SCPB: NA
QA: L

Civilian Radioactive Waste Management System
Management and Operating Contractor

Probabilistic Volcanic Hazard Analysis for Yucca Mountain, Nevada

BA0000000-01717-2200-00082, Rev. 0

June 1996

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Under Contract Number
DE-AC01-91RW00134

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YUCCA MOUNTAIN
PROBABILISTIC VOLCANIC HAZARD ANALYSIS

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LIST OF APPENDICES

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

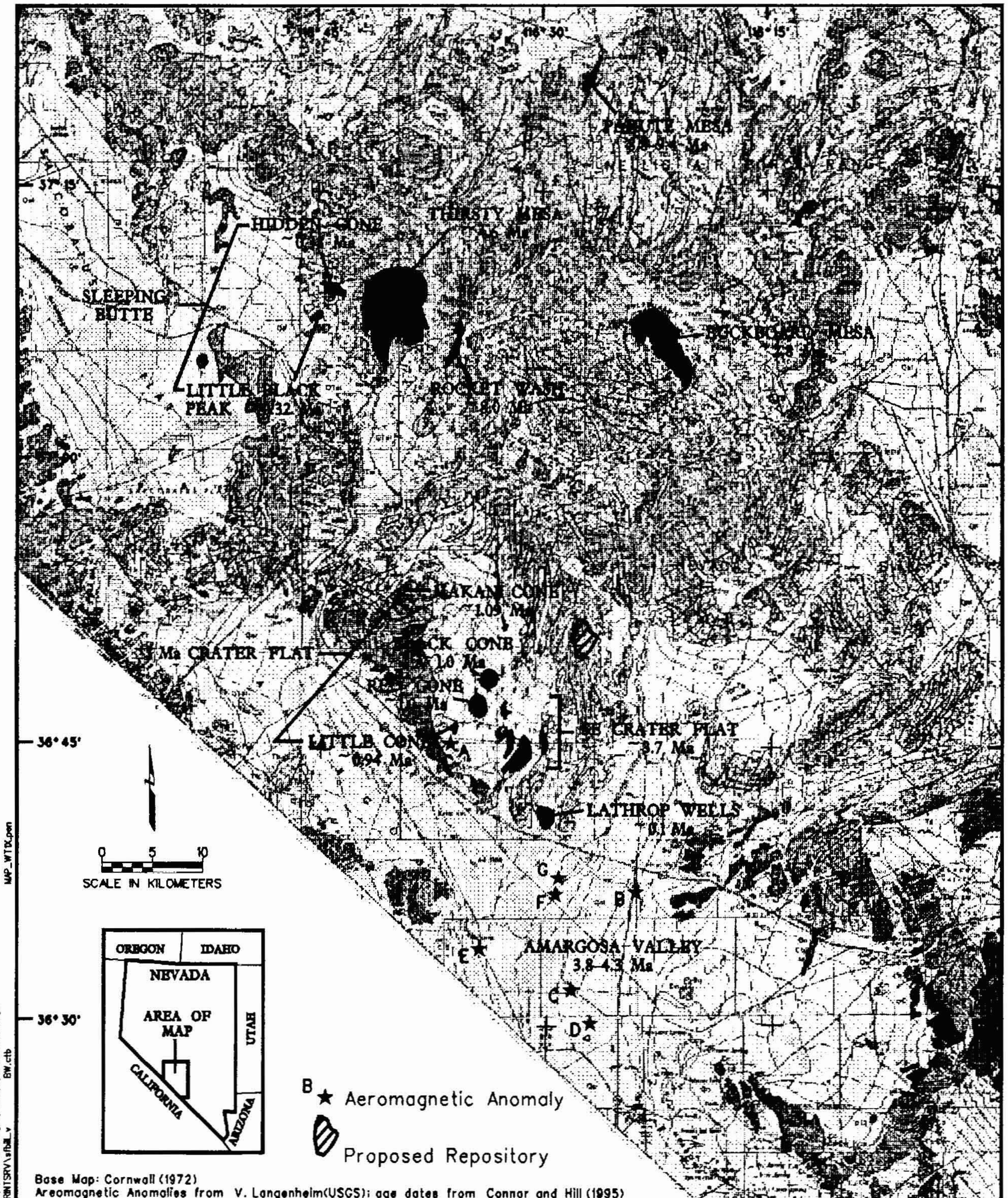
TABLE 1-3
TECHNICAL SPECIALISTS PARTICIPATING IN PVHA WORKSHOPS AND FIELD TRIPS

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.

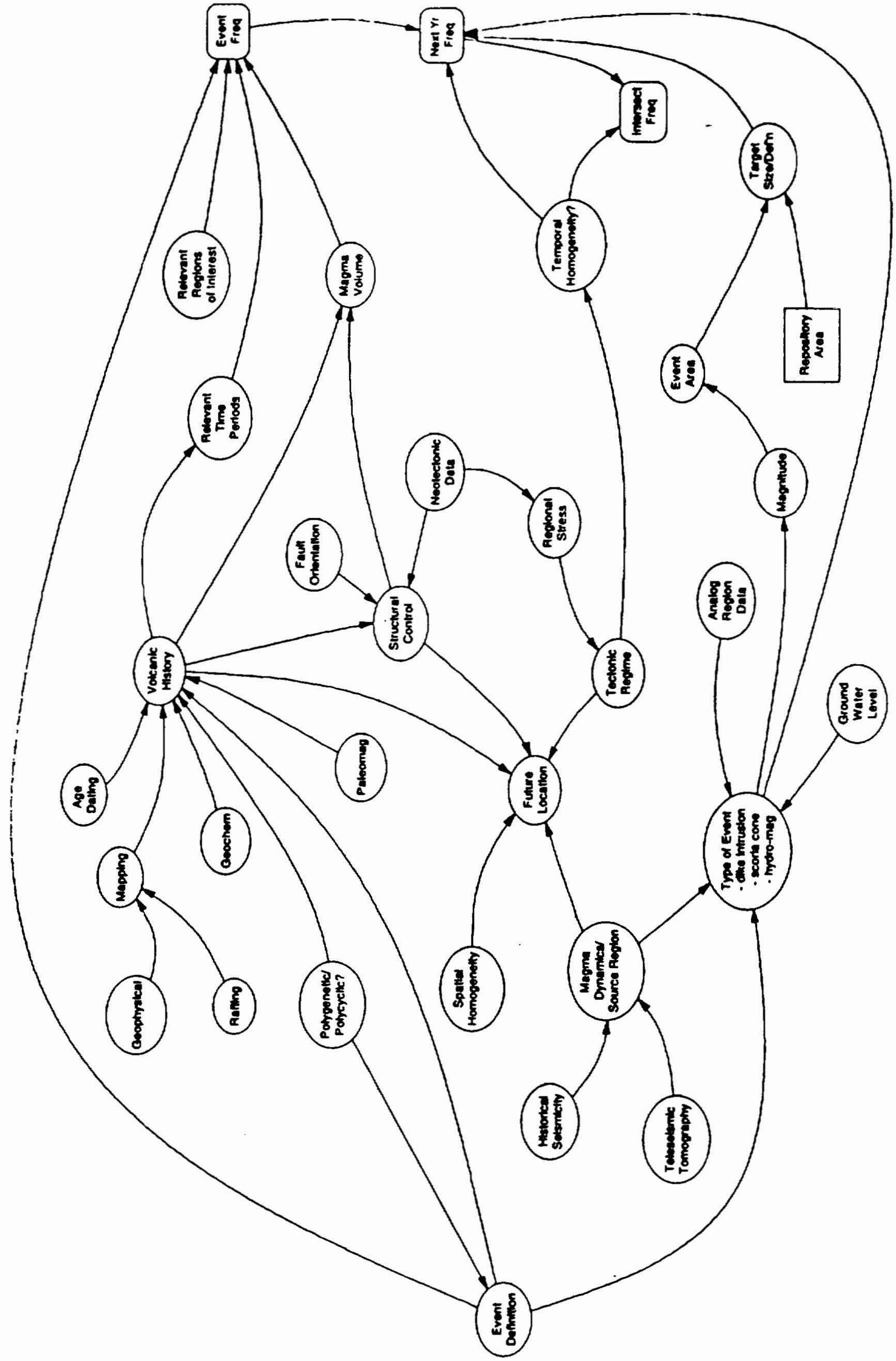


Figure 2-2 Influence diagram developed by the expert panel for the Yucca Mountain PVHA.

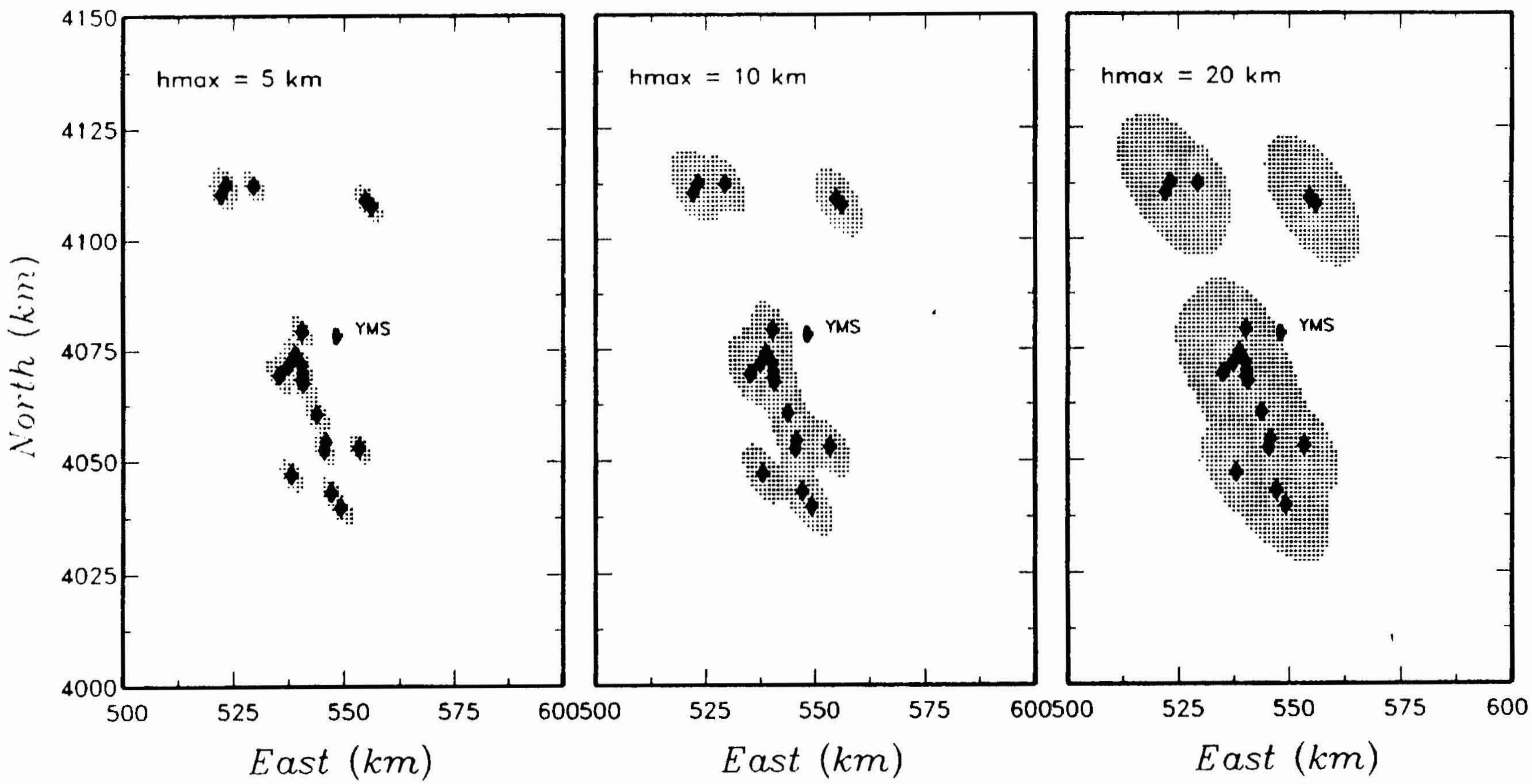


Figure 2-3 Kernel density estimates of the spatial distribution of future volcanic events. Stippled areas show the 95 percent density region computed using smoothing parameters of 5, 10, and 20 km. The density estimates were computed using the maximum number of events assessed for the post-5 Ma time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

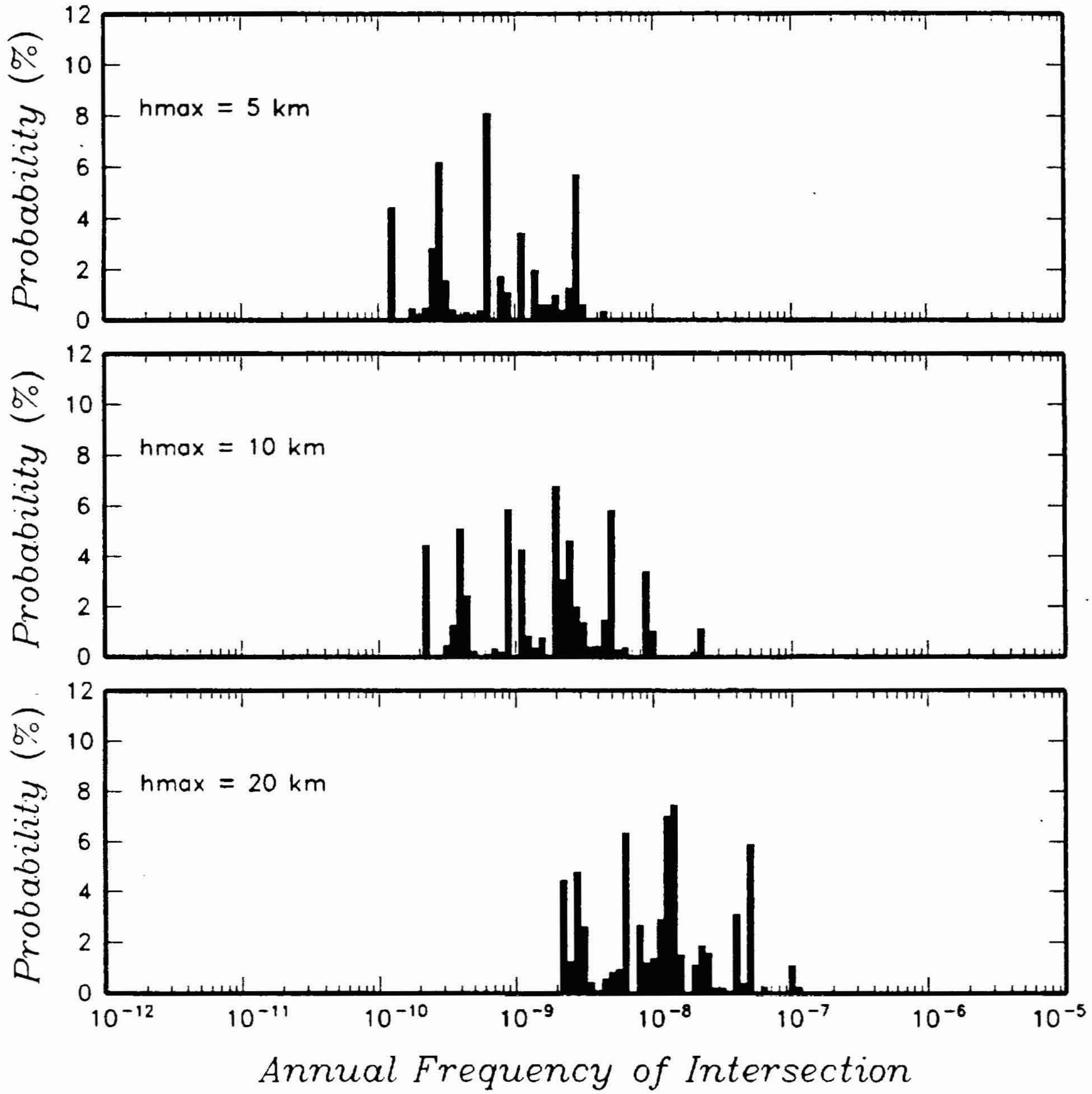


Figure 2-4 Effect of alternative values for the smoothing parameter on the computed distribution for annual frequency of intersecting the repository site. The hazard distributions were computed using the kernel density approach and smoothing parameters of 5, 10, and 20 km.