history of rock bodies, and to obtain ages on difficult to date material such as xenocryst-bearing rocks and young (Pleistocene) mafic rocks. He conducted research into the synthesis of high-grade industrial diamond for four years with Logicon/RDA. Dr. Nelson holds B.S. and M.S. (1984 and 1987) degrees in geology from Brigham Young University, and a Ph.D. in geology in 1991 from the University of California at Los Angeles.

Mr. J. Timothy Sullivan, the DOE Project Manager for the PVHA (following the departure of Jeanne Nesbit), is currently the DOE manager of the Geology Program at the Yucca Mountain Project (YMP) and has been involved in the YMP since 1989. His work has involved managing site characterization field activities, and issue resolution with the NRC on erosion, seismic hazards, and now volcanism. He concurrently serves as the DOE representative for the

Probabilistic Seismic Hazard Analysis for Yucca Mountain that began in 1995. Prior to joining DOE, he worked as a geologist for the Bureau of Reclaimation at the Engineering and Research Center. He planned and conducted both regional and site-specific seismic hazard studies for the Bureau's critical facilities at sites throughout the western U.S. Mr. Sullivan has a B.S. in Physics from St. Lawrence University, and a M.S. in Geological Sciences from the State University of New York at Buffalo.

Dr. Jeanne C. Nesbit, the U.S. Department of Energy (DOE) Project Manager for the PVHA from project initiation until September, 1995, was a physical scientist with DOE's Yucca Mountain Project between 1991 and 1995. In her position as Team Leader for Scientific Integration, she was responsible for overall integration of Yucca Mountain scientific programs with other project elements such as licensing; performance assessment; systems engineering; design; and environment, safety and health. Previously, she was responsible for managing test planning and coordination activities and interactions with groups such as the Nuclear Waste Technical Review Board and the U.S. Nuclear Regulatory Committee. From 1985 to 1991, she conducted research in the fields of igneous petrology and geochemistry primarily related to understanding the volcano-tectonic evolution of continental regions. This work included petrology and geochemistry of extrusive igneous rocks and their included xenoliths in the western United States. She received B.A., M.S., and Ph.D. degrees from Miami University in 1984, 1986, and 1991 respectively.

APPENDIX B

REFERENCES
DISTRIBUTED TO EXPERT PANEL MEMBERS

REFERENCES
DISTRIBUTED TO EXPERT PANEL MEMBERS
PROBABILISTIC VOLCANIC HAZARD ANALYSIS PROJECT

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APPENDIX C

SUMMARIES
PVHA WORKSHOPS

APPENDIX C

NOTE: The workshop summaries provided in this appendix were prepared after each workshop and then distributed to workshop participants. The overhead transparencies shown during the workshops, and summaries of the speaker's technical presentations, were also provided to workshop participants. These items, however, are not included in this appendix.

SUMMARY
WORKSHOP ON DATA NEEDS
PROBABILISTIC VOLCANIC HAZARD ANALYSIS PROJECT
YUCCA MOUNTAIN REGION, NEVADA

February 22 and 23, 1995
Phoenix, Arizona

The Workshop on Data Needs was the first in a series of four workshops being conducted for the Probabilistic Volcanic Hazard Analysis (PVHA) project. The project is sponsored by the U.S. Department of Energy (DOE) and is managed by Geomatrix Consultants. The goal of this workshop was to develop a comprehensive list of the specific data needed to make probabilistic assessments of volcanic hazard at Yucca Mountain. The approach to the workshop was to (1) identify the technical issues of most significance to probabilistic volcanic hazard analysis, (2) establish linkages between PVHA issues and the data most important to addressing the issues, (3) specify pertinent data available for the Yucca Mountain region, and (4) identify the particular data that are required by the experts to conduct the PVHA.

The overhead transparencies shown during this workshop are included with this summary, along with brief summaries of the speakers' technical presentations.

DAY 1 - WEDNESDAY, FEBRUARY 22

A welcome and introduction to the workshop was given by the PVHA project manager, Dr. Kevin J.Coppersmith of Geomatrix Consultants. He reviewed the workshop agenda and the various types of participation in the project. The members of the expert panel and the Methodology Development Team (MDT, the group that is planning and conducting the project) then introduced themselves and briefly described their areas of expertise. The members of the expert panel are Dr. Richard W. Carlson (Carnegie Institution of Washington), Dr. Bruce M. Crowe (Los Alamos National Laboratory [LANL]), Dr. Wendell A. Duffield (U.S. Geological Survey), Dr. Richard V. Fisher (University of California, Santa Barbara, Emeritus), Dr. William R. Hackett (WRH Associates), Dr. Mel A. Kuntz (U.S. Geological Survey), Dr. Alexander R. McBirney (University of Oregon, Emeritus), Dr. Michael F. Sheridan (State University of New York at Buffalo), Dr. George A. Thompson (Stanford University), and Dr. George P.L. Walker (University of Hawaii). Members of the MDT are Dr. Kevin J. Coppersmith, Dr. Peter A. Morris (Applied Decision Analysis), Dr. Stephen T. Nelson (Woodward-Clyde Federal Services), Dr. Jeanne C. Nesbit (DOE), Dr. Roseanne C. Perman (Geomatrix Consultants), Dr. Richard P. Smith

(Idaho National Engineering Laboratory [INEL]), Dr. J. Carl Stepp (Woodward-Clyde Federal Services), and Dr. Robert R. Youngs (Geomatrix Consultants) (who was unable to attend the workshop).

Opening statements were given by several members of the MDT. Kevin Coppersmith described the focus of the subsequent workshops, the workshops' ground rules and organization, the process used to select the panel members, and PVHA project goals. Jeanne Nesbit, project manager of the PVHA project for DOE, briefly discussed the ways that the results of this project may be used in the two major areas of DOE responsibility: (1) evaluating whether Yucca Mountain meets site suitability requirements, and (2) preparing a license application if the site is deemed suitable. She pointed out that the results of the PVHA project also could be used to evaluate where to place additional resources to reduce uncertainties. Peter Morris presented an introduction to uncertainty treatment and the process and principles of expert judgment elicitation. Kevin Coppersmith concluded the opening statements by describing the general framework of the PVHA project.

The second session included four presenters discussing the technical issues associated with PVHA methods. Chuck Connor (Center for Nuclear Waste Regulatory Analyses [CNWRA]) began the technical presentations with a talk on "Nonhomogeneous Probability Models." Both temporally and spatially dependent models were described, with specific applications to the Yucca Mountain Site. Bruce Crowe gave the next presentation, "Perspectives for Probabilistic Volcanic Risk Assessment." He discussed various probabilistic models and the uncertainties associated with the application of each. The afternoon session commenced with a presentation by Richard Smith entitled "Summary of Technical Issues for Volcanic Hazards Assessment at the INEL." He discussed the possible analogies between the Snake River Plain Region and the Yucca Mountain Region (YMR), citing the various technical issues pertaining to the volcanic hazards assessment at INEL. Alexander McBirney gave the final presentation of the day, entitled "Statistical Data and Geologic Realism." He stressed the importance of choosing statistical models that are consistent with sound geologic observations and data.

The technical presentations were followed by a discussion of the specific technical issues that need to be addressed to carry out the volcanic hazard assessment at Yucca Mountain. A comprehensive list of these issues was compiled by the members of the expert panel and the MDT, and is provided in Table 1.

The session ended with questions and short statements from some of the project participants and observers. Issues discussed included how to evaluate data loss due to the effects of erosion or burial of volcanic features, the distribution of volcanoes with respect to topography and the possible influence of neutral buoyancy. In addition, it was suggested that a paper discussing probabilistic seismic hazard analysis be read by the members of the expert panel.

DAY 2 - THURSDAY, FEBRUARY 23

The second day of the workshop began with Kevin Coppersmith leading a discussion focused on relating each of the technical issues identified the previous day to those data sets that could provide information to address that issue. A list of data was compiled during this discussion, and is provided in Table 2.

The next session included a discussion of Yucca Mountain data bases pertinent to PVHA technical issues. Eugene I. Smith (University of Nevada, Las Vegas [UNLV]) began the presentations with a description of data for the Crater Flats region and analog studies in the Basin and Range conducted by UNLV. Brent D. Turrin (U.S. Geological Survey) gave the next talk. He presented and discussed some of the geochronological data, particularly $^{40}Ar/^{39}Ar$ data, available for the YMR. Frank V. Perry (LANL) began the afternoon session with an overview of all of the data sets gathered as part of the LANL volcanic program for each of the volcanic centers in the YMR. Victoria E. Langenheim (U.S. Geological Survey) concluded the technical presentations for the workshop. She provided an overview of all of the geophysical data sets, published and unpublished, that exist for the YMR.

Kevin Coppersmith concluded the workshop by announcing that all of the Yucca Mountain data sets presented would be compiled on a master list by Geomatrix and distributed to the expert panel members so they could chose the specific data they would like to receive.

Discussions on a variety of issues followed, with questions and comments from the observers. Topics included observations of the rafting of portions of a scoria cone on an active lava flow, the quality of available age dates, the importance of evaluating fault data from the tectonics program, and the ability to resolve various technical issues and their relevance to hazard analysis.

TABLE 1
TECHNICAL ISSUES IDENTIFIED BY THE EXPERT PANEL WORKSHOP ON DATA NEEDS

1	Nature of YMR eruptions
2	Field relationships/mapping
3	Correlation of tectonic activity with recent or synchronous volcanism
4	Structural control of spatial distribution of regional/local volcanic features
5	Age, volume, and locations of eruptions
6	Nature of aeromagnetic anomalies
7	Reliability, quality, and uncertainty of age determinations
8	Definition of "event"
9	Model of magma generation and migration
10	Areal extent for regional recurrence rate
11	Lathrop Wells - recency and number of events
12	Polygenetic vs. monogenetic
13	Model for probability calculations - does it make a difference? (nonhomogeneous vs. homogeneous; physical constraints)
14	Influence of regional stress field
15	Geodetic/neotectonic strain rate
16	Existence, age, and configuration of a buried magma body; silicic vs. basaltic
17	Southern Basin and Range volcanism - time/space patterns
18	Appropriate analogs
19	Relation of topography to density of eruptions
20	Area of "repository"
21	Area of "event"
22	Evolution of Crater Flat - trends/volume/composition
23	Burial or loss of events - geologic record
24	Comparisons with composite cones
25	How well do models predict?
26	Archiving data bases
27	Dissemination of results

TABLE 2
DATA NEEDS FOR TECHNICAL ISSUES
WORKSHOP ON DATA NEEDS

TECHNICAL ISSUE	DATA
1	Field maps, size/shape/thickness of basalt Analogs (cinder cone roots) Pre-eruptive H_2O content; inclusions Viscosity indicators
2	Topographic maps Fault data/recency - Ash deposits/geochemistry
3	Detailed geologic maps
4	**Regional:** Geologic maps/gravity maps/(aero)magnetic maps Seismic reflection/refraction maps **Local:** Maps of individual vents Ground magnetic data
5	Geologic maps (all scales) Geochronology Depth information
7	Actual/raw data
9	Geochemical data H_2O content
10	Regional geologic maps Analogs Multiple filtered geophysical data Teleseismic data
11	Aerial photographs (various scales)
12	Geochron/geochemical data Field relationships

**TABLE 2 (continued)
DATA NEEDS FOR TECHNICAL ISSUES
WORKSHOP ON DATA NEEDS**

TECHNICAL ISSUE	DATA
14	Hydrofracture data/breakouts Focal mechanisms Fault slip vectors Cinder cone alignments
15	GPS data Fault history
16	Teleseismic tomography Seismic reflection data
17	Southern Basin and Range map (Luedke & Smith)
19	Borehole/density profiles Gravity data Analogs
21	Analogs Aeromagnetic data
22	Isotopic/geochemical data Number of dikes
23	Aeromagnetic data Shallow reflection data Borehole data Quaternary geomorphic maps

SUMMARY
WORKSHOP ON ALTERNATIVE HAZARD MODELS
PROBABILISTIC VOLCANIC HAZARD ANALYSIS PROJECT
YUCCA MOUNTAIN REGION, NEVADA

March 30 and 31, 1995
Stardust Hotel, Las Vegas, Nevada

The Workshop on Alternative Hazard Models was the second in a series of four workshops being conducted for the Probabilistic Volcanic Hazard Analysis (PVHA) project, which is sponsored by the U.S. Department of Energy (DOE) and managed by Geomatrix Consultants. The goals of this workshop were to review alternative methods and models for assessing probabilistic volcanic hazard and to assess their applicability to the Yucca Mountain PVHA. The workshop began with a discussion of general aspects of hazard modeling, followed by presentations and discussions of the various methods for modeling the spatial and temporal distribution of future volcanism in the Yucca Mountain Region (YMR). Workshop presenters described the assumptions inherent in their models and procedures, data required, and uncertainties and strengths of their methods. The presentations were followed by short discussions involving the expert panel and Methodology Development Team (MDT), which gave the experts an opportunity to question the relative merits and applicability of the various models.

Copies of the overhead transparencies shown during the workshop are included with this summary, along with brief summaries of the speakers' technical presentations.

DAY 1 - THURSDAY, MARCH 30

Opening statements were given by two members of the MDT. A welcome and introduction to the workshop was given by the PVHA project manager, Kevin Coppersmith of Geomatrix Consultants. He reviewed the ground rules of the workshops and described the purpose of this workshop and its approach. His opening statements continued with a brief description of a hazard analysis for a hypothetical site and region. Peter Morris (Applied Decision Analysis) then gave a short presentation on the "proponent" and "expert" roles that the members of the expert panel must consider when evaluating the various volcanic hazard models. He stressed the importance of a common understanding among the panel members regarding the assumptions, strengths, and weaknesses of alternative hazard models.

The presentations commenced with a talk on "Probabilistic Hazard Analysis" by Allin Cornell (CAC Co./Stanford University), an advisor to the MDT who has widely recognized expertise in probability, statistics, and decision analysis. He discussed the general aspects of modeling hazardous natural phenomena, using examples from his experience with probabilistic seismic hazard analysis. General and special models were described, as were the inherent parameter and model uncertainties associated with each.

Four speakers gave presentations in the session on "Methods for Characterizing the Recurrence Rate of Future Volcanism." Bill Hackett (WRH Associates) gave a presentation entitled "Event Counts," which was based on the volcanic geology of the Eastern Snake River Plain (ESRP), Idaho. He described the character of basalt flows in the ESRP and the structural features associated with emplacement of basaltic dikes therein. Mel Kuntz (US Geological Survey [USGS]) gave the final talk of the morning session. He also drew on examples from the ESRP, discussing recurrence intervals, magma-output rates, effusion rates, and eruption durations.

The afternoon session began with a presentation by George Thompson (Stanford University) entitled "Coupling of Basaltic Dike Injection to Stress and Strain in Extending Regions: Prediction Capability at Yucca Mountain?" He discussed the relationship between normal faulting and volcanism as a means of accommodating crustal strain in extending regions. Chih-Hsiang Ho (University of Nevada, Las Vegas [UNLV]) gave the final presentation of the day, entitled "Volcanic Hazard Analysis at the Yucca Mountain Nuclear Waste Repository Site." He discussed the applications of his Bayesian approach to modeling the future hazard at Yucca Mountain.

The session ended with questions and short statements from some of the project participants and observers. John Trapp, of the Nuclear Regulatory Commission (NRC), gave a brief presentation summarizing the NRC's concerns regarding probabilistic volcanic hazard modeling and associated parameters.

DAY 2 - FRIDAY, MARCH 31

The second day of the workshop began with presentations in a session on "Methods for Characterizing the Spatial Distribution of Future Volcanism." Bruce Crowe (Los Alamos National Laboratory [LANL]) gave the first talk on spatially homogeneous models. He discussed the application of his model, which treats spatially and structurally similar volcanic centers as "volcanic source zones," and summarized the results of some of the models described in the LANL status report on volcanism studies. Gene Smith (UNLV) gave the next presentation on spatially dependent volcanic hazard models. He described how his model incorporates zones of varying degrees of "risk" based on the ages of the volcanic centers, the volcanic "chain length," and the observed/interpreted structural controls in the YMR. Paul Delaney (USGS) gave the next presentation, entitled "Structures Associated with Dike Intrusion." He described the physical characteristics and kinematics of fracture systems in the Earth's crust, and pointed out that the rate of magma flow from a dike is very sensitive to the fracture geometry, whereas the rate of heat flow is not. Mike Sheridan (State University of New York, Buffalo) gave the final talk of the morning session, entitled "Monte Carlo Volcano Spatial Simulation." He discussed the assumptions and parameters inherent in the Monte Carlo model he has applied to the YMR, along with the model's strengths, weaknesses, and applicability.

Chuck Connor (Center for Nuclear Waste Regulatory Analyses) gave a presentation in the afternoon session, entitled "More Nonhomogeneous Probability Models." He discussed the assumptions inherent in his models and their parameters, along with the applicability of each.

The final presentation was followed by a discussion led by Kevin Coppersmith focusing on data interpretations and issues that should be addressed during the upcoming Workshop on Alternative Interpretations. A list of these issues was compiled by the expert panel and MDT and includes regional and local tectonic regimes, regional volcanic history (including the pre-Pliocene volcanism in the YMR), geometry of magma bodies, and paleomagnetic data for the YMR. Other issues to be discussed in the next workshop include parameter sensitivities of various hazard models and training in elicitation methods and concepts of probability.

SUMMARY
WORKSHOP ON ELICITATION TRAINING AND ALTERNATIVE INTERPRETATIONS PROBABILISTIC VOLCANIC HAZARD ANALYSIS PROJECT YUCCA MOUNTAIN REGION, NEVADA

May 16 and 17, 1995
Holiday Inn-Emerald Springs, Las Vegas, Nevada

The Workshop on Elicitation Training and Alternative Interpretations was the third in a series of four workshops being conducted for the Probabilistic Volcanic Hazard Analysis (PVHA) project, which is sponsored by the U.S. Department of Energy (DOE) and managed by Geomatrix Consultants. The purpose of this workshop was to provide probability assessment and elicitation training to the expert panel, and to review a variety of topics of potential significance to the PVHA assessment at Yucca Mountain. The topics of interest were those identified by the expert panel and the Methodology Development Team (MDT) during discussions at the previous PVHA workshop. The workshop began with a half day training session on elicitation procedures and concepts of probability. Following this was a series of presentations and discussions pertaining to issues and interpretations relevant to the PVHA at Yucca Mountain. Several of the presentations focused on studies of analog regions of potential applicability to Yucca Mountain.

An interactive meeting attended by the expert panel and the MDT was held prior to the workshop on May 15, 1995. This was an informal working meeting for the benefit of the expert panel, as some members of the panel had expressed an interest in obtaining a greater understanding of the available probabilistic models. The meeting commenced with an introduction to probability and uncertainty treatment presented by Peter Morris (Applied Decision Analysis). The expert panel then developed an influence diagram for PVHA that contains elements essential to the analysis and indicates where different data are used. Robert Youngs (Geomatrix Consultants) then described the various models that can be used for hazard analysis, progressing from a simple model to complex models. The goal of the meeting was to provide, through active discussion, information that will assist each panel member in deciding which models best represent his understanding of the physical processes important to future volcanism in the Yucca Mountain region (YMR).

Copies of the overhead transparencies shown during the course of the workshop are included with this summary, along with brief summaries of the speakers' technical presentations. A copy of the influence diagram developed during the May 15 interactive meeting is also provided.

DAY 1 - TUESDAY, MAY 16

A welcome and introduction to the workshop was given by the PVHA project manager, Kevin Coppersmith of Geomatrix Consultants. He briefly reviewed the various hazard models and the process of developing an influence diagram to outline the elements that need to be assessed for modeling the volcanic hazard at Yucca Mountain. He also reviewed the ground rules of the workshops and described the purpose of this workshop and its approach.

Workshop activities commenced with a four hour training session on elicitation and probability assessment, provided by Bruce Judd (Strategic Decisions Group), an advisor to the MDT who is an acknowledged elicitation expert. He discussed the process and procedures of eliciting and quantifying expert judgment, along with the process of assessing probabilities and the range of uncertainty associated with probabilistic assessments. The training session included several exercises in assessing probabilities that involved participation of the project team and workshop observers.

Three speakers gave presentations in the afternoon session on "Issues and Interpretations Relevant to PVHA." Gene Yogodzinski (University of Nevada, Las Vegas [UNLV]) gave a presentation entitled "Sr and Nd Isotopes and the Area of Interest for PVHA at Yucca Mountain." He discussed the geochemical characteristics of the Pliocene and younger basaltic rocks in the YMR and their isotopic signatures. He also defined the "Amargosa Valley Isotopic Province," which he interprets as a "natural boundary" outlining the magmatic system influencing the spatial distribution of the basaltic volcanism in the YMR. Mike Sheridan (State University of New York [SUNY] at Buffalo) gave the next talk, entitled "Volcanic History of the Southern Basin and Range." He described the geologic evolution of western North America from the early Miocene to the present, focusing on the major volcanic features in the Great Basin and southern Basin and Range. Duane Champion (U.S. Geological Survey [USGS]) gave the next presentation, entitled "Assessment of Volcanic Episodicity using Paleomagnetic Field Studies: Lessons Learned from the Yucca Mountain Repository Region." He discussed the temporal aspects of the Pliocene-and-younger volcanic centers in the YMR based on his interpretation of paleomagnetic data collected from the various centers. Mike Sheridan (SUNY at Buffalo) gave the final presentation of the day, entitled "Geometry of Basaltic Volcanic Fields." He discussed the physical characteristics of a variety of basaltic volcanic fields, focusing on the fields of southwestern North America.

The session ended with questions and short statements from some of the project participants and observers. Issues raised in the discussion included cognitive and motivational biases in assessing probabilities, and the elicitation process planned for the PVHA project.

DAY 2 - WEDNESDAY, MAY 17

The second day of the workshop continued with short presentations on "Issues and Interpretations Relevant to PVHA." George Walker (University of Hawaii) gave the first presentation on a wide variety of subjects, which included the level of neutral buoyancy, aa flow structures, flood basalts, and interpretations of the Lathrop Wells volcano. Wendell Duffield (USGS) gave the next presentation, entitled "Late Cenozoic Volcanism, Geochronology, and Structure of the Coso Range, Inyo County, California." He described the volcanic geology of the Coso Range and its significance as a potential analog to the YMR. George Thompson gave the next talk on the surface expression of magma bodies. He presented new data on strain accumulation in the YMR and discussed the possible relationship between deep seated magma bodies and near surface structures. Bruce Crowe (Los Alamos National Laboratory [LANL]) gave the next two presentations in sequence. The first was on the Lunar Crater and Cima volcanic fields, in which he discussed their significance as potential analogs to the YMR. The second was entitled "Volcanic Patterns of the Southwest Nevada Volcanic Field" and was presented in part by Frank Perry (LANL). Spatial and temporal aspects of volcanism in the YMR were discussed, as were isotopic variations and their stability through time. John Stewart (USGS) presented the next talk, entitled "Walker Lane Belt, Nevada and California - An Overview." He discussed the geologic evolution of the Walker Lane Belt, and its relationship to western North America tectonics.

The afternoon session began with a talk by John Wesling (Geomatrix Consultants) entitled, "Neotectonic Setting of Yucca Mountain." He discussed the regional seismicity pattern and the results of some of the trenching studies in the YMR, including recurrence rates and styles of faulting. James Faulds (University of Iowa) gave the next presentation, entitled "Tectonics of Crater Flat." He discussed the structural framework of the Crater Flat area and the potential structural controls on volcanism therein. The final talk of the afternoon session was given by John Geissman

(University of New Mexico). He presented paleomagnetic data from the YMR and discussed its significance with respect to the temporal distribution of the various volcanic centers.

A general discussion of PVHA issues and interpretations led by Kevin Coppersmith followed the technical presentations. Some of the issues discussed were the elicitation schedule and the general process and procedures. Potential topics for the final PVHA workshop were also discussed. The session ended with short statements and questions from some of the project participants and observers.

SUMMARY
WORKSHOP TO REVIEW PRELIMINARY ASSESSMENTS PROBABILISTIC VOLCANIC HAZARD ANALYSIS PROJECT YUCCA MOUNTAIN REGION, NEVADA

December 5 and 6, 1995
Holiday Inn-Emerald Springs, Las Vegas, Nevada

The Workshop to Review Preliminary Assessments was the last of four workshops conducted for the Probabilistic Volcanic Hazard Analysis (PVHA) project, which is sponsored by the U.S. Department of Energy (DOE) and managed by Geomatrix Consultants. The purpose of this workshop was to allow the expert panel members to present and discuss their preliminary assessments used to evaluate volcanic hazard at Yucca Mountain. The preliminary hazard calculations also were presented, and the sensitivities in the various hazard models were discussed. The majority of the presentations by the expert panel focused on the spatial and temporal issues most important to the various hazard models. The discussion of hazard model sensitivity to various PVHA issues was an important aspect of this workshop, as it provided the experts with a framework for evaluating and revising their initial assessments.

Copies of some of the overhead transparencies shown during the course of the workshop are included with this summary, along with brief summaries of the speakers' technical presentations. The preliminary calculated annual probabilities of intersection with the proposed repository aggregated across all experts is included for completeness. However, the probability distributions for individual experts are not provided because these results were preliminary and are being revised.

DAY 1 - TUESDAY, DECEMBER 5

A welcome and introduction to the workshop was given by the PVHA project manager, Kevin Coppersmith of Geomatrix Consultants. In acknowledgement of new workshop observers, he briefly reviewed the members of the expert panel and the methodology development team (MDT), as well as the presenters from previous workshops. In addition, he reviewed the workshop goals and ground rules, and discussed what has occurred since the last workshop held in May. The workshop agenda was shown, and a change noted to postpone discussion of preliminary calculated results until the afternoon.

Mel Kuntz (U.S. Geological Survey [USGS]) gave the first of four presentations pertaining to regional PVHA issues. He discussed the tectonic setting of Yucca Mountain, and the factors influencing the spatial occurrence of volcanism in the Yucca Mountain region (YMR) and the southwest Basin and Range in general. George Thompson (Stanford University) gave the next presentation, which focused on the structural controls of volcanism in the YMR. He discussed the crustal stress regime in the southwest Basin and Range, and the spatial characteristics of faulting and volcanism in the YMR. Rick Carlson (Carnegie Institute of Washington) gave the next presentation, which focused on the background source zone he considered as the region of interest in his hazard assessment. He discussed the primary factors controlling melt production in the YMR, and the applicability of the Amargosa Valley isotopic province (AVIP, defined by G. Yogodzinski in PVHA Workshop 3). R.V. Fisher (University of California, Santa Barbara) gave the final presentation on regional PVHA issues. He discussed his background source zones, pointing out that he considers the Quaternary volcanic fields in the YMR to be most relevant for assessing the background rate of volcanism at Yucca Mountain.

Following a short break, Kevin Coppersmith briefly discussed the criteria the experts considered in their definitions of a volcanic "event". Three presenters followed with discussions of their event definitions. Bill Hackett (WRH Associates) gave the first presentation, which drew largely on the analogy of volcanic events within the eastern Snake River Plain. Mike Sheridan (State University of New York, Buffalo) gave the next presentation on event definition. He discussed the various spatial, temporal, and geochemical aspects of an event, and pointed out that a definition should be based on available data for volcanism in the YMR and must be appropriate for the time scales considered for the hazard analysis. George Walker (University of Hawaii) gave the final presentation of the morning session. His presentation drew on numerous analogs, and he argued that observations suggest volcanic events are short lived (i.e., on the order of 100 years).

The afternoon session began with a presentation by Bruce Crowe (Los Alamos National Laboratory), which focused on event "counts" at selected volcanic centers in the YMR. He noted that the uncertainty in the number of events at various centers is reflected by a large distribution of events. R.V. Fisher gave the next presentation, which was the first of three on spatial issues. He briefly described his spatial models, (field shape, spatial smoothing and zonation), which are based on observations of the basaltic volcanic fields in the YMR and southwest Basin and Range. Mike Sheridan gave the next presentation. He discussed the spatial aspects of his field shape and zonation models, which take into account observations of the basaltic volcanic fields in the YMR and the behavior of fields in analog regions. Mel Kuntz gave the final presentation on spatial models. He briefly reviewed his four alternative models (uniform, zonation, spatial smoothing and field shape), and discussed the geologic features he considered for defining his source zones.

The next three presentations focused on interpreted volcanic source zones. The first speaker was Alexander McBirney (University of Oregon), who presented his source zone map and discussed the types of geologic structures he identified and used to define his zones (e.g., extensional basins, faulted blocks of exposed bedrock, etc.). Wendell Duffield (USGS) and Bill Hackett followed with brief presentations of their interpreted source zones, which are based principally on observed volcanic centers.

Bob Youngs (Geomatrix Consultants) gave the final presentation of the day. He described the three types of event calculations performed (i.e., a point event, a dike or dike set of random length centered on a point event, and a dike or dike set of random length randomly located on a point event), and discussed the preliminary hazard results based on each of the experts' assessments.

The session ended with short questions and comments from observers. Some of the comments and questions pertained to the spatial aspects of volcanism and faulting, the significance of volcanic ashes revealed in trench exposures (i.e., the temporal relationship between faulting and volcanism), and the timeframe used for estimating volcanic hazard in the analysis.

DAY 2 - WEDNESDAY, DECEMBER 6

A welcome to the second day of the workshop was given by Kevin Coppersmith, who announced that revisions to the day's agenda were going to be made to facilitate more discussion on the spatial and temporal issues most sensitive to the hazard results. Following this announcement, Bob Youngs presented and discussed the results of the sensitivity analysis. His analysis showed that spatial issues are more important to the volcanic hazard than are temporal issues. The important spatial issues include whether or not the site lies within a zone of high activity, the length of an event vs. distance to more active sources, the use of source zones vs. spatial smoothing, and smoothing distance factors. The temporal issues of importance include the event counts at a particular center, and the use of a homogeneous vs. a nonhomogeneous recurrence rate.

Following a short break, George Walker continued the presentations from the previous day on interpreted volcanic source zones. Based on his experience, he discussed an approach to defining source zones based on the thickness of underlying lithosphere, as well as the geometry and orientation of dikes and recurrent volcanism. Bruce Crowe gave the final presentation on source zones. He briefly reviewed his zones, and described the basis for the boundaries of his local Crater Flat source zone. Because of the proximity of Crater Flat to the proposed repository, his presentation prompted further discussion on the various structural/tectonic models of the Crater Flat basin, and in particular, the location of its eastern boundary. During this discussion, George Thompson reviewed the new USGS seismic reflection line across the basin and Yucca Mountain, and briefly described his interpretations of the Amargosa Valley aeromagnetic anomalies. The session concluded with a discussion on the ways of expressing the uncertainty in the location of the eastern Crater Flat boundary.

The afternoon session began with a continuation of the discussion on ways to express or capture uncertainty, led by Kevin Coppersmith. He presented each experts' weighted distribution of event counts at selected centers, their weighted distribution of spatial and temporal models, their weighted distribution of hidden event factors, their time periods of interest, and their weighted distribution of dike (event) lengths. George Walker then began a series of presentations on event geometries. He noted that data on dikes are relatively scarce, and that measured dike lengths are related to how much of the dike is exposed at the earth's surface. Bruce Crowe gave the next presentation. He discussed his dike length distribution, which is based primarily on dike exposures in southeast Crater Flat. He also discussed dike orientation and randomness in the regional stress field. Several members of the expert panel commented on their selected event lengths and orientations. Kevin Coppersmith urged the panel members to consider both the (aleatory) uncertainty in the length and orientation of the dikes within a volcanic field as well as the (epistemic) uncertainty in the length and orientation of events being defined for the PVHA.

Peter Morris (Applied Decision Analysis and MDT member) gave the next presentation, entitled "Aggregation of Expert Assessments". His presentation focused on a variety of topics, including the objective of aggregation, results of the elicitations, and conditions for equal weights; he also requested expert panel feedback on the elicitation and aggregation processes. Feedback comments from the expert panel highlighted the importance of the project field trips and training in estimating uncertainties. One suggestion for improving the elicitation process would be to perform an initial elicitation early in the project, to help the experts organize and focus their thoughts on the most relevant hazard issues.

Kevin Coppersmith led a final discussion regarding the schedule for the panel members to revise their elicitation judgements, and stressed the importance of thoroughly documenting the assessments. Carl Stepp (Woodward-Clyde Federal Services and MDT member) continued the discussion of documentation, stating that DOE might use the final document in the license application process. He pointed out that the documentation of the uncertainty of knowledge is critical, and that all data, hypotheses and alternatives, considered or not, need to be documented.

The day ended with comments and questions from some of the observers. One comment was that the final report should be prepared for the scientific community (i.e., suitable for submission to a technical journal) as well as for the license application. The question of "what new data or discoveries could significantly change the experts' assessments" was put to the panel. A wide variety of answers, including the occurrence of an earthquake swarm near Yucca Mountain and the identification of a Quaternary dike or a rhyolitic dome in the region, were mentioned and briefly discussed.

Kevin Coppersmith concluded the workshop by thanking observers for attending, and by thanking the major PVHA project participants, including members of the expert panel, members of the MDT, and the DOE and Yucca Mountain Project M & O participants.