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Probabilistic Volcanic Hazard Analysis Update (PVHA-U) for Yucca Mountain, Nevada

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CHANGE HISTORY

Revision Number	Interim Change No.	Date	Description of Change
00		July 2008	Initial issue
01		September 2008	Revision to address DOE comments.

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EXECUTIVE SUMMARY

The original Probabilistic Volcanic Hazard Analysis (PVHA) (CRWMS M&O 1996) was an expert elicitation of the probability of volcanic disruption (defined as the physical intersection of a basaltic dike with the repository) at Yucca Mountain, including the uncertainties associated with the estimated probability. The mean frequency of disruption assessed in the PVHA was 1.5e-8 per year, recalculated at 1.7e-8 per year to reflect subsequent changes to the repository footprint. The purpose of this update of the PVHA was to re-assess the probability of a volcanic event disrupting the repository at Yucca Mountain in light of potentially significant new data, including data from aeromagnetic surveys, drilling, and age-dating. The assessment was accomplished by an expert elicitation, following Office of Civilian Radioactive Waste Management (OCRWM) requirements, according to Lead Laboratory procedure SO-PRO-002, *Expert Elicitation*.

This report documents the expert elicitation methodology, the individual expert assessments and hazard results, as well as the updated aggregate assessment of the volcanic hazard at the Yucca Mountain repository site. The description of an igneous event has been expanded from the basaltic dike of PVHA and now includes several possible igneous features: volcanic dikes, sills, eruption column-producing conduits and non-column producing vents. The outputs of the Probabilistic Volcanic Hazard Analysis Update (PVHA-U) are a series of probability distributions that define the annual frequency of various igneous features intersecting the repository footprint.

The expert elicitation process used in the PVHA-U followed the guidance given by the U.S. Nuclear Regulatory Commission (NRC) in their Branch Technical Position on Expert Elicitation (Kotra et al. 1996) as well as guidance given in NUREG/CR-6732 (Budnitz et al. 1997) for formal expert elicitation methodologies in probabilistic hazard analyses. Conducted over four years, the PVHA-U process involved the following steps:

- Elictation planning, including selection of experts
- Compilation and distribution of data and information to experts for review
- Meetings of the experts and individual assessment interviews:
  - Five workshops and field trip, covering data, models, alternative approaches, preliminary assessments and feedback, including preliminary hazard calculations
  - Four assessment interviews, beginning with the development of influence diagrams and ending with individual feedback and finalization of the assessments
- Focused data collection in response to expert requests throughout the project, including drilling and age-dating of magnetic anomalies
- Final hazard calculations and aggregation of expert assessments
- Documentation.

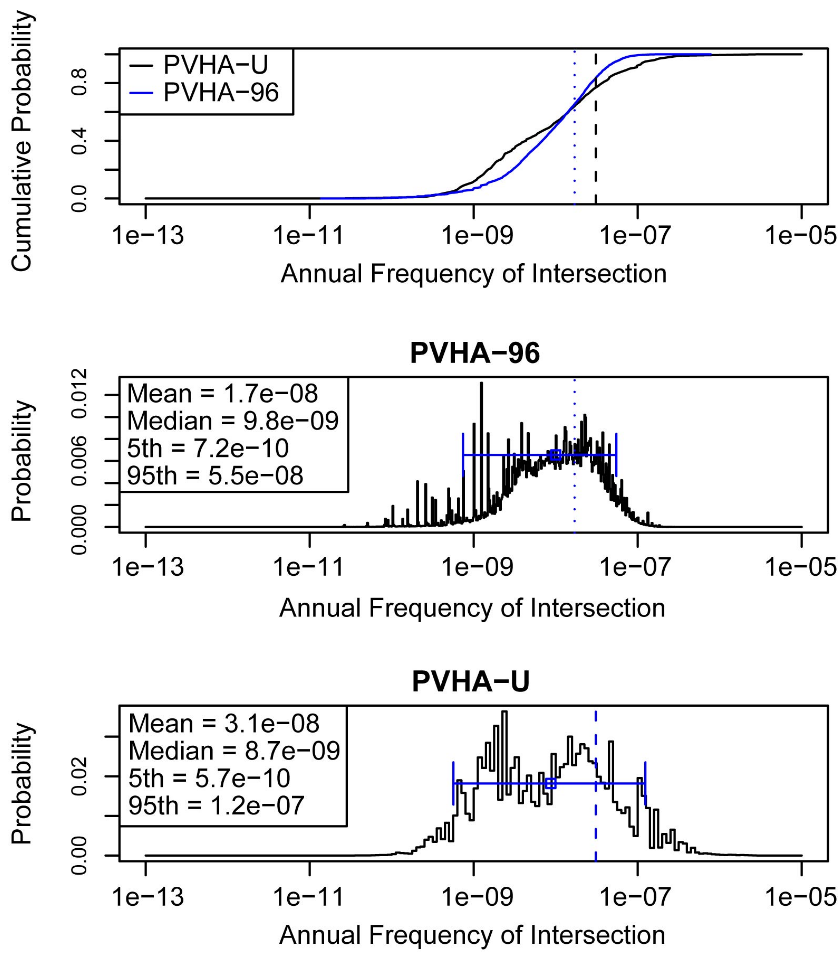
Each PVHA-U expert provided his assessment of the three basic components of the hazard analysis: the spatial and temporal distributions of igneous events and an assessment of the probability that an igneous event at any specific location will intersect the repository footprint. These expert assessments focused on identifying and quantifying uncertainties in the various model components, as required for a probabilistic assessment. Section 3 of this report describes the various models used by the individual members of the expert panel, and the Elicitation Summaries in Appendix D provide a detailed description of the modeling approaches, the key uncertainties, and the technical bases each expert used for his assessment.

Hazard results for each expert's assessments are presented in Section 4.1 of the report. Results are presented for the frequency of intersection of various igneous features with the repository footprint: both the mean frequency and uncertainty in that frequency are presented. Additional hazard results presented include the relative contributions of uncertainty in each model component to uncertainty in the mean hazard and to overall uncertainty, and the potential for multiple features within a single event to intersect the repository footprint.

Although the assessments were made individually by eight experts, the overall result of the study is an aggregation of those individual models and assessment, representing a single estimate of the probability of an intersection of the repository footprint by an igneous event. To develop such an estimate, the experts' assessments are combined (aggregated) with equal weights.

The figure below shows the aggregate hazard distributions for both PVHA-96 and PVHA-U, for the 10,000-year time period. The top panel shows the two cumulative distribution functions on a single plot, the middle panel shows the probability mass function (pmf) for the PVHA-96 results, and the bottom panel shows the pmf for the PVHA-U results. The panels illustrate that the PVHA-U results span a wider range than the PVHA-96 results, and that there is more weight in the tails of the distribution: both more probability associated with lower estimates and more probability associated with higher estimates than in PVHA-96. The comparison of the pmfs shows that the PVHA-U results have more mass at lower values (e.g., at about 1.1e-9) than the PVHA-96 results, and more mass at higher values (e.g., at about 1.0e-7). The expansion of uncertainty and the increased weight in the upper tail leads to an increase in the mean annual frequency of intersection: from 1.7e-8 for PVHA-96 to 3.1e-8 for PVHA-U. The addition of probability mass in the lower end leads to a decrease in the median annual frequency of intersection (from 9.8e-9 to 8.7e-9).

As discussed, the PVHA-96 focused on the frequency of intersection by an event defined as a basaltic dike, while the PVHA-U considers the frequency of intersection by various igneous features. The frequency of intersection shown in the figure is the aggregate frequency of intersection of any igneous feature. The table below shows the frequency of intersection of each of the four types of igneous features specified by the experts.



NOTE: Top panel shows two cumulative distribution functions, one for PVHA-U and the other for PVHA-96. Middle panel shows the probability mass function (pmf) for the PVHA-96 results, and the bottom panel shows the pmf for the PVHA-U results. Dashed vertical line marks the mean for each distribution and plot, open box indicates the median, and "error bars" show the 5th to 95th percentiles

Figure ES-1. Comparison of the Aggregate Hazard Distributions for PVHA-U 10,000-Year Assessment and PVHA-96

Table ES-1. Aggregate Frequency of Intersection for Various Igneous Features with the Repository Footprint, for the PVHA-U 10,000-Year Assessment

Feature	Mean	Median	5th percentile	95th percentile
Any feature	3.1e-8	8.7e-9	5.7e-10	1.2e-7
Dikes	3.1e-8	8.7e-9	5.6e-10	1.2e-7
Sills	3.6e-10	3.7e-11	0	1.2e-9
Eruption column-producing conduit	1.2e-8	2.8e-9	2.1e-10	5.4e-8
Non-column-producing vent	8.1e-9	9.4e-10	0	3.6e-8

NOTE: Two experts assigned zero probability to a sill occurring in an event in the Yucca Mountain Region, and one expert assigned zero probability to a non-column-producing conduit. These assessments result in the 5th percentile of the aggregate distribution being zero.

To support potential future total system performance assessment (TSPA) needs, PVHA-U experts made assessments for both the 10,000-year and 1-My future time periods. The aggregate mean frequency of intersection of any feature with the repository footprint for the 1-My assessment is 3.8e-8. The median frequency is 6.8e-9 and the 5th to 95th percentile range is 4.5e-10 to 1.6e-7. The 1-My distribution is wider and the mean hazard is higher than for the 10,000-year assessment. This expansion of uncertainty results from the assessment by several experts that the longer time horizon allows for the possibility of significantly different rate models than they include in their 10,000-year assessments.

There are several important differences between the PVHA-U and the original PVHA-96 studies that may contribute to the differences in the results. Fundamentally, the central estimates between the two studies, as represented by the median hazard values, are essentially the same. The key difference between the results is the broadening of the range of hazard results (as represented in the 5th to 95th percentile spread) in the PVHA-U, which also contributes to the increase in the mean hazard. A reasonable explanation for the broadening of the uncertainty in the hazard results relates to the evolution of the state of the science for probabilistic volcanic hazard analyses, and for probabilistic hazard analyses in general. At the time of the PVHA-96, the basic structure and framework for a probabilistic volcanic hazard analysis was fairly new and the manner of addressing the spatial and temporal components was still being developed and explored. With time, increased data availability, and additional understanding of the physical processes that give rise to igneous processes in the Yucca Mountain and analogous regions, the representation of the basic components of the PVHA-U has become increasingly detailed and physically realistic. This evolution is to be expected and the hazard-methodology tools have been refined to keep pace with the advances in scientific understanding. The experts in the PVHA-96 study focused their time and efforts on understanding those approaches and developing the necessary parameter estimates. By the time of the PVHA-U, the basic components were better understood, and more sophisticated modeling approaches were in common use. As the experts were now more familiar with the basic modeling approaches, they devoted considerable effort to considering a broader range of conceptual models, to capturing more complex models and approaches to defining the spatial and temporal behavior, and to characterizing the events more thoroughly. It is likely that inclusion of these additional models and approaches was the primary contributor to the broader range of hazard results.

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ACRONYMS AND ABBREVIATIONS

ACNW	Advisory Committee on Nuclear Waste
ACNW&M	Advisory Committee on Nuclear Waste and Materials
AEC	U.S. Atomic Energy Commission
AM	Andrew McBirney
AMISE	asymptotic mean-integrated squared error
ASTM	American Society for Testing and Materials
AVIP	Amargosa Valley Isotopic Province
BC	Bruce Crowe
BSC	Bechtel SAIC Company
CC	Charles Connor
CDF	cumulative distribution function
CF	Crater Flat
CF-AD	Crater Flat–Amargosa Desert
CNWRA	Center for Nuclear Waste Regulatory Analyses
CoV	coefficient of variation
CV	cumulative volume
DOE	U.S. Department of Energy
EPA	U.S. Environmental Protection Agency
FS	Frank Spera
GIS	Geographic Information System
GPS	Global Positioning System
GT	George Thompson
HLW	high-level radioactive waste
IPCC	International Panel on Climate Change
ka	1,000 years ago
KK NPP	Kashiwazaki Kariwa nuclear power plant
ky	1,000 years
KD	kernel density
KTI	Key Technical Issue
LANL	Los Alamos National Laboratory
Ma	million years ago
MDT	Methodology Development Team
MK	Mel Kuntz
MS	Michael Sheridan
My	million years

ACRONYMS AND ABBREVIATIONS (Continued)

NAS	National Academy of Sciences
NPP	nuclear power plant
NRC	U.S. Nuclear Regulatory Commission
NWPA	Nuclear Waste Policy Act
NWTRB	Nuclear Waste Technical Review Board
OCS	Office of the Chief Scientist
PADE	Pliocene Amargosa Desert East
PADW	Pliocene Amargosa Desert West
PCF	Paintbrush Canyon Fault
PDF	probability density function
PMF	probability mass function
PSECF	Pliocene SE Crater Flat
PSHA	Probabilistic Seismic Hazard Analysis
PVHA	Probabilistic Volcanic Hazard Analysis
PVHA-U	Probabilistic Volcanic Hazard Analysis-Update
QA	quality assurance
QCF	Quaternary Crater Flat
SCV	smoothed cross-validation
SD	standard deviation
SECF	Southeastern Crater Flat
SNVF	Southwest Nevada Volcanic Field
SRP	Snake River Plain
SSHAC	Senior Seismic Hazard Analysis Committee
OCRWM	Office of Civilian Radioactive Waste Management
TFI	Technical Facilitator/Integrator
TI	Technical Integrator
TSPA	total system performance assessment
USGS	U.S. Geological Survey
YM	Yucca Mountain
YMP	Yucca Mountain Project
YMR	Yucca Mountain region
WH	William Hackett
WWF	Windy Wash Fault

1. INTRODUCTION

1.1 OBJECTIVES

The original Probabilistic Volcanic Hazard Analysis (PVHA) (CRWMS M&O 1996) was an expert elicitation of the probability of volcanic disruption of the repository at Yucca Mountain, including the uncertainties associated with the estimated probability. In this context, "disruption" meant the physical intersection of a basaltic dike with the repository, and "probability" was defined as an annual frequency. The mean frequency of disruption assessed in the PVHA was 1.5e-8 per year. The PVHA-96 value was recalculated to reflect subsequent changes to the repository layout, and based on the latest recalculation the new mean frequency of intersection is 1.7e-8 (BSC 2004a). Note that throughout the text of this report, we use "PVHA" and "PVHA-96" to refer to the original study (CRWMS M&O 1996). We use "PVHA-Update" or "PVHA-U" to refer to this update.

The purpose of updating the PVHA was to assess the probability of a volcanic event disrupting the repository at Yucca Mountain in light of potentially significant new data, including data from aeromagnetic surveys, drilling, and age-dating. The assessment was accomplished by an expert elicitation, following Office of Civilian Radioactive Waste Management (OCRWM) requirements, according to Lead Laboratory procedure SO-PRO-002, *Expert Elicitation*. This report describes and documents the expert elicitation methodology used, presents each of the individual expert assessments that resulted from the elicitation process and identifies the data and publications provided to the experts as part of the process, and describes the elicitation results, sensitivity analyses, and updated assessments of the volcanic hazard at the Yucca Mountain repository site. The description of an igneous event has been expanded from the basaltic dike of PVHA and now includes several igneous features: volcanic dikes, sills, eruption column-producing conduits and non-column producing vents. The outputs of the PVHA-U are a series of probability distributions that define the annual frequency of various igneous features intersecting the repository footprint.

The report consists of five numbered sections and five appendices. Section 1 provides an introduction to the PVHA-U project and organization, and provides an updated description of the geologic setting of the Yucca Mountain site compared to the setting description that supported the 1996 PVHA. Section 2 describes the expert elicitation process used in the PVHA-U. Section 3 summarizes the expert assessments in terms of the models and parameters that were used in each hazard model. Section 4 provides the volcanic hazard results and sensitivity analyses conducted to identify the dominant contributors to the hazard results. Section 5 lists the references cited in the report. Biographies of the expert panel members are given in Appendix A. Appendix B summarizes the datasets that were provided to the expert panel to assist them in their assessments. The workshop summaries are given in Appendix C. The assessments made by each member of the expert panel are given in their Elicitation Summaries, which are contained in Appendix D. Finally, Appendix E provides details of the volcanic hazard analysis formulation and calculations.

1.2 RELATIONSHIP OF PVHA-U TO PVHA

1.2.1 History Leading to the PVHA Update

Following completion of the PVHA in 1996 (CRWMS M&O 1996), availability of new information and continued interest in the volcanic hazard by project staff and various oversight groups led to the decision to update the PVHA. Table 1-1 provides a timeline of the decision process that led to this update. New aeromagnetic and ground magnetic data (Blakely et al. 2000) suggested the potential for an increased number of buried volcanic centers in Crater Flat (O'Leary et al. 2002). In accordance with U.S. Department of Energy (DOE) expert elicitation procedures (PA-PRO-0202[1]) and consistent with guidance from the U.S. Nuclear Regulatory Commission (NRC) (Kotra et al. 1996, p. 18, 30), the new data were evaluated for their significance using sensitivity analyses. The DOE conducted a study (Ziegler 2002) that examined the sensitivity of the frequency of intersection of the repository footprint by a volcanic event, as indicated by the PVHA, to an increase in the number of buried volcanic centers in Crater Flat, northern Amargosa Desert, and Jackass Flats. The study was based on interpretation of the aeromagnetic data. The sensitivity study indicated that an assumption of additional buried volcanic centers would result in modest increases in the mean annual frequency of intersection of the repository. These increases, however, were less than a half an order of magnitude, and thus not considered to be significant according to the definition given in Brocoum (1997).

DOE provided the results of the sensitivity study to the NRC staff for review. The NRC staff concluded that the information DOE submitted did not provide an adequate technical basis to evaluate the likely impacts of the new aeromagnetic and ground magnetic data on the volcanic hazard estimate (Schlueter 2002). The NRC staff specified that additional information was needed to close Key Technical Issue (KTI) Igneous Activity Agreement (IA) 1.02. The agreement includes provisions for updating the PVHA expert elicitation in accordance with NUREG-1563, *Branch Technical Position on the Use of Expert Elicitation in the High-Level Radioactive Waste Program* (Kotra et al. 1996).

DOE made a regulatory commitment to complete a program of field studies (aeromagnetic survey, drilling, and sampling), data analysis, and an update to the PVHA completed in 1996, to "confirm the licensing basis for the characterization of the volcanic hazard for the Yucca Mountain repository" (Ziegler 2003). The field studies program was conducted as planned and this document completes the regulatory commitment to update the PVHA in light of the new data.

[1] The governing procedure at the time was Bechtel SAIC Company (BSC) procedure PA-PRO-0202 *Expert Elicitation*. Beginning October 1, 2006, the governing procedure is Lead Laboratory procedure SO-PRO-002, *Expert Elicitation*.

Table 1-1. Summary of the Key Events and Documents That Led to the Update of the PVHA (CRWMS M&O 1996)

Timeframe	Reference	Key Conclusions
1996	CRWMS M&O 1996. *Probabilistic Volcanic Hazard Analysis for Yucca Mountain, Nevada.* BA0000000-01717-2200-00082 REV 0. Las Vegas Nevada: CRWMS M&O.	PVHA completed.
2000-2002	Blakely, R.J.; Langenheim, V.E.; Ponce, D.A.; and Dixon, G.L. 2000. *Aeromagnetic Survey of the Amargosa Desert, Nevada and California: A Tool for Understanding Near-Surface Geology and Hydrology.* Open-File Report 00-188. Denver, Colorado: U.S. Geological Survey. O'Leary, D.W.; Mankinen, E.A.; Blakely, R.J.; Langenheim, V.E.; and Ponce, D.A. 2002. *Aeromagnetic Expression of Buried Basaltic Volcanoes Near Yucca Mountain, Nevada.* Open-File Report 02-020. Denver, Colorado: U.S. Geological Survey.	New aeromagnetic and ground magnetic data became available that suggest the potential for an increased number of buried volcanic centers in Crater Flat.
2002	Ziegler, J.D. 2002. "Transmittal of Report Addressing Key Technical Issue (KTI) Agreement Item Igneous Activity (IA) 1.02." Letter from, J.D. Ziegler (DOE) to J.R. Schlueter (NRC), September 26, 2002, Las Vegas, Nevada, U.S. Department of Energy.	DOE examined the sensitivity of the frequency of intersection of the repository footprint by a volcanic event, as indicated by the PVHA, to an increase in the number of buried volcanic centers in Crater Flat, as interpreted from the aeromagnetic data. Sensitivity study indicated a modest increase in the mean annual frequency of intersection of the repository; transmitted to NRC for review.
2002	Schlueter, J.R. 2002. "Request for Additional Information – Igneous Activity Agreement 1.02." Letter from J.R. Schlueter (NRC) to J.D. Ziegler (DOE), December 19, 2002, with enclosure, "NRC Review of DOE Documents Pertaining to Igneous Activity Key Technical Issue Agreement Item 1.02."	The NRC staff concluded that the information DOE submitted did not provide an adequate technical basis to evaluate the likely impacts of the new aeromagnetic and ground magnetic data on the volcanic hazard estimate and that additional information was needed.
2003	Ziegler, J.D. 2003. "Igneous Activity Agreement (IA) 1.02 Additional Information Needed (AIN-1): U.S. Department of Energy (DOE) Position on Volcanic Hazard at Yucca Mountain, Nevada, and Plans for Confirmatory Studies." Letter from, J.D. Ziegler (DOE) to J.R. Schlueter (NRC), November 11, 2003, Las Vegas, Nevada, U.S. Department of Energy.	DOE made a regulatory commitment to complete a program of field studies (aeromagnetic survey, drilling, and sampling), data analysis, and an update to the PVHA.
2004	Reamer, C.W. 2004. "Pre-Licensing Evaluation of Igneous Activity Key Technical Issue Agreement 1.02." Letter from C.W. Reamer (NRC) to J. Ziegler (DOE/ORD), November 5, 2004, 1110043890, with enclosures.	NRC encourages DOE to complete the testing and analysis program and concludes that completion of the planned activities may contribute to establishing a reasonable basis for constraining uncertainties. Issues are identified for consideration in the PVHA update.

As discussed in Section 2, the expert elicitation process used in the PVHA-U followed the guidance given by Kotra et al. (1996) as well as guidance given in NUREG/CR-6732 (Budnitz et al. 1997) for formal expert elicitation methodologies in probabilistic hazard analyses. The PVHA-U is unique in that it is an update to a previous expert elicitation. Although general guidance is given regarding updating (Kotra et al., 1996, p. 18, 30), specific guidance is not provided on when an update is necessary and, if so, how to update an elicitation. For example, Kotra et al. (1996, p. 30) note that the need to update an elicitation should be considered when new data and information are deemed to be "significant." The evaluation of the effect on the hazard estimate of new aeromagnetic data conducted by the DOE (Ziegler 2002) concluded that the new data would not lead to a significant change in the hazard results. However, the NRC staff disagreed with the DOE assessment and concluded that "the DOE Letter Report does not provide an adequate technical basis to evaluate the likely effects on DOE probability models from credible interpretations of new aeromagnetic and ground magnetic data" (Schlueter 2002). As a result, the DOE committed to a program of additional data collection and an update of the PVHA in light of those data (Ziegler 2003). However, the PVHA provides the fundamental licensing basis for the assessment of the probability and consequences of unlikely future igneous activity at the repository site. This update demonstrates the robustness of that licensing basis.

1.2.2 Consideration of 10,000-Year and 1,000,000-Year Time Periods

At the time of PVHA, the radiation protection standard developed by the Environmental Protection Agency (EPA) (40 CFR 191) prescribed a 10,000-year compliance period for the performance of the repository after permanent closure. A legal challenge to 40 CFR 191 led to the promulgation of a radiation protection standard specific to Yucca Mountain (40 CFR 197), and that rule was challenged. In July 2004, the U.S. Court of Appeals for the District of Columbia Circuit upheld a challenge to EPA's 10,000-year compliance period, ruling that EPA's individual radiation protection standard was not based upon and consistent with recommendations of a National Academy of Sciences (NAS) panel (National Research Council, 1995) as required by Title VIII, Section 801(a)(2) of the Energy Policy Act of 1992 (Pub. L. 102-486), and that EPA had not sufficiently justified its decision to apply compliance standards only to the first 10,000 years after disposal on policy grounds. The NAS stated that a compliance assessment was feasible "on the time scale of the long-term stability of the fundamental geologic regime—a time scale that is on the order of 10^6 years at Yucca Mountain" and recommended that compliance assessment be conducted for the time when the greatest risk occurs. In response to the Court's opinion, the EPA has proposed revising the standard (the Proposed Rule) (40 CFR 197) (70 FR 49014). The Proposed Rule calls for a two-tiered standard for postclosure performance. Two compliance periods are specified, each with an associated public dose limit: 10,000 years following closure, and from 10,000 to 1,000,000 years following closure.

To address the postclosure performance requirements, the Total System Performance Assessment (TSPA) has been calculated for time periods as long as 1,000,000 years (1 My). To support potential future TSPA uses, the assessments made by the experts in the PVHA-U are for both 10,000-year and 1 My future time periods. In the Supplementary Information to the proposed rule (70 FR 49014), the EPA provides guidance to be followed in developing the assessments for the 10,000 to 1 My timeframes. That guidance was summarized and provided to the experts with particular emphasis on the implications for the PVHA-U.

1.3 PROJECT ORGANIZATION

The responsibilities of various participants on the PVHA-U project are described below. The technical roles of the participants are described in detail in Section 2.3 of this report.

- *Methodology Development Team (MDT)* – This team designed, conducted, and managed the elicitation so that the established project objectives were met. The MDT was responsible for developing the elicitation plan, identifying qualified experts, providing datasets to the experts, organizing and running workshops, conducting the elicitation interviews, providing any supporting calculations requested by an expert, calculating preliminary and final hazard results, preparing the PVHA-U report, and submitting documents to the records system. Members of the MDT had several roles: *facilitators* were involved directly in eliciting the judgments of the members of the expert panel; *generalists* are familiar with scientific aspects of the analysis; *subject matter experts* have detailed knowledge of volcanism and familiarity with the relevant datasets; *normative experts* provide expertise in decision analysis and elicitation techniques; and *modelers* provide detailed modeling and calculation support to the experts and conduct the hazard analysis itself.

- *Elicitation Manager* – This individual was responsible for organizing and managing the workshops and elicitation interviews. The Elicitation Manager is a member of the MDT and the principal technical interface with the expert panel. Dr. Kevin Coppersmith was the Elicitation Manager for the PVHA-U.

- *Experts* – Qualified individuals who were members of the expert panel and who provided their judgments and assessments regarding models, parameters, and uncertainties pertaining to the volcanic hazard at Yucca Mountain.

- *Technical Specialists* – Individuals who provided written material and/or presented at workshops specialized data and interpretations to the experts.

- *Peer Reviewers* – Individuals who were independent of the PVHA-U elicitation and charged with reviewing the *process* being followed for conducting the expert elicitation. They were "participatory" peer reviewers (Budnitz et al. 1997) and provided their critiques and advice at various times throughout the PVHA-U elicitation.

The members of the MDT and their responsibilities for the PVHA project are summarized in Table 1.3-1. The roles of "generalists" and "normative experts" are consistent with those specified in DOE and NRC guidance concerning the procedures for expert elicitation (Kotra et al. 1996; Budnitz et al. 1997). The qualifications of each of the individuals on the MDT are summarized below.

The members of the expert panel and their affiliations are listed in Table 1.3-2. Brief biographies for members of the expert panel are provided in Appendix A. The roles and responsibilities of each expert 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, participation on the field trip, or through written reports. The participants in the workshops and field trip are given in Appendix C.

Drs. Robert J. Budnitz and J. Carl Stepp were the Peer Reviewers for the PVHA-U. Their qualifications are summarized below.

Methodology Development Team Qualifications

The MDT was composed of representatives from the DOE Office of the Chief Scientist (OCS), Lead Laboratory (Sandia National Laboratory), and subcontractors. The specific individuals and their roles are shown on Table 1.3-1. The DOE manager Eric Smistad and Lead Laboratory responsible manager Thomas Pfeifle[2] were responsible, within their respective organizations, for planning and managing the evaluation of the potential for igneous activity at the Yucca Mountain site, which includes the probabilistic volcanic hazard analysis (the focus of this report).

Dr. Kevin Coppersmith was the Elicitation Manager and a facilitator for the original PVHA elicitation and has had comparable roles for several expert elicitations, including the *Probabilistic Seismic Hazard Analyses for Fault Displacement and Vibratory Ground Motion at Yucca Mountain, Nevada* (CRWMS M&O, 1998a). Dr. Coppersmith's professional expertise lies in the quantification of uncertainties in earth sciences data and incorporating these uncertainties into probabilistic hazard analyses.

Dr. Frank Perry was a facilitator for the original PVHA and, as a volcanologist, he has extensive knowledge of the technical issues to be assessed. For many years, Dr. Perry has been active in the geologic data collection program in the Yucca Mountain region, which has provided the fundamental basis for the volcanic hazard analyses to date. His recent research addresses the potential for additional volcanic events in the Yucca Mountain region, including the aeromagnetic survey and the ongoing drilling and analysis program.

Dr. Roseanne Perman was a facilitator for the original PVHA, and she also possesses knowledge of the technical issues to be assessed as well as the process involved in conducting an expert elicitation. She has been involved in conducting several elicitations including the Probabilistic Seismic Hazard Analysis (PSHA) for Yucca Mountain. Her work on that elicitation, and on the original PVHA, included working with the experts to provide complete and clear documentation of their assessments.

Dr. Robert Youngs was a facilitator for the original PVHA and was responsible for the hazard calculations. He has also been involved with several other expert elicitations, including the PSHA for Yucca Mountain. For the PVHA-U, he worked with the experts to formulate their assessments, and provided oversight for the supporting calculations and all hazard calculations and sensitivity analyses.

Dr. Karen Jenni is a Decision Analyst with extensive experience as a normative expert in expert elicitation processes. She had two primary roles in this project: first, training experts in the

[2] With the transition of the PVHA-U from BSC to the Lead Laboratory in October, 2006, the responsible manager has transitioned from Michael Cline to Tom Pfeifle.

elicitation tasks and the use of probability to express uncertainty; and second, working with the experts to formulate and express their conceptual models and detailed assessments completely and consistently. She also provided assistance to other team members in modeling and conducting the hazard calculations and sensitivity analyses. She has served in similar roles for other elicitations, including acting as the normative expert for a recent probabilistic seismic hazard analysis for nuclear power plants in Switzerland.

Mr. Timothy Nieman is a Decision Analyst with significant quantitative modeling experience. He worked as a normative expert with other members of the MDT and the experts to formulate each expert's models, developed preliminary and feedback models for each expert and conducted supporting calculations as needed during the assessment process, and had primary responsibility for all hazard calculations and sensitivity analyses.

Mr. Terry Crump is a geologist with long-term experience in the igneous program for the Yucca Mountain project. His past participation on the PVHA-96 and igneous consequences activities provided continuity on the PVHA-U with other aspects of the Project. Mr. Crump worked in all aspects of the implementation of the PVHA-U process, including workshops, responding to data requests, and documentation.

Peer Reviewers

Dr. Robert Budnitz and Dr. Carl Stepp were peer reviewers. Both formerly held positions as senior members and supervisors on the staff of the U.S. Nuclear Regulatory Commission and for many years both have been involved with numerous nuclear reactor safety and high-level radioactive waste safety analyses, including expert elicitation studies and probabilistic hazard assessments.

Table 1.3-1. Methodology Development Team Members and Their Principal Responsibilities

NAME	AFFILIATION	RESPONSIBILITY
Eric Smistad	DOE/OCS	DOE Manager
Thomas Pfeifle	Sandia National Laboratories (SNL)	Responsible Manager
Kevin J. Coppersmith	Coppersmith Consulting, Inc.	Elicitation Manager Facilitator, Generalist
Frank Perry	Los Alamos National Laboratory (LANL)	Facilitator, Subject Matter Expert
Robert R. Youngs	Geomatrix Consultants, Inc.	Facilitator, Generalist, Modeler
Roseanne C. Perman	Geomatrix Consultants, Inc.	Facilitator, Generalist
Karen Jenni	Insight Decisions LLC	Facilitator, Normative Expert
Tim Nieman	Decision Applications, Inc.	Facilitator, Normative Expert, Modeler
Terry Crump	Integrated Science Solutions, Inc.	Generalist

Table 1.3-2. Expert Panel

Dr. Bruce M. Crowe Battelle Memorial Institute	Dr. Alexander R. McBirney University of Oregon, Emeritus
Dr. William R. Hackett Integrated Science Solutions Inc.	Dr. Michael F. Sheridan University at Buffalo
Dr. Charles B. Connor University of South Florida	Dr. George A. Thompson Stanford University
Dr. Mel A. Kuntz U.S. Geological Survey, retired	Dr. Frank J. Spera University of California at Santa Barbara

NOTE: Dr. Richard Carlson (Carnegie Institute of Washington) and Dr. Wendell Duffield (Northern Arizona University) resigned from the panel in 2006 because they could not devote sufficient time to complete the elicitation; see Section 2.3 for additional information.

1.4 GEOLOGIC SETTING

Volcanism within 50 to 60 km of Yucca Mountain is part of the Southwest Nevada Volcanic Field (SNVF) which lies within the central Basin and Range province. Volcanism and crustal extension within this portion of the Basin and Range began about 15 million years ago (Ma) (Sawyer et al. 1994; Sonder and Jones 1999), with the SNVF marking the southern extent of a sweep of silicic volcanism that began in the northern Basin and Range about 45 Ma (Dickinson 2006). The SNVF lies at the southern end of the north-south trending ranges that characterize the northern Basin and Range, and within the Walker Lane belt that imparts a component of dextral shear to many of the structural features of the SNVF.

Volcanism in the SNVF began with large-volume silicic eruptions that formed numerous nested calderas in the middle Miocene between about 15 and 11.4 Ma (Sawyer et al. 1994). The Timber Mountain caldera (See Figure 1.4-1) formed above older calderas beginning about 11.6 Ma. After the period of intense silicic magmatism ended at 11.4 Ma, smaller-volume caldera-forming magmatism migrated to the northwest in the SNVF (north of the region shown in Figure 1.4-1) to form the Black Mountain caldera at about 9.4 Ma and the Stonewall Mountain caldera at 7.5 Ma, the latter marking the end of silicic volcanism in the Yucca Mountain region (YMR as defined in Figure 1.4-1).

The end of the most intense silicic volcanism at 11.4 Ma marked the transition to middle Miocene basaltic volcanism from eruptive centers mainly to the south of the Timber Mountain caldera complex (Figure 1.4-1). The middle Miocene phase of basaltic volcanism (~11 to 9 Ma) produced relatively voluminous lava flows with typical volumes of 2 to 10 km^3, although these estimates are minimum values because of unknown amounts of erosion. After the middle Miocene phase of basaltic volcanism, smaller volume eruptions continued into the late Miocene throughout much of the SNVF, ending at about 7.2 Ma (Perry et al. 1998).

Following a hiatus in volcanism of about 2.6 million years, volcanism began again in the early Pliocene (4.6 Ma) with the advent of shield-forming eruptions that produced 2 to 3 km^3 lava flows at Thirsty Mountain, to the northwest of Yucca Mountain (Figure 1.4-1). Subsequent eruptive episodes occurred at approximately 3.8, 2.9, 1.1, 0.35, and 0.08 Ma with systematically decreasing eruption volumes (Figure 1-2). Individual Quaternary volcanoes, which first erupted during the 1.1 Ma episode (Makani, Red, Black, and Little Cones in Crater Flat), have small eruption volumes of 0.1 km^3 or less (Figures 1.4-1 and 1.4-2). The youngest volcano in the region is the Lathrop Wells volcano, 18 km south of Yucca Mountain, has an erupted volume of about 0.12 km^3 (including 0.07 km^3 for the fall sheet, and 0.05 km^3 for the flows and cone) and has been reliably dated using multiple methods at 77±6 thousand years (Heizler et al. 1999).

Crustal extension has occurred throughout the 15-million-year history of the SNVF, but has dramatically declined in the rate of extension since about 10 Ma (Fridrich et al. 1999). Extension has been episodic within the SNVF, and concentrated in localized domains now generally expressed as alluvial-filled basins surrounding the relatively unextended terrain of the central caldera complexes (Sawyer et al. 1994; Fridrich et al. 1999). Most of the basaltic eruptive episodes in the YMR occur within alluvial-filled basins. Because these basins have gradually filled with alluvium over time, several volcanic centers have been partially or completely buried, with progressively older centers buried to greater depths.

The ages and extents of buried basalts have been determined through use of aeromagnetic surveys and drilling (Figure 1.4-3). The highest-resolution aeromagnetic survey, conducted in 2004, revealed aeromagnetic anomalies that could be interpreted as either buried basalt or buried and faulted tuff bedrock (Perry et al. 2005). Subsequent drilling has shown that the sources of anomalies (basalt or tuff) can generally be predicted from the characteristics of the anomalies, including their shapes, and their relationships to nearby surface exposures of faults and tuff units. Of seven drill holes completed in 2005-2006, three encountered buried Miocene basalt ranging in age from approximately 9.5 to 11.2 Ma, while one encountered Pliocene basalt (anomaly G in the northern Amargosa Desert) dated at 3.9 Ma. This age represents the youngest of the basalts that are completely buried and hidden (represented by anomalies G and B, and by inference, anomalies F and H).

1.5 QUALITY ASSURANCE

The PVHA-U spanned the transition of responsibility for conducting scientific activities to the Lead Laboratory. Prior to the transition of the PVHA-U from Bechtel SAIC Company to the Lead Laboratory on October 1, 2006, the PVHA-U was conducted using a version of the Expert Elicitation plan that was consistent with the BSC procedure PA-PRO-0202, *Expert Elicitation*. Following the transition of the PVHA-U to the Lead Laboratory, the PVHA-U was conducted and documented using the Lead Laboratory Elicitation Plan (PLN-MGR-GS-000001; SNL 2007), which was developed to be consistent with the Lead Laboratory's expert elicitation procedure (SO-PRO-002, *Expert Elicitation*).

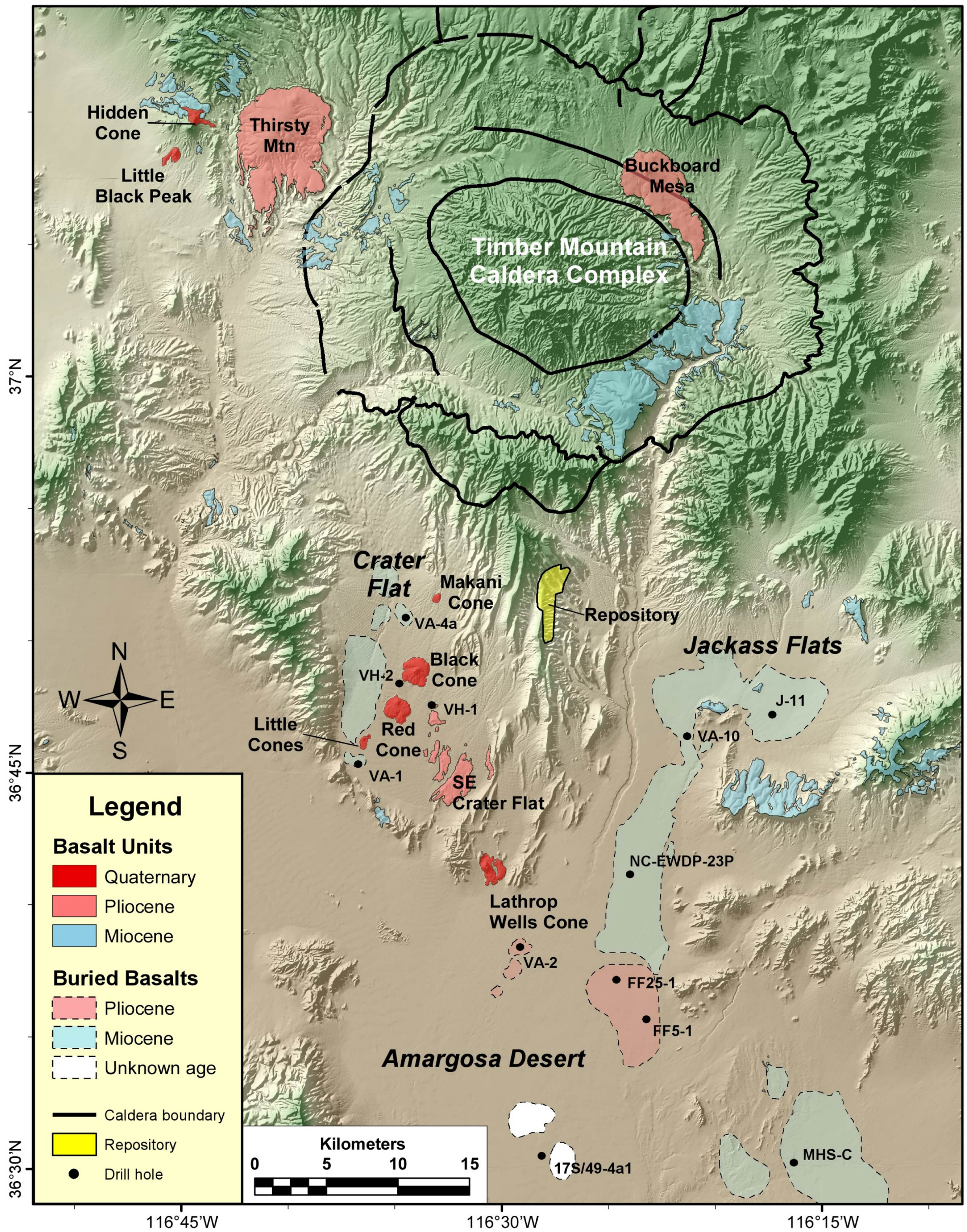
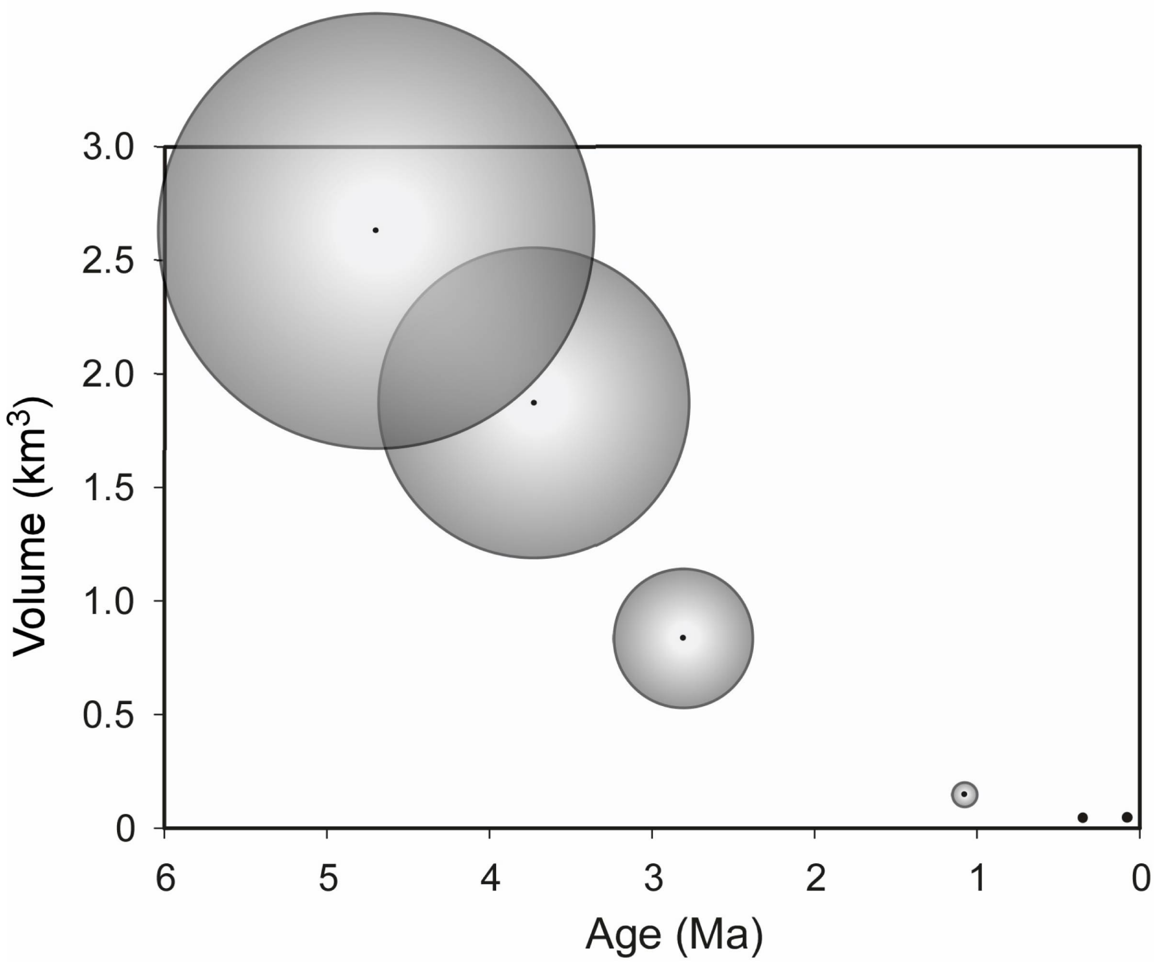
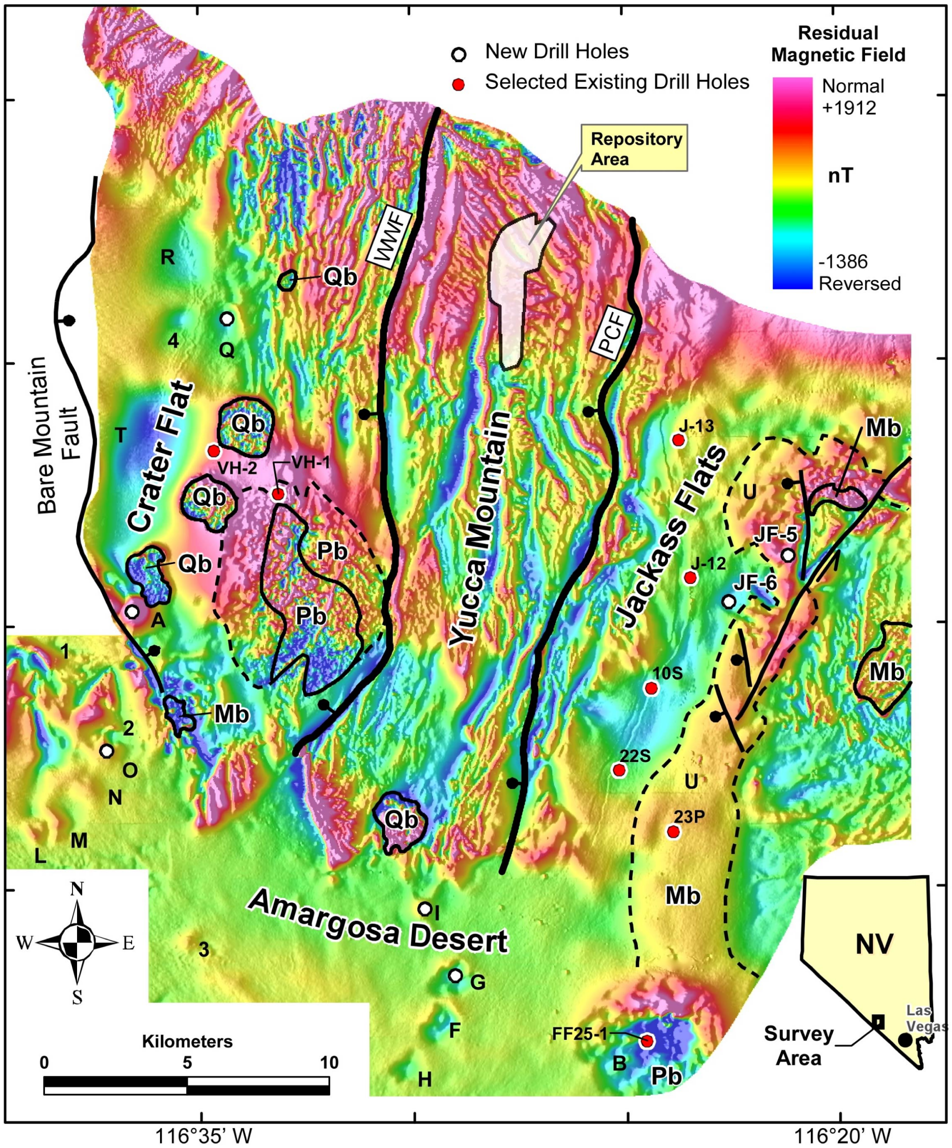


Figure 1.4-1. Distribution of Miocene, Pliocene, and Quaternary Basalt in the Yucca Mountain Region (YMR, defined as the area covered in this figure); Distribution of Buried Basalt in Crater Flat, Jackass Flats, and Amargosa Desert (indicated by patterns enclosed with dashed lines)



NOTE: Symbol diameters are proportional to the volume of each eruptive episode. The sources for the ages and volumes are given in Appendix B.

Figure 1.4-2. Volume versus Age for Pliocene and Quaternary Basalt of the SNVF



NOTE: Windy Wash Fault (WWF) and Paintbrush Canyon Fault (PCF) in the central part of the survey area define the approximate boundaries between uplifted Miocene tuffs of the Yucca Mountain range block and the Crater Flat and Jackass Flats basins. The Bare Mountain Fault defines the western edge of the Crater Flat Basin. Single-character alphanumeric labels indicate anomalies suspected of representing buried basalt. Solid lines enclose outcrops of Quaternary (Qb), Pliocene (Pb), and Miocene (Mb) basalt. The four Quaternary basalts in Crater Flat are 1.1 Ma volcanoes (scoria cones and flows).The Quaternary basalt south of Yucca Mountain is the 77 ka Lathrop Wells volcano. Dashed lines enclose areas of inferred buried basalt associated with outcrops of Pliocene and Miocene lava flows. Red dots indicate selected existing drill holes that confirm the presence of buried basalt. White dots indicate drill holes completed after the 2004 aeromagnetic survey was flown for the purpose of testing tuff versus basalt-sourced anomalies and to characterize the depth, age and composition of buried basalt. Basalt was encountered in drill holes at anomalies Q, A, G, and JF-5. Tuff was encountered in drill holes at anomalies O and I, and tuff is inferred to underlie alluvium at the bottom of the drill hole at JF-6.

Figure 1.4-3. Residual Magnetic Field (measured total field minus the International Geomagnetic Reference Field) from the 2004 Aeromagnetic Survey for Yucca Mountain and Surrounding Basins

2. ELICITATION PROCESS

This section describes the process followed to elicit and incorporate expert judgments about the data, models, and model parameters relevant to assessing volcanic hazards at Yucca Mountain as used to develop the PVHA-U. Described in this section are the methodology and general process followed, from the expert identification and selection process, through the elicitation of expert models and calculation and aggregation of results. The section also discusses relevant guidance on the expert elicitation methodology. Experience has shown that, to be credible and useful, technical analyses such as those performed for the PVHA-U must: (1) be based on sound technical information and interpretations, (2) follow a structured process that considers all available data, and (3) incorporate uncertainties (Budnitz et al. 1997). The technical information and interpretations used in this analysis will be discussed in Sections 2.3.2, 2.3.3 and in Appendix B. The structured process and mechanism for quantifying uncertainties is the use of formal expert elicitation, and is described in Section 2.3.

In the PVHA-U, the term “elicitation” is used in a broad sense to include the processes involved in obtaining the technical evaluations of multiple experts. These processes include reviewing available data, debating technical views with colleagues, evaluating the credibility of alternative views, expressing interpretations and uncertainties in elicitation interviews, and documenting interpretations. In this sense, the elicitation process began with the first workshop and ended with the finalization of the elicitation summaries by each expert. The subsequent steps involving the calculations of hazards based on each expert’s evaluation, aggregation of the expert evaluations, and report preparation were conducted by the MDT.

Consistent with NRC guidance (Kotra et al 1996) and Yucca Mountain Project (YMP) procedures (SO-PRO-002), the evaluations provided by the experts are considered to be fully qualified data.

In Section 2.1 the existing applicable guidance related to expert elicitation is summarized; Section 2.2 provides a schedule of the PVHA-U activities; Section 2.3 describes the process steps in the PVHA-U methodology; Section 2.4 summarizes the modeling and calculations conducted for the project; Section 2.5 explains the process used to aggregate the expert assessments; and Section 2.6 discusses consistency of the PVHA-U process with existing guidance for expert elicitations.

2.1 EXISTING GUIDANCE

The process for conducting the PVHA-U was described in the *Plan for the Expert Elicitation to Update the Probabilistic Volcanic Hazard Analysis (PVHA) for Yucca Mountain, Nevada* (SNL 2007). Applicable guidance for expert elicitation methodologies is given in NUREG-1563, *Branch Technical Position on the Use of Expert Elicitation in the High-Level Radioactive Waste Program* (Kotra et al. 1996). Also applicable is the methodology guidance given in *Recommendations for Probabilistic Seismic Hazard Analysis: Guidance on Uncertainty and Use of Experts* by the Senior Seismic Hazard Analysis Committee (SSHAC) (Budnitz et al. 1997, also referred to as the SSHAC report and NUREG/CR-6732). In particular, the processes for quantifying uncertainties through the use of formal expert elicitation, termed a Study Level 4, are applicable.

2.1.1 NUREG-1563 Guidance

In NUREG-1563 (Kotra et al., 1996), the NRC recognizes that the DOE may use expert elicitation as a means of developing information supporting the license application:

> NRC expects that subjective judgments of individual experts and, in some cases, groups of experts, will be used by DOE to interpret data obtained during site characterization and to address the many technical issues and inherent uncertainties associated with predicting the performance of a repository system for thousands of years. NRC has traditionally accepted, for review, expert judgment to evaluate and interpret the factual bases of license applications and is expected to give appropriate consideration to the judgments of DOE's experts regarding the geologic repository. Such consideration, however, envisions DOE using expert judgments to complement and supplement other sources of scientific and technical information, such as data collection, analyses, and experimentation. (p. iii)

Given the expectation that DOE will use formal expert elicitation, the NRC developed its Branch Technical Position to clarify its position by providing guidelines for when expert elicitations should be conducted and for acceptable procedures to follow:

> In this document, the NRC staff has set forth technical positions that: (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. (p. iii)

2.1.1.1 Conditions for Considering Expert Elicitation

The Branch Technical Positions in NUREG-1563 begin with the identification of the conditions that must be present to warrant consideration of an expert elicitation:

> (1) In matters important to the demonstration of compliance, the use of formal expert elicitation should be considered whenever one or more of the following conditions exist:
>
> > (a) Empirical data are not reasonably obtainable, or the analyses are not practical to perform;
> > (b) Uncertainties are large and significant to a demonstration of compliance;
> > (c) More than one conceptual model can explain, and be consistent with, the available data; or
> > (d) Technical judgments are required to assess whether bounding assumptions or calculations are appropriately conservative. (p. 15)

The volcanic hazard at Yucca Mountain is subject to the conditions identified in (a), (b), and (c). Empirical data that provide a unique interpretation of the probability of future igneous events are limited. The uncertainties associated with the key parameters in the hazard analysis are large and previous iterations of the total system performance assessment (TSPA-VA (CRWMS M&O 1998b) and TSPA-SR (CRWMS M&O 2000)) have shown that the probability of future igneous activity at the site is important to performance. Finally, multiple conceptual models have been defined that are consistent to varying degrees with the available data related to the spatial and temporal models that define the hazard. Accordingly, the DOE concluded that conditions existed that indicated the use of expert elicitation was appropriate for assessing the probability of a future igneous event at Yucca Mountain.

2.1.1.2 Steps in Expert Elicitation

NUREG-1563 defines the components of an acceptable expert elicitation as a series of steps:

Step 1: Definition of objectives
Step 2: Selection of experts
Step 3: Refinement of issues and problem decomposition
Step 4: Assembly and dissemination of basic information
Step 5: Pre-elicitation training
Step 6: Elicitation of judgments
Step 7: Post-elicitation feedback
Step 8: Aggregation of judgments (including treatment of disparate views)
Step 9: Documentation.

These steps have been followed in the PVHA-U, as discussed in Section 2.6.

2.1.2 SSHAC Guidance

Comprehensive guidance on processes to be followed for expert elicitations for hazard analyses has been set forth in the SSHAC report (Budnitz et al., 1997). The guidance was developed under sponsorship of the NRC, EPRI, and the DOE. The SSHAC study was conducted with the purpose of drawing on the experience gained from expert elicitation projects, particularly those conducted for nuclear power plants in the central and eastern United States, and developing a consensus position regarding acceptable methodologies. In reviewing the differences in PSHA estimates conducted by different groups for individual sites, the SSHAC study concluded that the differences were largely due to *procedural* differences in the manner in which the PSHA was conducted. Hence, the SSHAC study concluded that the procedural steps are as important as the technical analyses that comprise a PSHA.

A basic principle defined by the SSHAC (Budnitz et al., 1997, p. 21) is that:

> The underlying basis for the inputs [to a PSHA]… must be the composite distribution of views represented in the appropriate scientific community. Expert judgment is used to represent the informed scientific community's state of knowledge.

As noted in the SSHAC report (Budnitz et al., 1997, p. 21), the goal of any formal expert elicitation process is:

> 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.

In this context, "informed" signifies, hypothetically, that all in the community have a full understanding of the relevant site-specific and appropriate regional data, models, and methods. The SSHAC guidance specifies four "study levels," ranging from a Level 1 study conducted by a single Technical Integrator (TI) and based on data from the available literature, to a Level 4 study involving the formal elicitation of multiple experts by a Technical Facilitator/Integrator (TFI). The PVHA-U is a SSHAC Level 4 study and the PVHA-U methodology is consistent with the structured elicitation formalism associated with that study level, including the integration of the assessments of multiple experts.

2.1.2.1 Expert Roles

The SSHAC report (Budnitz et al., 1997, Section 3.1.3.4) defines the roles of expert *proponents, evaluators,* and *integrators.* An expert proponent advocates a particular technical hypothesis or interpretation, an expert evaluator considers the support for alternative hypotheses and interpretations in the available data and evaluates the credibility or weight to assign to the alternatives, and an expert integrator combines the evaluators' alternative interpretations into a composite distribution that includes uncertainties. The fundamental role of the experts on the project was that of evaluators. The expert evaluators were expected to forego the role of proponents in making their interpretations and evaluating uncertainties. Proponents of specific hypotheses or interpretations participated in the project as technical specialists at workshops and presented their points of view to the experts. Alternative proponent interpretations were presented to the experts and open scientific debate was encouraged. In some cases, individual experts on the panel were asked to "change hats" and to serve as proponents of particular models or interpretations at the workshops. The experts were also asked to assist the TFI in the process of integrating the evaluations across all experts and in ensuring that the composite distribution of evaluations was representative of the larger informed technical community.

2.1.2.2 TFI Team

Expert interactions are a central component of the elicitation process and must be properly facilitated. Experience from numerous seismic hazard studies has shown that experts interact frequently in their professional activities, and that workshops serve to provide information and interaction that encourage their consideration of hypotheses and data. Expert interactions on the PVHA-U were facilitated through multiple workshops. Presentation, technical challenge, and debate by the experts of alternative interpretations, including those developed by the experts, were the focus of these meetings.

For a Level 4 PSHA, the SSHAC guidance defines the role of a "Technical Facilitator/Integrator" or TFI. A technical *facilitator* is an individual – or a small group of individuals acting as a team – who has acknowledged technical expertise as well as expertise in probability and uncertainty treatment. In the case of the PVHA-U, the TFI-team consisted of a technical facilitator, individuals with expertise in uncertainty quantification and modeling, and an individual skilled in the development of volcanic hazard inputs.

In addition to facilitation, the TFI is also an integrator, integration being defined as the process of combining multiple experts' evaluations into an aggregate assessment across all experts. The SSHAC (Budnitz et al., 1997) process emphasizes the need to consider at the outset of a project the strategy for integration of the experts' evaluations. The terms expert evaluations and expert assessments are used interchangeably in this report. From the beginning of the PVHA-U, a strategy was defined to combine the evaluations of the experts using equal weights. The key procedural components of the project, ranging from the selection of the experts to the dissemination of data, were designed to allow the equal-weights strategy to be implemented in a defensible manner. As noted by the SSHAC (Budnitz et al., 1997), the goal of a multi-expert evaluation of inputs to a PSHA is to capture and express the range of uncertainty such that the aggregated hazard represents reasonably the uncertainty of the informed technical community. The final integration of the experts' evaluations was done using equal weights and the experts were made aware throughout the process that the aggregated results across all of the experts on the panel would be used as a reasonable representation of the current knowledge and uncertainty. This means that the results would not be systematically different from those of the larger technical community if they had performed the evaluations.

2.1.2.3 Principal Steps

The principal steps associated with the general approach outlined in the SSHAC report (Budnitz et al., 1997) consist of the following:

- Identification and selection of technical issues
- Identification and selection of experts
- Role of experts as evaluators, not proponents; Technical Facilitator/Integrator (TFI)
- Discussion and refinement of the technical issues
- Training for elicitation
- Facilitated group interactions and individual elicitation
- Feedback and sensitivity analysis
- Analysis, aggregation
- Documentation and communication.

The SSHAC methodology steps are very similar to those outlined in NUREG-1563 and listed in Section 2.1.2.2.

2.2 SCHEDULE OF ACTIVITIES

The activities comprising the PVHA-U and associated data collection activities occurred over a four year period. The principal activities in the PVHA-U are summarized in Table 2.2-1. Detailed descriptions of key components of these activities are provided in Section 2.3.

Table 2.2-1. Schedule of PVHA-U Activities

Activity	Schedule
Planning, and select and retain experts	August to September 2004
Distribute information to experts for review	Beginning September 2004 and through second round of elicitation interviews
Workshop 1 Key Issues and Available Data	October 11 to 15, 2004
Workshop 2 Alternative Models	February 15 to 18, 2005
Meetings to develop influence diagrams	May to June, 2005
Drilling and age-dating	August 2005 to April 2006
Workshop 2A Approaches to Volcanic Hazard Modeling	August 30 to 31, 2005
Field trip	May 2 to 4, 2006
First Round of elicitation interviews	July to August 2006
Workshop 3 Preliminary Expert Assessments	September 26 to 27, 2006
Second Round of elicitation interviews	November to December 2006
Preliminary hazard calculations and sensitivity analyses	January to April 2007
Workshop 4 Feedback	May 10 – 11, 2007
Feedback interviews	June 2007
Experts finalize Elicitation Summaries	August 2007
Final hazard calculations and aggregation of expert assessments	June 2007 to January 2008
Report preparation and finalization	January 2008 to July 2008

2.3 PVHA-U METHODOLOGY

This section provides a description of the key components of the expert elicitation process used to develop the expert assessments, construct the hazard models, perform the calculations, and arrive at integrated outputs regarding igneous event probability. The general approach implemented by the PVHA-U for eliciting the assessments of the experts is described in this section. Additional details regarding specific steps are given in sections 2.3.2 to 2.3.5.

Development of an Elicitation Plan

Consistent with the requirements of SO-PRO-002, the project began with the development of an Elicitation Plan (BSC 2005) that explained the background for the update, the objectives and issues to be addressed, project organization and key participants, the scope of the project, plans for document preparation, quality assurance procedures, and the proposed schedule. The Elicitation Plan was updated early in the project to reflect changes in the planned work activities and the change in management of the project from BSC to Sandia National Laboratories (SNL 2007).

Although the Elicitation Plan explained the overall structure of the project, flexibility was maintained to address additional needs as they arose and to ensure that project goals were achieved.

Selection of Experts

The MDT established criteria for the selection of experts (see further discussion in Section 2.3.1). These criteria were intended to ensure that each expert had appropriate professional stature within the technical community, technical expertise and experience to perform the required tasks, and sufficient motivation and commitment to complete the tasks in a timely manner. Because this project was an update of the previous PVHA (CRWMS M&O 1996), additional factors were also considered. To the extent practical, the members of the expert panel for the update to the PVHA were those experts who participated on the original PVHA expert panel in 1996. This promoted continuity from the previous study and allowed more efficiency in familiarizing the experts with the Yucca Mountain-related data. Two members of the panel were either deceased (Richard Fisher) or not physically able to participate (George Walker). Two members were added to the panel after considering the pool of candidates that had been developed for the PVHA and the selection criteria identified in the Elicitation Plan. Based on those selection criteria, Drs Charles Connor and Frank Spera were added to the panel.

Throughout the project the experts were informed that the selection criteria were also applicable criteria for their continued involvement on the project. Part way through the project, Drs. Carlson and Duffield informed the MDT that they were unable to maintain the level of commitment required for their participation due to other obligations. Reluctantly, the MDT accepted their resignations from the panel. In light of the resignations, the MDT considered the number and composition of the panel, and concluded that the panel of the remaining eight experts provided an adequate range of expertise, diversity of views, and range of backgrounds to complete the project without filling the two vacancies. The list of those experts that participated in the entire elicitation process is given in Table 1.3-2 (Section 1.3).

Data Compilation and Dissemination

The compilation and distribution of pertinent data, including published reference material, began early and continued throughout the project. A fundamental goal of the project was to provide all experts with consistent, uniform bases for their assessments. Further, the process for identifying data to include was designed to be responsive to experts' requests, and materials requested by the experts were provided in an expeditious manner. Before the first workshop, a number of anticipated references and data sets were entered into the PVHA-U database, which was administered and maintained by Los Alamos National Laboratory. The first workshop was focused on identifying the technical issues and provided a forum for the experts to define the data that they would need for their subsequent evaluations. This provided the basis for the first data delivery to the experts. At various times during the course of the project, the project honored multiple data requests, as summarized in Appendix B. When appropriate, mapped datasets were developed as a series of layers in a Geographic Information System (GIS).

Additional details on the data collection and dissemination effort are provided in Section 2.3.2.

Focused Data Collection

In addition to compiling available data, new data and information were developed to directly support the PVHA-U project. Prior to the project, high-resolution aeromagnetic data were gathered with the specific purpose of providing a more highly resolved interpretation of the anomalies identified from the previous aeromagnetic survey (Blakely et al. 2000; O'Leary et al. 2002). These data were gathered following Workshop 2A and prior to the first round of elicitation interviews.

Based primarily on requests for information identified by the expert panel regarding event definition, a field-based geologic program was carried out by LANL to map and interpret volcanic features at localities judged to be analogous to the Yucca Mountain site. These studies included compiling information from these analogue regions related to pertinent event characteristics, such as dike geometries, locations and geometries of conduits, presence of sills, and eruptive volumes. A field trip provided the experts with the opportunity to visit many of these analogue sites and provided a mechanism for the experts to observe and interpret first-hand the geologic evidence.

Meetings of the Experts

Structured, facilitated interactions among the experts took place during the workshops and field trip. The workshops were designed to identify significant issues, review available data, debate alternative models, discuss approaches to volcanic hazard modeling, present and debate preliminary interpretations, and discuss feedback. Proponents of particular technical positions provided their interpretations to the experts. Debate and technical challenge of alternative interpretations were facilitated to understand differences and identify uncertainties. At these meetings, technical specialists participated from a variety of organizations, presented pertinent data sets, and discussed alternative models and methods. At the first workshop a normative expert provided elicitation training in uncertainty and probability. The field trip provided opportunities for the experts to interact among themselves and with the technical specialists. Evening sessions were held with the specific purpose of discussing the field observations and their implications for the expert assessments. Each of the workshops and the field trip were public meetings and were attended by a variety of observers from regulatory and oversight groups.

Additional discussion of the workshops and the field trip is provided in Section 2.3.3, and detailed summaries of the workshops and the field trip are provided in Appendix C.

Elicitation Interviews

Three rounds of elicitation interviews were held, each lasting one day, with individual experts and representatives of the MDT team. The interview sessions provided opportunities for the experts to develop their assessments of the pertinent issues, to discuss the preferred and alternative evaluations, to express and quantify uncertainties, and to specify the technical bases for the assessments. The first round of interviews was focused on developing the overall structure of each expert's model, including the spatial, temporal, and event characterization elements. Also, preliminary assessments of model and parameter uncertainties were made.

Following discussion of the preliminary models at Workshop 3, a second round of interviews was held with the purpose of further specifying the model components and quantifying the associated uncertainties. Following these interviews, a number of sensitivity analyses and hazard calculations were conducted to explore the contributions of various issues to the hazard results. Workshop 4 Feedback was focused on these sensitivity analyses and hazard calculations, with particular emphasis on the range of assessments across the entire expert panel. The final round of elicitation interviews was aimed at discussing the specific feedback developed for each individual expert's model. This information allowed each expert to understand which parts of their models were most important and which contributed most to the total uncertainty.

Additional discussion of the elicitation interviews is provided in Section 2.3.4.

Supporting Calculations, Feedback, and Hazard Calculations

The workshops and elicitation interviews provided opportunities for the experts to identify and discuss methods and approaches to their evaluations. In many cases, implementation of those methods and approaches required calculations based on the approaches, algorithms, and input data requested by the experts. If requested by the expert, the MDT provided calculation support for these evaluations. In many cases, the supporting computations provided a basis for the experts to examine the implications of various approaches or the relative importance of different inputs to the calculated results. The experts could then use these results to inform their assessments. Prior to Workshop 4 Feedback, the MDT completed a suite of preliminary hazard calculations and sensitivity analyses. The purpose of these calculations was to elucidate similarities and differences in the various experts' models, and to provide an indication of the relative importance of various technical issues to overall uncertainty in the preliminary hazard results. Following the finalization of all expert assessments, a set of hazard computer codes was finalized and qualified according to the applicable Project procedures. These codes were then used to calculate the PVHA-U hazard results and sensitivity analyses, which are given in Section 4.

Documentation of Expert Assessments

The Elicitation Summaries are the fundamental documentation of the experts' assessments and the associated technical bases. Further detail on the development of the Elicitation Summaries is provided in Section 2.3.5 and all Elicitation Summaries are included as part of this report in Appendix D.

The documents were reviewed by the MDT for completeness and each expert has signed an Acknowledgement Form verifying that the Summary provided his complete and final assessment. As discussed in Section 2.6.1.2, the experts developed preliminary assessments early in the project and were free to modify their thinking and models throughout the series of workshops and elicitation interviews. The final assessments are those given in the Elicitation Summary and they are the assessments used in subsequent hazard calculations.

Aggregation of Expert's Assessments

For the experts' assessments to be used in subsequent performance assessments, they must be combined or aggregated. From the start of the project and as indicated in the Elicitation Plan (BSC 2005; SNL 2007, Section 4.2.9), the intent was to aggregate the assessments using equal weights. As discussed in the SSHAC report (Budnitz et al. 1997, p. 37), a certain set of conditions must be present for equal weights to be appropriate:

> …there are two fundamental conditions that must hold for equal weighting to be appropriate: first, the experts must either be completely independent – i.e., rely on independent data bases and models (this is virtually impossible), or be equally interdependent … By exposing the expert panel to all models and data bases, the TFI process encourages equal interdependence. Second, the experts must be equally credible. In the TFI process, experts are methodically screened for their ability to be excellent scientific evaluators.

The report also concludes that "intensive interaction is perhaps the most effective way to create conditions under which equal weights are appropriate."

As discussed in Section 2.5, the PVHA-U project was structured with the specific goal of creating conditions under which equal weights were appropriate. This goal was communicated to the experts at every workshop, as was the structure of the process being implemented. Consistent with the SSHAC guidance, facilitated interactions among the experts were priorities in all workshops and other meetings of the experts. As a result, the eight expert assessments could be, and were, aggregated using equal weights. For clarity, the individual expert assessments and results are presented (see Section 3.2 for a summary of the assessments and Section 4.1 for the individual results) along with the aggregate results (Section 4.2).

2.3.1 Selection of Expert Panel

The selection of experts was conducted in accordance with guidance provided in *Plan for the Expert Elicitation to Update the Probabilistic Volcanic Hazard Analysis (PVHA) for Yucca Mountain, Nevada* (BSC, 2005). This plan was consistent with the BSC line procedure LP-AC.1Q-BSC, *Expert Elicitation* (and with SO-PRO-001 after Lead Lab assumed responsibility for the activity), and NUREG-1563 (Kotra et al. 1996) for expert elicitation. Specifically, the Plan stated:

> The goal of the expert selection process is to identify a group that: *individually* consists of experts who are capable and willing to evaluate a full range of possible models and parameters, and who *collectively* express a diverse range of views that can be considered representative of the larger technical community. To the extent practical, the members of the expert panel for the update to the PVHA (CRWMS M&O 1996) will be those experts who participated on the original PVHA expert panel in 1996. (BSC 2005, p. 5)

The Plan stated that if additional members of the expert panel had been required, the guidelines for selection that were used for the PVHA-96 should have been used for the selection of new members (see Table 2.3.1-1 for the selection criteria).

Guidance on selection of experts provided in NUREG-1563 was also followed. This guidance states, "the panel of experts selected for elicitation should comprise individuals who: (a) possess the necessary knowledge and expertise; (b) have demonstrated their ability to apply their knowledge and expertise; (c) represent a broad diversity of independent opinion and approaches for addressing the topic(s) in question; (d) are willing to be identified publicly with their judgments; and (e) are willing to identify, for the record, any potential conflicts of interest" (Kotra et al. 1996, p. 23).

The selection of experts involved five steps: (1) determining the original expert panel members who were available and willing to participate; (2) reviewing the collection of returning members to identify whether any individuals with specific expertise or different approaches should be added to the panel; (3) developing a list of potential candidates to be added to the expert panel to fill specific identified needs; (4) selecting and inviting the candidates to participate; and (5) verifying acceptance by the selected candidates to participate. The selection panel consisted of MDT members and other knowledgeable YMP individuals. The panel included Mike Cline (BSC), Kevin Coppersmith (Coppersmith Consulting), Terry Crump (BSC), Jerry King (BSC), Karen Jenni (Geomatrix), Roseanne Perman (Geomatrix), Frank Perry (LANL), Eric Smistad (DOE) and Bob Youngs (Geomatrix).

In August 2004, eight of the original expert panel members could participate in the update (Dr. Richard Fisher was deceased and Dr. George Walker was ill and not able to participate). A list was developed of candidates who could be added to enhance the breadth of scientific expertise and technical knowledge of the panel members. The list was derived from the list of 70 candidates originally nominated for PVHA-96 (CRWMS M&O 1996, Section 2.3.2) plus three candidates from the Igneous Consequences Peer Review Panel (Dr. Larry Mastin, Dr. Allen Rubin, and Dr. Frank Spera.)

The candidates for the expert panel were chosen in accordance with expert selection criteria in the Project Plan (BSC 2005), which is also consistent with NUREG-1563). Careful consideration was given to balancing the panel with respect to modeling and field expertise, as both were judged to be valuable for PVHA-U. Individuals already familiar with the volcanic setting of the Yucca Mountain site were given priority, as the new panel members would be joining the eight experts who had participated in PVHA-96. Two experts, Drs. Charles Connor and Frank Spera, were selected and invited to participate in the expert elicitation. Both accepted and subsequently became panel members. Dr. Connor had considerable experience relative to Yucca Mountain datasets during his prior employment with the Center for Nuclear Waste Regulatory Analysis, and he has focused his subsequent scientific research on geologic settings that are potentially analogous to the Yucca Mountain region. Dr. Spera was familiar with Yucca Mountain datasets as a result of his participation on the Igneous Consequences Peer Review Panel and has conducted research on scientific topics of potential significance to the volcanic hazard at Yucca Mountain.

Consistent with the guidance of NUREG 1563 and the Project Plan all experts were asked to document any conflicts of interest related to their roles as experts for assessing volcanic hazard at Yucca Mountain. Each expert completed a conflict-of-interest statement, which is included as part of the records of the PVHA-U project. None of the selected experts was precluded from participating in the project on the basis of conflicts of interest.

At the first PVHA-U workshop, the expert panel members were reminded of the selection criteria for panel members, including the commitment to devoting a significant amount of time and effort to the project and a willingness to explain and defend technical positions. The experts were also reminded of their roles as expert evaluators, who consider a variety of viewpoints, challenge the interpretations of others, and arrive at a reasoned position that includes a representation of the uncertainties. 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.

Midway through the project (in Spring 2006, about 20 months after the project start) two members of the expert panel, Drs. Richard Carlson and Wendell Duffield, resigned from the project, citing schedule conflicts that prevented them from devoting the necessary time and effort to the project. The MDT reviewed the areas of technical expertise of the other eight panel members and concluded that the panel was sufficiently well balanced that additional panel members would not be needed.

Table 2.3.1-1. Criteria for Selection of Experts

Criterion	Description
1	Earth scientist of high professional standing 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 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 individual technical interpretations and assessments of uncertainties.
5	Selection would contribute to a balanced panel of experts with diverse opinions, areas of technical expertise, and institutional/organizational backgrounds (e.g., from government agencies, academic institutions, and private industry).

Source: BSC 2005, p. 6

2.3.2 Data Provided to the Experts

The assembly and dissemination of basic information was an important aspect of the expert elicitation. For PVHA-U the step of assembling and disseminating information to the expert panel members included not only providing available information but also new data gathered explicitly to address the technical issues related to each expert's assessment. Members of the MDT were responsible for accommodating requests by the expert panel members for data and for maintaining a database in the form of a secure FTP site where datasets could be accessed by the expert panel. Appendix B contains the list of data provided to the expert panel. Much of the data provided to the panel were spatial in character and appropriate for display on maps (e.g., geophysics data, faults, aeromagnetic anomaly location). These data were therefore managed in a common Geographic Information System (GIS) database that allowed visualization of the relationship between the data and regional topography and basaltic volcanism in the Yucca Mountain region.

The major objectives of Workshop 1 (Key Issues and Available Data) included familiarizing the experts with the technical issues to be addressed in PVHA-U, data and published scientific studies that had become available since completion of PVHA-96, and data to be collected during the course of the PVHA-U. The technical issues addressed included event definition, spatial evaluation and temporal evaluation issues. Presentations at Workshop 1 and subsequent workshops, plus the field trip, were designed to provide information that related to these issues and could be used by the experts in their assessments. A list of references published since 1995 was provided to the expert panel members in Workshop 1. The list included new information published about the topic areas of crustal strain rate, geochronology/petrology, geologic mapping, geophysics, tectonics/structure, and volcanic hazards/probability models.

Throughout the project the expert panel members were asked to request the data and information that they anticipated needing. An initial list of information requested by panel members was developed at Workshop 1 (this list is included in the Workshop 1 summary in Appendix C). Subsequently a process was developed for the experts to request datasets and to notify experts when datasets were added to the database or updated. The database enabled common access by all experts to technical references, data, data visualizations (e.g., GIS-produced maps), and special work products needed to develop their hazard assessments. Materials were distributed to the expert panel members in the specific form that they requested (e.g., hard copy, email attachment, or posted to a secure FTP site). Certain datasets were sent to all panel members if an item was determined to be of general interest (e.g., data and summaries describing results of drilling and age dating efforts).

At each workshop MDT members or technical specialists provided an overview of database information recently developed. For example, at Workshop 3, LANL staff described datasets that included local models of tomographic inversions and results from dating and chemical analyses of drilling samples. Preliminary Ar/Ar age-dating results from Black Cone, revised estimates of volumes of volcanic episodes based on buried volcanoes recently encountered by drilling, and estimates of the ages of anomalies based on burial depth and burial rate were discussed. Also described were development of a numerical 3-dimensional grid for contour maps that represented the estimated cumulative percent of extension for Crater Flat; event geometry based on the example of East Basalt Ridge (a Miocene-age analogue); and depth to groundwater beneath Yucca Mountain.

Key aspects of the data collection effort are described below in Sections 2.3.2.1 through 2.3.2.3.

2.3.2.1 Aeromagnetic Survey and Drilling Program

An integrated program consisting of a high-resolution aeromagnetic survey, a drilling program, and geochemical and geochronological analyses was designed to investigate a selected subset of the aeromagnetic anomalies identified from earlier surveys reported by Blakely et al. (2000) and O'Leary et al. (2002). The high-resolution survey was completed in 2004, prior to Workshop 1 of PVHA-U. The 2004 survey was conducted to map magnetic anomalies within the upper 400 m of the subsurface, to distinguish between magnetic tuffs and basalts, and to provide uniform, high-resolution aeromagnetic coverage of the area of interest (Figure 1.4-3 in Section 1). The new aeromagnetic data were combined with information obtained from previous studies in the area, including drill-hole and ground magnetic investigations. In addition, analyses of the geochemistry and ages of basalts encountered in drill holes were performed. The goals of this additional data collection effort were to constrain the number, location and ages of volcanic events, to reduce uncertainty, and to facilitate consideration of alternative conceptual models for the PVHA-U.

At Workshop 1, the criteria for selecting anomalies for drilling were described to the expert panel, as were the rationales for potentially drilling or not drilling specific anomalies. Expert panel members discussed these criteria and rationales and the relative importance of drilling in Crater Flat versus Jackass Flats and the importance of characterizing features such as possible alignments of volcanic cones. The panel members also made recommendations for additional processing of the aeromagnetic data (e.g., subduing features located at great depths, as these were of lesser interest because they were not suspected of representing young basalt).

Drilling began on the first anomaly, Anomaly Q, on August 1, 2005. A total of seven drill holes were completed in Crater Flat, Jackass Flats, and the northern Amargosa Desert. The locations of those drill-holes are shown on Figure 1.4-3 in Section 1. Information obtained from the drilling, and from geochemical and geochronologic studies, provided bases for correlating basalts encountered in the new drill-holes and basalts identified in outcrops and from previous drill holes. Both the drilling and the aeromagnetic survey clarified episodes of Miocene volcanism in Crater Flat and Jackass Flats.

2.3.2.2 Analogue Studies

Data on characteristics of dikes and dike swarms, numbers of vents (conduits) and their locations along a dike system, and characteristics of the conduits at repository depth were requested by the expert panel and studied by LANL geologists at potential analogue sites in the western United States. Criteria used to select analogues for the YMR included an extensional tectonic setting, and magma volume and composition similar to those of volcanoes near Yucca Mountain.

At Workshop 2A, LANL staff described observations and interpretations from field mapping at Paiute Ridge, Basalt Ridge, and the 3.7 Ma basalts in Crater Flat. Results from investigations at Grants Ridge in New Mexico, located on the edge of the Colorado Plateau, also were described. Workshop participants discussed which other sites in the Great Basin might serve as appropriate analogues to Yucca Mountain.

In discussions associated with the field trip (May 2-4, 2006), LANL geologists provided information from their studies of volcanic centers in the YMR. Data collection was focused on erosion and eruption characteristics of the volcanoes and on the event geometry (number, size, shape, and vertical extent of conduits and feeder dikes) represented by the analogues and on the appropriateness of analogue information for describing a basaltic volcanic system at repository depths.

The field trip provided an opportunity for the expert panel members to observe directly the characteristics of volcanic and intrusive features in the YMR so they could refine and finalize their definitions of igneous events. Field trip stops included the 10 Ma Solitario Canyon dike, 11.3 Ma basalt flows near Bare Mountain, 9.1 Ma basalt at Basalt Ridge and 8.6 Ma basalt at Paiute Ridge, 4.6 Ma basalt at Thirsty Mountain, 3.7 Ma basalts in southeast Crater Flat, and 77 ka basalt at Lathrop Wells.

2.3.2.3 Technical Reports

Panel members requested several interpretative analyses of specific data related to development of conceptual and hazard models for the PVHA-U. These were provided in the form of short technical reports and included topics such as detectability of dikes from magnetic data, effects of topography and structure on dike propagation, the history of Quaternary volcanism in Crater Flat, geochemical data related to mantle melting and eruption volume, and assessments of mantle tomography data and Amargosa trough structural data from the YMR.

2.3.3 Workshops

Five workshops and a field trip were held as part of the PVHA-U with the common goals of providing information to the expert panel and facilitating interactions among the experts. Each workshop is summarized in Appendix C and presentations made at the workshops were included in the CDs made following each workshop. The workshops were structured to promote discussions among the expert panel and, if appropriate, with technical specialists invited specifically for their expertise in certain technical topics. The workshops were public meetings, and observers were present representing a variety of groups, including the U.S. Nuclear Regulatory Commission, Advisory Committee on Nuclear Waste and Materials, Nuclear Waste Technical Review Board, affected units of government, Electric Power Research Institute, Nuclear Energy Institute, and the general public. Observers were provided with the CDs containing distributed materials following each workshop.

The purposes of each workshop and the focus of the discussions are described below:

Workshop 1: Key Issues and Available Data

The purposes of Workshop 1 were the following:

- To introduce the expert panel members to the PVHA-U project in terms of project objectives, expectations, and schedule
- To review the project ground rules, expert roles, and expert elicitation processes
- To identify the key issues that will need to be addressed by the experts during the course of the project
- To review the available data and identify those datasets that will be used by the experts in their evaluations
- To train all experts in elicitation processes and in approaches for expressing uncertainties in probabilistic assessments.

The workshop began with an extended discussion of the overall project as well as a description of the structure and format for all expert interactions. The PVHA-U was described as an update of the original PVHA that considered new event definitions, new and updated conceptual models, and new calculation methods. An explanation was included that an SSHAC process was being followed with respect to the roles that the experts would play as "evaluators" and not "proponents." The process for expert interactions was defined (and would be repeated in all subsequent workshops), which call for professionalism and mutual respect on the part of all participants. The methodology for the project was described as including aggregation of the final assessments of the experts using equal weights and creation of the conditions for doing so. The process used to select the experts was explained to emphasize that the selection criteria would also be the criteria used to evaluate the experts for their continued participation on the project as the work progressed. For example, a key selection criterion called for the capability and willingness for the expert to provide the necessary time commitment required. Each expert agreed to do so at the time they were asked to participate on the panel and, if they were not able to do so at some point, they were asked to terminate their participation.

After a discussion of the original PVHA and the use of the results in subsequent igneous consequences analyses, the technical issues that were addressed by PVHA-U were defined and discussed. These issues included many of the same issues addressed in PVHA-96, but also included new information about spatial and temporal patterns of igneous activity related to igneous event definition. For example, the PVHA-U issues include assessments of the number, location, and geometry of various igneous features (including dikes, sills, eruption-column producing conduits and non-column producing vents) that might be associated with an igneous event.

The bulk of the workshop focused on the data and information that had been developed and compiled since the time of PVHA-96. The database was developed by LANL and included references from the professional literature, Yucca Mountain Project reports, and a variety of mapped data held within a GIS. The panel discussed the types of data that would be required to address the technical issues and a process was set up whereby experts could request and receive data (electronically or in hard copy) throughout the course of the project. Many of the experts asked for the same information, and numerous requests were for information about event characteristics, particularly from analogue regions comparable to the Yucca Mountain region. In response to this request, LANL carried out studies and compiled data at a number of analogue localities to provide to the experts. A subsequent field trip was also conducted (see below) to allow the experts to observe first-hand the field relationships at many of these analogue localities.

At the final session of the workshop, the normative expert on the MDT carried out a training session with the panel reviewing concepts of probability and approaches to addressing and quantifying uncertainties. Discussions in this workshop noted that the experts did not need to have any particular expertise in probabilistic modeling or statistical analysis (although some members of the panel were adept in these areas). The discussions also clarified that the MDT was prepared to provide needed modeling analyses.

Workshop 2: Alternative Models

The purposes of Workshop 2 were the following:

- To review the PVHA-U project objectives, the roles of the project participants, the process of expert elicitation, and the project schedule
- To review the technical issues the expert panel must address
- To discuss alternative interpretations of the tectonics [tectonic history] of the Yucca Mountain region
- To discuss alternative models for assessing the spatial and temporal distribution of potential future volcanism
- To discuss characteristics of volcanic events
- To discuss alternative approaches to performing probabilistic volcanic hazard analysis, including approaches used in international volcanic hazard studies.

The purposes of the workshop were accomplished by a series of topical sessions designed to provide a forum for presentation and discussion of alternatives. Following the introductory session, each session included several presentations related to the following topics: tectonic framework, models related to spatial distribution of future igneous events, models related to temporal distribution or recurrence, and event definition characteristics. In some cases, presenters were proponents for particular models; in other cases, presenters were asked to summarize a series of models or interpretations. Representatives were present from other countries to give the panel a perspective on the manner in which similar issues were being addressed elsewhere. The presentations provided a focus for discussion among the expert panel of the applicability and viability of alternative models related to assessments of PVHA at Yucca Mountain. Often, the discussions focused on the history and expected style of volcanism in the Yucca Mountain region, and the degree to which analogues and experience at other locations and tectonic environments might be applicable to the PVHA-U.

In the original vision of the PVHA-U project, Workshop 2 was intended to include both alternative models for the Yucca Mountain region *and* alternative approaches to conducting volcanic hazard assessment. However, following Workshop 2, the experts began to develop and structure their approaches to address the various technical issues. Workshop discussions provided a mechanism for the experts to share the range of possible alternative approaches and, as a result, a separate workshop focused on hazard modeling approaches, designated Workshop 2A, was held.

Workshop 2A: Approaches to Volcanic Hazard Modeling

The purposes of Workshop 2A were the following:

- To review the PVHA-U project objectives, expectations, and schedule
- To summarize the data and information that have been compiled in the PVHA-U database
- To summarize the ongoing field efforts (drilling, field reconnaissance) to provide information for use by the experts in their evaluations
- To provide a forum for discussion among the experts of their potential approaches to modeling the volcanic hazard at Yucca Mountain, including their approaches to defining igneous “events,” modeling temporal processes, and modeling spatial processes (these issues are summarized in influence diagrams that have been developed by each expert)
- To identify additional data and information that the experts need to exercise their hazard approaches.

Because the workshop was focused on the approaches being considered by the experts, the workshop used a format designed to encourage and enhance discussions among the experts, while minimizing formal presentations. Following the introductory session, a session was devoted to summarizing the status of the PVHA-U database (which was actively being compiled based on requests from the experts) and the results of the ongoing drilling program. The remainder of the workshop was devoted to the experts discussing their potential approaches to volcanic hazard modeling. Each of these sessions entailed summary presentations by a subset of the experts, followed by extensive discussion periods to allow participation by all panelists.

The session concluded with a summary of the additional data and information needs identified during the course of the workshop. These needs were fulfilled prior to the first elicitation interview, which followed this workshop. The experts also expressed their interest in the ongoing study and compilation of information at analogue locations. In response to requests from the experts, plans were developed to conduct a field trip to allow the panel to observe the analogue locations first-hand.

Field Trip

The purpose of the field trip was to provide expert panel members an opportunity to directly observe characteristics of volcanic and intrusive features in the YMR to assist them in developing definitions of igneous events. The activity began with a meeting and briefing to establish the purpose of the trip and to review the field trip logistics. Both before and during field trip stops, LANL geologists gave presentations based on their research on eroded analogue volcanic centers in the region. The field trip examined issues such as (1) how eruptive style and the unique characteristics of magma feeder systems change through geologic time; (2) the relationships between faults and dikes/fissures in the region; and (3) the role of topography, versus other mechanisms such as mantle source characteristics or crustal structure, in determining the locations of volcanoes. At the initial briefing the LANL geologists noted that they would provide their views as "proponents" based on their interpretations of the available data. The experts were reminded that their role as "evaluator" experts was to consider the data and interpretations from the standpoint of their own experience and to arrive at their own conclusions.

Field trip stops included the 10 Ma Solitario Canyon dike, 11.3 Ma basalt flows near Bare Mountain, 9.1 Ma basalt at Basalt Ridge and 8.6 Ma basalt at Paiute Ridge, 4.6 Ma basalt at Thirsty Mountain, 3.7 Ma basalts in southeast Crater Flat, and 77 ka basalt at Lathrop Wells. In addition to field trip localities throughout the region, the meeting also included a visit to the Sample Management Facility to observe drill-cores from the ongoing drilling program. In addition, presentations were made regarding the modeling of topographic effects on dike propagation and two-dimensional analysis of deep structures to address the conditions under which a dike could be captured by a fault.

Workshop 3: Preliminary Expert Assessments

Following the field trip, the first round of expert interviews was conducted. Workshop 3 provided a forum for a discussion of the preliminary assessments coming from those interviews. The purposes of the workshop were the following:

- To review the PVHA-U project objectives, expectations, and schedule
- To provide an update on the data and information that have been compiled in the PVHA-U database
- To summarize the expert elicitation process being followed, including the first round of elicitation interviews held in July and August, 2006
- To provide a forum for the members of the expert panel to present and discuss their preliminary assessments of the technical issues, which were made at the elicitation interview
- To provide an opportunity for the expert panel members to review, understand, and challenge the technical assessments made by their colleagues on the panel
- To focus the discussions on the uncertainties in models and parameters, such that the experts would be prepared for the second round of elicitation interviews in November and December 2006
- To outline the scope and schedule of future elements of the PVHA-U.

The purposes of the workshop were accomplished using a format designed to encourage and enhance discussions among the experts, while minimizing formal presentations. The introductory session included a summary of the results of the drilling, age-dating, and geochemistry program, as well as a description of the database compilation efforts. The MDT emphasized that, due to anticipated changes in the EPA regulation related to Yucca Mountain, the assessments by the experts would need to consider two potential future time periods: 10,000 years and 1,000,000 years. Then, a series of sessions was devoted to several topics that were being addressed by the PVHA-U experts as part of their elicitations, such as dike and sill geometries, eruptive conduits, types of future eruptions, spatial intensity models, and Poissonian and episodic temporal models. For each topic, two or three members of the panel provided summaries of their preliminary assessments. A discussion directly followed, thus allowing all members of the panel to review pertinent aspects of the models and assessments. The focus of the presentations was on alternative conceptual models and potential approaches, with less focus on parameter uncertainties.

Workshop 4: Feedback

The purposes of Workshop 4 were the following:

- To focus on feedback on the models and assessments from the elicitation interviews, the methods and approaches that were used by each expert, their associated uncertainties, and sensitivities of interim results to elements of the analysis

- To discuss and consider possible differences in definitions used by each expert and other sources of diversity in interpretation that result from different assumptions or models

- To allow the expert panelists to understand the relative importance of various technical issues

- To focus on feedback across the range of panel assessments and, following the workshop, to provide the experts with feedback on the various model approaches used across the panel. Experts were encouraged to consider whether they felt any changes in their own assessments were appropriate in light of these discussions.

Following the introductory session, new database products that had been provided to the experts were summarized. This was followed by three topical sessions in which the MDT summarized the expert assessments and models, their associated uncertainties, and ranges of interpretations. Sensitivity analyses and preliminary calculations of interim results were presented and provided a basis for discussing the importance of various technical issues. The presentations were designed to illustrate the dominant contributors to the hazard results and to the uncertainty in the hazard. This information provided a basis for the experts to know which technical issues should be given most attention during the finalization of their assessments.

2.3.4 Elicitation Interviews

The assessments made by the experts were conducted principally through a series of three elicitation interviews. The day-long interview sessions were held individually with each expert and were attended by members of the MDT, which included a normative expert, subject matter expert, modeler, and recorder. Each session was treated as a working session in which the expert would work through a series of assessments. For example, the expert might begin by providing the elements of his spatial model, then assessing the parameter distributions that defined the model. In many cases, the experts completed the assessments of models and parameters following the meeting. Notes were taken during the interviews by members of the MDT and were provided subsequently to the expert for use in developing his Elicitation Summary. Experience has shown that it is more effective for the MDT to take these notes, rather than require the expert to record his assessments as the interview progresses. In general, the assessments began with general topics and proceeded through more specific aspects of the models and parameters. In all cases, the experts were asked to identify the uncertainties associated with their assessments and to provide the technical bases for their assessments.

All of the experts had been trained during Workshop 1 in the use of probabilities to quantify their uncertainties, and regarding the potential biases that experts commonly confront and need to avoid. The normative expert reminded each expert of these issues and provided assistance when necessary. Experience and expertise in the use of probabilistic approaches varied across the panel, such that some experts required additional support in expressing their uncertainties and in developing appropriate probability distributions to reflect their knowledge and uncertainties. Assistance was also provided, as requested, to experts who were interested in translating a particular conceptual model into a mathematical model that could be used in the hazard analysis. For example, an expert might have needed help in constructing a model that would properly capture the notion of an episodic temporal distribution or a time-dependent temporal distribution that varies with time. The MDT was able to provide possible alternative mathematical models to the expert, explore and compare the implications of the model relative to the expert's conceptual model, and assist the expert in making his assessment of the uncertainties. In many cases, the interview sessions provided the expert opportunities to identify possible alternative models and/or approaches to dealing with a particular technical issue and to identify exploratory calculations that the MDT could conduct to help in making the assessment. Subsequent to the interview, the results of these exploratory analyses were provided to the experts to assist with their thinking.

As shown in the project schedule in Section 2.2, the elicitation interviews occurred between topical workshops such that the experts could consider the information provided at the previous workshop and they could discuss their assessments at the subsequent workshop. The topics and focus of the elicitation interviews are summarized by the following:

First Interview – The first elicitation interview followed an extended period of information gathering, consideration of alternative models, and discussion of alternative approaches to volcanic hazard modeling. The interview focused on developing an overall structure and approach to addressing all of the technical issues. Influence diagrams and logic trees provided tools for assisting the experts in developing this structure and for specifying the models and parameters that would need to be addressed. The interview also provided a vehicle for identifying and prioritizing the types of data that experts wanted to consider during development of their assessments. For example, in his consideration of the tectonic history of the Yucca Mountain region, an expert might have concluded that systematic changes in the nature of volcanism over the past 15 My meant that the most representative volcanic features for assessing future igneous events are those that have occurred in the post-Miocene period. Further, he might have concluded that specific aspects of these features (e.g., location, volume, geochemistry) would be most important to assessments of future activity. As a result, he would give priority to assembling data related to those characteristics. In this way, the first interview provided valuable additional direction to the database developers on the project.

Second Interview – The second interview was held after the experts presented and debated their preliminary interpretations at Workshop 3. Part of the discussions at Workshop 3 included the strengths and weaknesses of various approaches to addressing the technical issues, in light of the available data. For example, the merits and difficulties of using time-dependent temporal models were discussed, and these discussions assisted the experts in deciding on the approaches that they intended to take. The second elicitation interview, therefore, began with assessments of the approaches and overall structure that each expert intended to follow. Then the expert developed the conceptual models required to address all of the technical issues. Alternative conceptual models and the relative weights for those models were assessed, and the uncertainties in parameter values were also assessed. As needed, the MDT worked with the expert to identify and quantify these uncertainties. In some cases, the expert identified specific models and parameter distributions for which he wanted feedback from the subsequent calculations to assist in finalizing and weighting alternative models.

Third Interview – The third and final elicitation interview occurred following Workshop 4 Feedback. The workshop provided feedback regarding the relative importance of issues across the entire panel. The interview provided additional feedback related to the specific assessments made by each expert. For example, an expert might have specified a particular parameter distribution for a spatial model, and the interview provided an opportunity to review the resulting variation in spatial intensity to assist in deciding on the final parameter distribution. Likewise, specific test cases that might have been requested previously by the expert were reviewed, thus helping the expert to make decisions regarding the relative weights associated with alternative conceptual models. The interview session was also designed to be interactive and to allow for the expert to see the immediate impacts of certain assessments. For example, the implications of assessments related to the future spatial distribution (e.g., events to be considered, smoothing kernel, combinations of geologic data) were displayed and discussed with the expert. Likewise, the implications of various models for the time variation in temporal distributions were displayed and considered. The expert models were essentially finalized at the interview, with some minor changes occurring in the weeks following. The notes from the interviews were provided to each expert to assist in the final documentation of his assessments in the Elicitation Summary.

2.3.5 Expert Elicitation Summaries

Documentation of the individual interviews as summaries began with notes taken by the MDT during the course of the interviews. During these interviews, the experts made a large number of assessments, to quantify uncertainties, and to provide the technical basis for the interpretations. By having the elicitation team take notes, the expert was free to focus on thinking through the assessments and thoroughly expressing his interpretations. Also, the interview could be structured to follow the logic most familiar to the expert while also ensuring that each element was ultimately covered.

Following each interview, the elicitation team provided the expert with a written summary of the interview, organized by model component. Each summary was reviewed by multiple members of the MDT to ensure that the summary was internally consistent and that any unclear or ambiguous statements were identified. Each expert was instructed to review, revise and expand the description of his assessment in the elicitation summary so that his interpretation was fully reflected.

During the first interview with each expert panel member, influence diagrams were constructed to illustrate the initial assessment approaches planned by each expert. Each expert's approach to defining igneous events and modeling spatial and temporal processes was refined during the subsequent elicitation interviews.

After Workshop 4, the experts made additional revisions to their assessments and Elicitation Summaries to reflect any changes in their judgments following the review of the feedback information as well as the discussions and interactions with other panel members. A final interview was held in which sensitivity information on each expert's assessments was provided so that the individual could better understand the implications of the various components of his assessments. In addition, any remaining gaps in the models/issues to be addressed were identified by the elicitation team and elicited during these interviews and/or subsequent telephone calls.

Each expert then completed his final Elicitation Summary. An acknowledgement form stating that the Elicitation Summary represented his assessments was signed by each expert.

2.4 MODEL DEVELOPMENT AND CALCULATIONS

The process developed for the PVHA-U project was designed such that the MDT would: (1) assist the experts in developing their models, (2) provide supporting calculations as requested to assist the experts in their assessments, (3) provide preliminary calculations and sensitivity analyses to provide feedback to the experts, and (4) complete the final hazard calculations and sensitivity analyses for documentation in this report. The process allowed the experts to develop their models or approaches they felt were appropriate, without the need to consider potential difficulties or complexities with developing computer codes for those models or carrying out the calculations. Likewise, due to differences in skill sets among the experts regarding modeling, the MDT was prepared to provide sufficient modeling support to match the needs of each expert. Fundamentally, the experts were chosen to participate on the panel because of their expertise in considering the technical issues, not because of their abilities to model their assessments for purposes of hazard calculations.

Each expert constructed a series of assessments of the volcanic hazard issues identified at the outset of the project. The assessments, together with the overall logic and structure, we term the "expert model." Development of each expert's model began formally with individual meetings with the experts to develop influence diagrams. Given the topics that were addressed, each expert was asked to identify the issues, models, and data that would influence his assessments. This exercise provided information to the MDT regarding the types of data that would be relied upon and provided insights into the types of modeling approaches that might need to be implemented. Early in the project, a decision was made that the experts would develop sophisticated models but that model development would not be constrained by limitations in their respective modeling skills.

During the early development of the expert models, technically supportable differences were apparent among individual expert's views of the types of events that could occur in the future in the Yucca Mountain region. Rather than constrain the experts to follow a single event definition, the experts were encouraged to arrive at their own event definitions and to develop their models in a manner that consistently implemented their definitions. For example, if an expert defined an igneous event as a collection or alignment of volcanic features having the same age, then that type of event was also considered when considering the spatial distribution or recurrence rates of future events. The MDT made sure that the experts were aware of the need for this consistency and reviewed each expert's elicitation summary with this perspective.

As the elicitation interviews progressed, the expert models became progressively more refined in terms of consideration of alternative conceptual models and parameter distributions. In many cases, new conceptual models were specified by the expert and then implemented by the MDT. For example, one expert developed his assessments of event geometries based on a library of analogue event characteristics that he had developed. An event simulator (see Section 3.1) was developed to allow these event geometries to be used directly in the manner specified by the expert.

As another refinement, many of the experts were interested in combining multiple independent datasets in specifying the spatial distribution of future events. Various approaches were discussed in Workshop 2 by technical specialists who had carried out these types of analyses in other contexts. In light of the conceptual models developed by the experts, the MDT developed the modeling approaches needed for these assessments and reviewed with the experts in Workshop 3 (and in subsequent elicitation interviews) the types of data and assessments the experts needed to utilize such models. Likewise, in the interview sessions, the MDT assisted the experts in combining their spatial distributions using observed events and geologic datasets of various types (e.g., lithostatic pressure, tomography).

As a third refinement, the MDT often provided assistance to the expert in choosing from alternative probability distributions for a given parameter. Based on a dataset provided by the expert, the MDT would plot alternative probability distributions that were fitted to the data, or to the assessed fractiles for a parameter. The expert could then make an informed decision on the appropriate probability distribution to use to model the parameter or the dataset.

A key part of the modeling and calculation effort on the PVHA-U project was the development of feedback, both for the entire panel in Workshop 4 and for individuals in their third elicitation interview. To develop the feedback, the experts' models were fully specified (if only in a preliminary form). Hazard results and sensitivity analyses of the type given in Section 4 of this report were provided to assist the experts in identifying the most important issues and in understanding the relative importance of their specific assessments. A variety of presentational approaches and displays were used to illustrate the importance of various models and parameters, and the contributions that specific model elements make to the total distribution of hazard. A particularly innovative aspect of the feedback development process on the PVHA-U was the use of interactive feedback and modeling in the third elicitation interview. The MDT provided displays in real time of the implications of various alternative models and parameter distributions at the request of the expert. This informed the expert's decision-making and expedited the finalization of his models and associated parameters.

2.5 AGGREGATION OF EXPERT ASSESSMENTS

A single estimate of the hazard represented by a future igneous event at the site was needed, and to develop such an estimate, the experts' models were combined or aggregated. The issue of aggregation was a major point of emphasis in the SSHAC study (Budnitz et al. 1997, Section 3.3.3 and Appendix J) and provided the underpinnings for the PVHA-U approach. Problems have occurred on other multi-expert studies, which have led to the need in some cases to consider alternatives to weighting the expert assessments equally (Budnitz et al. 1997, p. 33-34). These problems include: experts playing the role of a proponent and being unwilling to evaluate alternative interpretations; outlier experts whose interpretations are 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, or awareness of, pertinent data sets such that the experts are relying on different data to arrive at their interpretations without adequate consideration 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. These problems were avoided during the PVHA-U project because deliberate efforts were made throughout the entire process to avert them.

The PVHA-U project was structured with the specific goal of creating conditions under which 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. In the case of two experts who were unable to make that commitment, their participation on the expert panel was terminated.
- Identifying and disseminating comprehensive and uniform data to all experts; data provided at the request of any individual expert were made available to all experts.
- Educating and training the experts in issues related to elicitation methodologies, probability encoding, and uncertainty treatment.
- Encouraging and facilitating interaction of the experts in workshops and the field trip such that a free exchange of data and interpretations and scientific debate of all hypotheses occurred.
- Providing feedback and sensitivity analyses to the experts, checking for unintentional errors or differences in definitions, and facilitating discussion and challenge to preliminary interpretations.
- Providing an opportunity for experts to revise their assessments throughout the project, such that they were able to take advantage of feedback from their colleagues on the panel and from feedback provided by the MDT.
- Obtaining agreement from each expert that the other experts' interpretations are understood and are valid alternative interpretations.

- Providing consistent guidance throughout the project regarding the roles of experts as evaluators rather than proponents.

- Providing consistent guidance throughout the project that evaluator experts should provide assessments that are representative of the larger informed technical community.

- Agreement as a panel that their assessments would not differ significantly from that of another panel, should that panel go through the same PVHA-U process.

In light of the actions taken, the MDT concluded that a defensible basis exists for aggregating the expert assessments using equal weights. For purposes of understanding each expert's model, the individual assessments and associated results are also included in this report (Section 4).

2.6 CONSISTENCY WITH GUIDANCE FOR EXPERT ELICITATIONS

The applicable guidance for expert elicitation methodologies was summarized in Section 2.1. The methodology followed in the PVHA-U described in Sections 2.2 through 2.5 was developed with the existing guidance in mind and it is consistent with that guidance. As discussed in Section 1.5, the PVHA-U followed the Elicitation Plan (BSC 2005, SNL 2007) and the Plan was consistent with Procedure SO-PRO-002 *Expert Elicitation.* The consistency of the PVHA-U methodology with NUREG-1563 and SSHAC are discussed in Sections 2.6.1 and 2.6.2, respectively.

2.6.1 Consistency with NUREG-1563 Branch Technical Position

The process steps recommended in NUREG-1563 are listed in Section 2.1.1.2 and they generally follow the recommended components of expert elicitations given in the Decision Analysis literature (e.g., Keeney and von Winterfeld 1991; Meyer and Booker 2001). As discussed in Section 2.3, the methodology followed for the PVHA-U included the steps given in NUREG-1563. Further, the elicitation planning took advantage of the experience gained since the completion of NUREG-1563 in utilizing specific methodology components to improve the study. For example, Step 4 calls for the assembly and dissemination of basic information to the experts. This activity was conducted in the PVHA-U and included not only available information, but also new data, which included high-resolution aeromagnetic data, drilling data, and geochronologic/geochemical analyses of basalt samples, all gathered explicitly to assist with the interpretation of igneous probability issues. In addition, geologic data related to potential analogue regions for defining events were gathered based on requests made by the expert panel. As another example, Step 7 calls for providing post-elicitation feedback to the experts so that they are able to see the implications of their assessments to the hazard results. This step was accomplished by way of a feedback workshop (Workshop 4; Appendix C), which provided information on hazard significance to the entire panel, and individual feedback interviews, which provided information related to each expert's individual assessment.

2.6.1.1 Updating an Expert Elicitation

The PVHA-U is an update to the PVHA (CRWMS M&O 1996) and the guidance provided in NUREG-1563 was reviewed and evaluated in deciding whether or not an update to the PVHA was warranted. According to Branch Technical Position 3 in NUREG-1563:

> If information from an expert elicitation is to be submitted in support of a license application, and if additional data or information becomes available, subsequent to the completion of the elicitation, which could change opinions or judgments obtained in the formal elicitation, the results of the elicitation should be re-examined and updated, as appropriate. In addition to the information requested above, documentation should include a detailed description of the updating process. (p. 18)

Section 1.2 describes the process that was followed to evaluate the significance of new data and information that became available subsequent to the completion of the PVHA. Sensitivity analyses were conducted to evaluate the potential implications that the data might have relative to the expert assessments. Although the DOE concluded that the implications of the new data were not significant to the results of the PVHA, the NRC staff disagreed and concluded that the new data could have significant implications to the experts' evaluations of alternative conceptual models (Schlueter 2002). The DOE agreed to gather additional applicable data and to update the PVHA (Ziegler, 2003). This report provides the detailed description of the updating process, as required by Branch Technical Position 3 in NUREG-1563.

2.6.1.2 Relationship of PVHA-U Documentation to NUREG-1563 Recommendations

The documentation of individual elicitations in the PVHA-U has been comprehensive and complete and is consistent with the guidance for documentation described by the NRC in their Branch Technical Position NUREG-1563 (Kotra et al. 1996). The approach taken and its rationale are given in the Elicitation Plan (SNL 2007, Appendix B) and are summarized here.

Each expert's judgments are documented in individual Elicitation Summaries that are appended to this report (Appendix D). The "elicitations" were not one-time events, but occurred over a series of workshops and interviews with each expert (see Section 2.2). For example, the first interview focused on structuring volcanic hazard models and preliminary assessments, and it occurred following three workshops and a field trip to observe geologic relationships in the region. The second interview focused on quantifying the parameters and the uncertainties in each expert's models. The Feedback Workshop provided each expert opportunities to learn from models and interpretations developed by other experts and to identify the technical issues of greatest significance to the hazard results. The experts also were given individual feedback in interview sessions and had the opportunity to update their judgments. The Elicitation Summary for each expert documents his final judgments, including the models and parameter values adopted, uncertainties about the models and parameter values, and the technical basis for interpretations. The Elicitation Summaries are the net result of the entire elicitation process.

Key products of the PVHA-U are the final Elicitation Summaries for each expert. One of the selection criteria for experts was "availability and willingness to participate as a named panel member," including "a willingness to explain and defend technical positions" (Section 2.3.1).

The NRC Branch Technical Position states that experts should be selected who "are willing to be identified publicly with their judgments" (Kotra et al. 1996, p. 15). The Elicitation Summaries are "owned" by each expert, as indicated by their signatures, and are intended to represent and document their inputs to the PVHA-U analysis.

2.6.1.2.1 Alternatives for Documentation of Elicitations

NUREG-1563 emphasizes the importance of documenting the expert elicitation process and the individual elicitations (Kotra et al. 1996, p. 18). In the diagram of the process, (Kotra et al. 1996, Figure 1), documentation is shown as an ongoing activity throughout the process—that is, each step of the elicitation process is to be documented. In the description of the documentation step it is stated that documentation should "indicate what was done, why, and by whom" (Kotra et al. 1996, p. 18).

In several places, NUREG-1563 suggests documentation of specific steps, interactions, and updates in the experts' judgments after their initial assessments. For example, Section 3, Step 7 (Postelicitation Feedback) states that "Each expert should be queried as to the need for revision or clarification of his respective judgments based on that feedback. As is the case for all the elicited judgments, the rationale for any revisions should be scrupulously documented."

The detailed discussion in Section 4 of NUREG-1563 reiterates this point in Step 8 (Aggregation of Judgments). In this step, the SSHAC approach to aggregation, which is the approach used in the PVHA-U (Section 2.1.2), is described as a combination of behavioral and mechanistic aggregation. NUREG-1563 states: "Should interaction among experts, after the individual elicitations, result in any changes of judgments by the individual experts … the descriptions and implications of the changes should be included in updated representations of the individual experts' state of knowledge."

2.6.1.2.2 Discussion

The documentation methodology for the PVHA-U was fully consistent with the documentation recommendations in Step 9 in the Branch Technical Position (Kotra et al. 1996, p. 18). However, the degree of consistency with the more detailed "Discussion" section in the Branch Technical Position requires clarification. The apparent intent of the Discussion section is to ensure that the rationale for any modifications following the initial elicitation interview is documented, and the implications of those changes are explored.

A difference between documentation approaches used for PVHA-U and the recommendations outlined in NUREG-1563 relates to the degree of detail provided regarding "intermediate assessments" of individual experts and any subsequent refinements or changes to each expert's judgments that are reached prior to completion of each expert's final elicited position. The MDT did not favor documenting the intermediate assessments because of concerns identified below.

The point of difference is that the experts' judgments are documented in one elicitation summary for each expert. If an expert modified his judgments and/or changed his opinions during the course of the elicitation process from the post-elicitation feedback, interactions and discussions with other experts through the workshops, and/or simple reflection and reconsideration, he was not required to describe the rationale for those modifications in his Elicitation Summary.

Three reasons justify use of a single integrated Elicitation Summary for each expert, rather than an initial summary supplemented by explanations of the rationales for changes. These three reasons are summarized below, followed by a detailed explanation of each:

(1) The entire interview and feedback process, including the workshops, was considered part of a single elicitation.

(2) Requiring experts to explain in detail any deviations from their initial judgments reinforces the anchoring bias and may distort the experts' true judgments.

(3) The process included sufficient safeguards against real or perceived coercion of, or undue influence of the group or other individuals on any expert's judgments.

The elicitations were documented in a single Elicitation Summary for each expert because the PVHA-U methodology defined the elicitation not as one-interview event, but rather as the entire process including the elicitation interview following Workshop 2A through the post-Workshop 4 updates. Consistent with the SSHAC process and the desire to ensure that equal weighting of the experts' judgments is warranted (discussed further in Section 2.5), the extensive interactions among experts and the feedback they received in Workshops 3 and 4 were intended to inform the experts, provide opportunities for learning, and ensure that all experts have the same technical bases and adequate technical understanding. The interactions were designed to provide the experts with the latest information and to ensure that all experts updated their judgments based on appropriate consideration of the information available to them. Thus, changes in experts' judgments were not seen as aberrations requiring special documentation, but as parts of the process of experts constructing their inputs and judgments.

The second reason the PVHA-U process did not require documentation of every change of opinion that the expert might have after the initial interview is that such a requirement puts too much weight on an initial assessment by reinforcing the "anchoring" effect. Anchoring is a strong and well-known cognitive bias that affects judgment and estimation, wherein an individual overweights an initial value (the "anchor") and then adjusts that estimate insufficiently when more information is available (see, for example, Kahneman et al. 1982, Chapter 1). A documented position imposes a strong anchor, and requiring the elicitation team to extract from the expert the rationale for any changes of opinion would further reinforce that anchor by creating the impression that learning and changes of opinion are not expected and must be defended.

Finally, the project recognizes that the NUREG-1563 recommendations for documenting the rationale behind an expert's evolving opinions derives from a legitimate concern about the effects of group dynamics on individuals' expressed judgments and the potential for one or more experts to feel pressured to modify their judgments counter to their true expert opinions. Documenting changes of opinion or judgment is one way to see if such effects, assuming they exist, result in significant changes in the results of the overall assessment. The PVHA-U process, however, includes sufficient safeguards against this potential problem. These safeguards include:

- Interactions among experts were at workshops that were open to the public, facilitated by an experienced technical facilitator-integrator, and documented, so undue influence on an individual expert would have been seen and countered.

- Every workshop reiterated that the ultimate goal of the elicitation was *not* consensus on a final "aggregate" model or assessment, but that the panel's judgments represented the range of judgments among the informed technical community. The facilitators emphasized that a range of viewpoints was expected and agreement on all issues was not a goal.

- Experts were given opportunities to review and revise their judgments after the final workshop, and were not required to defend those final judgments to the rest of the expert panel, giving them opportunities to express their true expert opinions without peer pressure, even if the opinions were counter to the judgments of other panel members.

- Experts who served on the panel have agreed to be publicly associated with their assessments and the rationale behind them; hence, they feel professional obligations to a larger group (the technical community) to explain their assessments, countering pressures from group dynamics.

2.6.2 Consistency with SSHAC Guidance

The PVHA-U followed the procedural guidance set forth in the SSHAC report (Budnitz et al., 1997) both in spirit (e.g., recognition of the importance of facilitated expert interactions) and, as applicable, in details of implementation (e.g., suggestions for conducting workshops and elicitation interviews). For example, the experts were provided with training to help them express their uncertainties in probabilistic terms. The distinction between aleatory variability and epistemic uncertainty was discussed using examples of each. The experts were also made aware of the possible motivational and cognitive biases that are common to all forms of expert judgment, such that these biases could be mitigated. The experts were informed early in the project, and reminded throughout, of the need to express full ranges of uncertainty; that is, they were asked to express alternative interpretations permitted by the available data weighted by the degree that each was supported by the data.

3. EXPERT ASSESSMENTS

This section presents the probabilistic volcanic hazard analysis update (PVHA-U) model(s) developed for this study. Section 3.1 describes the three basic components of the PVHA-U and provides examples of the various modeling approaches used for each. Details of the mathematical formulation and calculations are provided in Appendix E. Section 3.2 summarizes each of the individual experts' models in terms of the three components discussed below, and the detailed technical bases for the expert assessments are given in each expert's Elicitation Summary in Appendix D. The results of the hazard analysis are discussed in Section 4.

3.1 PROBABILISTIC VOLCANIC HAZARD ANALYSIS UPDATE COMPONENTS

The quantitative result of this study is the annual probability of an intersection of the repository footprint by an igneous event. Because the probability is small, it can be estimated to a close approximation by the expected frequency of intersection,[1] which we represent as $v_I(t)$. Mathematically, the annual frequency of intersection at any point in time can be represented by:

$$v_I(t) = \iint_R \lambda(x,y,t) \cdot P_I(x,y)dxdy \qquad \text{(Eq. 3-1)}$$

where $\lambda(x,y,t)$ is the rate density (the frequency of events per unit time per unit area), $P_I(x,y)$ is the conditional probability that an igneous event occurring at location x, y would intersect the repository footprint, and R is the region of interest. In most cases, the models defined by the experts consider the temporal and spatial aspects separately, so that equation 3-1 can be rewritten as:

$$v_I(t) = \iint_R \lambda(t) \cdot f(x,y) \cdot P_I(x,y)dxdy \qquad \text{(Eq. 3-2)}$$

where $\lambda(t)$ is the rate parameter (frequency of events in the region of interest per unit time), and $f(x,y)$ is the conditional spatial density (events per unit area, given an event occurs).

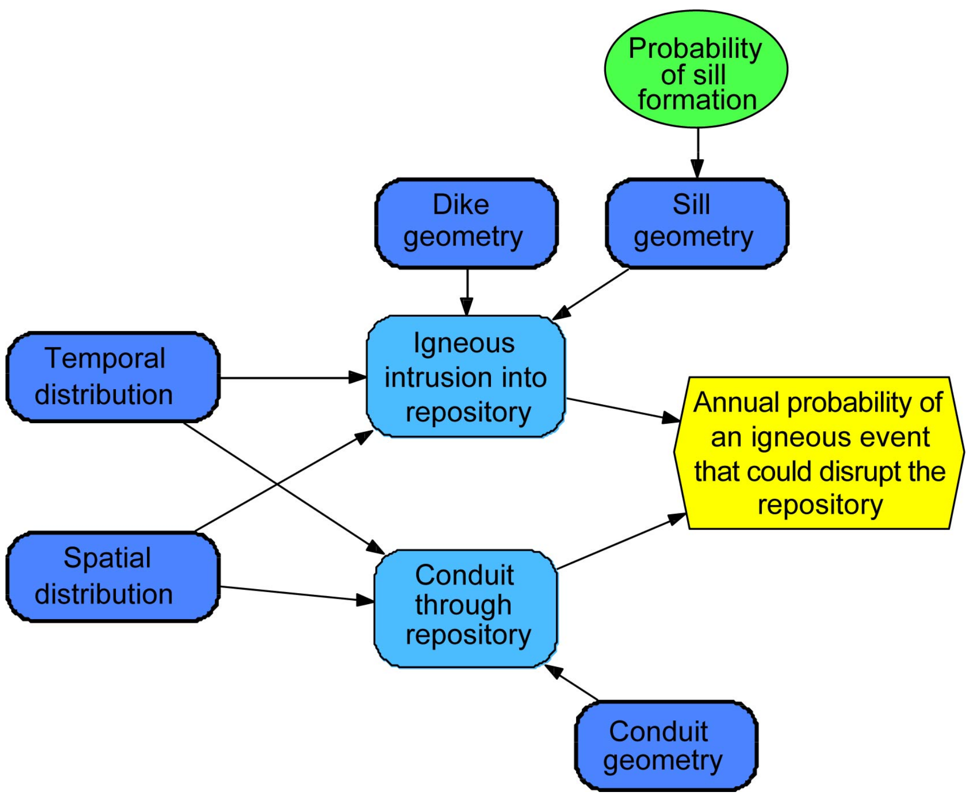
Together, the three components of the integral in Equation 3-2 identify the three basic components of this PVHA-U: the spatial and temporal distributions of igneous events and an assessment of the probability that an igneous event at any specific location will intersect the repository footprint. The latter requires a description of the characteristics of an "event," including the number, geometry, and placement of various igneous features.

The overall structure for an example expert model is given in the influence diagram in Figure 3.1-1. The yellow hexagon represents the final result of the assessment: the annual probability of an igneous event that could disrupt the repository. In this example, the igneous event that could disrupt the repository is identified as an igneous intrusion into the repository or the development of a volcanic conduit through the repository. These types of events are represented by the light blue nodes with arrows leading into the final result (light blue rounded

[1] The probability of one or more intersections is P(1) + P(2) +…. , which is less than the expected frequency of intersection, or the mean number of intersections: 0xP(0) + 1xP(1) + 2xP(2) +…

rectangles represent values calculated from other inputs). Each of these possibilities is a function of the geometries of dikes and sills (for intrusions) and conduits, as well as the spatial and temporal distribution of events, all represented by dark blue ovals indicating submodels. An igneous intrusion into the repository could result from either a dike or a sill, as represented by the dike geometry and sill geometry submodels. The likelihood of an igneous intrusion from a sill is a function first of the probability of a sill forming in an event, as shown by the green node (green ovals represent variables for which experts made a direct assessment), and then of the geometry of the sill and its location within an event (represented by the Sill Geometry node).

A probabilistic assessment requires that uncertainties in these components be identified, quantified, and, to the extent possible, incorporated into the analysis. With time, increased data availability, and additional understanding of the physical processes that give rise to igneous processes in the Yucca Mountain and analogous regions, the representation of the basic components of the PVHA-U has become increasingly detailed and physically realistic. This evolution is to be expected and the hazard-methodology tools, as discussed below, have been refined to keep pace with the advances in scientific understanding.



NOTE: The yellow hexagon represents the final result of the assessment. Dark blue rounded rectangles represent submodels; light blue nodes represent values calculated from other inputs; the green oval represents an uncertain input for which a direct assessment has been made; and arrows indicate influence of one variable on one or more others.

Figure 3.1-1. Influence Diagram Illustrating the Overall Structure of an Example Model

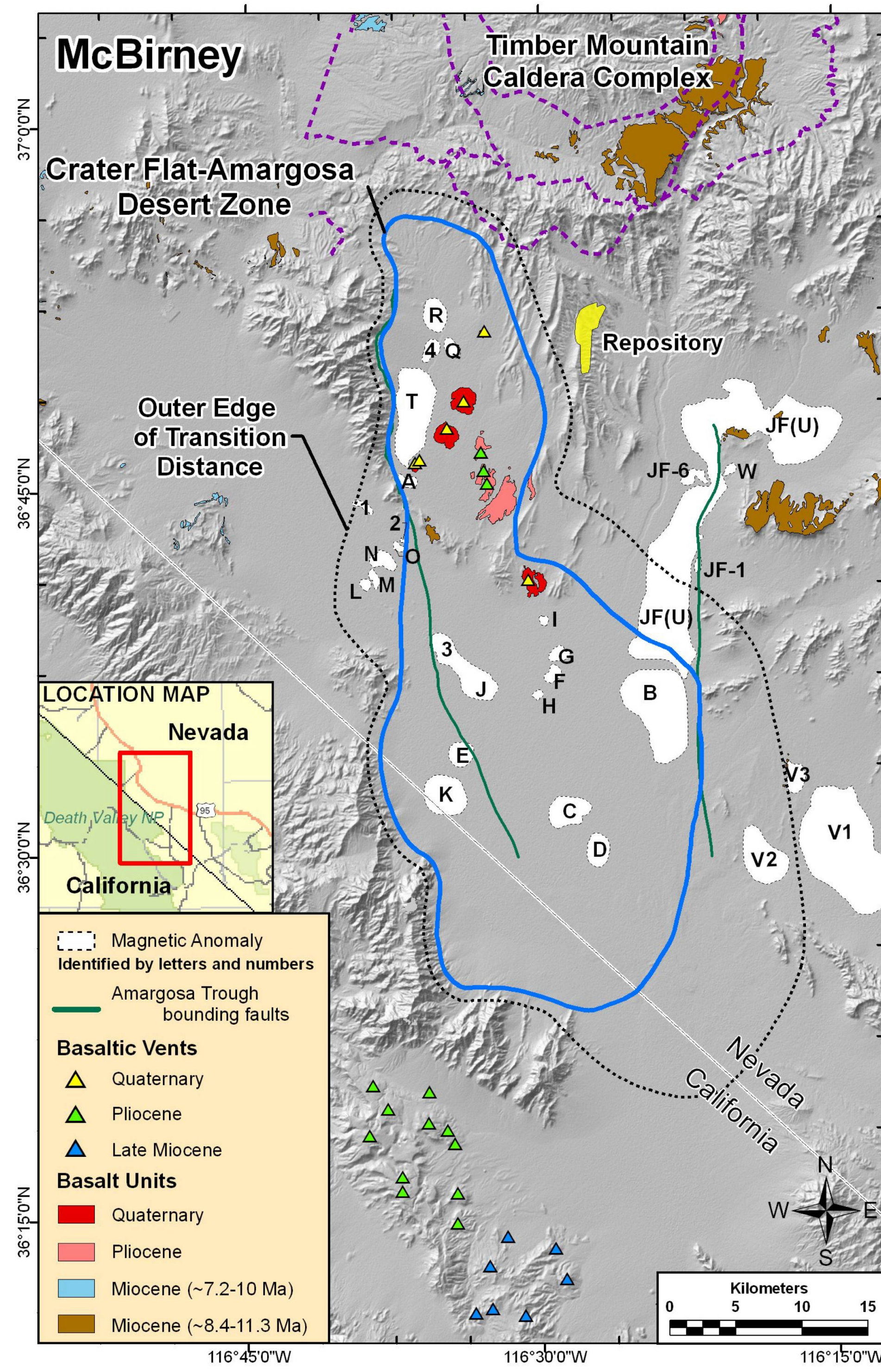
3.1.1 Alternative Spatial Modeling Approaches

Four basic spatial modeling approaches were used by the experts in their assessments. Each is described briefly in this section. The mathematical formulations are developed in Appendix E, and the specific models used by each expert are described in Section 3.2 and the elicitation summaries in Appendix D.

Locally Homogenous Spatial Zones. The first approach is that of locally homogenous spatial zones. In this approach, the expert defines one or more zones in which the rate of future events is assumed to be different than in other zones or outside of the zone, and is assumed to be uniform within each defined zone. Figure 3.1.1-1 shows an example of a locally homogeneous zone (defined by the blue line) composed of a relatively small region with a concentration of past activity, and a larger region with more diffuse activity, termed the "background zone." In its simplest form, the boundary between zones represents a point where there is an abrupt change in rate density. Some experts chose to define a gradual transition in rate between the zones, and in such cases they defined a transition distance. A rate transition boundary that varies in size around the zone is illustrated by the black dashed line in Figure 3.1.1-1. The zone boundaries and the rate transition boundaries can be treated as uncertain.

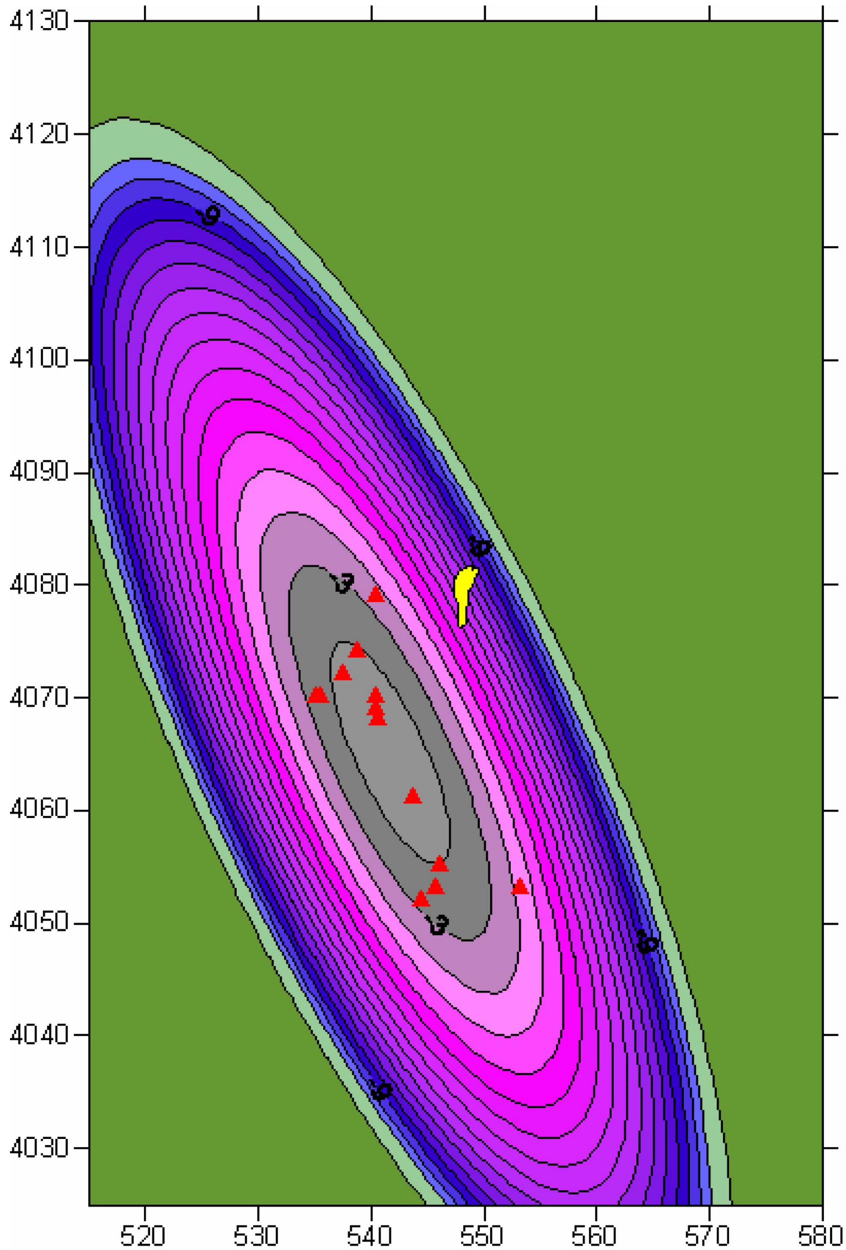
Parametric Spatial Density Function: Bivariate Gaussian Field Shape. Sheridan (1992) developed a model for volcanic fields wherein the conditional spatial density of events is represented by a "field shape" with a bivariate Gaussian distribution. In this spatial modeling approach, the volcanic field has an elliptical shape, defined by five parameters (the x, y coordinates of the center of the field, the length of the two axes, and the orientation of the field). The parameters for the model can be specified directly by the expert or they can be estimated based on the locations of observed events in the field. In this PVHA-U analysis, experts using this spatial modeling approach chose to fit the field parameters to identified past events. Figure 3.1.1-2 illustrates a bivariate Gaussian field shape model fit to a set of past events.

Uncertainty in the conditional spatial density calculated using this approach can come from uncertainty in the appropriate set of past events, and from uncertainty in estimating the field parameters from a limited set of data. The latter uncertainty is captured by explicitly modeling uncertainty in each of the five fitted field parameters by varying them +/- one standard error. Figure 3.1.1-3 shows examples of a few of the field shapes that can arise from uncertainty in the fit of the parameters to a small set of data.



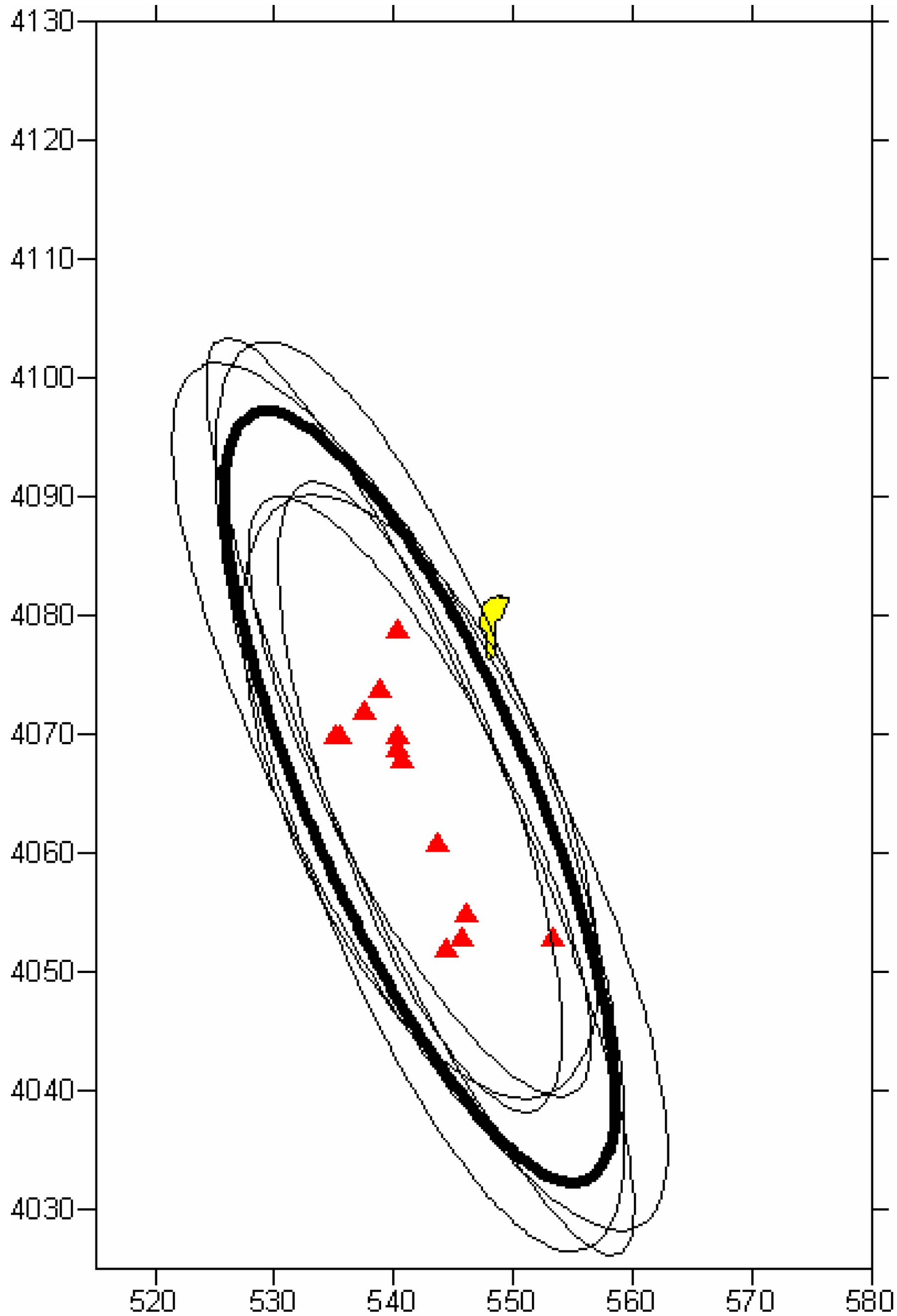
NOTE: The blue line marks the boundary of the locally homogenous zone; the black dashed line represents the outer boundary of the rate transition zone. Example from assessment of Alexander McBirney.

Figure 3.1.1-1. Example of a Locally Homogenous Zone within a Background Zone / Region of Interest



NOTE: Contours are labeled with the $\log_{10}$ of the conditional spatial density (so $-3 = 10^{-3}$). Contours represent the bivariate Gaussian field fit to the 13 events shown as red triangles. Repository footprint is shown as a yellow polygon. Map grid ticks are based on UTM meters shown in kilometers; tick intervals are 10 km.

Figure 3.1.1-2. Example of a Conditional Spatial Density Calculated Using a Bivariate Gaussian Field Shape Model



NOTE: Bold contour is the 10^{-5} conditional spatial density for the best fit of the bivariate Gaussian field shape to the 13 events shown as red triangles. Other contours are the 10^{-5} conditional spatial density for various alternative fits to those events, chosen simply to represent some of the uncertainty in the conditional spatial density calculated using this model. Repository footprint is shown as a yellow polygon. Map grid ticks are based on UTM meters shown in kilometers; tick intervals are 10 km.

Figure 3.1.1-3. Example of the Uncertainty in Field Shape and Size Resulting from Uncertainty in the Fit of the Field Parameters to a Small Set of Events

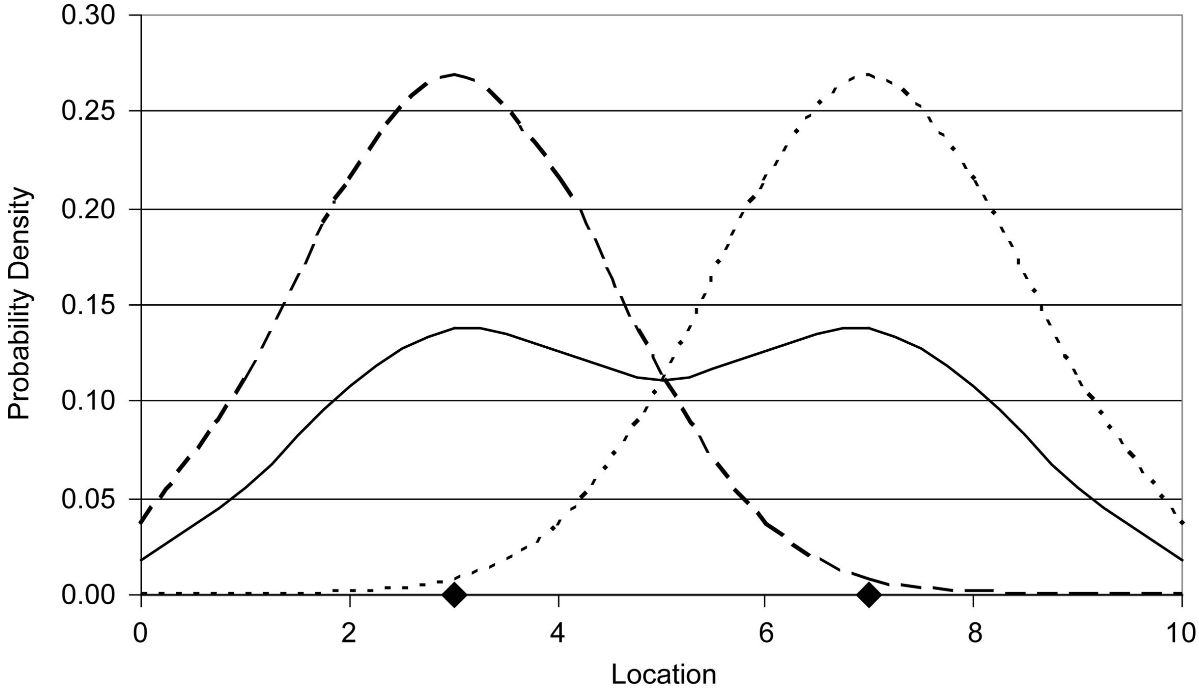
Nonparametric spatial density function: Kernel density estimation. Kernel density estimation is a statistical approach for estimating spatial density in which a specified density function (the kernel) is averaged across a set of observed data to create a smooth "map" of spatial density across the region of interest. Conceptually, this approach is based on the assumption that future events would occur "near" past events; how near is defined by the kernel function and its dimensions.

Figure 3.1.1-4 illustrates kernel density estimation in one dimension: a Gaussian kernel function is centered on each of the two "events" and then the value of the two estimates at each location along the x-axis is averaged to yield the density estimate at each point along the line. Figure 3.1.1-5 illustrates a conditional spatial density map in the YMR based on kernel density estimation using a set of events identified as relevant by one of the PVHA-U experts.

The basic kernel density estimate can be modified by differential weighting of the past events; this approach is considered appropriate if some past events are judged more relevant to the location of future events than others. In the PVHA-U analysis, experts used a variety of event-weightings based on functions of the event ages (younger events being judged more relevant to the location of future events, thus the inverse of the age is given higher weight) and/or their volumes (higher volume events being judged more relevant). Figure 3.1.1-6 illustrates examples of (a) inverse-age weighting, and (b) volume weighting in a kernel density estimate of conditional spatial density.

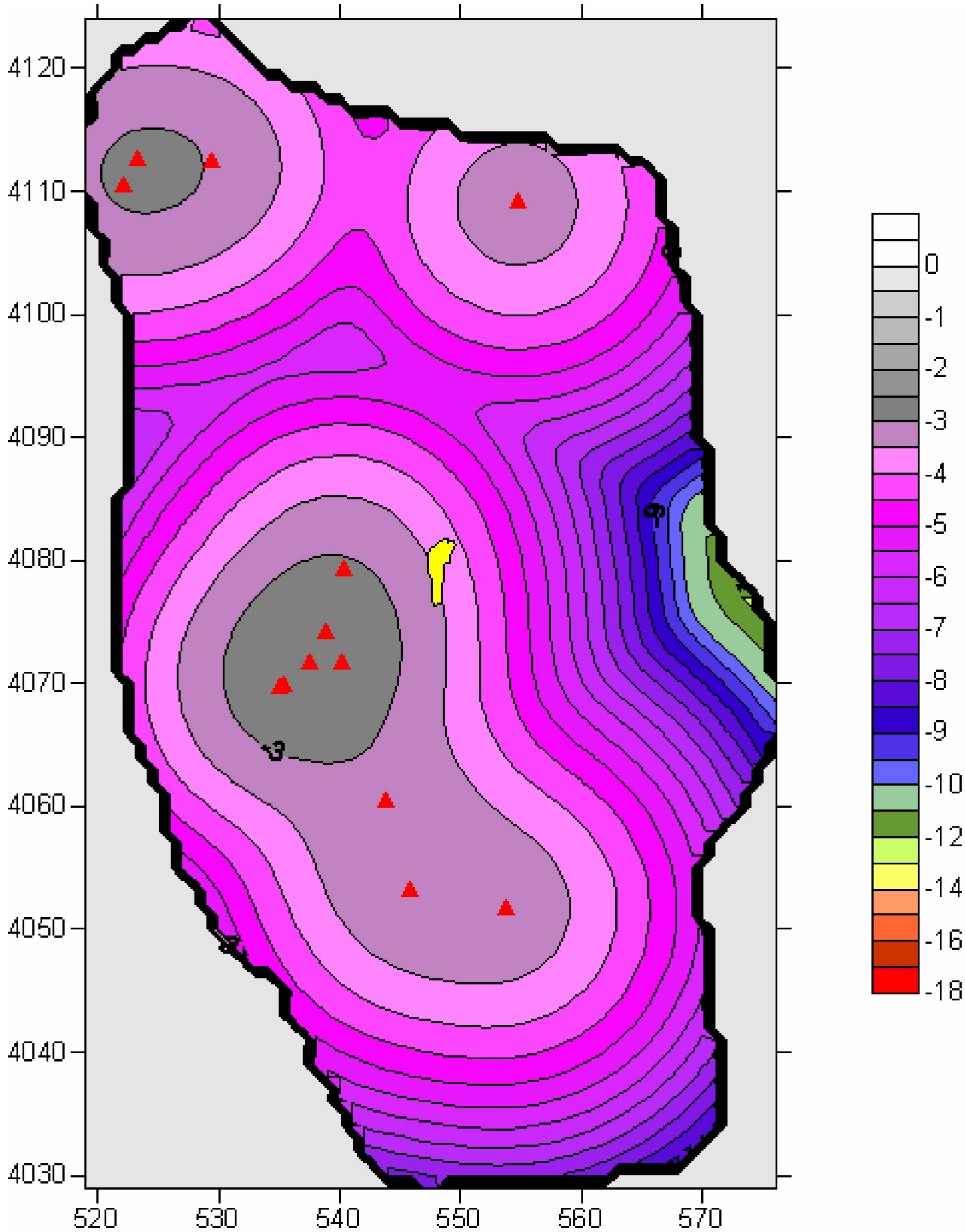
In all expert models in the PVHA-U that used kernel density estimation, a Gaussian kernel was specified. One expert (Connor) specified an anisotropic (elliptical) Gaussian kernel which introduces a preferred orientation for spatial smoothing. Figure 3.1.1-7 illustrates an example of the conditional spatial density from kernel density estimation with an anisotropic Gaussian kernel.

Uncertainty in the conditional spatial density calculated using this approach can come from uncertainty in the appropriate set of past events used to fit the density estimate, from alternative kernel functions, from uncertainty in the parameters for the kernel functions, from uncertainty in the appropriate weighting of past events, and from uncertainty in fitting the kernel to a limited set of data. Following a suggestion from Charles Connor during Workshop 2, subsequently described in Connor and Connor (forthcoming), the latter uncertainty is captured through a statistical simulation approach known as the "bootstrap" (Efron 1981). Conceptually, the bootstrap method addresses uncertainty by treating the past events as one observation of an infinite variety of event sets that could be produced by some underlying spatial density. The underlying spatial density is approximated, and then treated as a sampling distribution for simulation. For each set of samples, a new kernel density estimate is generated, and each of these density estimates is treated as an equally likely representation of the conditional spatial density. The mathematical basis and formulation for this approach is described in Appendix E. Figure 3.1.1-8 illustrates the results of several different realizations of the bootstrap simulation for the kernel density estimate shown in Figure 3.1.1-5.



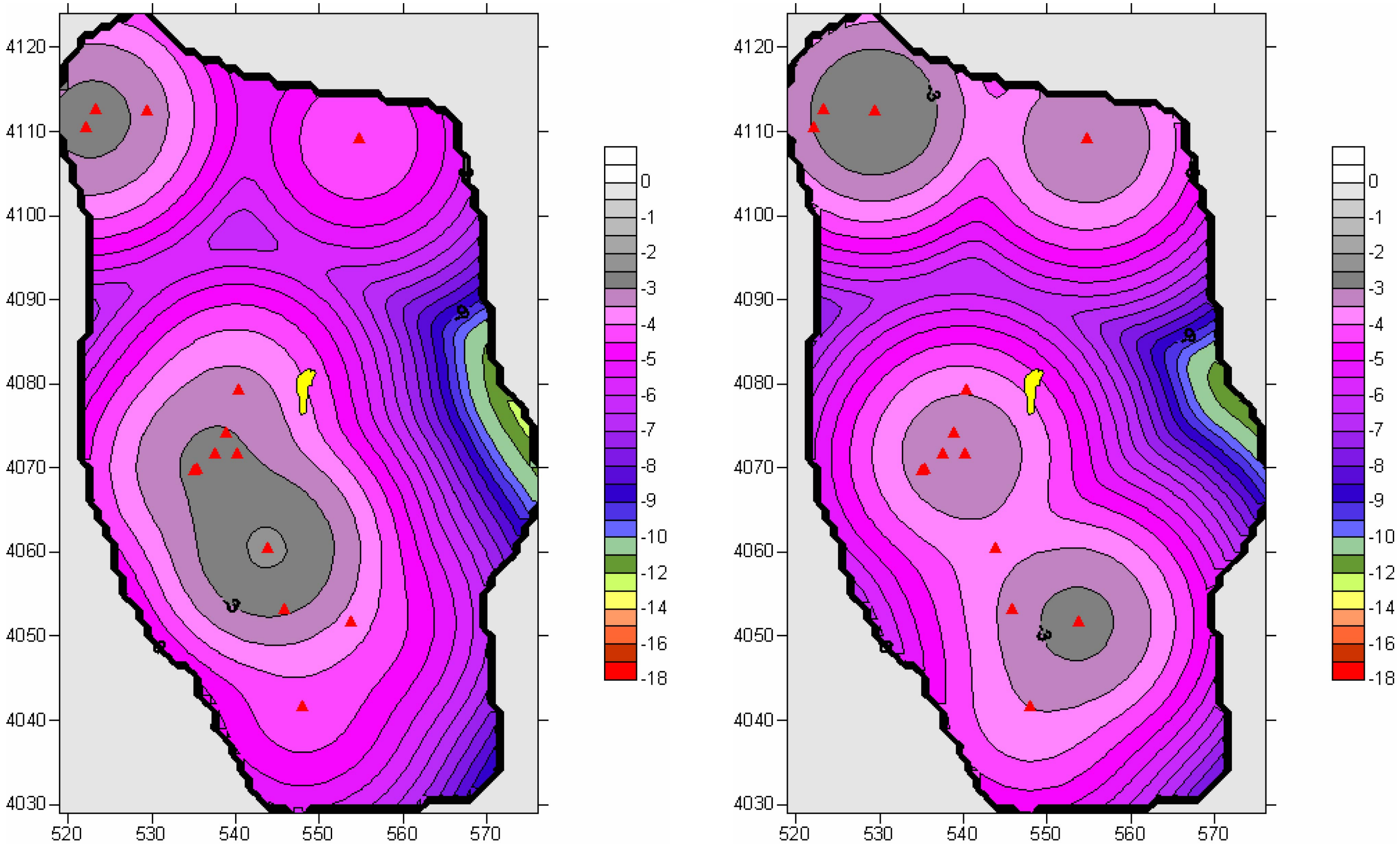
NOTE: Solid black diamonds at 3 and 7 indicate the location of two events; dashed lines show the individual kernel density centered on each event using a Gaussian kernel function with a bandwidth of 1.5 km. The solid line shows resulting kernel density estimate (the relative probability of a future event at any location along the line) calculated by averaging the two functions shown.

Figure 3.1.1-4. Illustration of a Kernel Density Estimate in One Dimension



NOTE: Contours are labeled with the $\log_{10}$ of the conditional spatial density. Kernel density estimate based on a Gaussian kernel with a bandwidth of 5 km fit to the events shown as red triangles. Density estimate is bounded by a region of interest (the dark outer line). Repository footprint is shown as a yellow polygon. Map grid ticks are based on UTM meters shown in kilometers; tick intervals are 10 km.

Figure 3.1.1-5. Example of a Conditional Spatial Density Based on Kernel Density Estimation

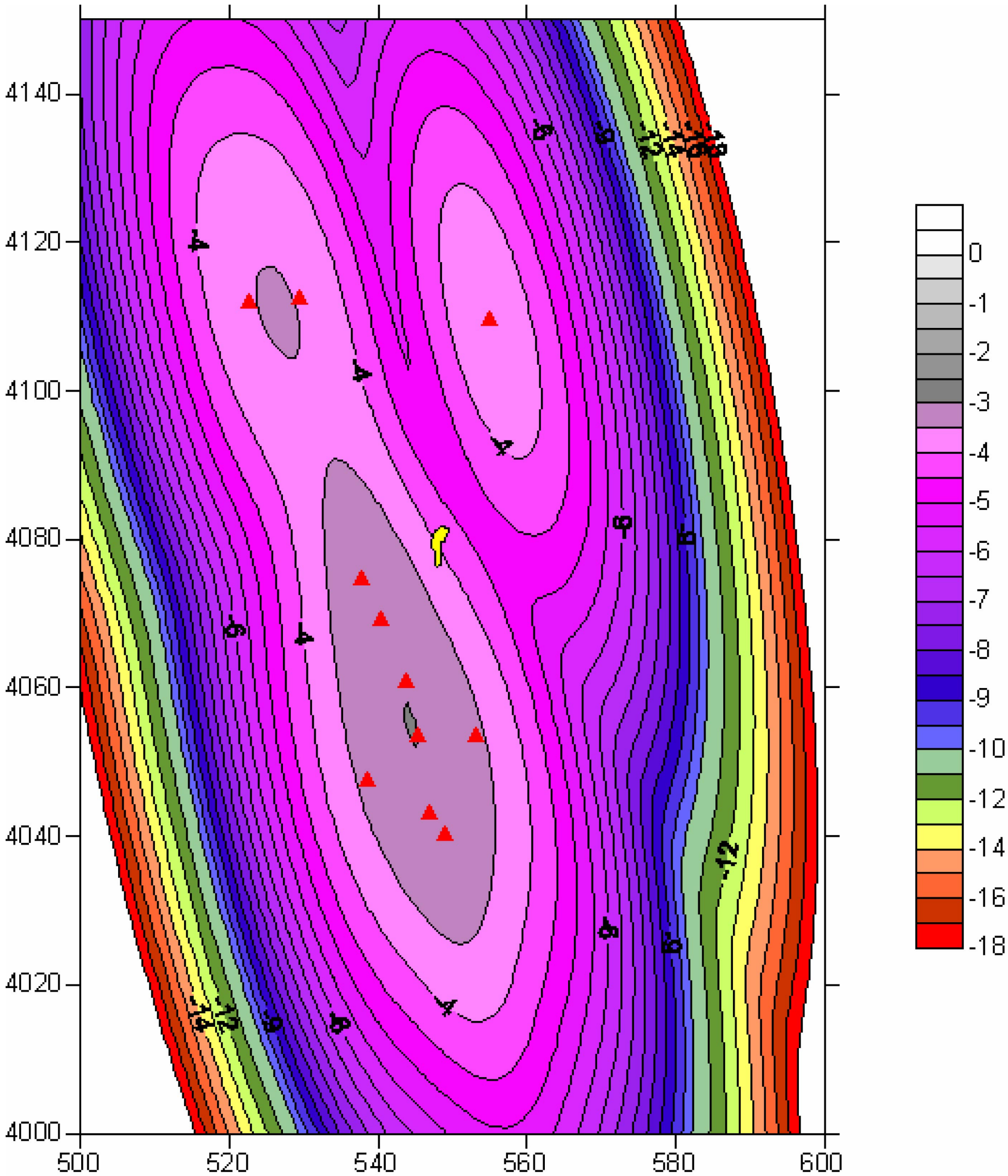


(a) Events weighted by the inverse of their age. Highest probability contour is around the youngest event.

(b) Events weighted by volume. Highest probability contours are around the highest volume events.

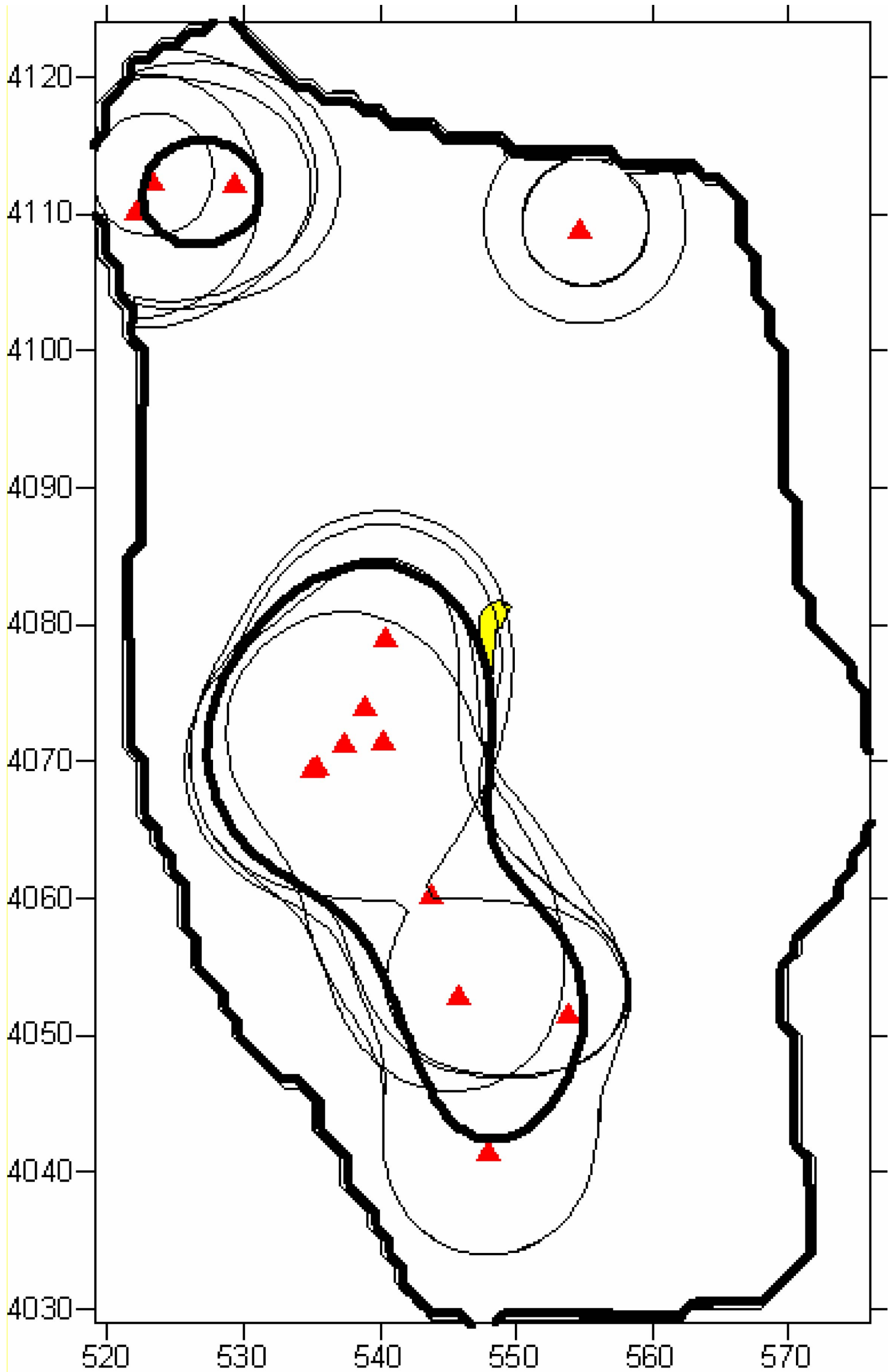
NOTE: Contours are labeled with the $\log_{10}$ of the conditional spatial density. Kernel density estimate based on a Gaussian kernel with a bandwidth of 5 km fit to the events shown as red triangles. Repository footprint is represented with a yellow polygon. Map grid ticks are based on UTM meters shown in kilometers; tick intervals are 10 km.

Figure 3.1.1-6. Examples of Conditional Spatial Densities Based on Kernel Density Estimation with Alternative Weightings of Past Events



NOTE: Contours are labeled with the $\log_{10}$ of the conditional spatial density. Anisotropic kernel density estimate based on a Gaussian kernel with an expert-specified bandwidth matrix fit to the events shown as red triangles. Repository footprint is represented with a yellow polygon. Map grid ticks are based on UTM meters shown in kilometers; tick intervals are 20 km.

Figure 3.1.1-7. Example of a Conditional Spatial Density Based on Kernel Density Estimation with an Anisotropic Gaussian Kernel Function



NOTE: Bold contour is the $10^{-3.5}$ conditional spatial density for the fit of the kernel estimation to the events shown as red triangles. Other contours are the $10^{-3.5}$ conditional spatial density for fits of the kernel estimator to alternative event sets generated in the bootstrap method, chosen simply to represent some of the uncertainty in the conditional spatial density calculated using this model. Repository footprint is shown as a yellow polygon. Map grid ticks are based on UTM meters shown in kilometers; tick intervals are 10 km.

Figure 3.1.1-8. Example of Uncertainty in Conditional Spatial Density Based on Bootstrap Modeling from a Kernel Density Estimate

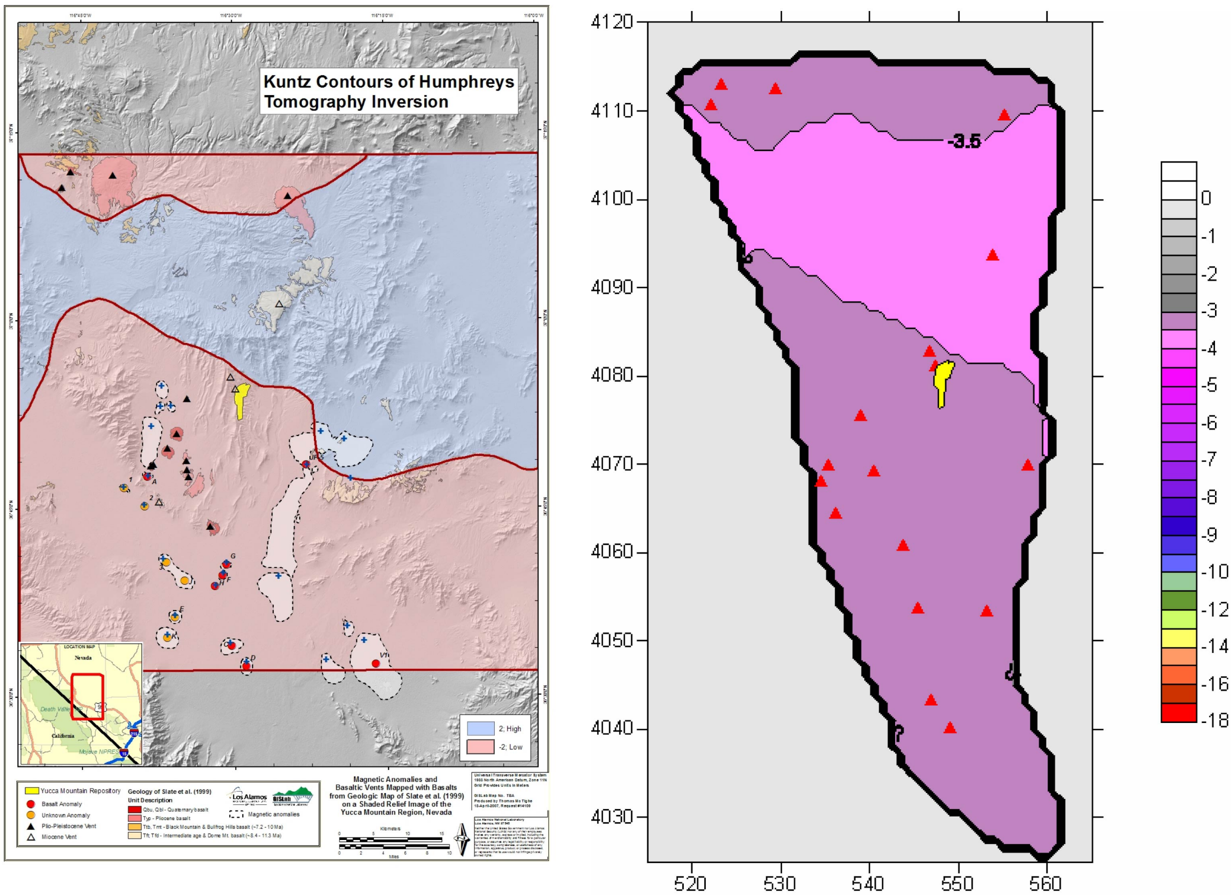
3.1.2 Use of Geology Datasets in Spatial Models

Among the data provided to the PVHA-U experts were a variety of geology datasets, as described in Appendix B. Experts chose to use those datasets in several different ways in their assessments of the spatial distribution of events, ranging from qualitative consideration of the data to explicit quantitative models based on the data values at specific locations.

One expert (McBirney) who used a spatial zones model based his zone boundary in part on tomographic data. Another expert (Crowe) who also used a spatial zones model defined his zones explicitly by the lithostatic pressure at each location. Each of these models is described in detail in the individual elicitation summaries for that expert (see Appendix D).

More common in this assessment are models that combine spatial densities from either the parametric or non-parametric spatial density estimates described above with an expert's interpretation of specific geology data and its relationship to the location of future events. This approach embodies a conceptual model that future events are more likely to occur near past events *and* that geologic data provide independent information on the location of future events.

The mathematical basis used to combine expert judgments about the relationship of geology data and the location of future events with the geology data itself to yield a "geology-based" conditional spatial density is known as Bayesian updating (Gelman et al. 1995) and is described in detail in Appendix E. An example of a conditional spatial density estimate based on expert judgment about the relevance of tomographic data is shown in Figure 3.1.2-1. In practice, all experts who chose to use geology data in this way also combined their geology-based conditional spatial densities with a kernel density estimate or bivariate Gaussian estimate with weights they specified to yield a "geology-informed" conditional spatial density. One example of such combination of models to yield a single conditional spatial density estimate is shown in Figure 3.1.2-2.

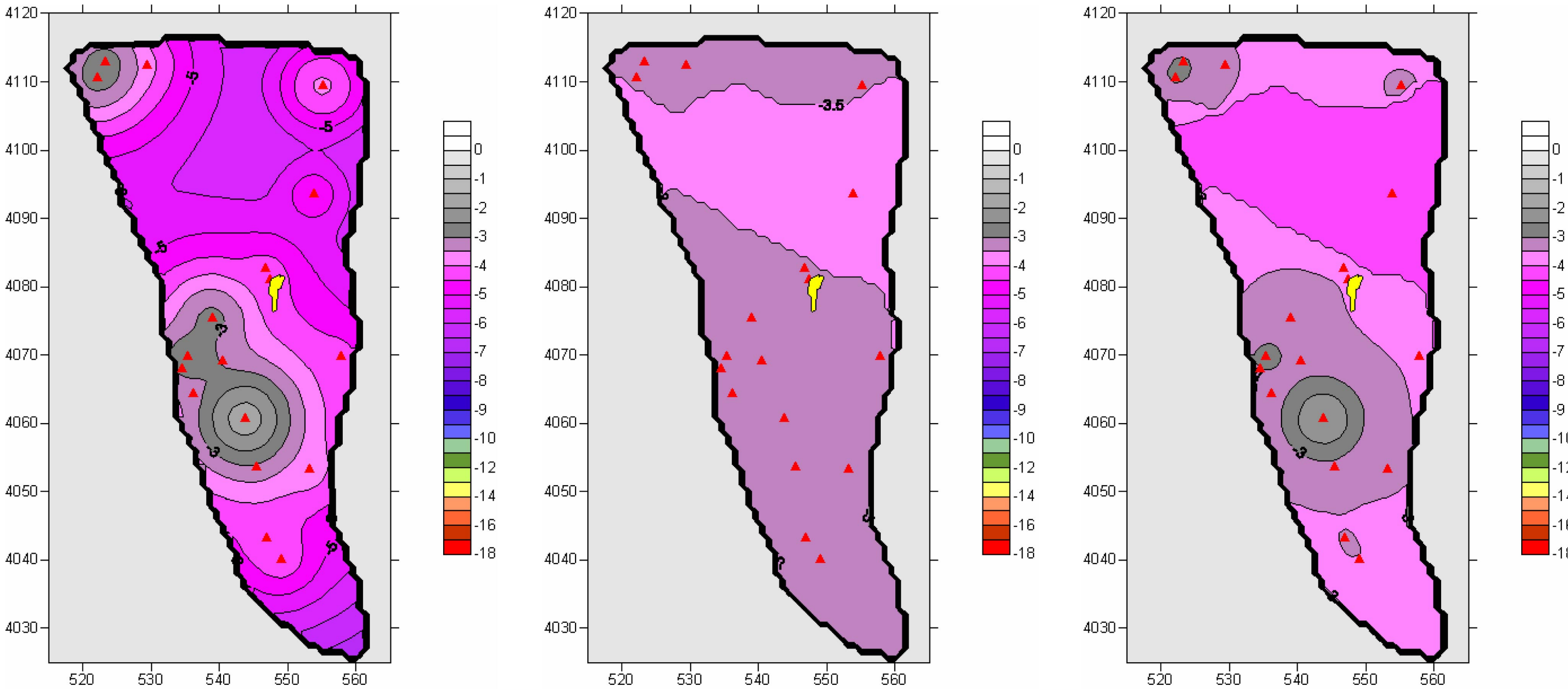


(a) Expert identification of areas of low and high velocity based on tomography data.

(b) Result of combining the low and high velocity regions with expert judgment about the relationship between velocity and event location. Contours are $\log_{10}$ of conditional spatial density.

NOTE: Maps are on different scales. Past events are represented by black triangles in panel (a), red triangles in panel (b). Repository footprint is represented with a yellow polygon in both figures.

Figure 3.1.2-1. Examples of the Application of Expert Assessment about the Relevance of Tomographic Data to the Location of Future Events



(a) Conditional spatial density based on a kernel density estimate fit to the events shown as red triangles

(b) Conditional spatial density based on interpretation of tomography data

(c) "Geology informed" conditional spatial density based on weighted combination of the maps shown in panels (a) and (b)

NOTE: Contours are labeled with the $\log_{10}$ of the conditional spatial density. Past events are shown as red triangles. The repository footprint is represented with a yellow polygon. Map grid ticks are based on UTM meters shown in kilometers; tick intervals are 10 km.

Figure 3.1.2-2. Example of a "Geology-Informed" Conditional Spatial Density Estimate Calculated by the Weighted Combination of a Kernel Density Estimate with a Geology-Derived Spatial Density

3.1.3 Alternative Temporal Modeling Approaches

Three basic temporal modeling approaches were used by the experts in their assessments. Each is described briefly in this section. The mathematical formulations are developed in Appendix E, and the specific models used by each expert are described in Section 3.2 and the elicitation summaries in Appendix D.

Homogenous Poisson Model. Homogenous Poisson models are commonly used to represent hazard from rare events, and form the basis of the probabilistic seismic hazard methodology developed by Cornell (1968, 1971). They have also been used to represent the combined effects of contributions from multiple independent processes, even when those individual processes are not Poisson (Brillinger 1982). The primary reason most PVHA-U experts cited for choosing the homogenous Poisson model was the lack of data to support more complex models. A probability distribution for the rate of a homogenous Poisson model can be estimated based on the number and age of relevant events in the region of interest, as specified by the expert. This estimate is described mathematically in Appendix E.

Uncertainty in the rate arises both from uncertainty in the identification of relevant events and from estimating the true rate from a small data set.

Time-Volume Rate Estimate. In the 1996 PVHA (CRWMS M&O 1996), Richard Carlson adapted the instantaneous volume-predictable rate model of Crowe et al. (1995):

$$\lambda(t) = \frac{dV_M(t)/dt}{V_E(t)} \qquad \text{(Eq. 3-3)}$$

by specifying parametric functional forms for $V_M(t)$, the instantaneous rate of magma production, and for $V_E(t)$, the time-varying volume per event. Several PVHA-U experts found the conceptual model of decreasing magma volume over time useful, and elected to use this formulation to derive a time-dependent rate estimate. To do so, they specified a functional form for each of the two elements, which were then fit to the ages and volumes of past events identified by that expert as relevant to his model or models.

Uncertainty in the rate estimate from this model arises from uncertainty in the relevant events, in the functional form used to model $V_M(t)$ and $V_E(t)$, and in the fit of those functional forms to the small data sets.

Temporal Clustering. One expert (Sheridan) specified a temporal clustering model, wherein events are assumed to occur in clusters: clusters follow a Poisson arrival process with one rate, and within a cluster, events follow a Poisson arrival process with a different, higher rate. The mathematical formulation of this model is described in Appendix E, and the specific estimates used to fit the model are described in Section 3.2.6 and the Elicitation Summary for Michael Sheridan in Appendix D.

Uncertainty in the rate estimate from this model arises from uncertainty in the relevant events, in the identification of past temporal clusters, in the duration of a cluster, and in the estimates of the two arrival rates based on limited data sets.

3.1.4 Alternative Event Descriptions

"Events" are generally defined by the PVHA-U experts as spatially and temporally related groups of igneous features. Events of interest in this analysis are those that have the potential to disrupt the repository, which is defined as an igneous intrusion into the repository (which could be a dike, a sill, or both), or an extrusion that passes through the repository, bringing magma to the surface (which could be a column-producing conduit or non-column producing conduit, termed a "vent" in this analysis). Each expert has a unique definition of what an igneous event in the Yucca Mountain region would look like. The PVHA-U did not require that all experts use the same event description, as there is no expectation that all experts would share a common view of the nature of future igneous events in the YMR, just as there is no expectation that all experts would use the same spatial or temporal approach. It is necessary, however, that each expert *consistently* use one event definition throughout his individual assessments. That is, however the expert defines events (e.g., as having a duration of some period of time and consisting of multiple features such as dikes and conduits), this type of event is the basis for his spatial distribution and for identifying the recurrence rate of observed events in the geologic record.

PVHA-U experts identified two to four types of igneous features that could disrupt the repository. All experts included the potential for dikes and for column-producing conduits in their event descriptions. Some experts also included the potential for sills and for non-column producing vents. To model events, it was necessary for the experts to define the characteristics of each of these features, including the number and dimensions of such features, and their locations relative to one another in an "event." All of these characteristics are uncertain, and the PVHA-U experts generally characterized them with probability distributions (e.g., the length of a dike might be between 0.2 km and 15 km, and be described by a distribution that is lognormal in shape). The details and the bases for each assessment are described in each expert's individual elicitation summary in Appendix D.

Figure 3.1.4-1 illustrates an example of the major components of an event description in an influence diagram. In this example events might include dikes, conduits, and sills. Conduits might be column-producing or not. Green ovals represent uncertainties that were assessed by the expert, and the blue rounded rectangles represent values that were calculated from those uncertain values, and the desired result of the assessment: the location of each igneous feature in an event. Because each of the variables defining an igneous event is uncertain, an wide variety of potential events exists that are consistent with each expert's event definition. Section 3.1.5 describes the modeling approach used to capture this uncertainty in event characteristics for each individual expert and to accurately and appropriately represent that wide variety of potential events.

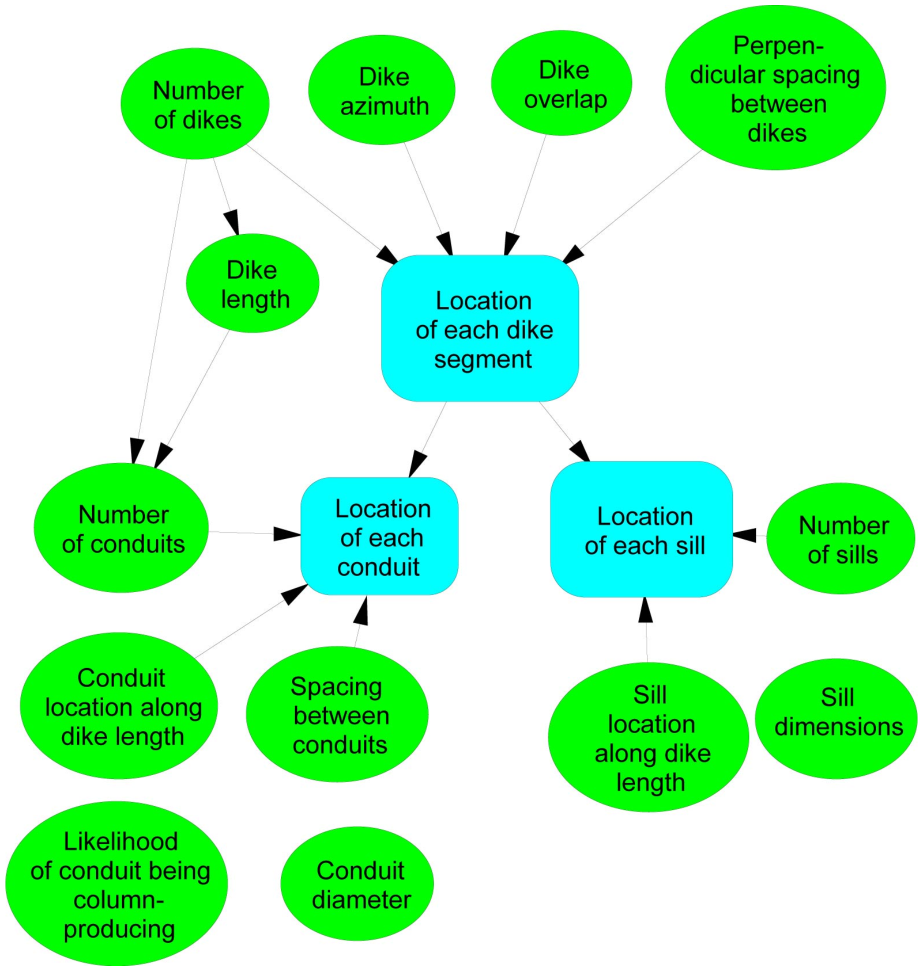
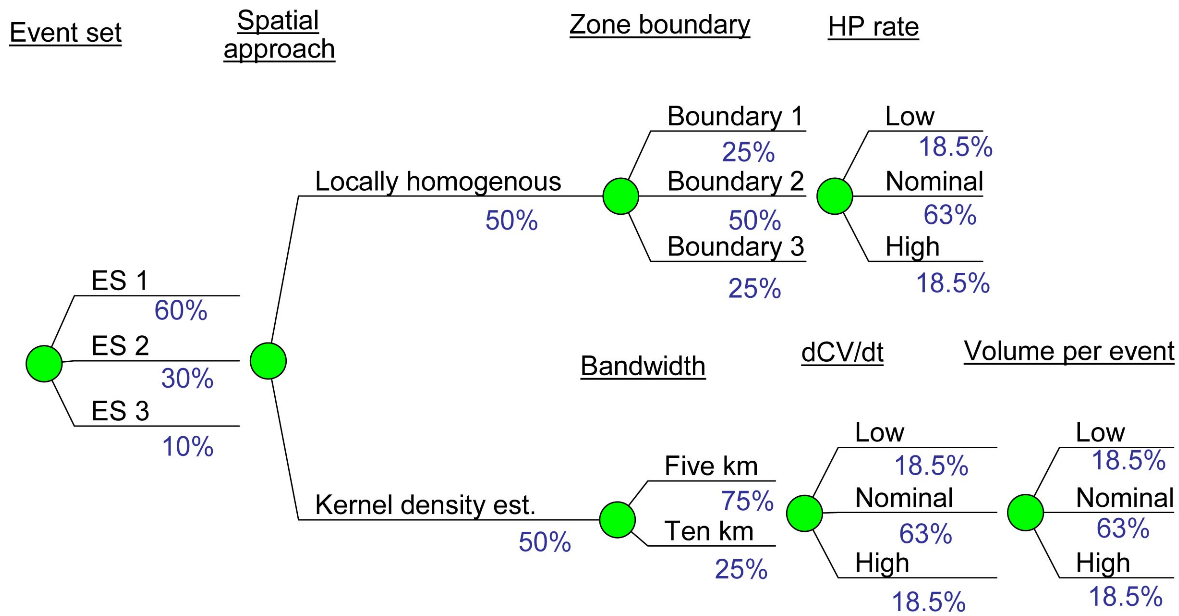


Figure 3.1.4-1. Example Influence Diagram Illustrating Some of the Major Components of an Event Description

3.1.5 Treatment of Uncertainty

In any assessment of the likelihood and the effects of rare events, considerable uncertainty exists in selecting the appropriate models, model parameters, and data to support those models. It is standard practice to explicitly incorporate those uncertainties into probabilistic hazard analyses, as is done in this PVHA-U. The analysis employs two approaches to capturing uncertainty in expert assessments and models: a logic tree approach for incorporating uncertainty in spatial and temporal models, and a simulation approach for capturing uncertainty in the event descriptions and the conditional probability of intersection.

Logic Trees for Capturing Uncertainty in Spatial and Temporal Models. The logic tree approach has been used extensively in probabilistic seismic hazard analyses, as well as in the original PVHA study (Kulkarni et al. 1984; Coppersmith and Youngs 1986; Reiter 1990; Bommer et al. 2005; CRWMS M&O 1996). In this approach, the components of the model(s) are represented by nodes in the logic tree, with branches representing alternative models and/or alternative parameters for those models. Figure 3.1.5-1 shows a simplified logic tree to illustrate the approach.



NOTES: ES = event set; HP rate = rate for the homogenous Poisson temporal model; dCV/dt = rate of change of cumulative volume over time.

Figure 3.1.5-1. Simplified Logic Tree Illustrating Spatial and Temporal Models and Uncertainties for a Hypothetical Expert Model

A logic tree is composed of a series of nodes and branches. Each node represents a component of the PVHA-U model, and each branch on a node represents an alternative possible value or outcome for that component. Probabilities assigned to each branch represent the relative likelihood or credibility that the branch (alternative model, parameter value, etc.) represents the "correct value" or "true state" of the input. Alternatively, probabilities can be interpreted as the relative credibility or applicability of the outcome of the model and parameters represented by that branch.

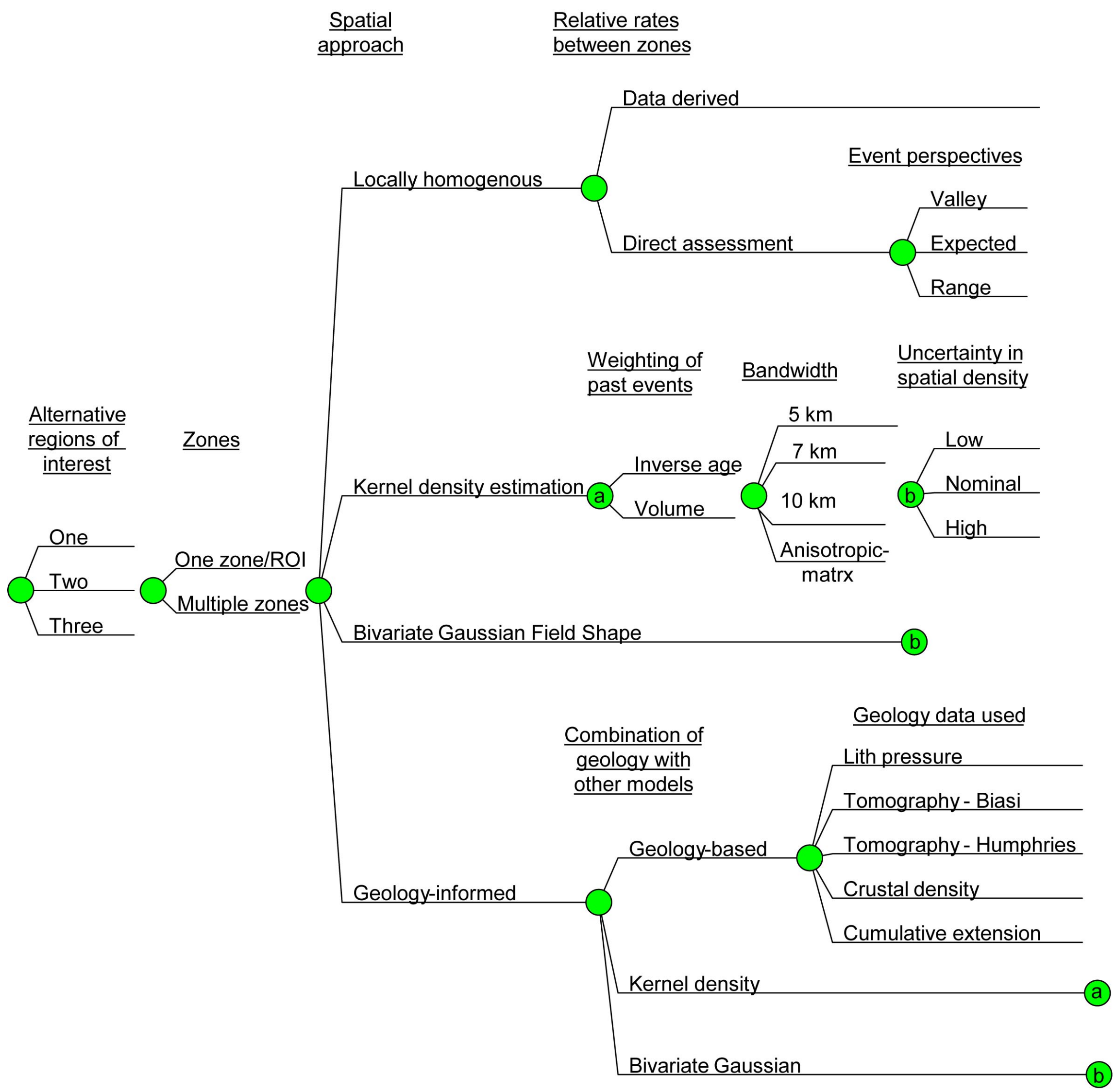
There has been discussion in the recent literature about different interpretations of "probabilities" on logic tree nodes in probabilistic hazard assessments (Abrahamson and Bommer 2005). Some professionals prefer the term "weights" to "probabilities," but the interpretation of those "weights" is exactly as described above. Further, "weights" are interpreted as probabilities in the mathematical treatment of logic trees, so in this section and in Appendix E we use the term "probabilities." In the elicitation summaries in Appendix D, some experts use the term "weights" to describe the same values.

The probabilities on the branches of a node are either provided directly by the expert assessments, or derived from a statistical model fit to data specified by the expert. In the example in Figure 3.1.5-1, the first node indicates that three alternative characterizations of past events have been identified (Event Sets ES1, ES2, and ES3). ES1 is assigned the highest probability, reflecting a judgment that it is the most likely or "best" interpretation of past events for that expert. For each of those event sets, two spatial models and two temporal models are considered: the locally homogenous zones model with a homogenous Poisson rate, and a spatial model based on kernel density estimation and a time-volume rate model. In this example, those two models are assigned equal probability, as shown in the second node of the figure. Following the top branch in the logic tree, three alternative zone boundaries were identified and probabilities assigned, and then the rate for a homogenous Poisson model was estimated based on each event set. All the probabilities along the top branch, except for the last node, represent direct expert assessments. Along the bottom branch, two alternative bandwidths were specified and uncertainty in the rate of change of cumulative volume and in the volume per event were estimated based on the age and volume of events in each event set.

For some nodes (the rate for the homogenous Poisson model, the rate of change of cumulative volume and volume per event in the example figure), experts typically specified that models of a particular form be fit to data (past events) they specified. In such cases, uncertainty exists in the "true value" of the parameter that arises from the use of a limited data set. Appendix E describes in detail the various mathematical approaches used to fit distributions to the appropriate dataset. In those cases, the resulting fit may take the form of a continuous distribution; however, to represent that uncertainty in the logic tree the distribution must be discretized. Keefer and Bodily (1983) reviewed various approaches for representing continuous distributions with three-point approximations and found that the extended Pearson-Tukey approximation, which consists of the 5th percentile, the median value, and the 95th percentile of the distribution with probabilities of 0.185, 0.63, and 0.185, generally gave good results. Smith (1993) further reviewed methods and shows that this approach generally matches the mean of the underlying continuous distribution to within 0.1% and the variance to within 2%, even for skewed distributions such as the lognormal. For a highly skewed distribution, the error can be reduced by using more branches to represent the distribution, generally using a moment-matching discretization approach as described by Miller and Rice (1983). The extended Pearson-Tukey three-point approximation is the source of the probabilities on the last few nodes of the example logic tree in Figure 3.1.5-1.

Figure 3.1.5-2 shows a logic tree representing all the major components of the spatial models defined by the PVHA-U experts. No individual logic tree is this complex, and the detailed logic trees for each individual expert, including the probabilities assigned to the different branches, are shown in Section 3.2.

The first node in the tree indicates that as many as three alternative regions of interest (ROIs) were defined (five of eight experts defined one region of interest, three experts defined alternative regions of interest). The second node indicates that one or more zones might be defined, and the third node indicates that four alternative approaches to spatial models were used. The four branches on the "Spatial approach" node represent the four spatial modeling approaches described above in Section 3.1.1. For each approach, the subsequent nodes correspond to the uncertainties that are relevant for that modeling approach. For example, for kernel density estimation relevant uncertainties are related to the weighting of past events, the bandwidth parameter, and the fit of the kernel to the past events, represented by the three nodes on that branch of the logic tree. Not shown in this figure is the dependence of the spatial models on the alternative past event sets identified by each expert. In practice, the expert-specified spatial and temporal models are fit individually to each alternative event set. Those dependencies are illustrated in the individual logic trees in Section 3.2.



NOTES: Lettered nodes indicate that the sub-tree which follows is reproduced in its entirety at any subsequent node in the tree with the same letter.

Although in general alternative kernel functions are allowed for kernel density estimation, all PVHA-U experts using this approach specified a Gaussian kernel. Similarly, although any bandwidth is allowed, PVHA-U experts using this approach used only one or more of the values shown in the tree.

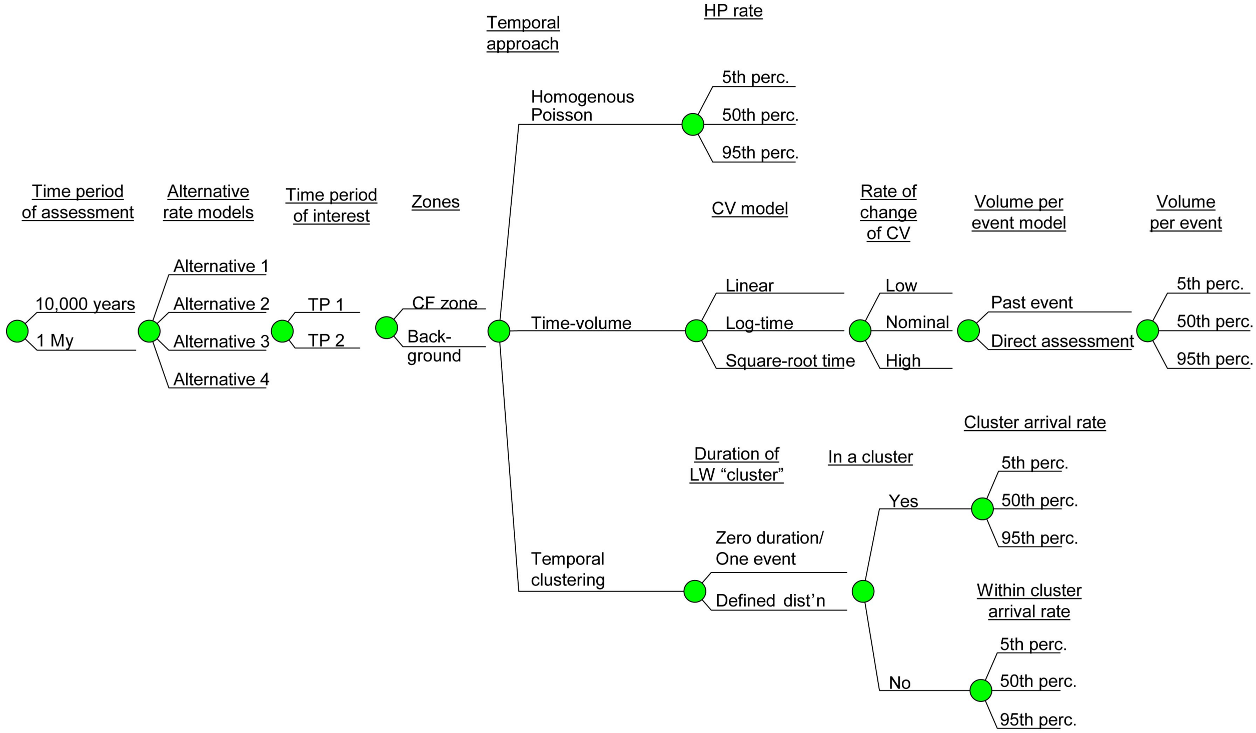
Uncertainty in spatial density for the kernel density estimate is modeled through a simulation approach known as the bootstrap; this is shown schematically with three branches but in practice the number of branches is the same as the number of iterations for the bootstrap.

Uncertainty in spatial density for the bivariate Gaussian field shape spatial approach is modeled by considering all combinations of the uncertainties in the fitted field parameters; in practice the number of branches for this uncertainty is 243.

Figure 3.1.5-2. Logic Tree Illustrating Alternatives and Uncertainties in Spatial Models Defined by PVHA-U Experts

Figure 3.1.5-3 shows a logic tree representing the major components of the temporal models defined by the PVHA-U experts. Again, no individual logic tree is this complex, and the detailed logic trees for each individual expert, including the probabilities assigned to the different branches, are shown in Section 3.2.

The first node in the tree indicates that alternative temporal approaches may be specified based on the two different compliance periods. The second node indicates that alternative rate models may be defined, the third indicates that alternative time periods of interest may be defined, and the fourth indicates that different temporal approaches may be taken for different zones (where different zones are identified). The fifth node shows the three temporal approaches described above in Section 3.1.3. For each approach, the subsequent nodes correspond to the uncertainties that are relevant for that modeling approach. Not shown in this figure is the dependence of the temporal models on the alternative past event sets identified by each expert or other dependencies between the spatial and temporal models. In practice, the expert-specified spatial and temporal models are fit individually to each alternative event set, and where spatial and temporal models are dependent, those dependencies are modeled explicitly. All model dependencies are illustrated in the individual logic trees in Section 3.2.



NOTES: Lettered nodes indicate that the sub-tree which follows is reproduced in its entirety at any subsequent node in the tree with the same letter.

TP = time period, HP rate = rate for the homogenous Poisson temporal model, CV = cumulative volume, LW = Lathrop Wells.

Figure 3.1.5-3. Logic Tree Illustrating Alternatives and Uncertainties in Temporal Models Defined by PVHA-U Experts

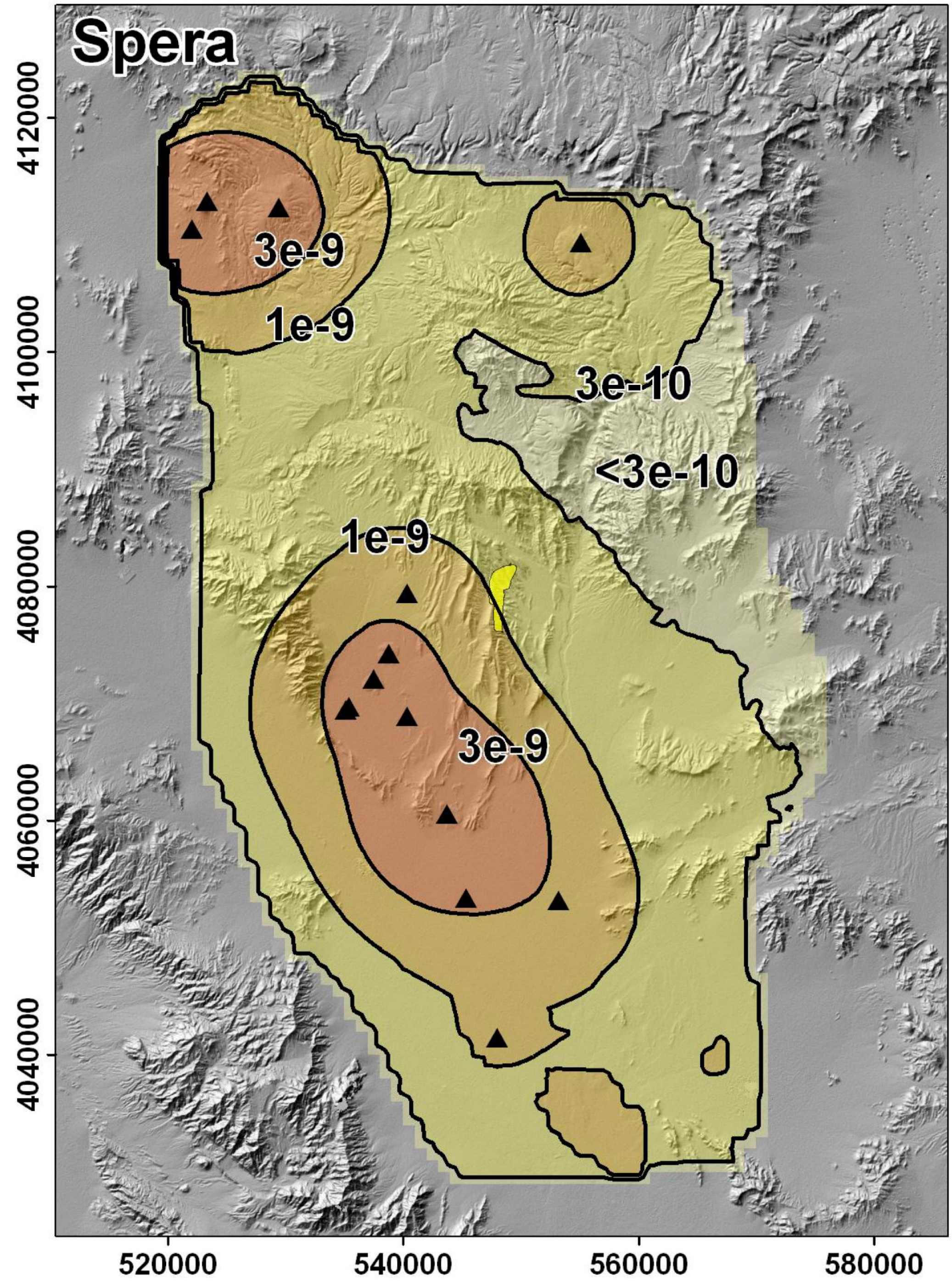
Mean rate density

As described in Equation 3-1, the combination of the spatial and temporal models for an expert results in an estimate of the *rate density,* $\lambda(x,y,t)$. The rate density is the frequency of events per unit time per unit area at a particular *x, y* location and at time *t*. Each parameter set (each path though the logic tree) results in a rate density estimate and an associated probability for that estimate (the product of the probabilities along each branch of the logic tree defining that parameter set). As a summary measure of the spatial and temporal models, we consider the *mean* rate density across the region of interest through a mean rate density map. Figure 3.1.5-4 shows an example of the mean rate density map. To create these maps, the rate density is calculated at each *x, y* location within the expert-defined region of interest for every alternative parameter set, and then the mean rate density is calculated by taking the probability weighted average of the rate density at each location. Those values are then contoured and plotted as shown in the figure.

Each contour is labeled with the mean rate density at those locations. Locations inside a particular contour (e.g., inside the 3e-8 contour in the example figure) have a rate density greater than or equal to that value; locations outside a particular contour (e.g., outside the 3e-9 contour on the NE portion of the example figure) have a rate density less than that value. The shaded region on the map indicates area over which the rate density is calculated (the region of interest); the rate outside that region is not considered relevant to the hazard estimate and so is not calculated. Contours are plotted for each order of magnitude in rate density (1e-*x*) and for value approximately half of a log value (3e-*x*). The rate density and the specific values on the contours depend on the individual expert's models. Section 3.2 includes the mean rate density maps for each expert's assessments.

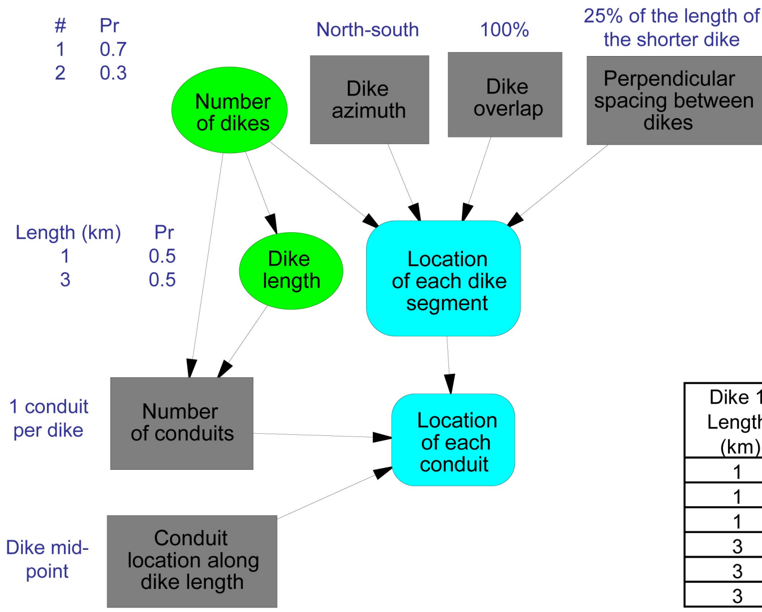
Event Simulation for Capturing Uncertainty in Event Characteristics. To model alternative events for each expert, a computational approach known as Monte Carlo simulation is used (e.g., Robert and Casella 2005). In a simulation approach, each of the relevant characteristics is defined by a probability distribution, then one sample is drawn from each distribution defining each of the characteristics of an event, and together those samples define a single event. Figure 3.1.5-5 illustrates a very simple example. The example contains only two uncertainties: events consist of 1 or 2 dikes, each dike can be either 1 or 3 km in length. All other components are assumed to be deterministic: each dike has exactly one conduit placed exactly in the center of the dike, dikes are oriented north-south, and when there are multiple dikes they are placed parallel to each other at a distance equal to ¼ the length of the shorter dike. In this example, six types of events are possible, as described in the table on the right side of the figure. The relative likelihood of each type of event can be calculated from the probability distributions, as shown. In practice, every event in a simulation has the same probability, but over thousands of simulations (or more), about 35% of the events would have one dike that is 1 km in length, and so on.

When all the event characteristics are modeled as uncertainties, and most of those uncertainties are defined by continuous distributions, then as mentioned above, a wide variety of events could be produced. The simulation approach allows representation of that infinite variety by a finite number in a manner that is consistent with the probabilistic definition: over many iterations of an event simulator, events that are more common as defined by the component distributions would



NOTE: Contours show mean rate density in events per year per km^2. Repository footprint is shown as a yellow polygon. Past events considered in the expert's spatial model are shown as black triangles. Shaded area includes the entire region of interest specified by the expert; areas without shading are outside that region of interest and not relevant to the hazard estimate. Map grid ticks are UTM meters; tick intervals are 20 km.

Figure 3.1.5-4. Example of a Mean Rate Density Map



Dike 1 Length (km)	Dike 2 Length (km)	Spacing between Dikes (km)	Probability
1	NA	NA	0.7 x 0.5 = 0.35
1	1	0.25	0.3 x 0.5 x 0.5 = 0.075
1	3	0.25	0.3 x 0.5 x 0.5 = 0.075
3	NA	NA	0.7 x 0.5 = 0.35
3	1	0.25	0.3 x 0.5 x 0.5 = 0.075
3	3	0.75	0.3 x 0.5 x 0.5 = 0.075

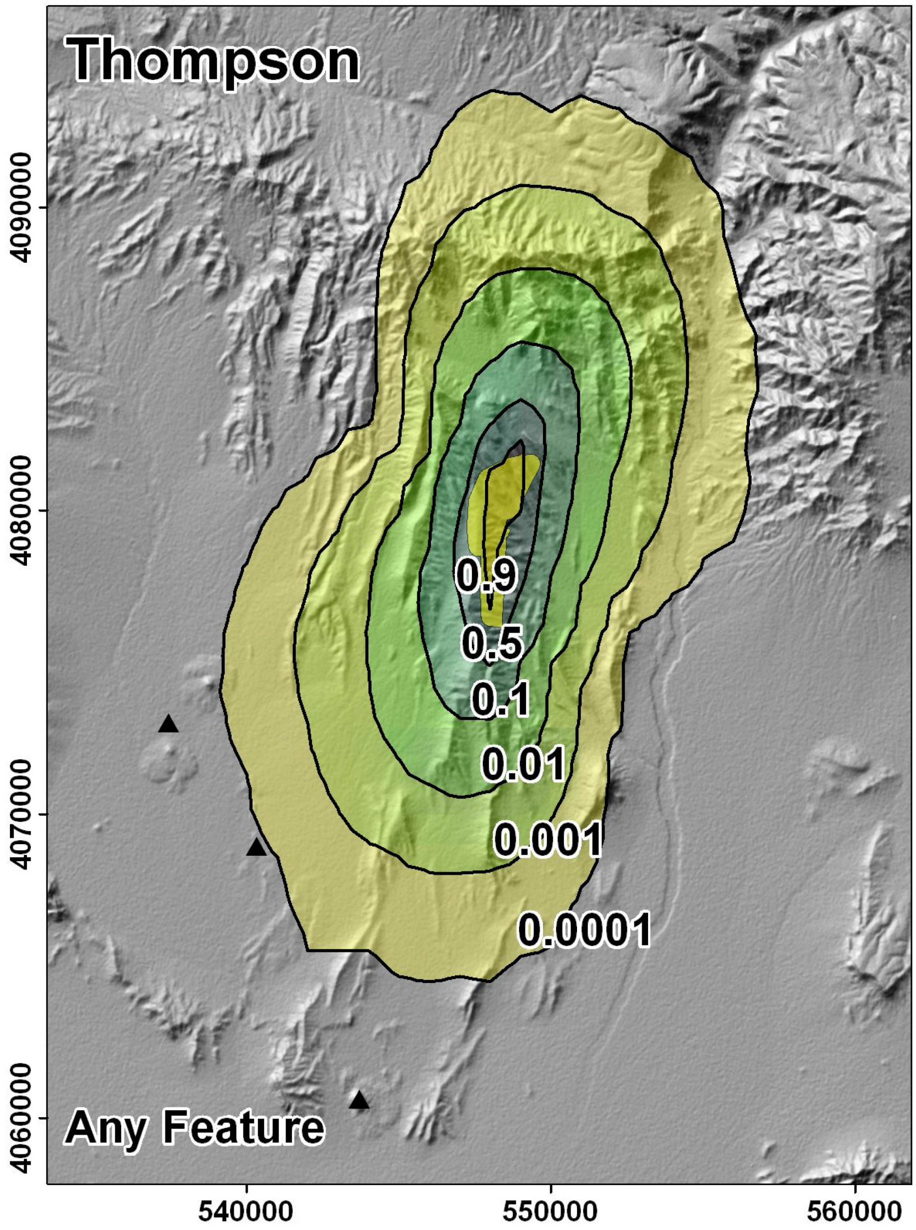
NOTE: This event description consists of two uncertainties, each of which is modeled with a discrete probability distribution with two outcomes. All other characteristics are treated as certain. The table on the right side of the figure describes the six possible events that can be produced by this event description.

Figure 3.1.5-5. Simplified Example Event Description and Summary of Potential Events

be produced more frequently than those that are defined by the tails of the component distributions, but with sufficient iterations those rare events are also be produced in proportion to their likelihood.

Conditional Probability of Intersection. The results of event simulation lead to an estimate of the conditional probability of intersection at each location in the region (the $P_I(x,y)$ of Equation 3-1). The conditional probability of intersection at each location is calculated by assuming an event occurs at each point in a 1-km by 1-km grid in the vicinity of the repository footprint and calculating the probability that an event at that location would intersect the repository footprint. Each of the simulated events was assumed to occur within 1 km^2 surrounding that grid point, and the fraction of those simulated events that result in a feature intersecting the footprint is interpreted as the (conditional) probability that a feature intersects the repository. Close to the footprint, the conditional probability of intersection is high, and that probability decreases as the distance from the repository increases. At the extremes, an event centered in the repository footprint would have a conditional probability of intersection of close to one, and an event centered sufficiently far from the repository that the longest dike in that event could not possibly reach the repository footprint would have a conditional probability of intersection of zero.

Figure 3.1.5-6 shows an example of a map of the conditional probability of intersection of any feature with the repository. The highest probability contour shown on this map is the 0.9 contour, indicating that there is a 90% (or higher) chance that an event located at (or within) the contour will result in an intersecting feature. As will be described in Section 3.2, the various igneous features within an event, as described by each expert, are spatially dispersed so that even events "centered" within the repository footprint may not lead to a 100% chance of an intersecting feature. The outermost contour is the 0.0001 contour, indicating that there is 1 chance in 10,000 (or lower) that an event located at (or outside) the contour will result in an intersecting feature. The shape of this contour, as well as the others, derives from and can be explained by the individual event descriptions. Section 3.2 includes conditional probability of intersection maps and discussion for each expert's individual PVHA-U models.



NOTE: Contours represent the probability of intersection of any feature with the repository footprint (represented with the yellow polygon), assuming an event occurs at each location. The 0.9 contour, for example, indicates that the probability of intersection for an event occurring on or within this contour leads to an intersection with the repository footprint at least 90% of the time. Map grid ticks are UTM meters; tick intervals are 10 km.

Figure 3.1.5-6. Example Conditional Probability of Intersection Map

3.2 VOLCANIC HAZARD MODELS SPECIFIED BY EACH EXPERT

This section presents each expert's individual assessments in the common framework of a logic tree and event simulator as discussed in Section 3.1.5 and presented in Figures 3.1.5-2 through 3.1.5-4. The models are presented by expert in alphabetical order. Note that the discussion in this section provides the salient elements of each expert's model, but does not provide the technical basis or reasoning for the assessments. Appendix D contains the elicitation summaries prepared by each expert and each elicitation summary documents the basis for each assessment described here. Hazard results for each expert are presented in Section 4.

3.2.1 Charles Connor

Spatial and Temporal Models

Figure 3.2.1-1 presents the logic tree describing the basic structure of the spatial and temporal models developed by Charles Connor (CC) for PVHA-U. CC initially specifies two alternative event sets to be used as the basis for his spatial and temporal models, which he calls the "YMR data set" and the "AVIP data set," represented by the two branches on the first node in the logic tree. Table 3.2.1-1 lists the events included in the YMR data set. "Events" in the YMR data set were identified by spatially and temporally clustered surface features, and CC specified a location for each event, as shown in the table. Table 3.2.1-2 lists the AVIP data set, consisting of 34 vent locations specified by CC in a larger region. Figure 3.2.1-2 illustrates the location of the YMR events and the AVIP events. CC placed 2/3 probability on models based on the YMR data set and 1/3 probability on models based on the AVIP data set.

Two alternative approaches to modeling the spatial distribution of future events based on the YMR data set were specified: (1) spatial smoothing using kernel density estimation and (2) an estimate that scales the kernel density estimate by a weighting function based on the mean crustal density at each location. These models were assigned equally probability.

CC specified the use of a single parameterization of the kernel density estimator: a bivariate Gaussian kernel function with a bandwidth matrix given by:

$$\mathbf{H} = \begin{bmatrix} 57.4 & -105.4 \\ -105.4 & 440.8 \end{bmatrix}$$

Because only one parameterization was specified, no nodes are specified in the logic tree representing the kernel function or the bandwidth.

CC defined a function to be used to convert the mean crustal density at any point in the region of interest into a relative weight, which is then multiplied by the calculated conditional spatial density from the kernel density estimate to obtain a modified spatial density. The resulting values are renormalized to generate a conditional spatial density that can be compared with the density from other spatial models. The weighting function is shown in Table 3.2.1-3.

For the AVIP data set, a single spatial model was specified: spatial smoothing using kernel density estimation with a bivariate Gaussian kernel function and a single bandwidth matrix. The bandwidth matrix to be used with the AVIP data set is:

$$\mathbf{H} = \begin{bmatrix} 27.4 & -10.9 \\ -10.9 & 165.1 \end{bmatrix}$$

Again, because only one spatial model with one parameterization was specified for the AVIP data set no nodes are specified in the logic tree in Figure 3.2.1-1 representing alternative spatial models or parameterizations.

For all three spatial models, additional uncertainty in the spatial density results from fitting the kernel density estimators to the relatively small data sets. As described in Section 3.1 and Appendix E, uncertainty in the spatial density is modeled through a simulation approach known as bootstrapping. This is represented conceptually by the “Uncertainty in Spatial Density” node in the logic tree of Figure 3.2.1-1; in the actual bootstrapping analyses, more than three representations are used.

A homogenous Poisson temporal model is used, with three different conceptual models for the temporal evolution of the volcanism in the regions: (1) a “steady-state” model wherein rates in the future are assumed to be best predicted by rates in the YMR or AVIP in the Quaternary, (2) an “increased rate” model wherein the rates in the future are assumed to increase such that they approximate the rates in the highest rate fields in the western Great Basin, and (3) a “field extinction rate” model wherein rates in the future are assumed to decrease as the field dies out. For the 10,000-year assessment, these three models were assigned probabilities of 80%, 10%, and 10%, respectively, as shown in Figure 3.2.1-1. For the 1-My assessment period (see discussion below), the probabilities assigned to the three models were 40%, 30%, and 30%, respectively.

As described in Section 3.1 and Appendix E, the rate for a homogenous Poisson process can be estimated by the number of relevant past events and the age of the oldest such event. The uncertainty in the Poisson rate estimated from the small number of events is represented by the 5th, 50th (median), and 95th percentiles of the distribution on the rate parameter, as illustrated by the last node in the logic tree. For CC’s models the mean estimated rates are 1.8e-6 events per year in the YMR region of interest, and 4.5e-6 events per year in the AVIP region of interest.

For the increased rate model, the rate was estimated directly by CC based on consideration of the rates in other fields: he specified that the rate in events per year for the “field,” as defined by each of the two data sets, should be represented by a log-Uniform distribution bounded by 10^{-4} and 10^{-5}, resulting in a mean estimated rate of 3.9e-5 events per year in the YMR (or the AVIP) region of interest.

For the “field extinction” model, the rate was derived so as to reproduce the largest observed time gap between events in the YMR data set of 1.8 Ma. Using the assumption of a homogenous Poisson model, rate parameters were identified such that they produced an inter-arrival time of 1.8 Ma with a cumulative probability of 0.05, 0.5, and 0.95. These estimates were then treated as the 5th, 50th, and 95th percentiles of the distribution on the Poisson rate for the field extinction conceptual model.

Figure 3.2.1-3 illustrates uncertainty in the estimated rate (5th to 95th percentiles of the distribution on rate) for the various rate models used by CC.

Mean Rate Density and Mean Recurrence Rate

Figure 3.2.1-4 illustrates the mean rate density for igneous events calculated from CC's spatial and temporal models, for the 10,000-year assessment. Differences in the 1-My assessment are described below. The events shown in the figure (as black rectangles) are the events from the AVIP data set, but the mean rate density was calculated using each data set as appropriate for the various spatial models. This map covers a larger region than the maps that follow for other experts, because this data set spans a larger region of interest. Contours are shown for each order of magnitude change in mean rate density.

A mean recurrence rate for events in the region of interest can be calculated simply by summing the mean rate density at each grid point. Based on the mean rate density shown in Figure 3.2.1-4, the mean recurrence rate for events in this region is 7.3e-6 events per year, giving recurrence intervals between 7,000 and 410,000 years (5th to 95th percentile of the distribution on recurrence interval), with a mean recurrence interval of about 137,000 years for events in the region illustrated.

Event Simulation Model

Figure 3.2.1-5 summarizes the components of CC's event simulator in an influence diagram. In this model, an *event* consists of 1 to 5 *centers;* each center consists of a set of igneous features (dikes, vents and vent-like bodies, and, potentially, sills).

Two alternative assessments were provided for the number of centers in an event, based on each of the two data sets. Figure 3.2.1-6 illustrates some of the event characteristics in the form of a logic tree. In events with more than one center, those centers are arranged along a N30°E alignment, with the distance between the two most distant centers defined by a Uniform distribution with parameters dependent on the number of centers, as shown in the figure. For events with three or more centers, other centers are located randomly between the outermost centers.

Each center in an event is independent of the others, with dimensions and characteristics sampled from defined distributions. A center is defined by a rectangle with a north-south orientation. Figures 3.2.1-7 through 3.2.1-10 illustrate the details of the center characteristics: the length and width of a center, the number of dikes in a center, and the number of sills in a center. The number of vents and vent-like bodies in a center is 0 to 6, with equal probability. The width of a center is constrained to be less than or equal to the length. Any igneous feature associated with a center could extend beyond the boundaries of that center's "rectangle," but the midpoints, as defined by CC, of all features lie within the boundaries of the rectangle. Dike midpoints are located randomly within the rectangle defining the center. Placement of other features within a center is discussed below.

CC provided his assessment of the dimensions of each type of igneous feature as a database of sample dikes, vent and vent-like bodies, and sills. For each feature in a simulated event, the appropriate type of feature is sampled randomly from the database. The dikes database contains 93 individual "dikes"; each dike was defined by a set of x-y points representing a segmented dike, on a local grid where 0,0 represents the dike "mid-point." Figure 3.2.1-11 illustrates two of the dikes in the database. The dike database is provided as a supplement to CC's Elicitation Summary in Appendix D.

The vent database contains 38 individual vents and vent-like bodies. Figure 3.2.1-12 illustrates two of these vents, and the database is provided as an attachment to CC's Elicitation Summary in Appendix D. Vents and vent-like bodies are modeled as occurring at dike nodes (defined by the points specified for each dike in the dike database). In event simulation, a dike node is selected at random from the dikes in the center, and a vent is assumed to be located at that node. In any center that contains vents and vent-like bodies, CC specified that there is a 6/7 chance that one of the vents would be a column-producing conduit. In such cases, the largest vent is assumed to be the column-producing conduit.

The sill database contains three sills and the sill outlines are shown in Figure 3.2.1-13. The sill database is provided as an attachment to CC's Elicitation Summary in Appendix D. Sills, when they exist, are located at dike nodes.

Figure 3.2.1-14 illustrates two examples from the event simulator for events associated with the YMR data set. Figure 3.2.1-15 illustrates the relative frequency of events with different numbers of dikes and column-producing conduits in CC's simulated events, for 100,000 simulations. As shown, up to 50 dikes in an event is possible (though rare). Up to 5 conduits is possible in an event.

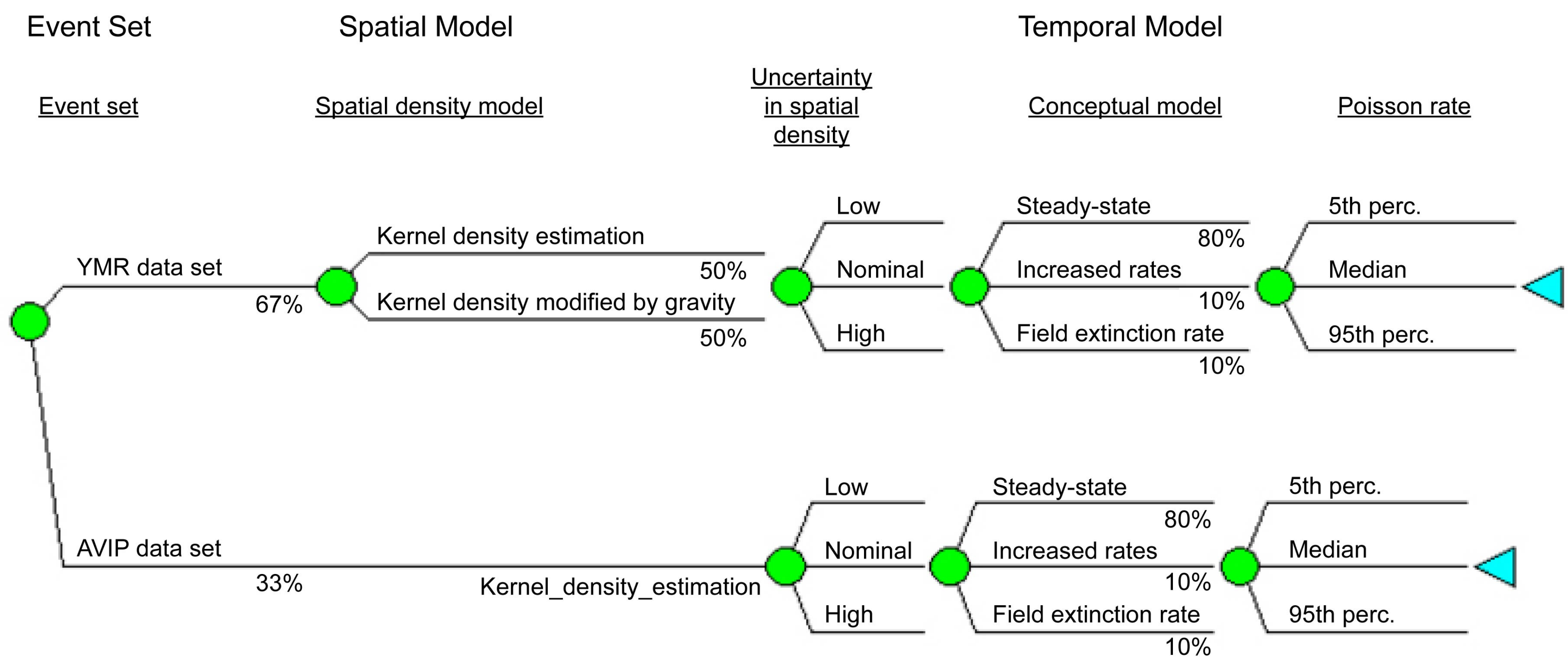
Conditional Probability of Intersection

Figure 3.2.1-16 illustrates the conditional probability of the intersection of any igneous feature with the repository footprint based on the two event models described by CC. Panel (a) shows the conditional probability of intersection based on the event description used with models associated with the YMR data set, and panel (b) shows the conditional probability of intersection based on the event description used with models associated with the AVIP data set. As described above, the only difference in the two event descriptions is the distribution on the number of centers in an event, with events associated with the YMR data set having a higher likelihood of including multiple centers. This effect can be seen in the maps only by closely comparing the contours – the higher likelihood of multiple centers leads to slightly higher conditional probability of intersection associated with the first data set than with the second. The overall NNE trend of the contours is a function of both the N30°E azimuth for events, and the NS orientation of dikes within each center.

As described above, CC's events include at least one dike, and may include column-producing conduits, vents, and sills. Figure 3.2.1-17 shows the conditional probability of intersection for each of these types of igneous features, for events associated with models based on the YMR data set. The conditional probability of dike intersection is very similar to the conditional probability of intersection for any feature shown in the previous figure. Conduits are smaller in size than dikes, and they occur along dikes, and so the conditional probability of conduit intersection is lower than for dikes at any given location (as indicated by the smaller contour boundaries), The number of vents and vent-like bodies in an event is uncertain, but on average there are more vents and vent-like bodies than there are conduits, and so the conditional probability of vent intersection is greater than for conduits. Finally, sills occur only rarely in an event, so the conditional probability of sill intersection is lower than for any other feature. The conditional probability of sill intersection is never as high as 0.1. Conditional probability of intersection maps for events associated with the AVIP data set are not reproduced here, as they are very similar to those shown in Figure 3.2.1-17.

Differences Between the 10,000-year and 1-My Assessments

The assessments that differ based on the time period of the assessment are the probabilities assigned to the three conceptual models for the temporal evolution of the field. For the 10,000-year assessment, the steady-state model is assigned a probability of 80%, and the increased rate and the field extinction model are each assigned a probability of 10%. For the 1-My assessment, 40% probability is assigned to the steady-state model and 30% each to the other models. Figure 3.2.1-18 shows a comparison of the mean rate density map for the 10,000-year assessment and the mean rate density map for the 1-My assessment. These maps are on a more local scale than the mean rate density map presented previously, to better show the detail in the vicinity of the repository footprint. The higher weight on the increased rate model associated with the 1-My assessment results in an increase in the mean rate density, as shown by the "expansion" of the higher-rate contours (e.g., the 3e-9 contour encompasses more area in the mean rate density for the 1-My assessment).



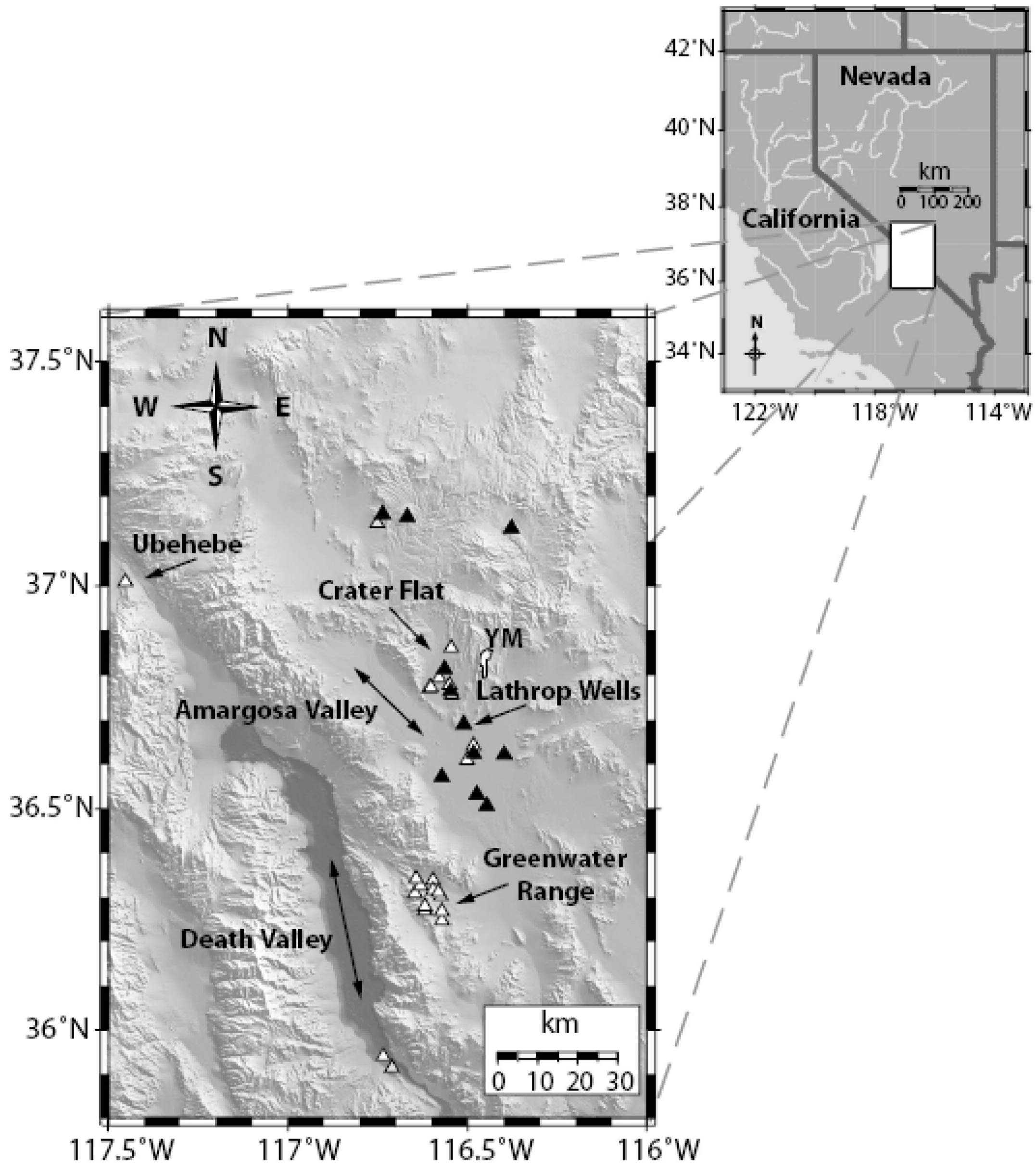
NOTES: All probabilities shown on the branches are those assigned by the expert for the 10,000-year assessment. Differences in the 1-My assessment are discussed in the text.

Uncertainty in spatial density and uncertainty in the Poisson rate are modeled based on the approaches described in Section 3.1.5, and the probabilities for those branches are defined by the modeling approach.

A single parameterization of the kernel density estimation approach was specified, so no uncertainties relative to those parameters appear in the logic tree.

A single spatial modeling approach was specified for the model based on the AVIP data set, so no uncertainty related to the spatial model appears on the lower branch of the tree.

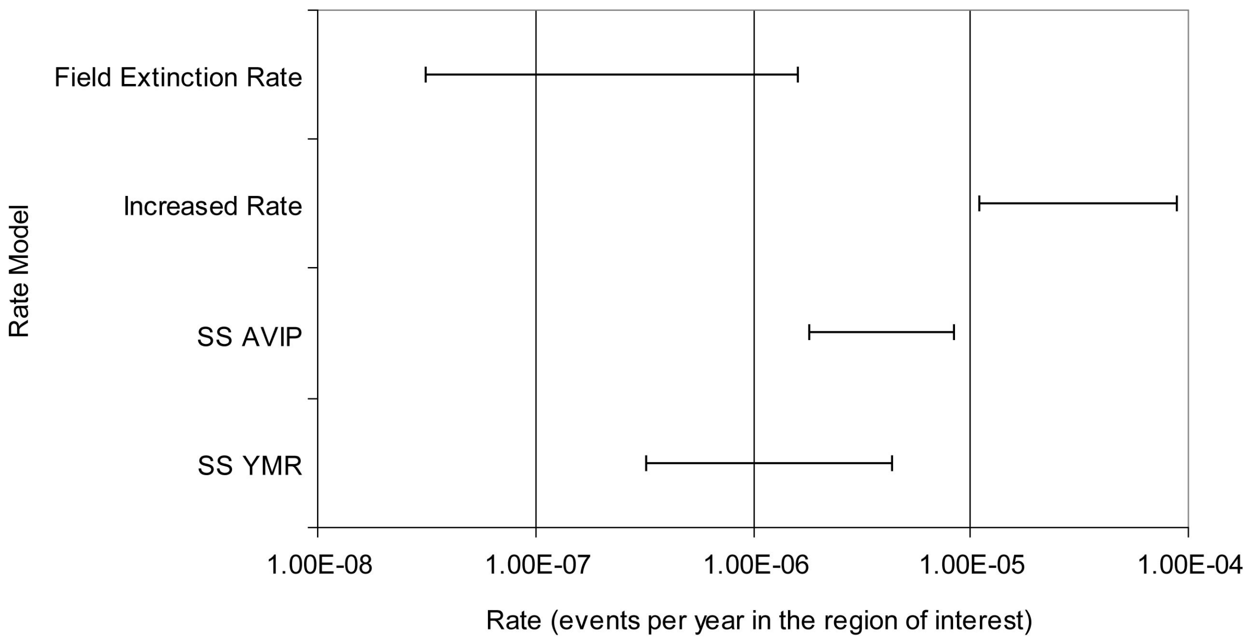
Figure 3.2.1-1. Logic Tree Representing the Spatial and Temporal Components of the PVHA-U Model Specified by Charles Connor



NOTES: Figure identical to Figure D.1-1 from the Elicitation Summary for Charles Connor in Appendix D.

Events in the YMR data set are shown with the black triangles. Events in the AVIP data set are shown with the white triangles.

Figure 3.2.1-2. Locations of Events in the YMR Data Set and the AVIP Data Set as Specified by Charles Connor

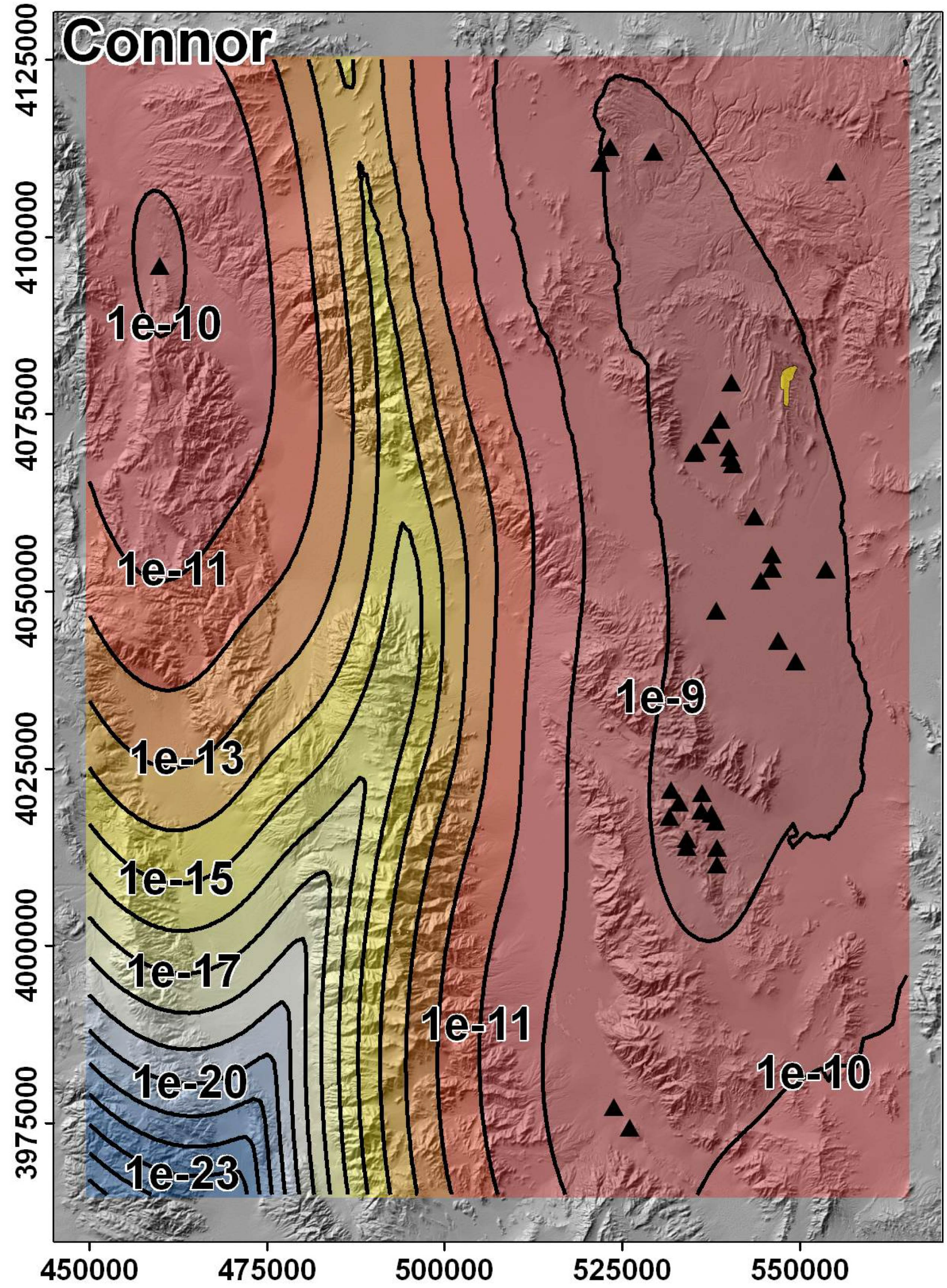


NOTES: Bars represent the 5th to 95th percentile of the uncertainty in the rate for each alternative rate model.

SS AVIP = steady-state rate model based on events in the AVIP data set; SS YMR = steady-state rate model based on events in the YMR data set.

Caution is recommended in comparing these rate distributions. Note that for each model, the estimated rate applies to that specific region of interest, which may vary from model to model, and the rate is spatially varying (as described in the text of the report).

Figure 3.2.1-3. Uncertainty in the Estimated Rate for Each of Four Alternative Rate Models Specified by Charles Connor



NOTE: Contours represent the mean rate density (events per year per km^2). Yellow polygon represents the repository footprint. Black triangles represent past events (the AVIP data set specified by CC). Map grid ticks are in UTM meters; tick interval is 25 km.

Figure 3.2.1-4. Mean Rate Density for the 10,000-Year Assessment Based on Models Specified by Charles Connor

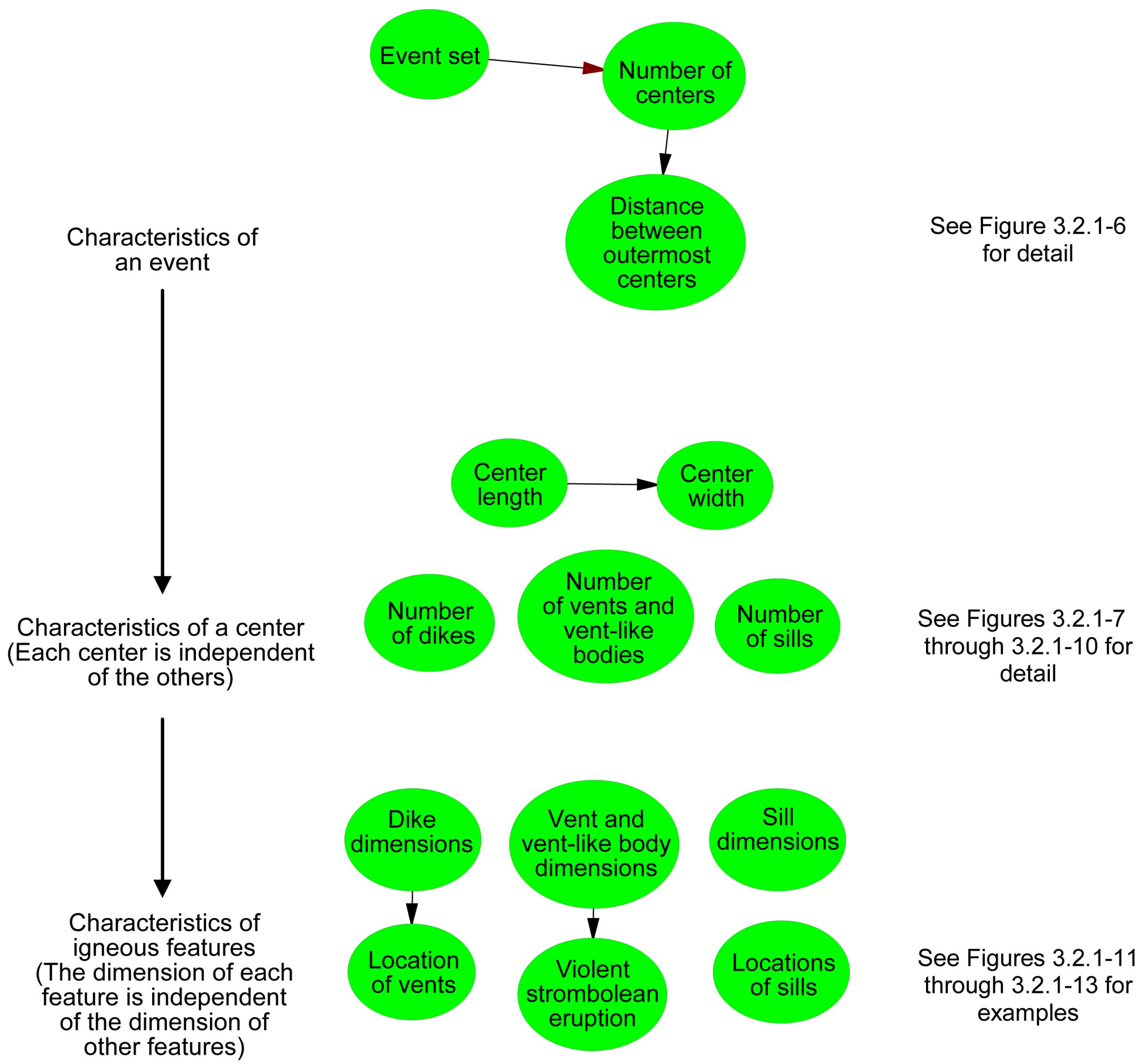


Figure 3.2.1-5. Components of an Event Simulator as Specified by Charles Connor

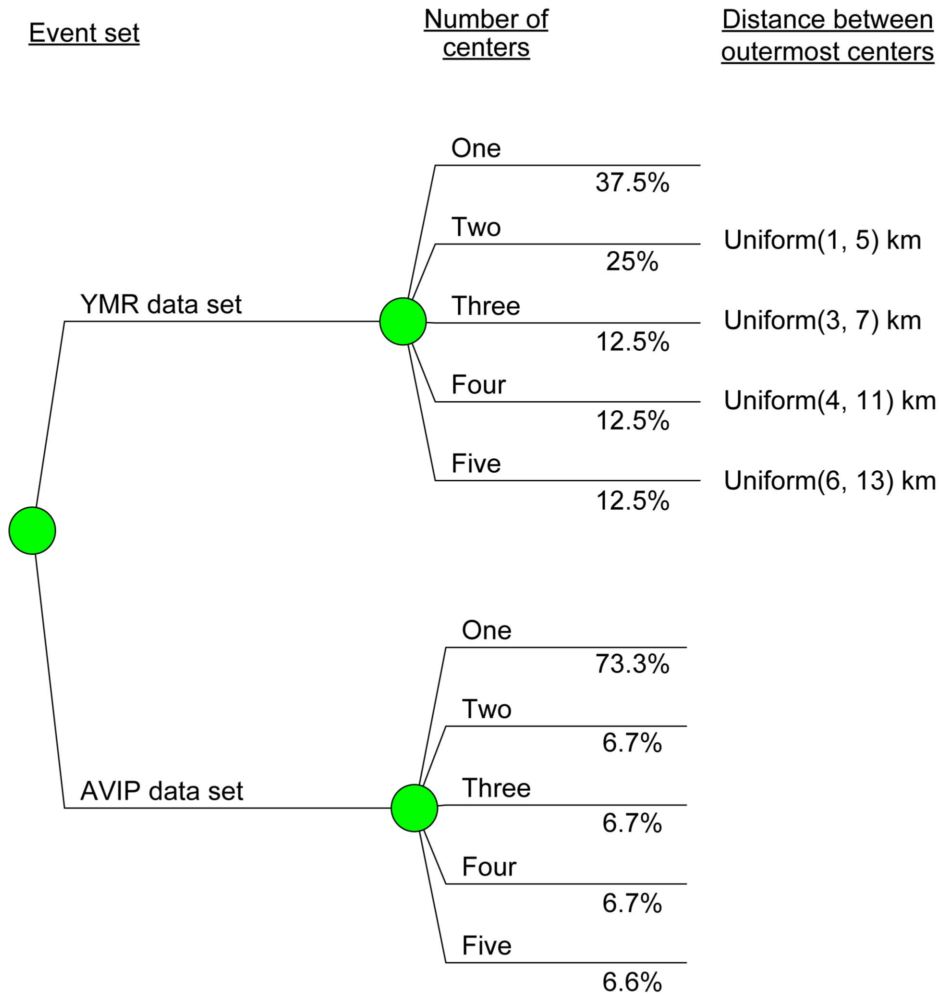
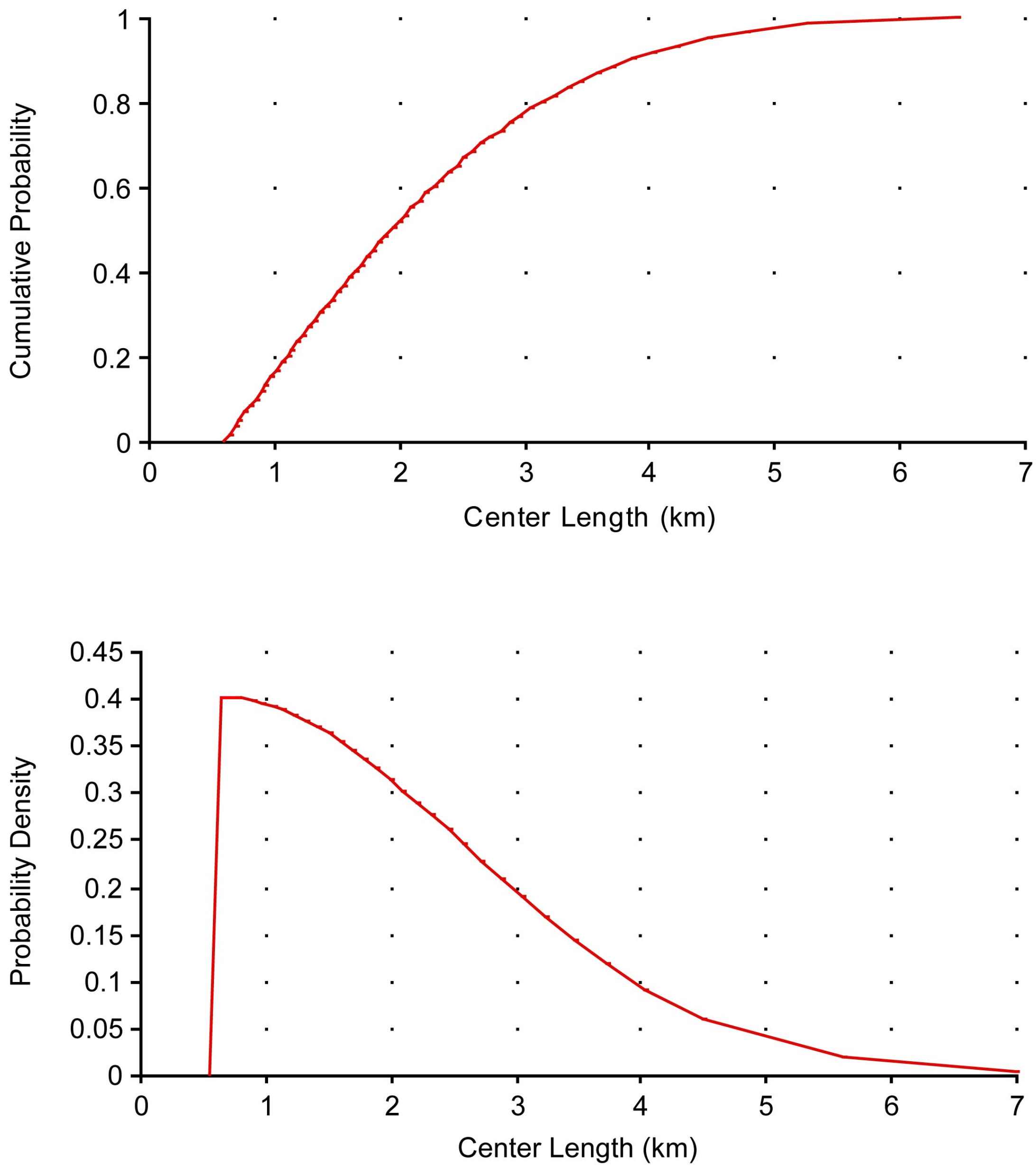


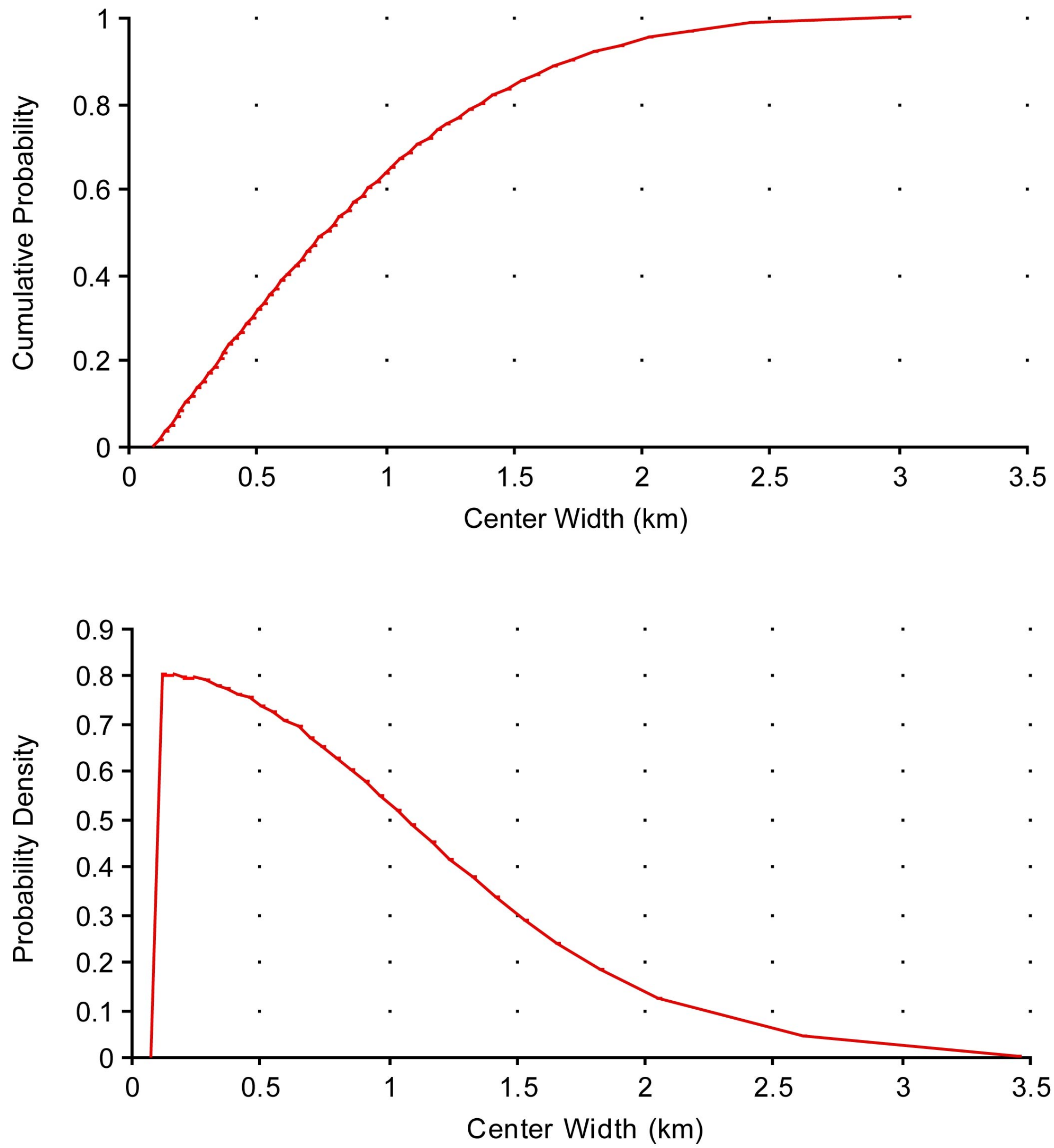
Figure 3.2.1-6. Logic Tree Representation of the Number and Spacing of Centers in an Event Based on the Assessments Provided by Charles Connor



NOTES: Top graph is a cumulative distribution function; bottom graph is a probability density function.

Distribution was specified as a Normal distribution with mean of 0.6 km and standard deviation of 2 km, truncated to the left of the mean.

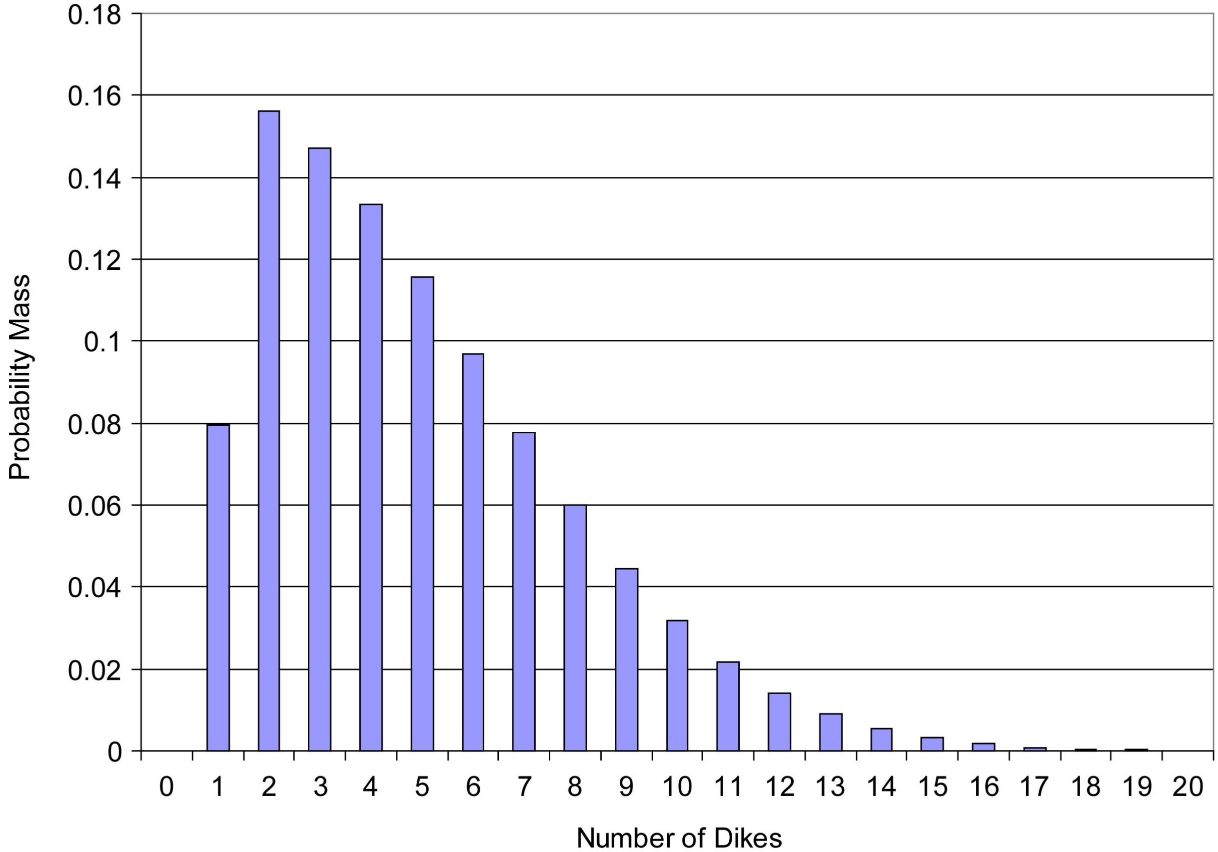
Figure 3.2.1-7. Distribution for the Length of a Center in the North-South Direction as Assessed by Charles Connor



NOTES: Top graph is a cumulative distribution function; bottom graph is a probability density function.

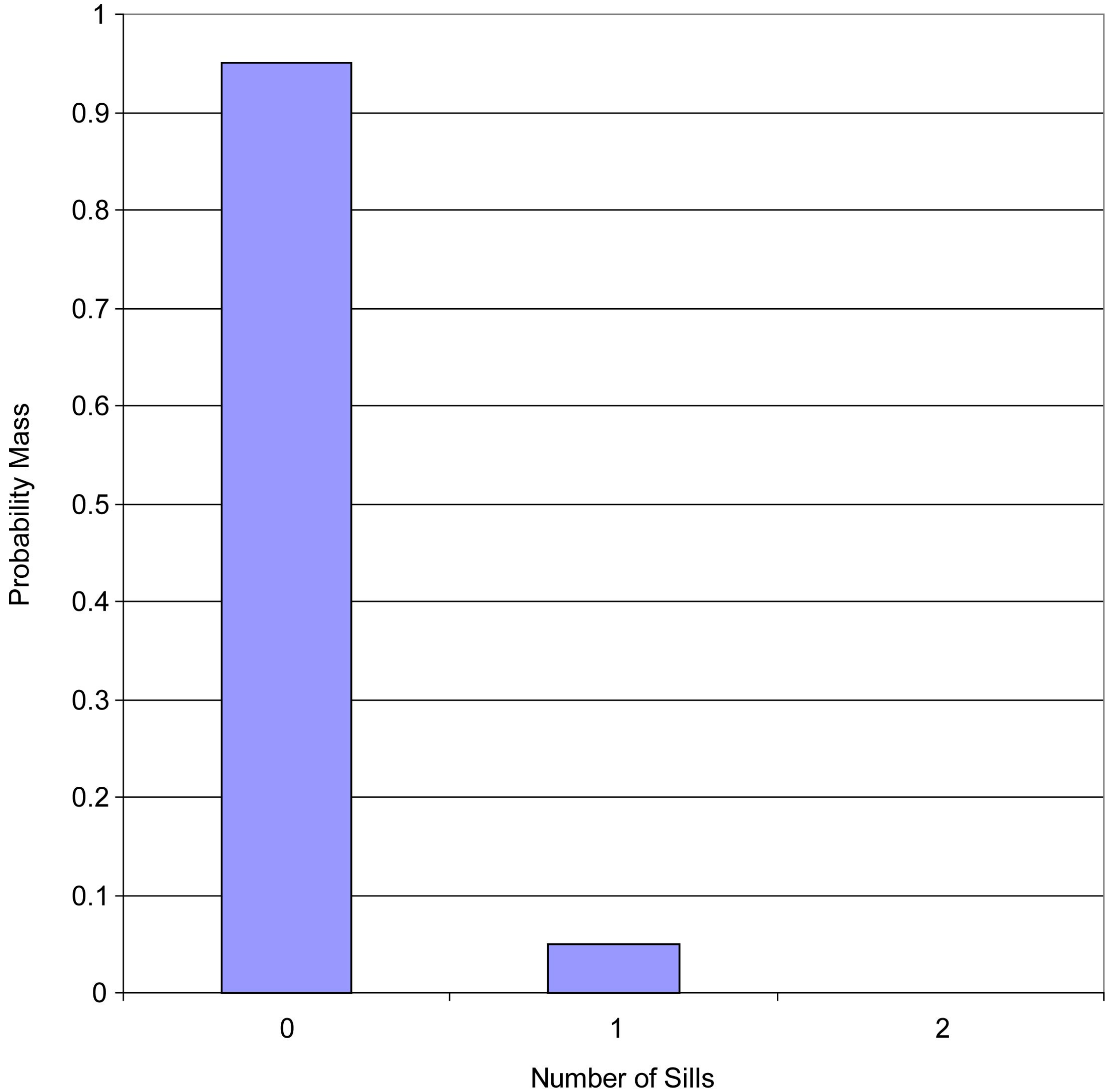
Distribution was specified as a Normal distribution with mean of 0.1 km and standard deviation of 1 km, truncated to the left of the mean.

Figure 3.2.1-8. Distribution for the Width of a Center in the East-West Direction as Assessed by Charles Connor



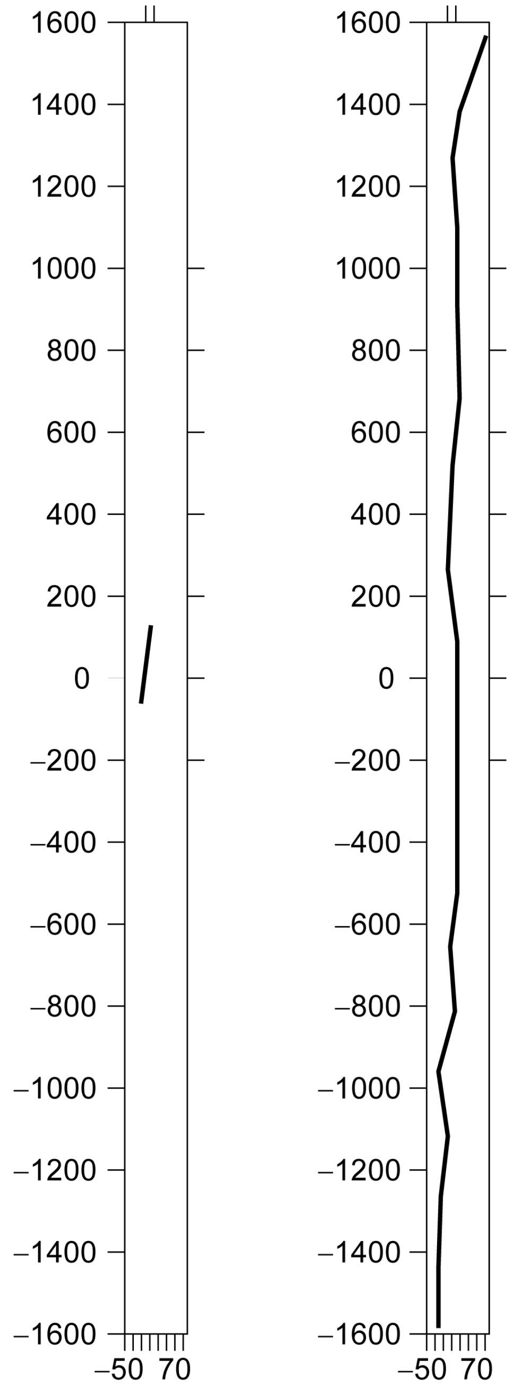
NOTE: Graph is a probability mass function from a simulation from the assessed distribution: a half-Normal distribution with mean of 1 and a standard deviation of 5, rounded to the nearest integer value. A half-Normal distribution is a Normal distribution truncated to the left of the mean. Result displayed is from 10,000 simulations.

Figure 3.2.1-9. Distribution for the Number of Dikes in a Center Based on Assessments of Charles Connor



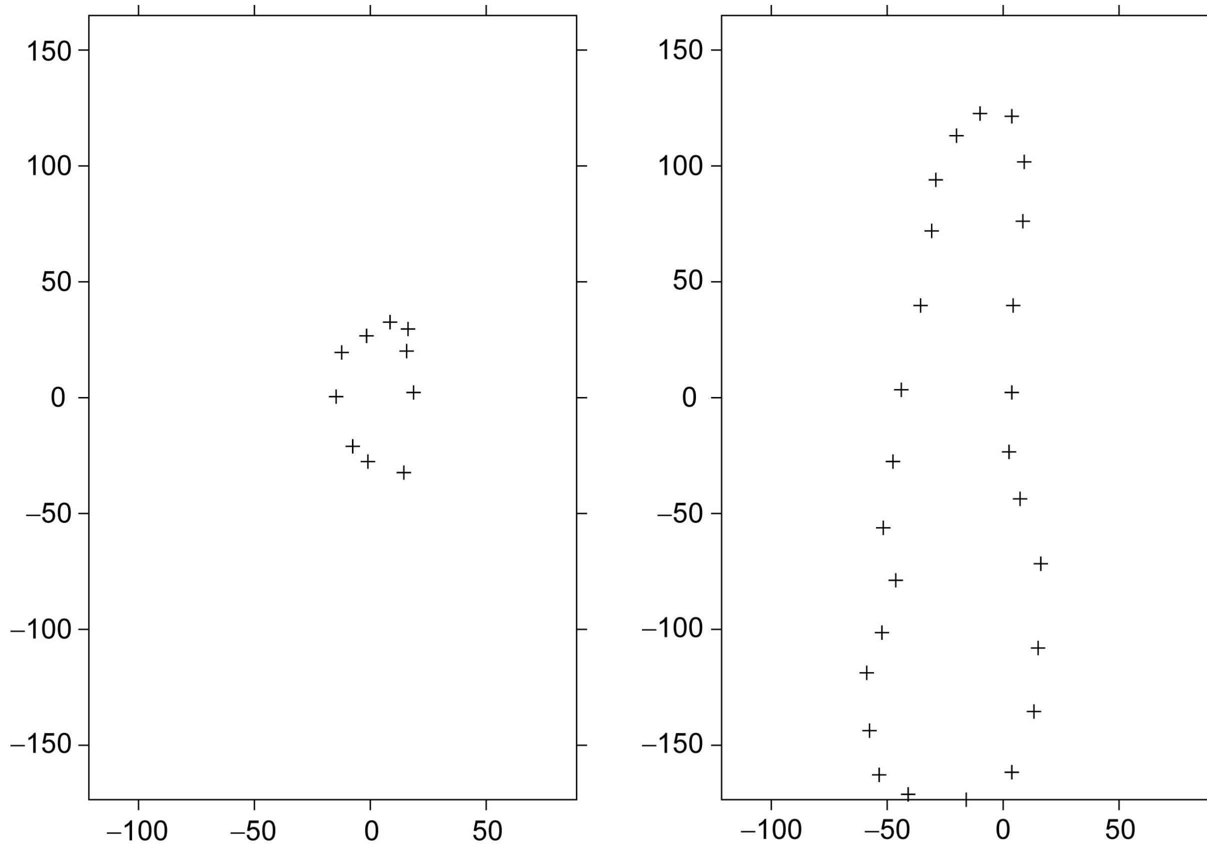
NOTE: Graph is a probability mass function from a simulation from the assessed distribution: an exponential distribution with a rate parameter of 0.167 rounded to the nearest integer value. Result displayed is from 10,000 simulations. Probability mass associated with 2 sills is 0.0001.

Figure 3.2.1-10. Distribution for the Number of Sills in a Center as Assessed by Charles Connor



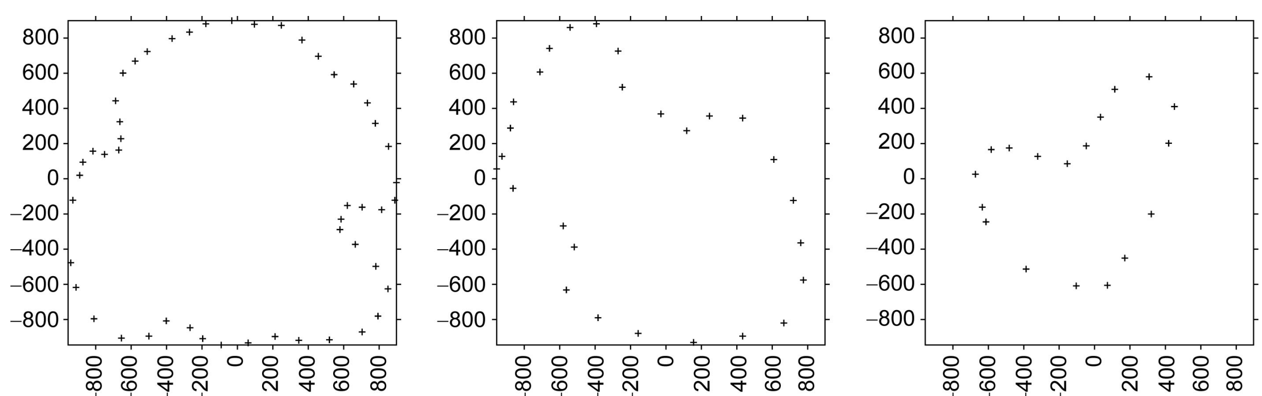
NOTE: Simple (left) and complex (right) dikes. Scale is in meters. Simple dike is less than 200 m in length, complex dike is approximately 3.2 km in length.

Figure 3.2.1-11. Examples from the Dike Database Provided by Charles Connor



NOTE: "Plus signs" represent the outline of the vent or vent-like body. Scale is in meters.

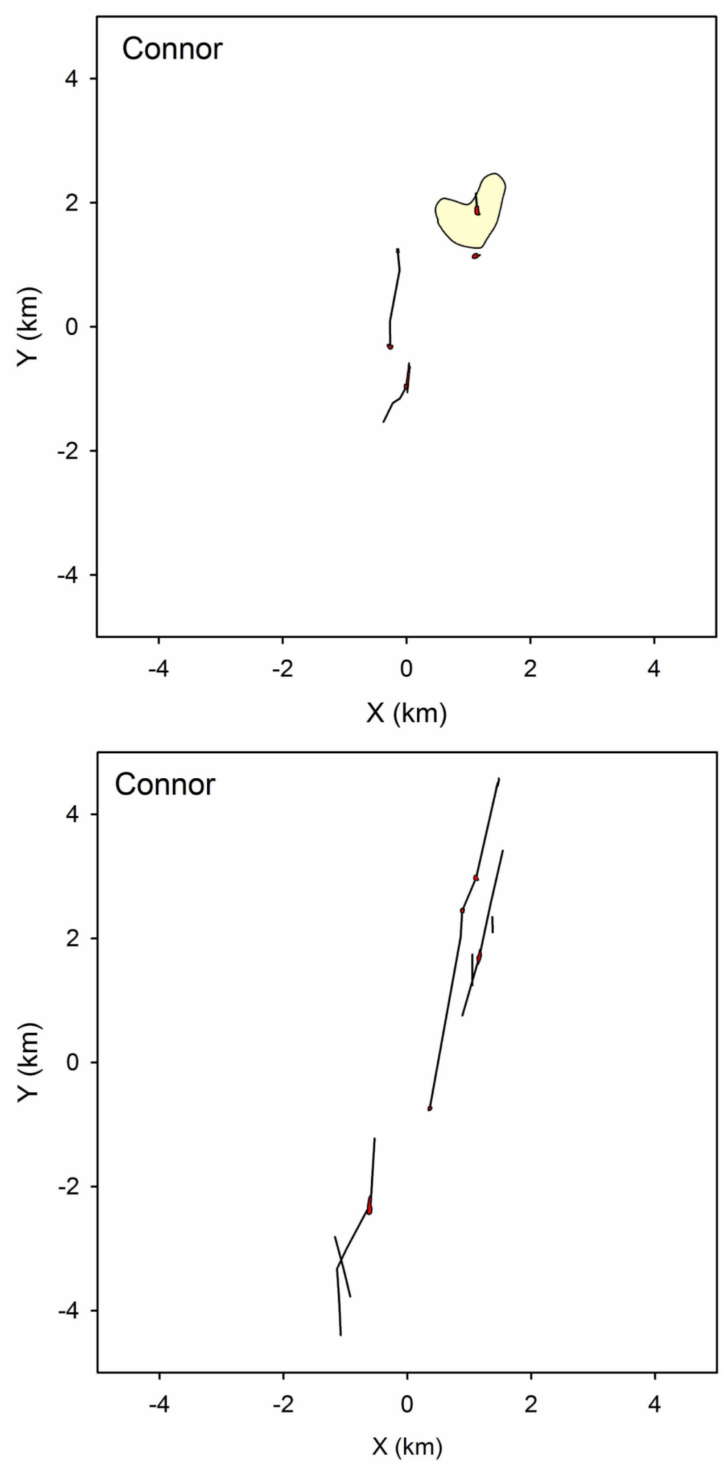
Figure 3.2.1-12. Examples from the Vent Database Provided by Charles Connor



NOTES: "Plus signs" represent the outline of the sill.

Three sills in the sill database are presented on the same scale: approximately 1.9 km on each side.

Figure 3.2.1-13. Sills in the Sill Database Provided by Charles Connor



NOTE: Dikes are represented as black lines, their lengths on the figure are the lengths of the simulated dikes. Conduits, vents, and vent-like bodies are represented as small red circles or polygons and are not differentiated in the figure. Sills, if they exist, are represented by light yellow ovals or polygons.

Figure 3.2.1-14. Examples of Simulated Events from the PVHA-U Model for Charles Connor

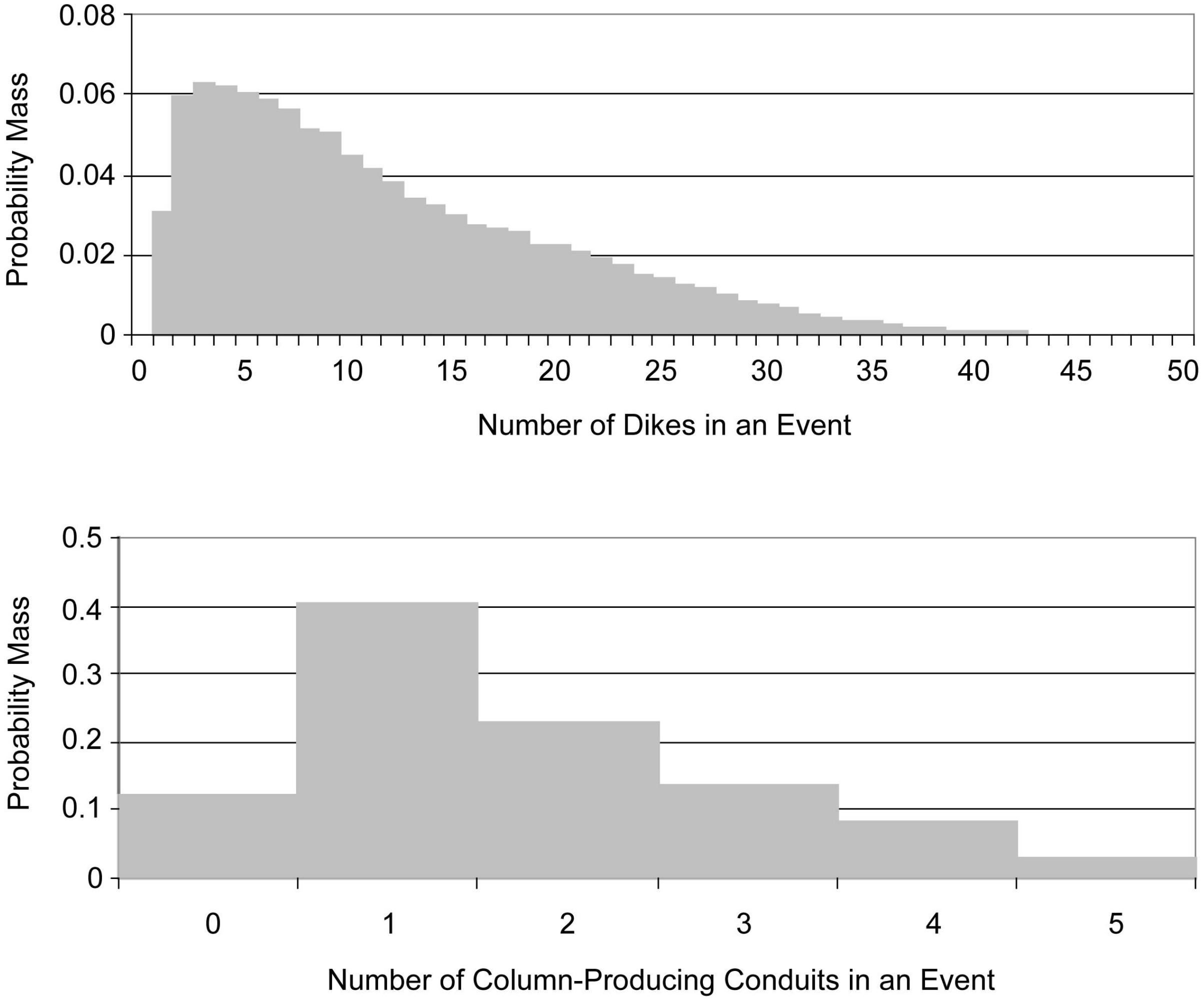
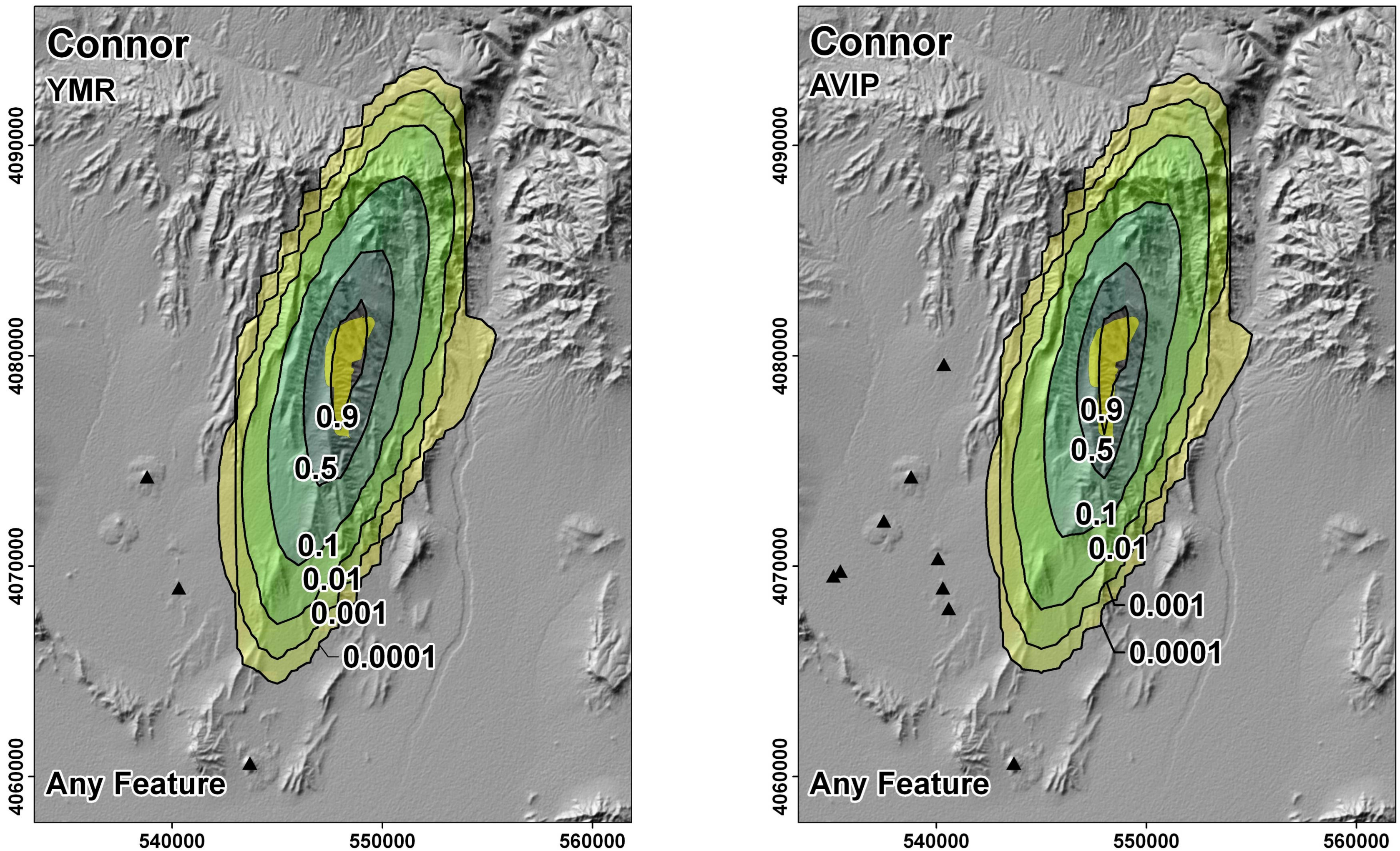


Figure 3.2.1-15. Number of Dikes and Number of Conduits in Simulated Events Based on CC's Event Descriptions Associated with the YMR Data Set

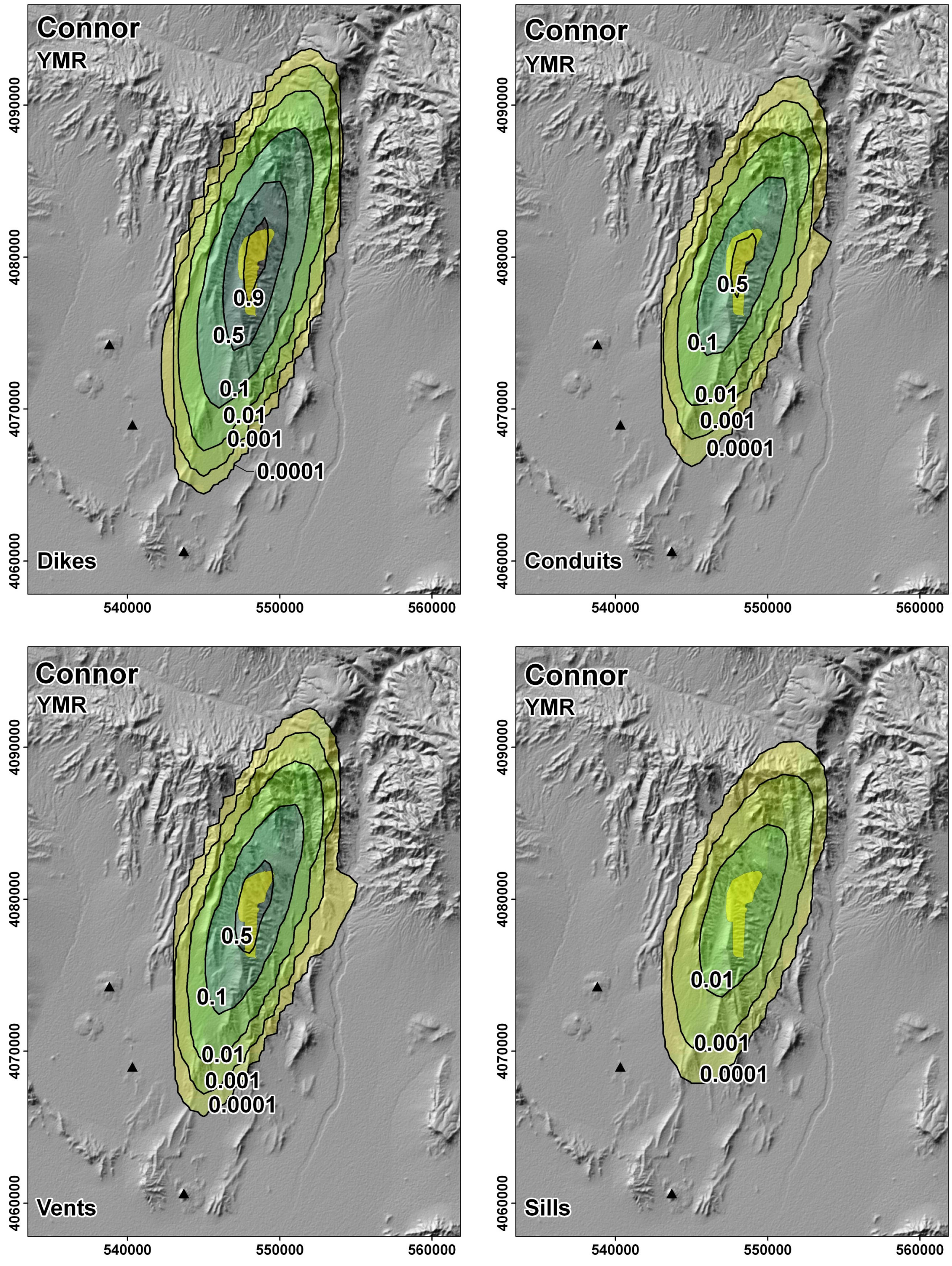


(a) For events associated with the YMR data set.

(b) For events associated with the AVIP data set.

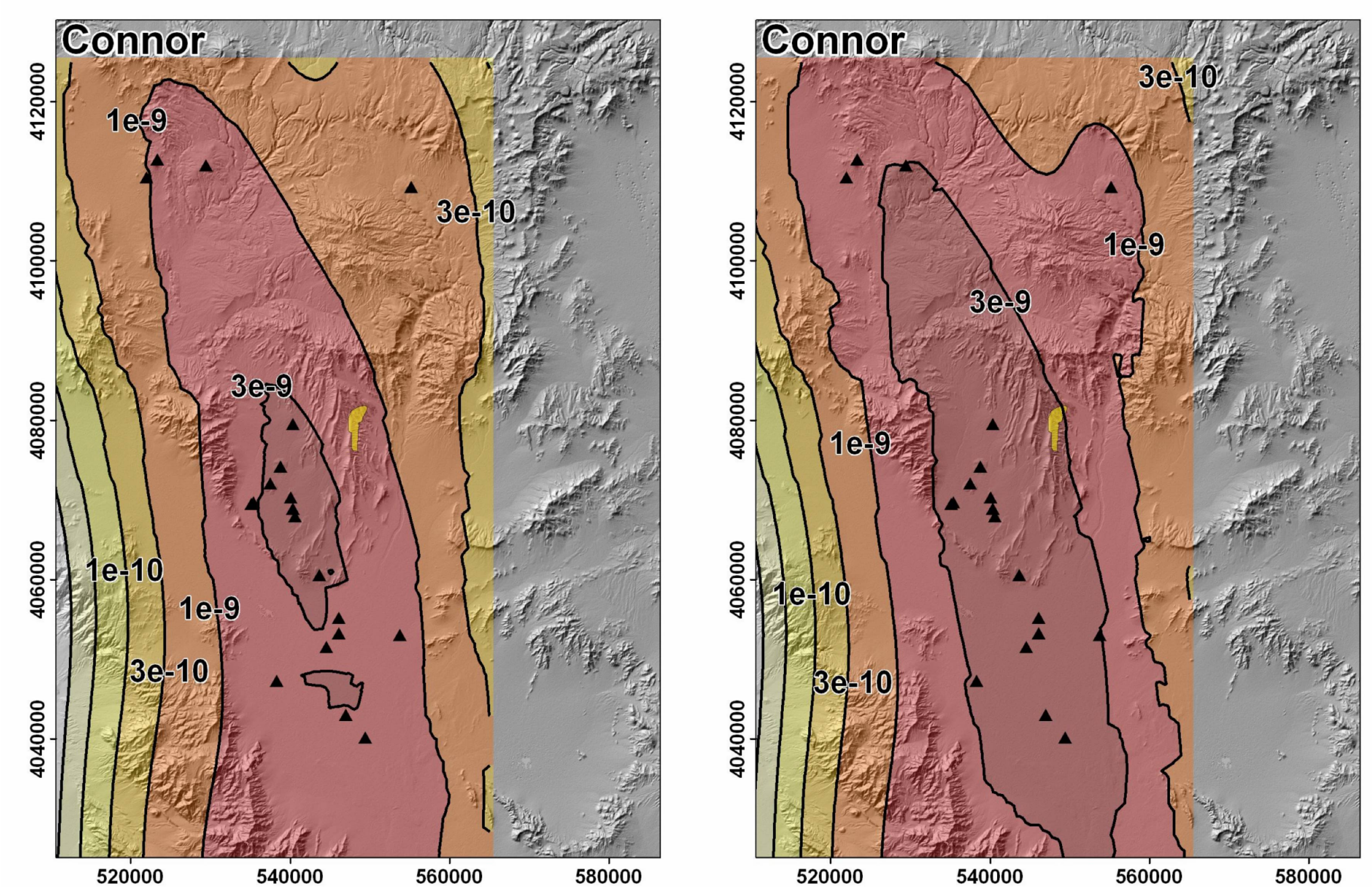
NOTE: Yellow polygon represents the repository footprint; black triangles represent past events. Map grid ticks are UTM meters; tick intervals are 10 km.

Figure 3.2.1-16. Conditional Probability of Intersection of Any Igneous Feature for Event Models Specified by Charles Connor



NOTE: Yellow polygon represents the repository footprint; black triangles represent past events. Map grid ticks are UTM meters; tick intervals are 10 km.

Figure 3.2.1-17. Conditional Probability of Intersection of Specific Igneous Features for Events Associated with the YMR Data Set



NOTES: The left figure is the mean rate density for the 10,000-year assessment, the right figure is the mean rate density for the 1-My assessment. Yellow polygon represents the repository footprint; black triangles represent events in the AVIP data set. Map grid ticks are UTM meters; tick intervals are 10 km.

Figure 3.2.1-18. Mean Rate Density for the 10,000-Year and the 1-My Assessment, Based on Charles Connor's PVHA-U models

Table 3.2.1-1. The YMR Data Set as Specified by Charles Connor

Event Name	Location (UTM coordinates)[a]		Age (Ma)
	Easting	Northing	
Lathrop Wells	543.706	4060.63	0.08
Sleeping Butte	523.355	4112.76	0.35
Quaternary Crater Flat	538.813	4074.25	1.1
Buckboard Mesa	555.223	4109.32	2.9
Anomalies G, F, and H	546.137	4053.29	3.8
Pliocene Crater Flat	540.332	4068.96	3.8
Anomaly B	553.738	4053.11	3.9
Anomaly C	546.997	4043.09	3.8 to 5.8
Anomaly D	549.431	4040.22	3.8 to 5.8
Anomaly E	538.295	4047.37	3.8 to 5.8
Thirsty Mesa	529.473	4112.03	4.7

[a] Locations for events provided by Charles Connor. As discussed in the text, some events are collections of features and the specified event location may not match the event location for an event of the same name as specified by other experts.

Table 3.2.1-2. The AVIP Data Set as Specified by Charles Connor

Location (UTM coordinates)[a]		Age[b] (Ma)
Easting	Northing	
535.116	4069.54	
535.445	4069.77	
537.515	4072.15	
538.813	4074.25	
540.38	4079.59	
522.004	4110.51	
523.355	4112.76	
543.706	4060.63	
540.6	4067.98	
540.332	4068.96	
540.1	4070.36	
529.473	4112.03	
555.223	4109.32	
546.126	4055.28	
546.137	4053.29	
544.536	4051.61	
553.738	4053.11	
546.997	4043.09	
549.431	4040.22	
538.295	4047.37	
459.902	4096.01	0.006 (Ubehebe)
523.931	3977.33	0.3 (Split Cone in Death Valley)
526.162	3974.46	0.7 (Shoreline Butte in Death Valley)

Table 3.2.1-2. The AVIP Data Set as Specified by Charles Connor (Continued)

Location (UTM coordinates)[a]		
Easting	**Northing**	**Age[b] (Ma)**
538.381	4011.6	
538.383	4013.9	
534.199	4014.02	
534.168	4015.11	
531.709	4018.27	
533.067	4020.3	
536.227	4021.59	
536.176	4019.21	
538.17	4017.65	
537.61	4018.69	
531.951	4022.08	

[a] Locations provided by Charles Connor. As discussed in the text, the AVIP data set consists of the locations of 34 vents in the Amargosa Valley Isotopic Province. Vent locations in the YMR are not necessarily the same as "events" identified in the YMR data set.

[b] Ages for vents prior to the Quaternary are not relevant for the temporal models specified by Charles Connor and so are not provided. Ages for vents in the YMR correspond to the ages for the events in Table 3.2.1-1.

Table 3.2.1-3. Weighting Function for Mean Crustal Density Data in the YMR by Charles Connor

Mean Crustal Density (gm/cm^3)		
Values greater than:	And less than or equal to:	**Weight**
2.68[(a)]	(no upper bound)	0
2.65	2.68	0.1
2.62	2.65	0.3
2.59	2.62	0.5
2.56	2.59	0.6
2.53	2.56	0.8
2.50	2.53	0.9
(no lower bound)	2.5	1.0

(a) Table D.1-16 in the Elicitation Summary is ambiguous about the weight for values between 2.68 and 2.71; the interpretation in this table is the best fit with the structure of the table and the assessment.

3.2.2 Bruce Crowe

Spatial and Temporal Models

Figure 3.2.2-1 presents the logic tree describing the basic structure of the spatial and temporal models developed by Bruce Crowe (BC) for the PVHA-U. BC defined several components of his overall model as differing based on three alternative regions of interest (ROIs). The alternative ROIs are shown in Figure 3.2.2-2, and are represented by the first node in the logic tree.

BC specified a spatial model consisting of four locally homogenous zones, with the zones defined by lithostatic pressure and geologic structure. Because only one conceptual model for spatial distributions was defined, no nodes are specified in the logic tree pertaining to alternative spatial models. The four zones are shown within the largest of the three regions of interest in Figure 3.2.2-3. The boundaries between the four zones are the same for all ROIs.

The spatial distribution of events within a zone is considered to be spatially homogenous, and BC used three alternative perspectives in developing his assessment of the relative frequency of events in each of the four zones. These are represented by the three branches of the "Event perspective" node. Each perspective corresponds to a specific assessment of the relative frequency of events in each of the four zones. Figure 3.2.2-4 illustrates that assessment.

The underlying temporal model is a homogenous Poisson model. Four alternative conceptual models for the future rate models of events are defined, as illustrated in the logic tree in Figure 3.2.2-1: a steady-state rate model, an increased rate model, a background rate model, and, in some cases, a new volcanic cycle model. For each conceptual model and each region of interest, BC provided a direct assessment of the recurrence rate, including uncertainty. As shown by the last node in the logic tree of Figure 3.2.2-1, he provided estimates for the minimum rate, the 25th, 50th, and 75th percentiles, and for the maximum rate.

Figure 3.2.2-5 illustrates the probability BC assigned to each model for the two time periods of assessment and the three ROIs. The figure also shows the median (50th percentile) rate estimate corresponding to each model. Figure 3.2.2-6 illustrates uncertainty in the rate estimate (the 5th to 95th percentiles) for all models used in the 10,000-year assessment. BC's Elicitation Summary in Appendix D contains the complete details of the uncertainty in rate for all models.

Mean Rate Density and Mean Recurrence Rate

Figure 3.2.2-7 illustrates the mean rate density for igneous events calculated from BC's spatial and temporal models for the 10,000-year assessment. Differences in the 1-My assessment are discussed below. The appearance of the mean rate density map corresponds directly to the spatial zones shown in Figure 3.2.2-3. The "hole" in the mean rate density north of the repository footprint results from the high lithostatic pressure in that area and BC's judgment that events will not occur in that zone.

A mean recurrence rate for events in the region of interest can be calculated by summing the mean rate density at each grid point. Based on the mean rate density shown in Figure 3.2.2-7, the mean recurrence rate for events in this region is 3.4e-6 events per year, giving recurrence intervals between 15,000 and 881,000 years (5th to 95th percentile of the distribution on recurrence interval), with a mean recurrence interval of about 294,000 years in the region illustrated.

Event Simulation Model

BC's model includes five basic *event types.* Almost all event characteristics, such as the size of an event, and the number, size, and spacing of various igneous features, are specified separately for different event types and for different rate models. Overall, BC developed 13 distinct event descriptions, each with a unique assessment of the event size, and the number, size, and location of features in the event. Figure 3.2.2-8 illustrates a logic tree defining the bases for those 13 event descriptions, along with the relative likelihood of each event description applying.[2] The probabilities on the first node of the logic tree, the rate models, differ for the different time periods of assessment, as described above.

Figure 3.2.2-9 illustrates the various event characteristics and some of the relationships between them in an influence diagram. All event characteristics except for event and dike azimuth were defined separately for each of the 13 basic event descriptions.

As an example, a three-cone event would have three conduits, three or four dikes, and three to six vents (the number of vents must be at least as large as the number of dikes, and all conduits are also vent, so there would be zero to three non-column producing vents in addition to the three column-producing conduits). The distance between any pair of cones is a function of the event length: under the steady-state or increased rate models, given the distribution on event length, the distance between cones is a uniform distribution between 3.3 and 5.2 km. The event azimuth gives the direction between conduits, and is illustrated in Figure 3.2.2-10. Each conduit is associated with a dike, and dikes are oriented according to the dike azimuth distribution shown in Figure 3.2.2-11. If more dikes than conduits occur, the additional dikes are located adjacent to conduit-bearing dikes, separated by a distance given by the distribution shown in Figure 3.2.2-12. Each "additional" dike bears a vent (a feature that vents to the surface but does not produce an eruption column), located at a distance from the associated conduit given by Figure 3.2.2-13. Finally, if more vents than dikes occur, the additional vents are located on a conduit-bearing dike at a distance from the conduit given by the distribution shown in Figure 3.2.2-13. Figures 3.2.2-14 and 3.2.2-15 show the conduit and vent diameters for any event under the steady-state or increasing rate models. Larger diameters are specified for the background and new cycle rate models.

The basic logic of the relative location of features is consistent across twelve of the thirteen event descriptions, and the detail is contained in the Elicitation Summary for BC in Appendix D. Large-footprint events are modeled somewhat differently, consisting of widely spaced clusters of three-cone events. The details are contained in BC's Elicitation Summary.

Figure 3.2.2-16 illustrates two example events from the event simulations associated with the steady-state rate model. Table 3.2.2-1 describes the number of column-producing conduits and

[2] The logic tree shows 15 branches (3 rate models × 5 event types), but two of those branches are assigned zero probability for the 10,000-year assessment, leaving a total of 13 event descriptions.

vents (combined) and the number of dikes in an event, and how frequently such events occur in the event simulation. The table indicates, for example, that the most common type of event simulated using the event characteristics defined for the steady-state rate model consist of two cones or vents and two dikes. 16.2% of all simulated events are of this type (as shown in bold in the table), and an example is illustrated in the top half of Figure 3.2.2-16). A less common type of event (3.4% of simulated events), consisting of 5 conduits and vents and 3 dikes, is shown in the bottom half of Figure 3.2.2-16.

Conditional Probability of Intersection

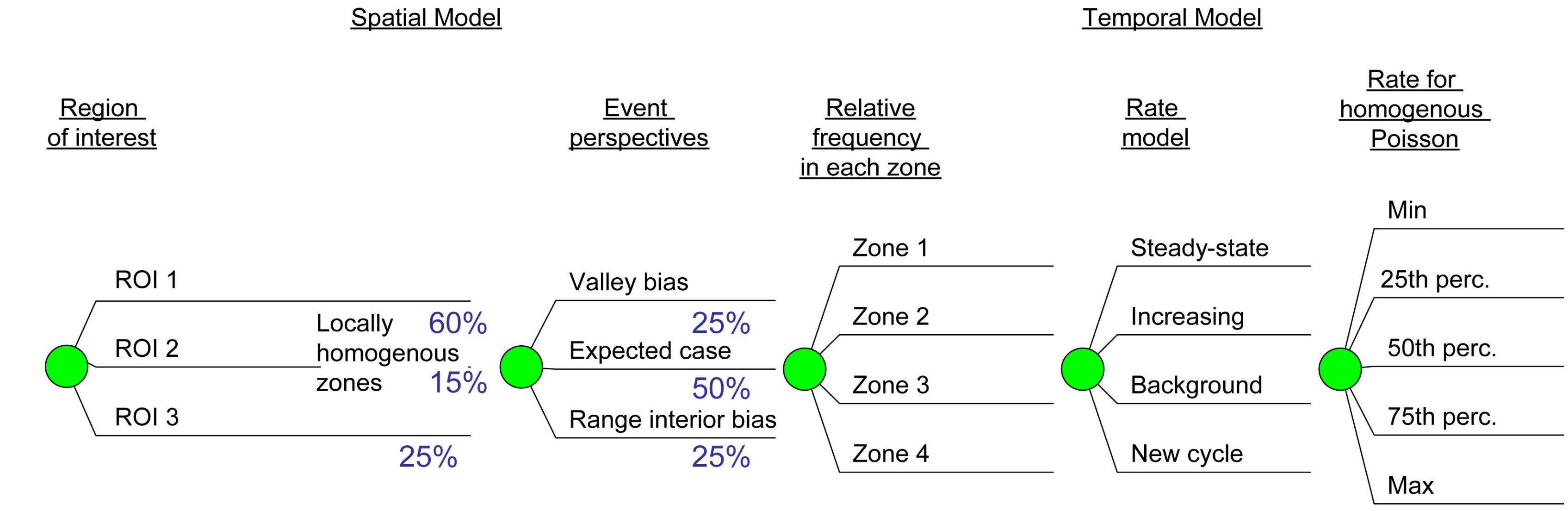
Figure 3.2.2-17 illustrates the conditional probability of the intersection of any igneous feature with the repository footprint based on the three event models described by BC. As described above, BC defined different event characteristics for events associated with: (a) the steady-state and increasing rate models, (b) the new cycle rate model, and (c) the background rate model.

As discussed above and described in detail in BC's Elicitation Summary in Appendix D, the new cycle rate model includes the potential for what BC terms "large-footprint events." Such events are assessed to occur relatively rarely, but they have a large spatial extent, as shown in panel (b) of the figure (note the change in scale for this panel). These large footprint events are defined as consisting of three or four distinct clusters of igneous features, which are located away from the defined "event center." This defined placement of the clusters is evident in the shape of the lower-probability contours in panel (b): events centered directly east or west of the repository footprint are less likely to intersect the footprint than are events centered north or south by the same distance.

As described above, BC's events include at least one dike and one column-producing conduit, and may also include vents. Figure 3.2.2-18 shows the conditional probability of intersection for each of these types of igneous features, for events associated with the steady state and increasing rate models. These maps reflect the same spatial distribution of features as the intersection of any feature, indicating there is no particular clustering of features within an event. The conditional probability of intersection for conduits and vents is lower than for dikes for an event at any given location due to their smaller size and their distribution along a dike.

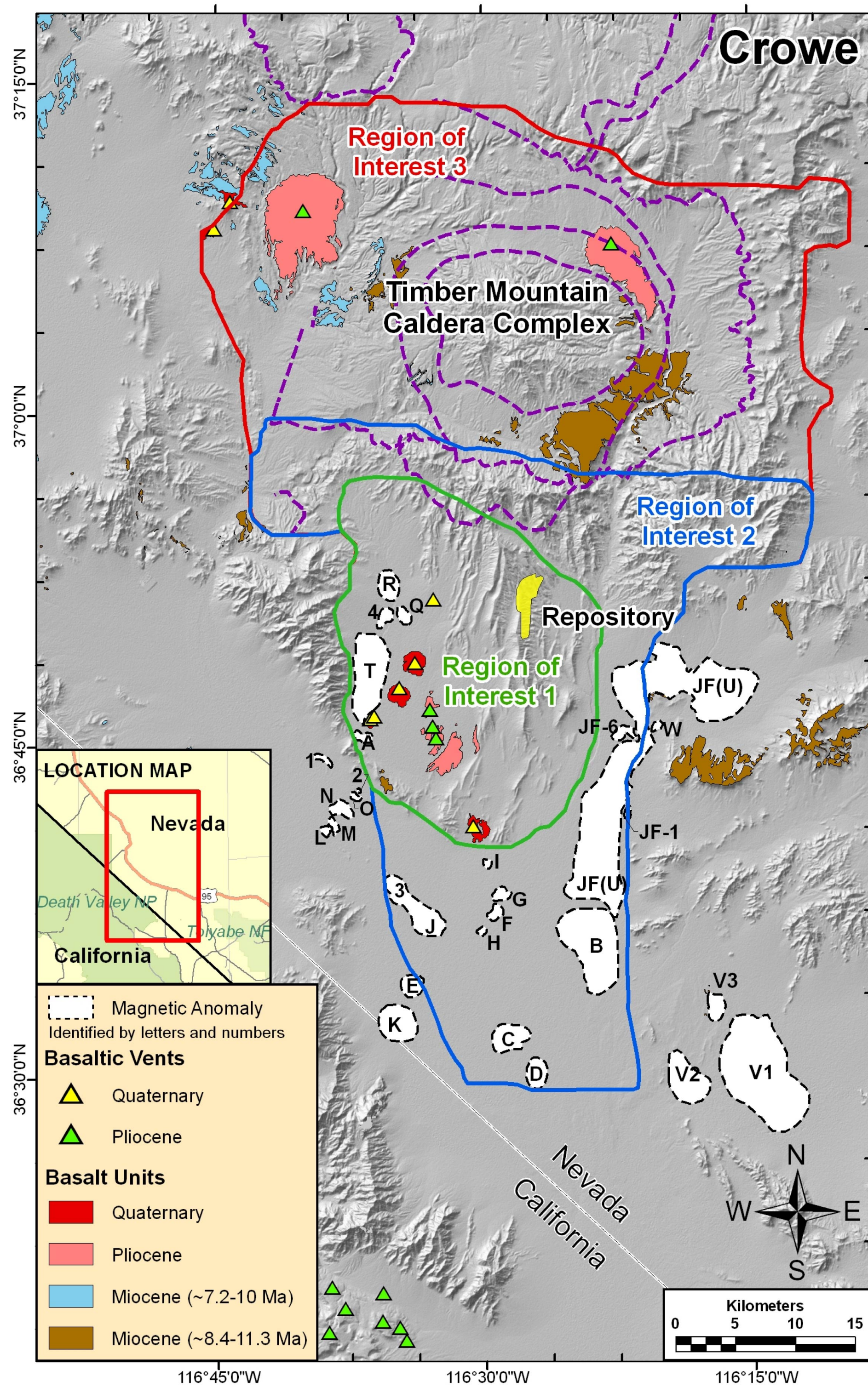
Differences Between the 10,000-year and 1-My Assessments

The relevance of the three regions of interest and the four rate models, as specified by the probabilities applied to each, differ for the 10,000-year assessment and the 1-My assessment. Figure 3.2.2-5 described above shows the different probabilities applied to the regions of interest and rate models for models corresponding to the different time periods of assessment. Figure 3.2.2-19 shows a comparison of the mean rate density map for the 10,000-year assessment and the mean rate density map for the 1-My assessment. Differences are very hard to discern, due to the use of the zones-based spatial model and the very small difference in *mean* rate for the two assessment periods.



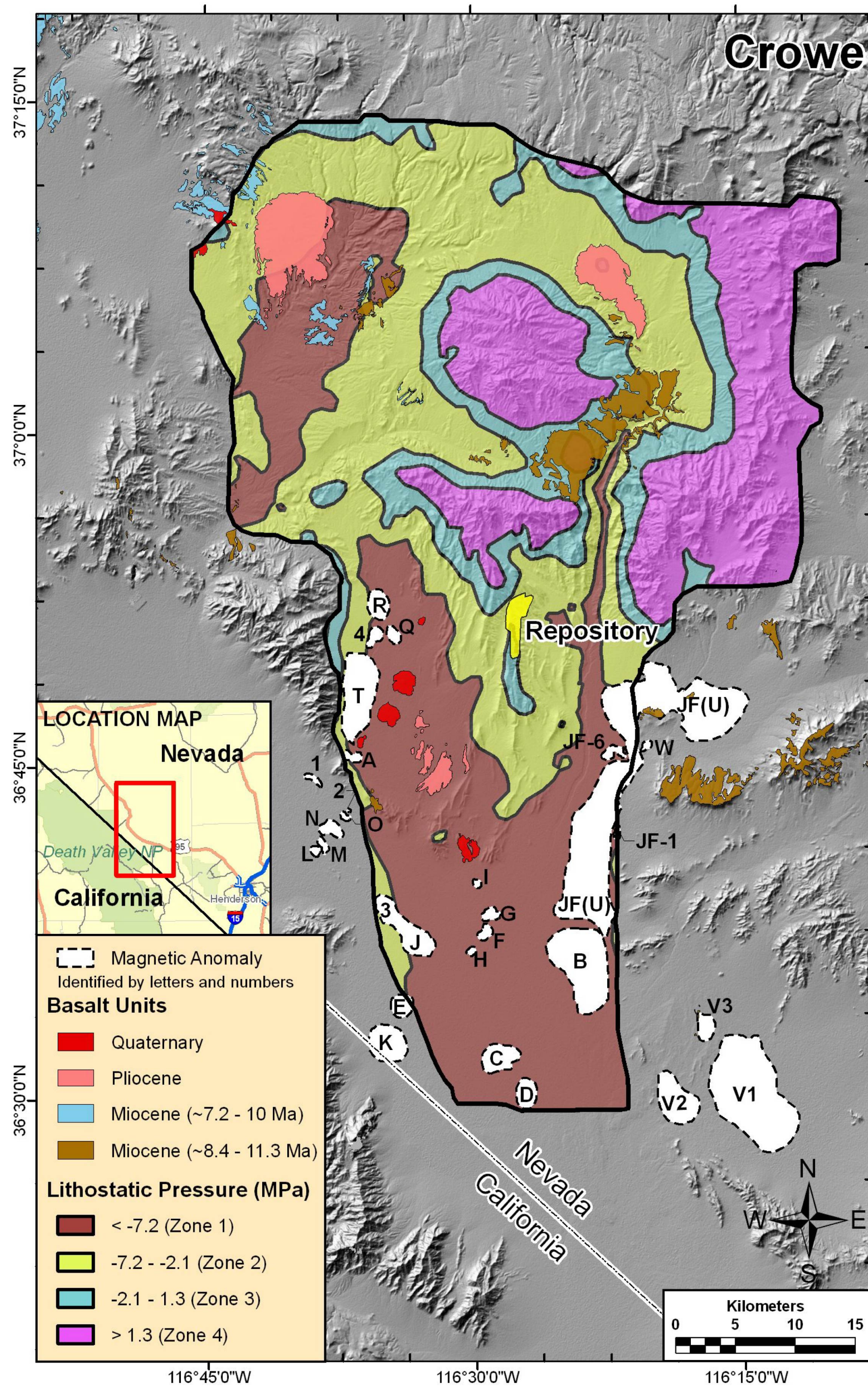
NOTE: Probabilities shown on the branches are as assigned by the expert. In this example, probabilities shown on the ROI branches are those assigned for the 10,000-year assessment. The structure of the logic tree is the same for the 10,000-year assessment and 1-My assessments but the probabilities assigned to the branches differ. Details are discussed at the end of Section 3.2.2.

Figure 3.2.2-1. Logic Tree Representing the Spatial and Temporal Components of the PVHA-U Model Specified by Bruce Crowe



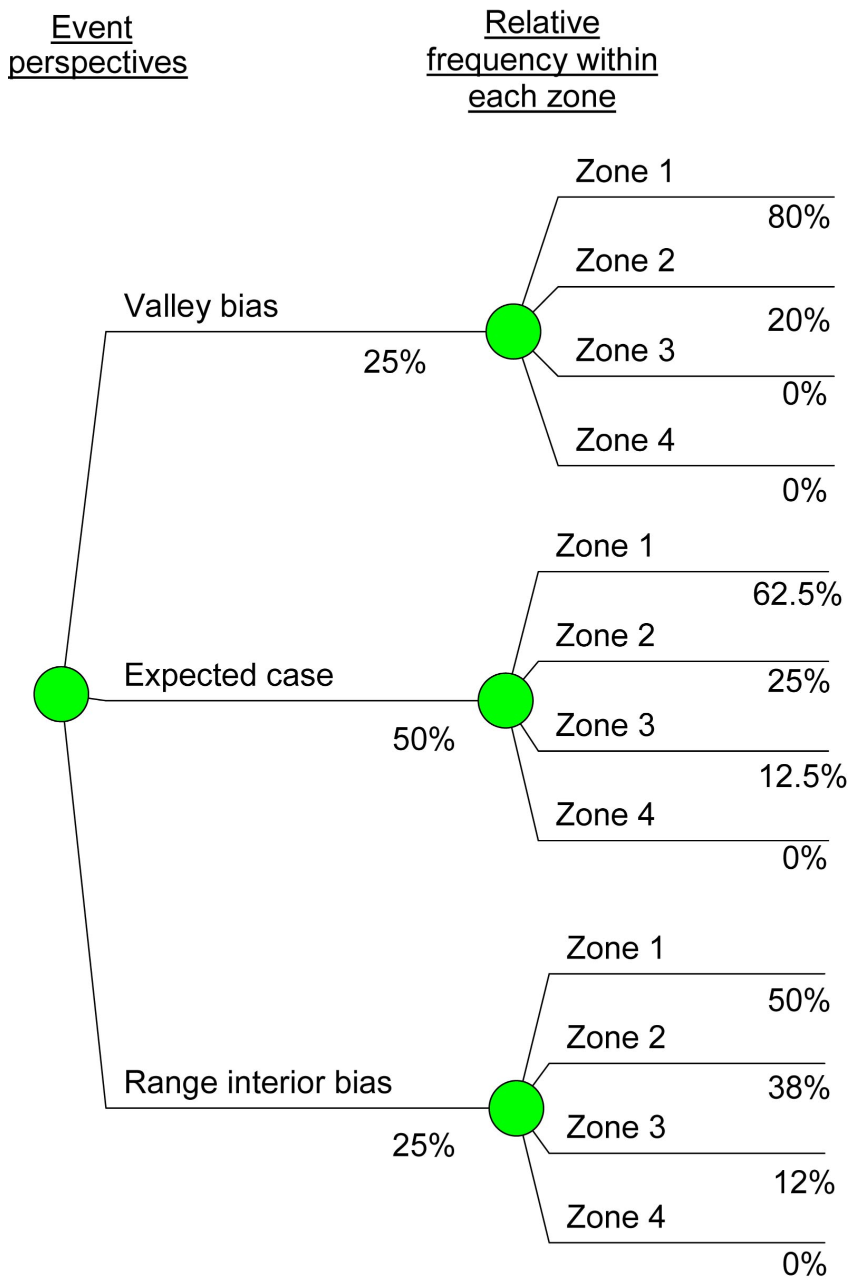
NOTE: Green line represents ROI 1; ROI 2 fully contains ROI 1, and is further outlined by the blue line. ROI 3 fully contains ROI 2, and is further outlined by the red line.

Figure 3.2.2-2. Three Alternative Regions of Interest Defined by Bruce Crowe



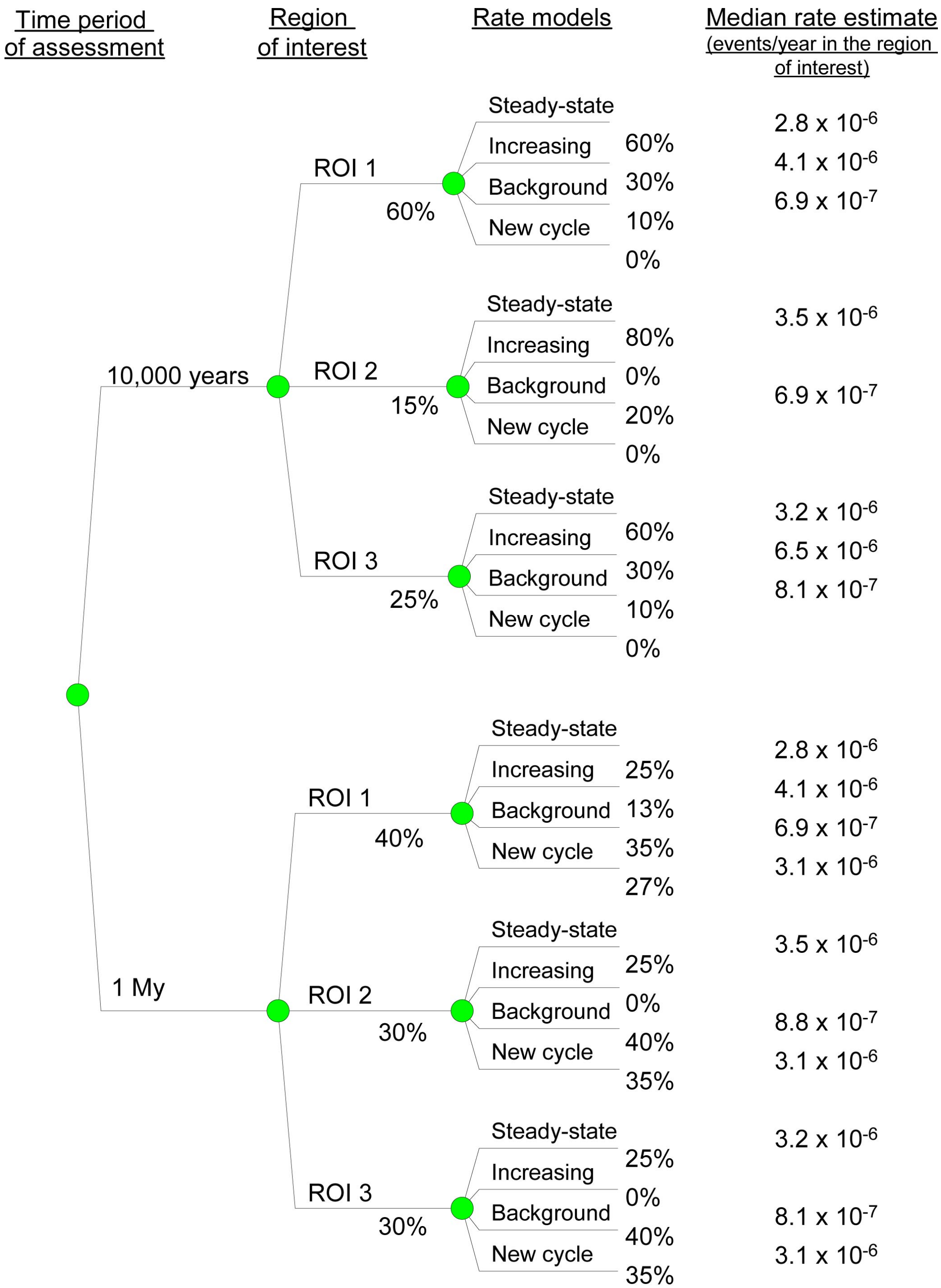
NOTE: Four colors represent the four zones; zones were defined by the expert based on lithostatic pressure contours.

Figure 3.2.2-3. Four Locally Homogenous Spatial Zones Defined by Bruce Crowe



NOTE: Probabilities shown on the branches are as assigned by the expert.

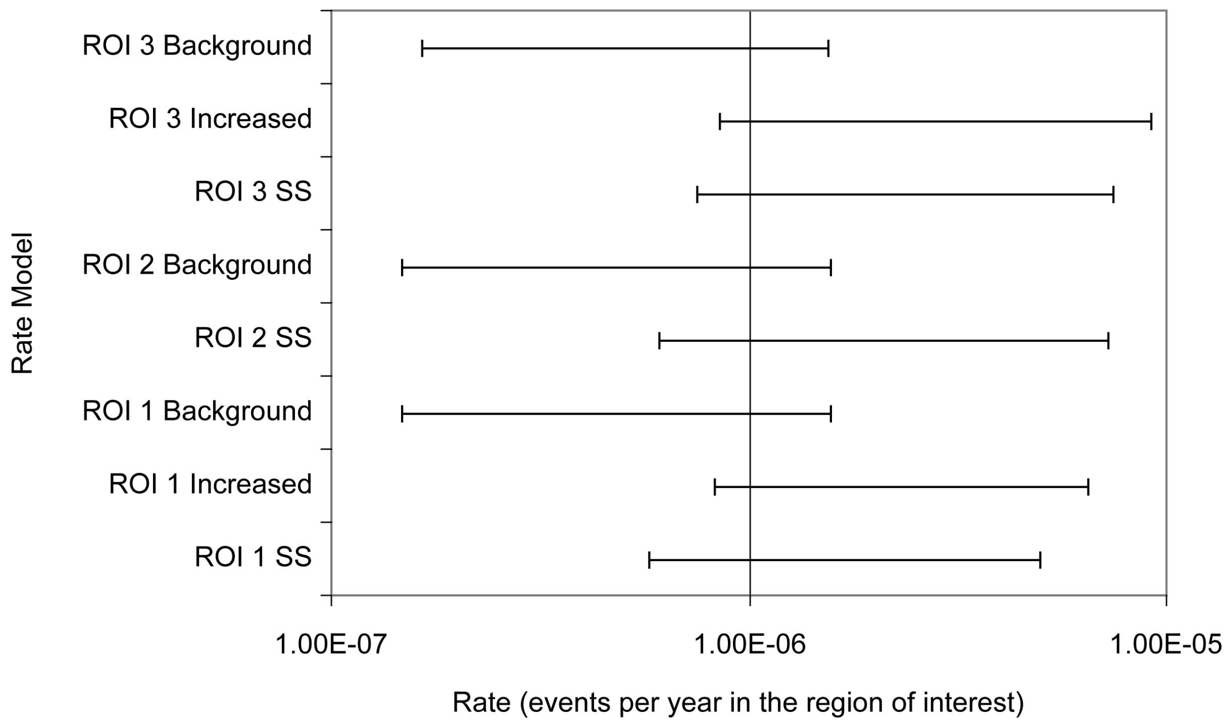
Figure 3.2.2-4. Logic Tree Illustrating the Relative Frequency of Events in Four Zones for Three Event Perspectives as Assessed by Bruce Crowe



NOTES: Probabilities shown on the branches are as assigned by the expert.

Median rate estimate corresponding to each model is shown at the end of each branch, except those with zero probability.

Figure 3.2.2-5. Logic Tree Illustrating the Probabilities for Alternative Rate Models in Three Regions of Interest and Two Time Periods of Assessment, as Specified by Bruce Crowe

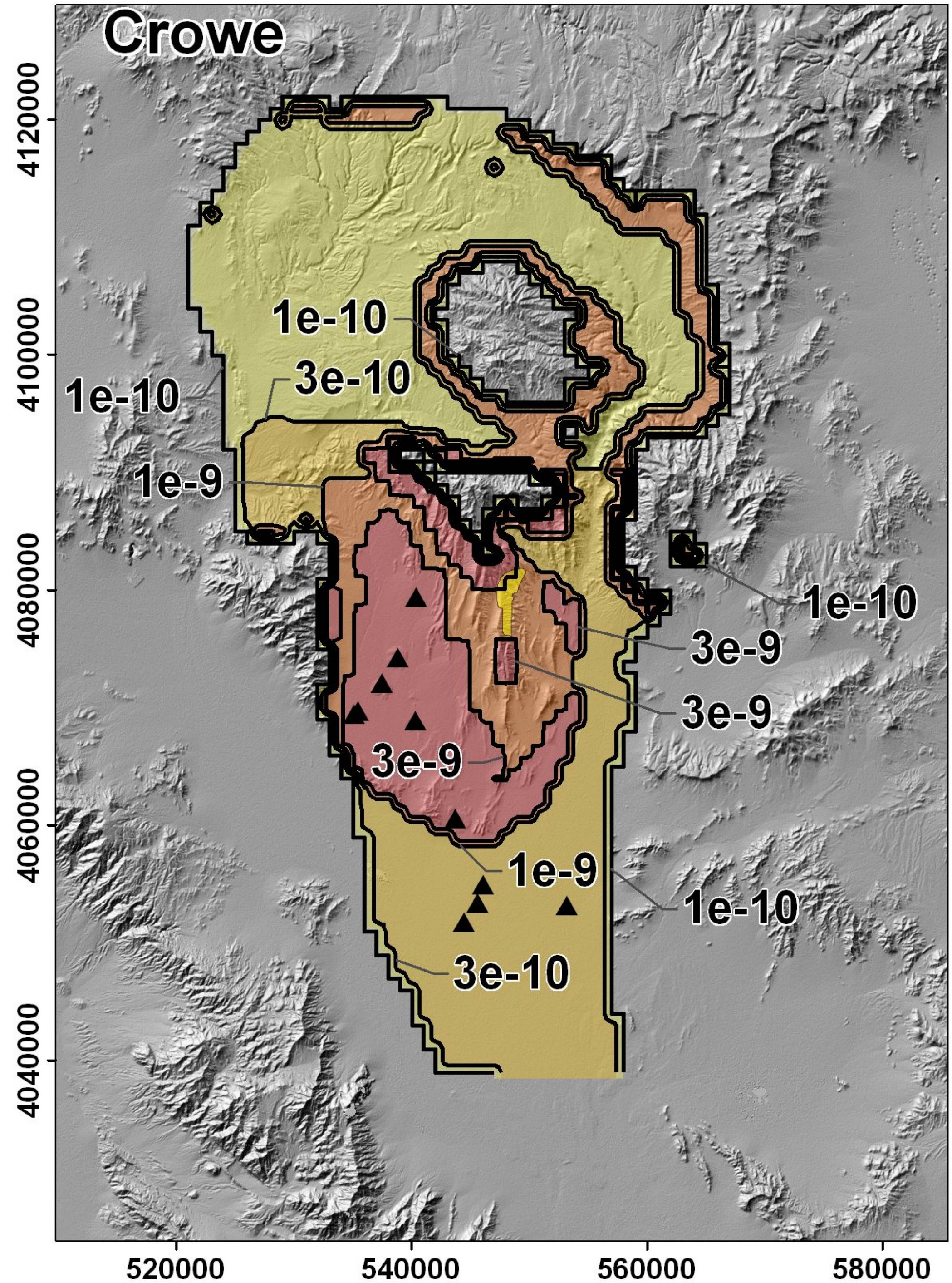


NOTES: Bars represent the 5th to 95th percentile of the uncertainty in the rate for each alternative rate model.

SS refers to the steady-state rate model.

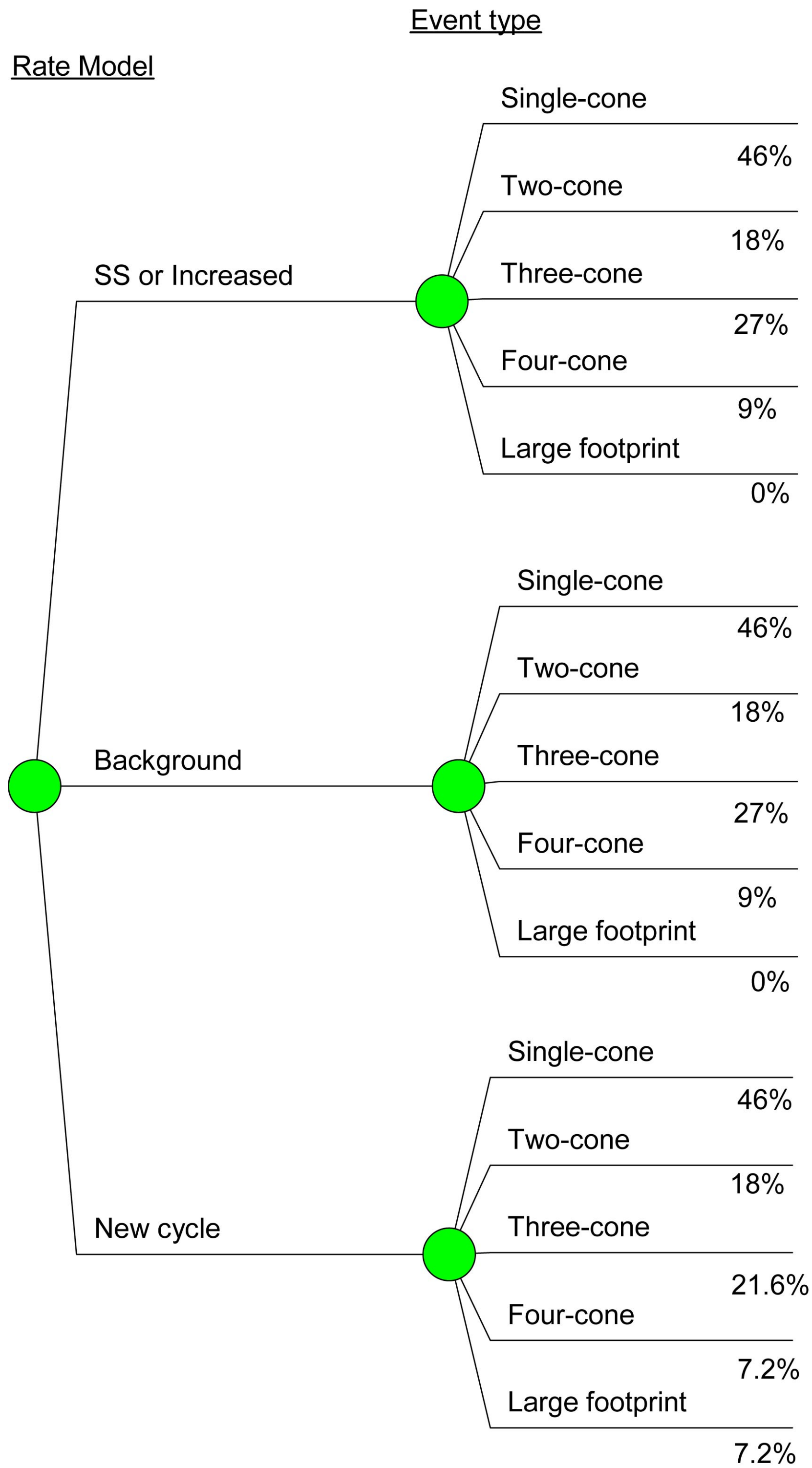
Caution is recommended in comparing these rate distributions. Note that for each model, the estimated rate applies to the specific region of interest (ROI), the areas of which vary, implying different rate densities. In addition, the rate is spatially varying (as described in the text of the report).

Figure 3.2.2-6. Uncertainty in the Estimated Rate for Alternative Rate Models for the 10,000-Year Assessment as Specified by Bruce Crowe



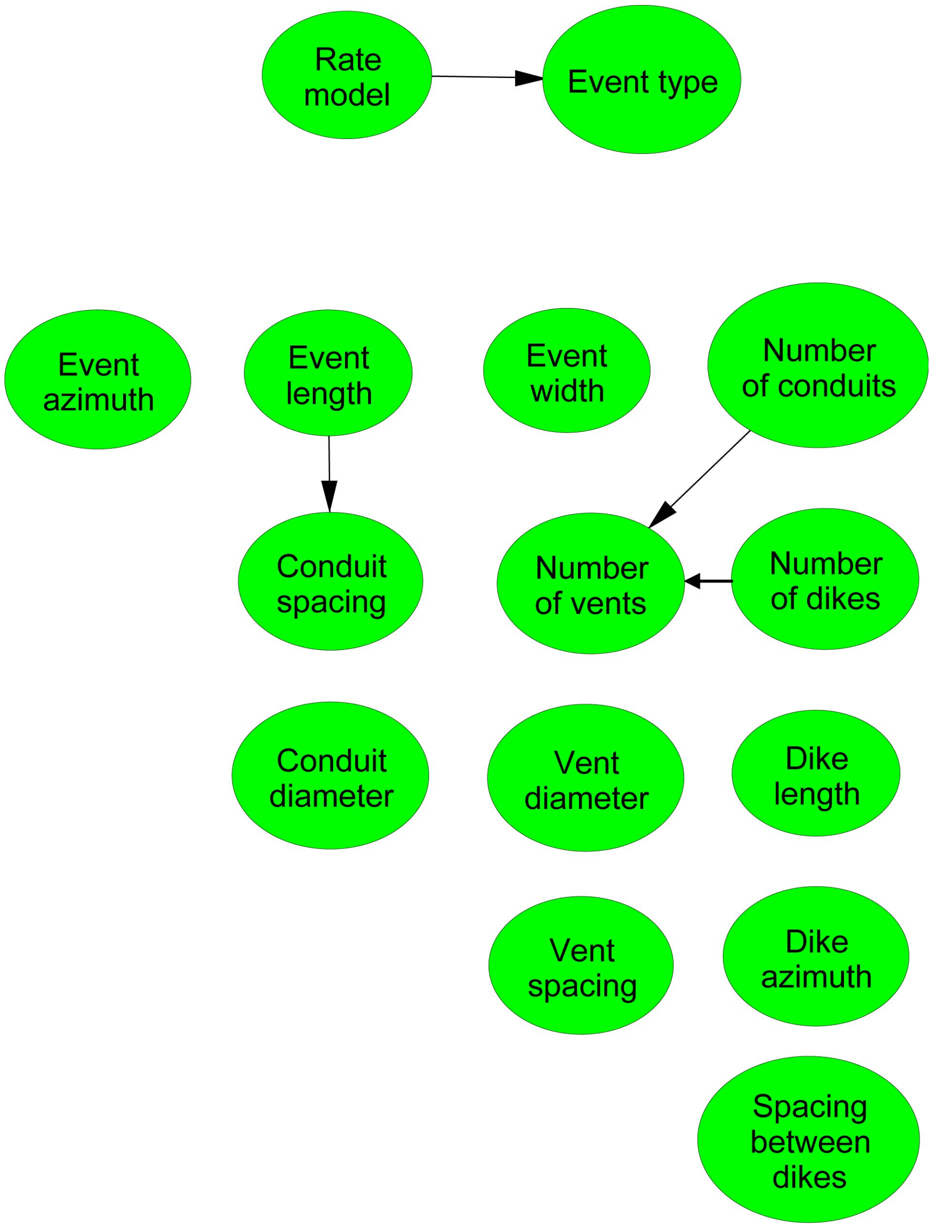
NOTE: Contours represent the mean rate density (events per year per km^2). Yellow polygon represents the repository footprint. Black triangles represent past events. Map grid ticks are UTM meters; tick intervals are 20 km.

Figure 3.2.2-7. Mean Rate Density for the 10,000-Year Assessment Based on Models Specified by Bruce Crowe



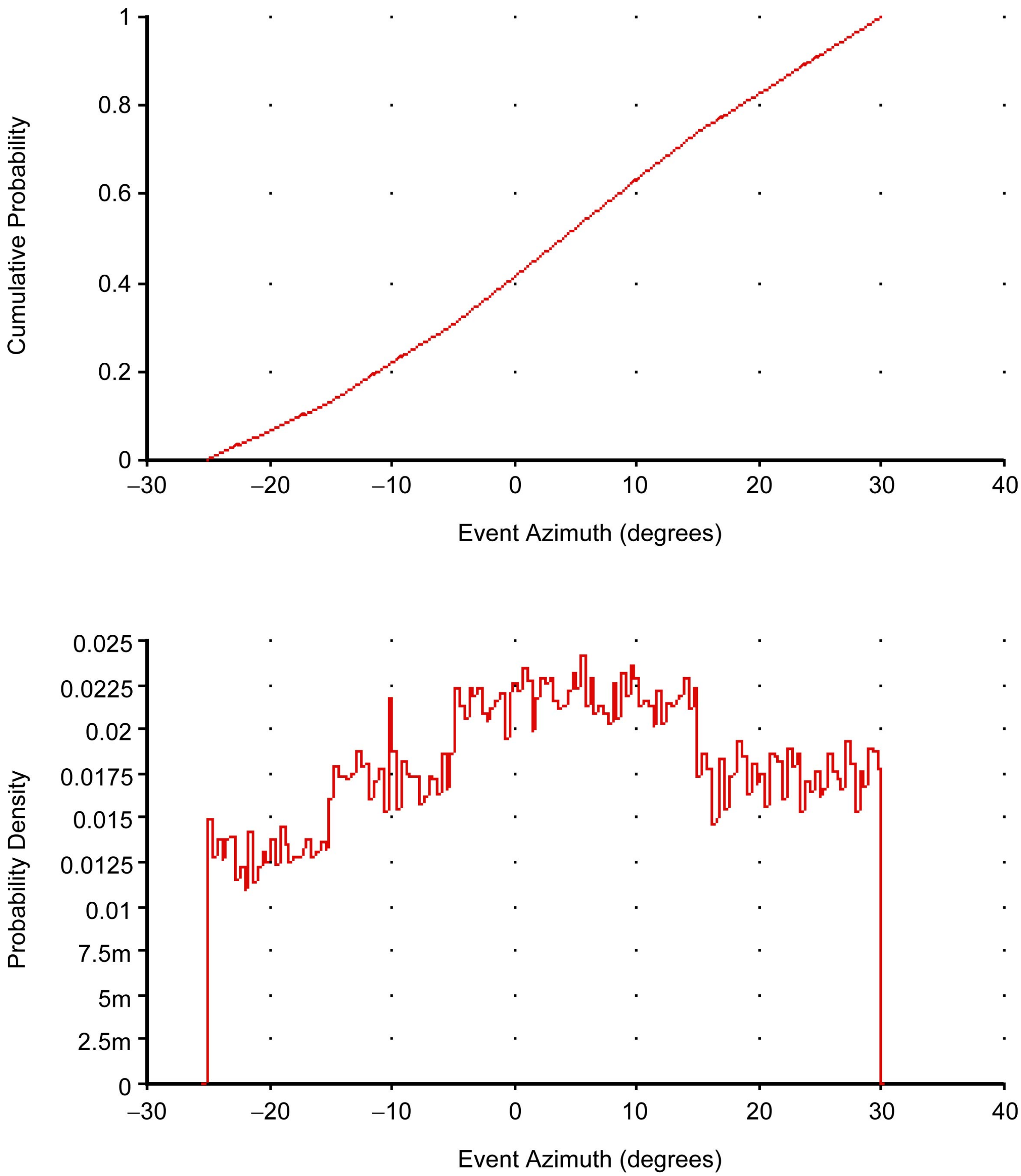
NOTE: All probabilities shown in the tree are as specified by the expert. Probabilities for the rate models are specified conditional on the time period of assessment, as illustrated in Figure 3.2.2-5.

Figure 3.2.2-8. Logic Tree Illustrating the 13 Basic Event Types Specified by Bruce Crowe



NOTE: All assessments of event characteristic except event and dike azimuth are a function of the rate model and event type. Arrows represent dependencies between characteristics: for example, conduit spacing is defined as a function of event length; number of vents is constrained by the number of conduits and the number of dikes.

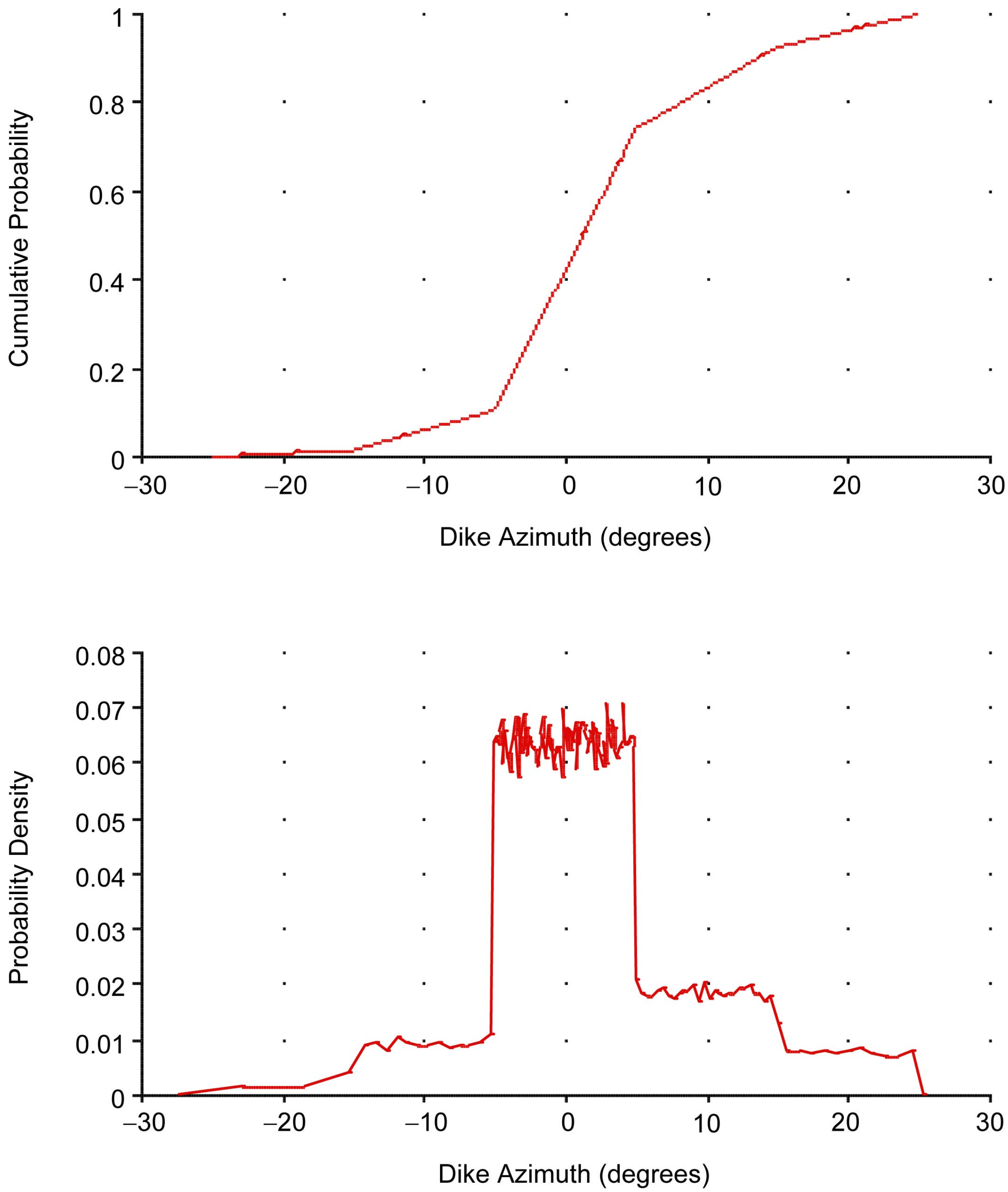
Figure 3.2.2-9. Influence Diagram Illustrating Event Characteristics and the Relationships among Them for Event Descriptions Specified by Bruce Crowe



NOTES: Top graph is a cumulative distribution function; bottom graph is a probability density function. For values less than 0.01 on the y-axis, suffix notation is used (m = 10^{-3},so 5m = 0.005). Roughness in the probability density is an artifact of the simulation of a mixture of uniform distributions. Results shown are for 30,000 iterations.

Azimuth of zero represents North.

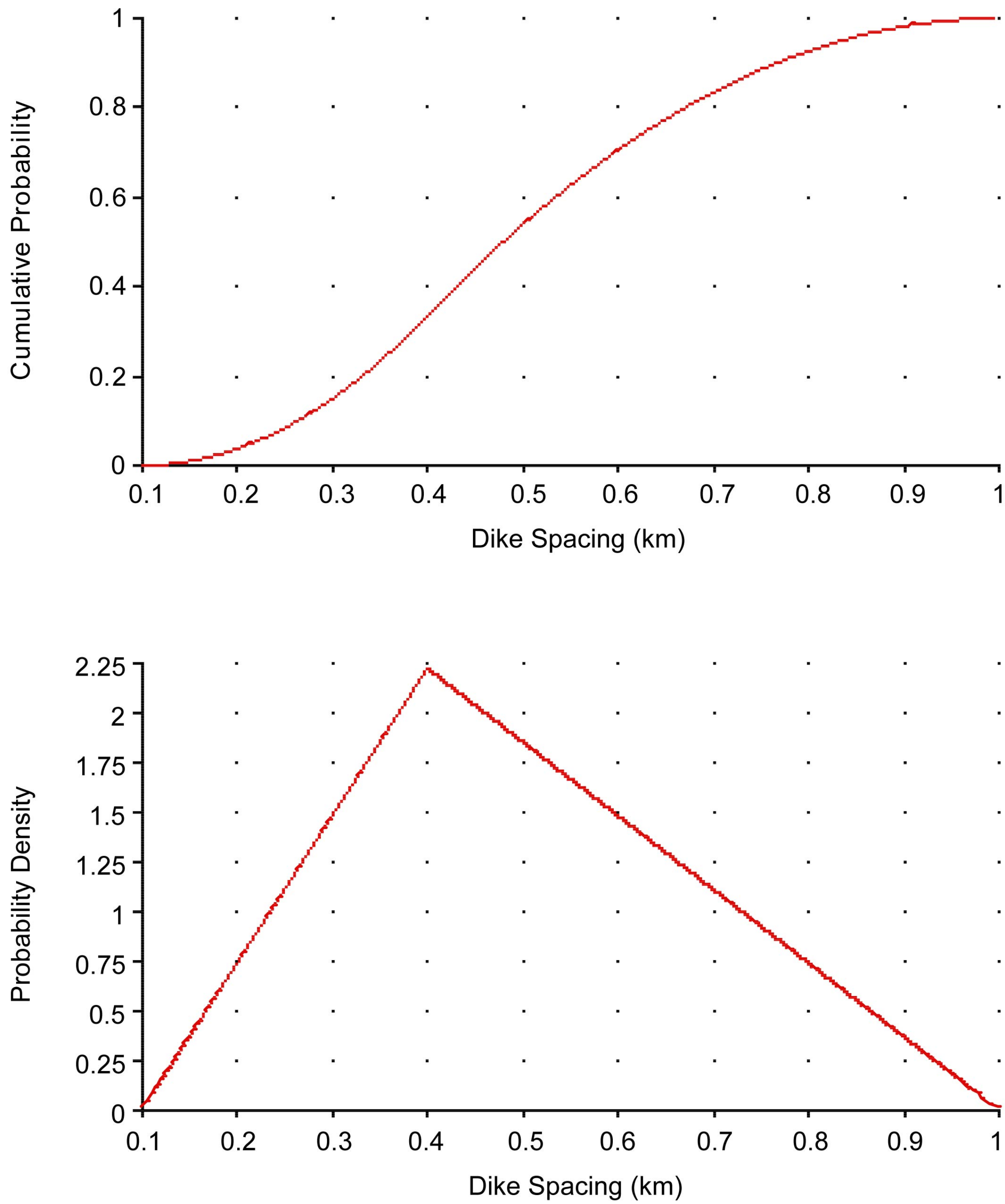
Figure 3.2.2-10. Distribution for Event Azimuth Based on Assessments of Bruce Crowe



NOTES: Top graph is a cumulative distribution function; bottom graph is a probability density function. Roughness in the probability density function is a function of simulation from a mixture of uniform distributions. Results shown are for 30,000 iterations.

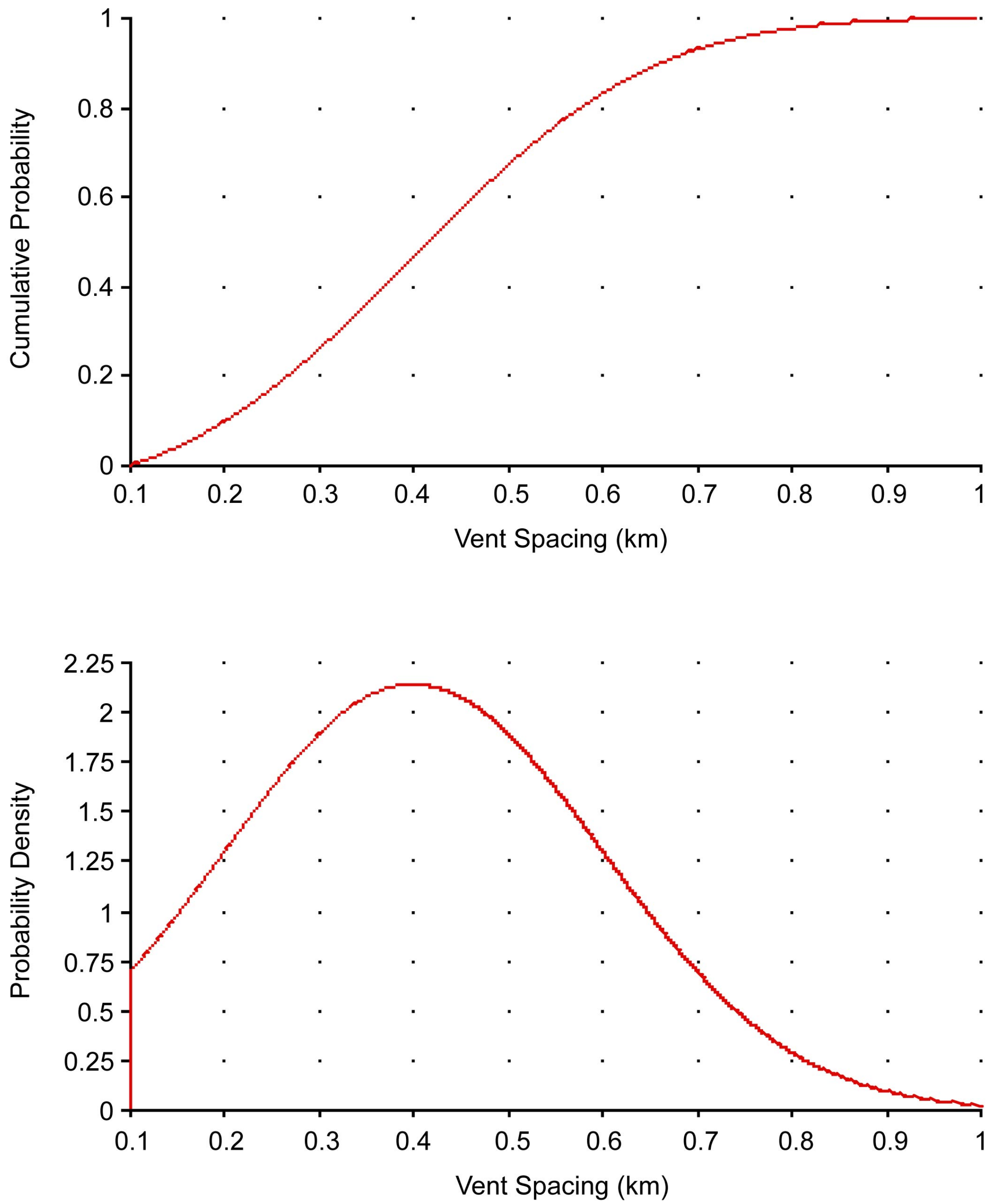
Azimuth of zero represents North.

Figure 3.2.2-11. Distribution for Dike Azimuth Based on Assessments of Bruce Crowe



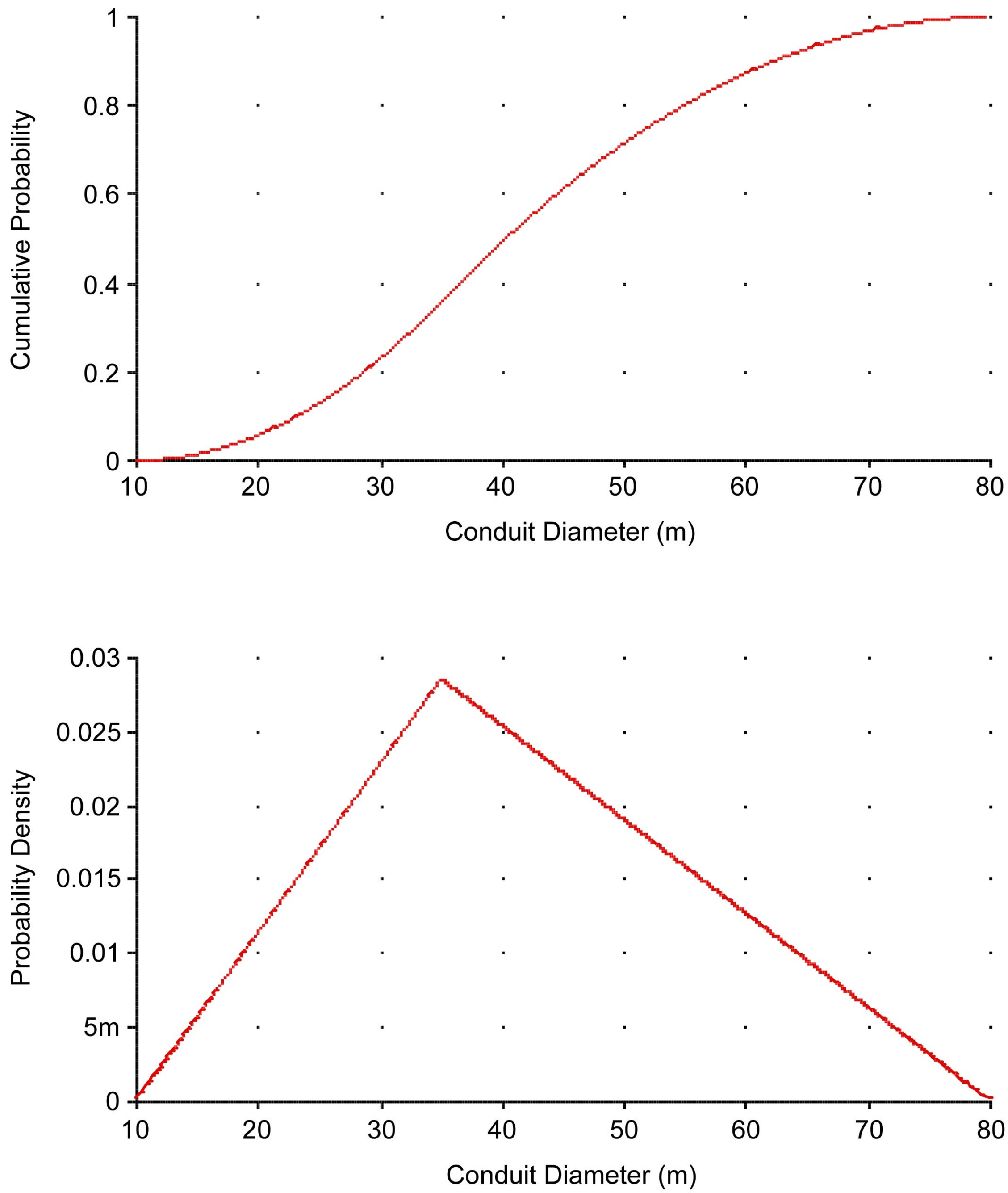
NOTE: Top graph is a cumulative distribution function; bottom graph is a probability density function.

Figure 3.2.2-12. Distribution for the Spacing between Dikes in the Direction Perpendicular to Dike Azimuth as Assessed by Bruce Crowe



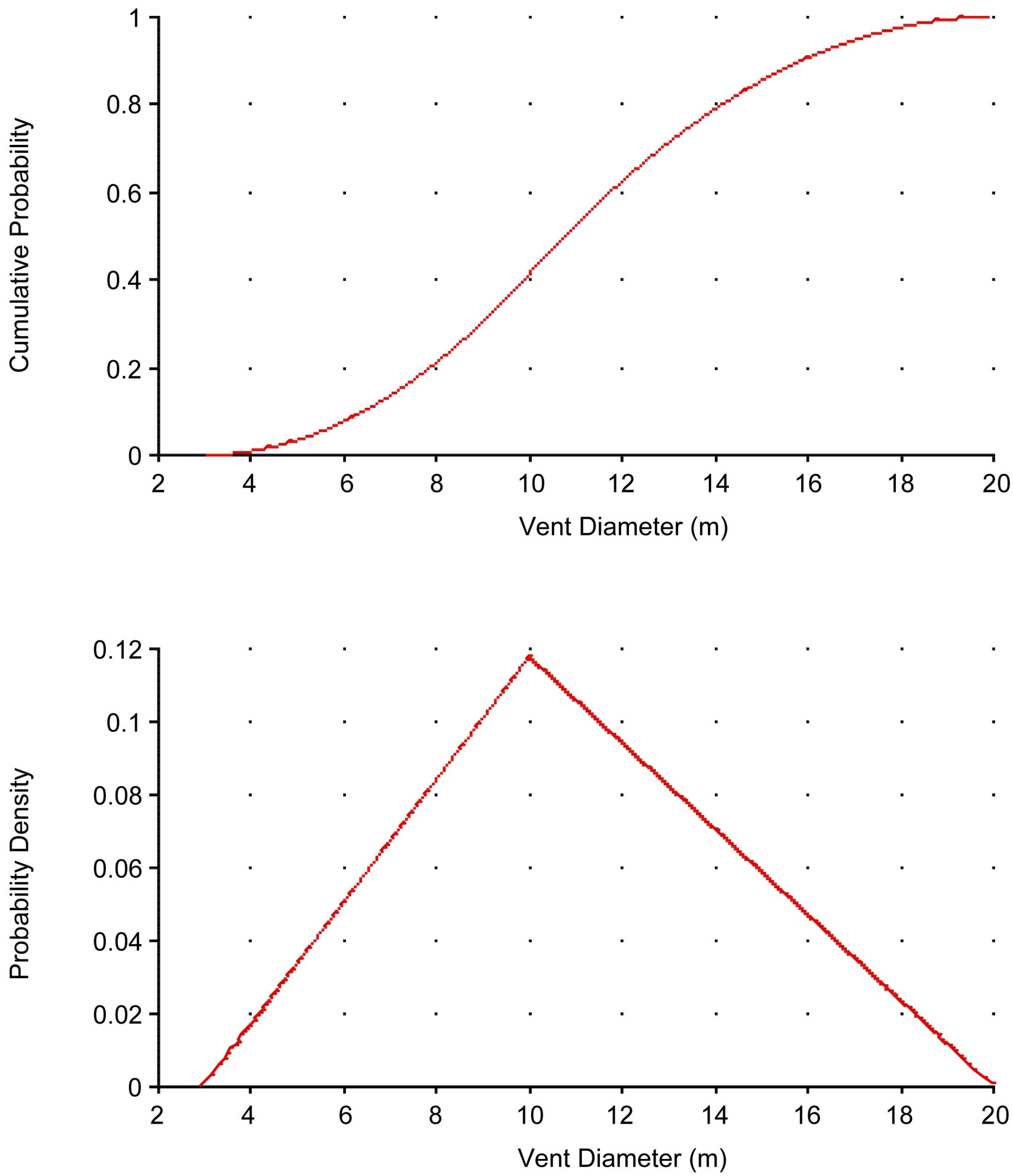
NOTE: Top graph is a cumulative distribution function; bottom graph is a probability density function.

Figure 3.2.2-13. Distribution for the Spacing between a Conduit and an Associated Vent, in the Direction Parallel to Dike Azimuth, as Assessed by Bruce Crowe



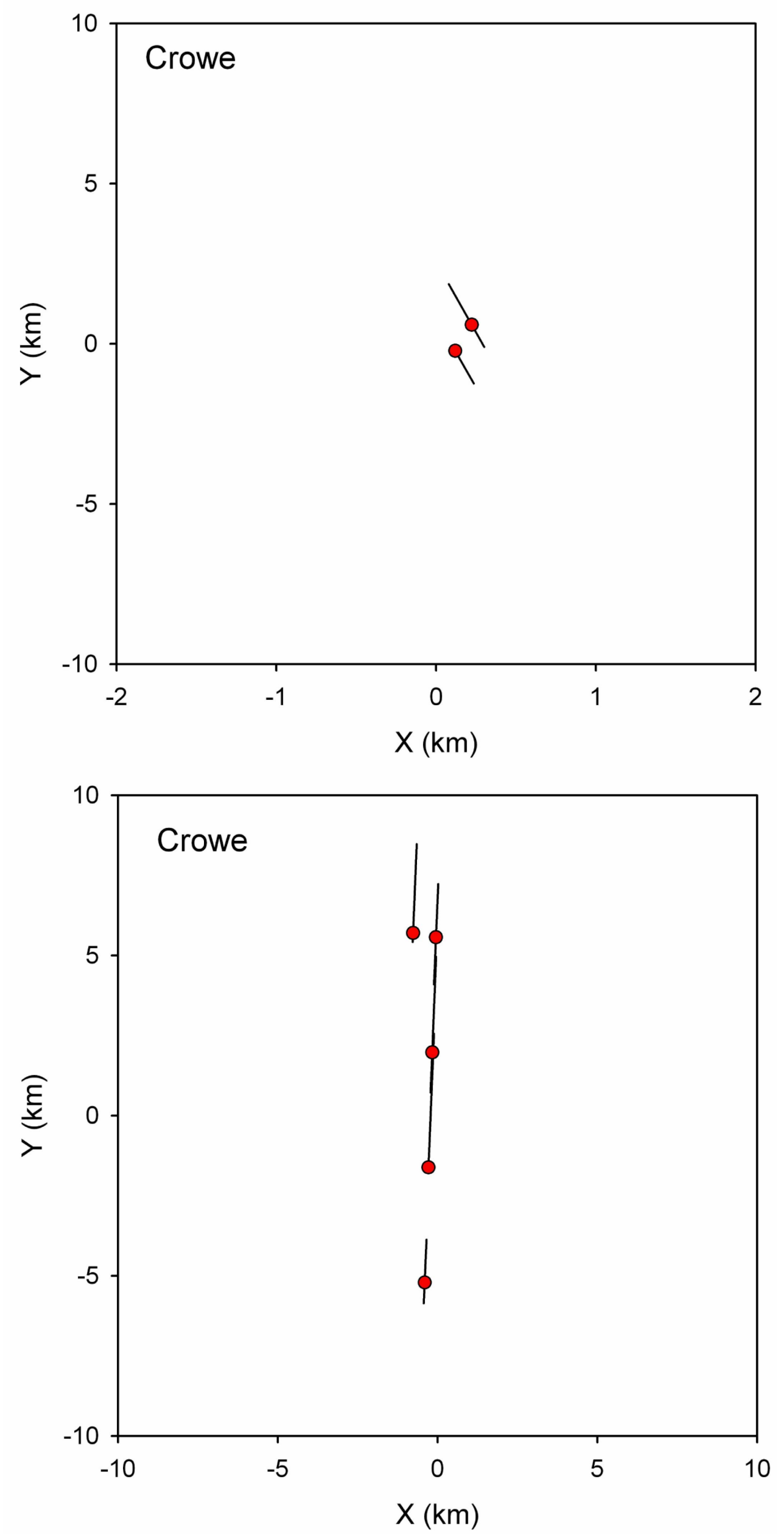
NOTE: Top graph is a cumulative distribution function; bottom graph is a probability density function. For values less than 0.01 on the y-axis, suffix notation is used (m = 10^{-3},so 5m = 0.005).

Figure 3.2.2-14. Distribution for Conduit Diameter for the Steady-State Rate Model as Assessed by Bruce Crowe



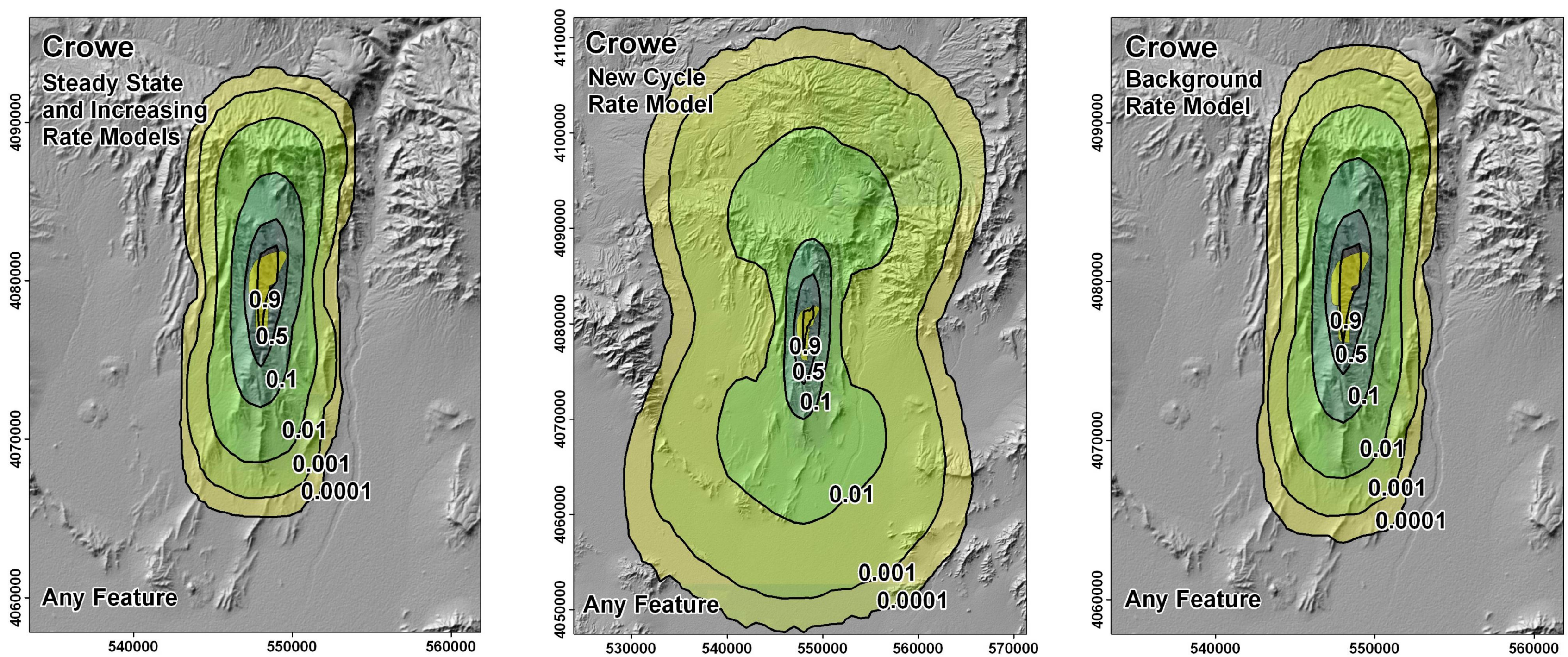
NOTE: Top graph is a cumulative distribution function; bottom graph is a probability density function. In event simulation, the lower bound for vent diameter is the dike width. In this figure, the lower bound is set to the most likely value of the dike width distribution (3 m).

Figure 3.2.2-15. Distribution for Vent Diameter for the Steady-State Rate Model as Assessed by Bruce Crowe



NOTE: Dikes are represented as black lines; their lengths on the figure are the lengths of the simulated dikes. Conduits and vents are represented as small red circles; they are not differentiated and their diameters are not represented. Sills, if they exist, are represented by light yellow ovals or polygons.

Figure 3.2.2-16. Examples of Simulated Events from the PVHA-U Model Specified by Bruce Crowe



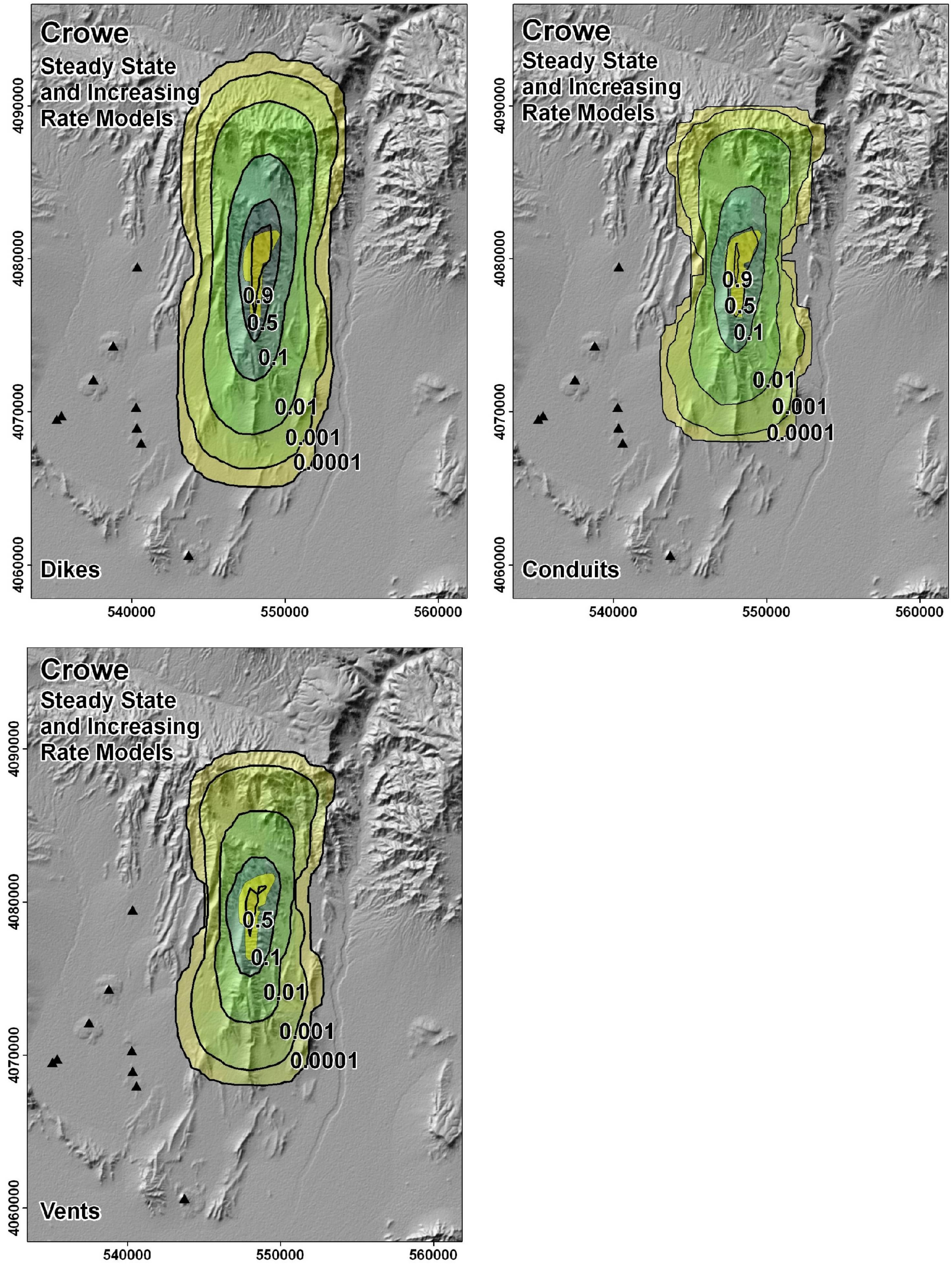
(a) Conditional probability of intersection under the steady-state and increased rate temporal models.

(b) Conditional probability of intersection under the new cycle rate model (applicable for the 1-My assessment only). Note the change in scale for this figure.

(c) Conditional probability of intersection under the background rate model.

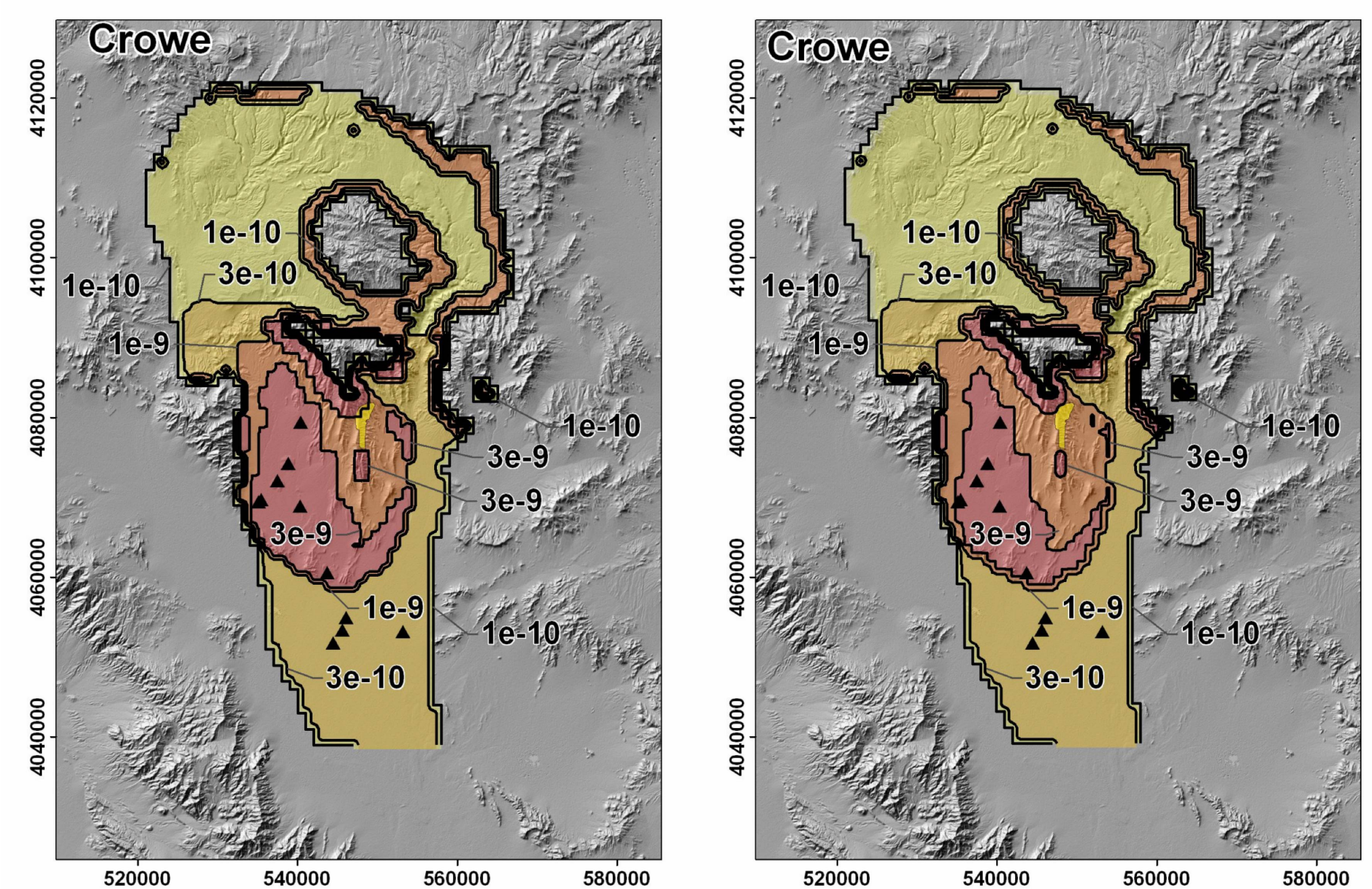
NOTE: Yellow polygon represents the repository footprint. Map grid ticks are UTM meters; map grid tick intervals are 10 km.

Figure 3.2.2-17. Conditional Probability of Intersection of Any Feature with the Repository Footprint Based on Event Descriptions Developed by Bruce Crowe



NOTE: Yellow polygon represents the repository footprint. Map grid ticks are UTM meters; map grid tick intervals are 10 km.

Figure 3.2.2-18. Conditional Probability of Intersection of Each Igneous Feature with the Repository Footprint Based on Event Descriptions Developed by Bruce Crowe



NOTE: The left figure is the mean rate density for the 10,000-year assessment, the right figure is the mean rate density for the 1-My assessment. Yellow polygon represents the repository footprint. Map grid ticks are UTM meters; map grid tick intervals are 20 km.

Figure 3.2.2-19. Mean Rate Density for the 10,000-Year Assessment and the 1-My Assessment Based on Bruce Crowe's PVHA-U Models

Table 3.2.2-1. Frequency of Number of Dikes and Conduits/Vents in Simulated Events Based on the Assessments of Bruce Crowe for the Steady-State Rate model

		Number of Conduits and Vents in an Event					
		1	2	3	4	5	6
Number of Dikes in an Event	1	7.5%	7.6%	7.4%	0.0%	0.0%	0.0%
	2	0.0%	**16.2%**	16.0%	0.0%	0.0%	0.0%
	3	0.0%	0.0%	12.4%	3.4%	3.4%	3.5%
	4	0.0%	0.0%	0.0%	6.1%	6.1%	5.9%
	5	0.0%	0.0%	0.0%	0.0%	2.4%	2.3%

3.2.3 William Hackett

Spatial and Temporal Models

Figure 3.2.3-1 presents the logic tree describing the basic structure of the spatial and temporal models developed by William Hackett (WH) for PVHA-U. WH specified several alternative characterizations of past events, and spatial and temporal models that are dependent on those alternative event sets. Table 3.2.3-1 lists the past events in the region of interest judged relevant by WH to his spatial and temporal models. Figure 3.2.3-2 illustrates the region of interest and the location of the events specified in the table. The table includes alternative interpretations of some events, along with the relative probability WH assigned to each interpretation. In combination, WH's assessments defined 3,072 unique interpretations of the number of past events in the region of interest. These are represented schematically in the first node of the logic tree: separate spatial and temporal models are fitted to each of these alternative event sets. The probability for each event set is calculated from the probabilities (weights) assigned to different interpretations as summarized in Table 3.2.3-1.

The basic spatial model used is a combination of spatial smoothing using kernel density estimation with spatial density estimates derived from various geologic data sets. Two relevant data sets were identified, lithostatic pressure and cumulative extension. These two data sets are assigned equal probability. The geology-derived models are combined, individually, with the kernel density estimate with probabilities of 1/3 to 2/3. The second and third nodes of the logic tree show this combination of spatial models.

For the kernel density estimate of conditional spatial density, WH specified a single parameterization of the kernel density estimator: a Gaussian kernel function with a bandwidth of 5 km and past events weighted by a function of the age of the event. Specifically, Quaternary, Pliocene, and Miocene events are weighted 11, 4, and 1, respectively. Because only one parameterization was specified, there are no nodes in the logic tree representing the kernel function, the bandwidth, or the event weighting.

WH provided an assessment of the likely values of lithostatic pressure at the location of a hypothetical future event in his region of interest, as illustrated in Figure 3.2.3-3. This assessment was combined with the lithostatic pressure at each point in the region of interest through the Bayesian updating approach described in Section 3.1 and Appendix E to create a conditional spatial density estimate based on lithostatic pressure. This spatial density estimate was then combined with the conditional spatial density estimate from the kernel smoothing approach with probabilities as specified.

Similarly, WH provided an assessment of the likely values of cumulative extension at the location of a hypothetical future event in his region of interest as illustrated in Figure 3.2.3-4. This assessment was combined with the cumulative extension at each point in the region of interest to create a spatial density estimate based on extension. This spatial density estimate was then combined with the conditional spatial density estimate from the kernel density estimation approach with probabilities as specified.

For each of these three spatial models, additional uncertainty exists in the spatial density resulting from fitting the kernel density estimators to the relatively small data sets. As described in Section 3.1 and Appendix E, uncertainty in the spatial density is modeled through a simulation approach known as bootstrapping. This is represented conceptually by the "Uncertainty in Spatial Density" node in the logic tree of Figure 3.2.3-1; in the actual bootstrapping analyses, more than three representations are used.

Two alternative conceptual models were specified for estimating the rate of future events: a homogenous Poisson model and a time-volume model, as illustrated in the logic tree.

The rate for the homogenous Poisson model was estimated based on the number of Quaternary events and the age of the oldest such relevant event using the approach described in Section 3.1. The mean of the estimated rate based the most likely event set from Table 3.2.3-1 is 6.4e-6 events per year in the region of interest. Uncertainty in the rate is calculated using the approach described in Section 3.1 and is represented by the 5th, 50th, and 95th percentiles of the distribution on rate, as shown in the last node in the logic tree of Figure 3.2.3-1.

To develop a rate estimate based on the time-volume model, WH specified that the cumulative volume over time should be modeled as a linear function of the log of time over the past 5 Ma. Fitting that model to the estimated volumes of events from Table 3.2.3-1 yields the following:

$$CV(t) = 3.71 + 1.55 \times \log(5 + t) \qquad \text{(Eq. 3.2.3-1)}$$

Where t is the time at which cumulative volume (CV) is to be predicted and is given in My from the present time. For example, CV(−3.8) is the estimated cumulative volume 3.8 Ma before the present (and equals 4 km^3); CV(1) is the estimated cumulative volume 1 My from the present. The 90% confidence interval on the slope of the regression line is used to define the 5th and 95th percentiles of the uncertainty on the slope.

WH specified that the average volume per event for future events should be estimated based on the mean and variance of the volume of Quaternary events. To incorporate uncertainty in the volume per event for future events, volume per event is modeled with a lognormal distribution with mean and variance matching the mean and variance of the volume of Quaternary events, and the 5th, 50th, and 95th percentiles of that distribution are used in the logic tree. The estimated volume per event differs for different event sets.

Figure 3.2.3-5 illustrates uncertainty in the estimated rate based only on the event set identified as most likely in Table 3.2.3-1. Each bar represents the 5th to 95th percentiles of the distribution on rate for the various rate models used by WH.

Mean Rate Density and Mean Recurrence Rate

Figure 3.2.3-6 illustrates the mean rate density for igneous events calculated from WH's spatial and temporal models for the 10,000-year assessment. Differences between the 10,000-year and 1-My assessments are discussed below. The effect of the kernel density estimation model with age-weighting of events can be seen in the general shape of contours and the higher rate density surrounding the younger events in Crater Flat and the Sleeping Buttes/Thirsty Mesa events northwest of the Timber Mountain caldera. The less regular contours on the eastern half of the region of interest show the effect of the consideration of lithostatic pressure data. The effect of consideration of the cumulative extension data is difficult to discern in the figure, in part because the extension data covers only a portion of the region of interest, and that portion corresponds to where the density of past events is highest, so that the kernel density estimate in that area would tend to dominate the effect of the extension-based results.

A mean recurrence rate for events in the region of interest can be calculated by summing the mean rate density at each grid point. Based on the mean rate density shown in Figure 3.2.3-6, the mean recurrence rate for events in this region is 1.4e-5 events per year, giving recurrence intervals between 3700 and 214,000 years (5th to 95th percentile of the distribution on recurrence interval), and a mean recurrence interval of about 71,000 years for events in the region illustrated.

Event Simulation Model

Figure 3.2.3-7 illustrates the key features of an event simulator for WH's PVHA-U model in an influence diagram. In this model an *event* is characterized by a combination of dikes, conduits, and sills: the number, locations, and dimensions of each of these features define the event.

The total length of dikes in an event ranges from about 0.2 km to a maximum of 13 km, following the distribution shown in Figure 3.2.3-8. The number of dikes depends in part on the total dike length: Figure 3.2.3-9 illustrates the number of dikes in simulated events based on the assessments provided by WH for total dike length and the number of dikes as a function of total dike length. When multiple dikes exist in the event, the total length of dikes is divided among the dikes such that equal-length dikes are the most likely outcome, but it is possible for one dike to be as much as three times longer than another in the same event. When multiple dikes exist, they are arranged en echelon, and are allowed to overlap or underlap at the dike tips by as much as 25% of the length of the shorter dike. Right-stepping en echelon arrangements are more likely than left-stepping (80% versus 20%). Dike azimuth is described by the distribution in Figure 3.2.3-10. The total width of the dike system in the direction perpendicular to dike azimuth is defined as a function of the total dike length. Figure 3.2.3-11 illustrates the total dike system width for 30,000 simulations based on the assessments provided by WH for total dike length and the ratio of length to width of a dike system.

Figure 3.2.3-12 illustrates the assessment of the number of conduits in an event. If a single conduit exists, its location along the dike system is defined by a triangular distribution with a mode at the midpoint of the dike system. If multiple conduits exist, each must be separated from any other conduit by at least the same distance as the spacing between dikes. Figure 3.2.3-13 illustrates the distribution on conduit diameter. The probability that an event would include a column-producing conduit is 0.8.

A sill can occur only in events that do not have conduits (about 10% of the events described above do not have conduits). Given that such an event occurs, the probability of a sill forming ranges from 0.001 to 0.01. Based on simulation results, the probability that an event would include a sill is about 6e-4. If a sill occurs in an event, it is semi-circular in shape and is located along a dike following a triangular distribution with a mode at the mid-point of the dike system.

The diameter of the sill ranges from 100 m to 1,000 m with a most likely value of 300 m (defined by a triangular distribution).

Figure 3.2.3-14 illustrates two examples of simulated events, and Table 3.2.3-2 describes the number of dikes and the number of conduits and vents (combined) in an event, and how frequently such events occur in the event simulation. The table indicates, for example, that them most common type of event consists of a single conduit or vent and a single dike – 42.5% of simulated events (shown in bold in the table) are of this type, and an example is shown in the top of Figure 3.2.3-14. The bottom half of the figure shows a less common type of event, with two conduits or vents and three dikes. The least common type of event simulated (0.01% of simulated events) consists of 3 conduits or vents and 5 dikes. Note that events may also include sills, which are not represented in this table.

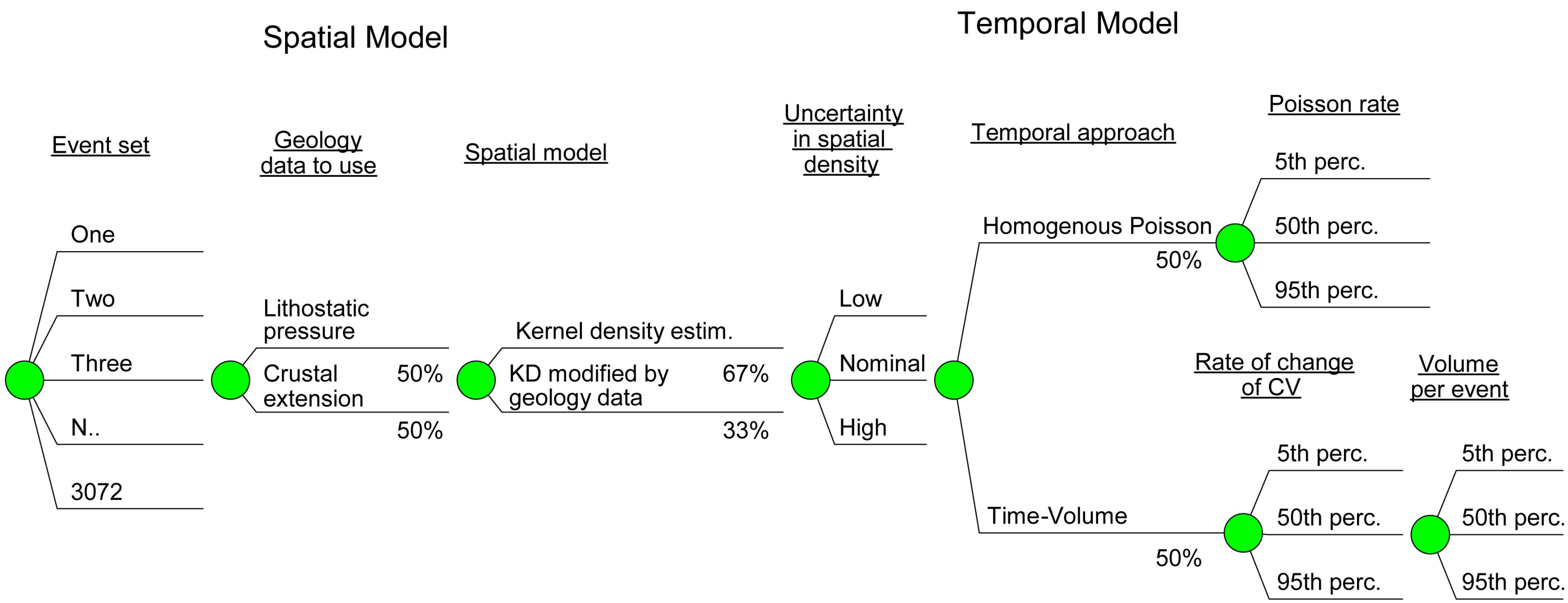
Conditional Probability of Intersection

Figure 3.2.3-15 illustrates the conditional probability of the intersection of any igneous feature with the repository footprint based on WH's event descriptions. The slightly northeast direction of the contours results from the preference for right-stepping en echelon dike systems; the predominant NS orientation of the contours results for the highly-weighted N5W azimuth, although some effect of the N25E azimuth can also be discerned.

As described above, WH's events include at least one dike, and may include column-producing conduit(s), vents, and sills. Figure 3.2.3-16 shows the conditional probability of intersection for each of these types of igneous features. These maps reflect the same spatial distribution of features as the intersection of any feature, indicating that no particular clustering of features within an event occurs. The conditional probability of intersection for conduits and vents is lower than for dikes for an event at any given location due to their smaller size and their distribution along a dike. Sills occur rarely, as reflected in the low probability contour.

Differences Between the 10,000-year and 1-My Assessments

Although no structural differences exist in WH's spatial model or event assessments based on the different time periods of assessment, the use of the time-volume temporal model described above results in a rate estimate that varies over time. The rate decreases slightly over time, and that slight change in rate can be seen by careful examination of the mean rate density maps for the 10,000-year and 1-My assessments shown Figure 3.2.3-17. Note in particular the change in the size of the of the region encompassed by the 1e-8 contour and the absence of a 1e-9 contour in the middle-right of the figure near in the Jackass Flats events.



NOTES: All probabilities shown on the branches are those assigned by the expert. Uncertainty in spatial density, uncertainty in the Poisson rate and uncertainties in the rate of change of cumulative volume (CV) and the volume per event are modeled based on the approaches described in Section 3.1.5, and the probabilities for those branches are defined by the modeling approach.

A single parameterization of the kernel density (KD) estimation approach was specified for spatial density, so no uncertainties relative to those parameters appear in the logic tree.

Figure 3.2.3-1. Logic Tree Representing the Spatial and Temporal Components of the PVHA-U Model Specified by William Hackett

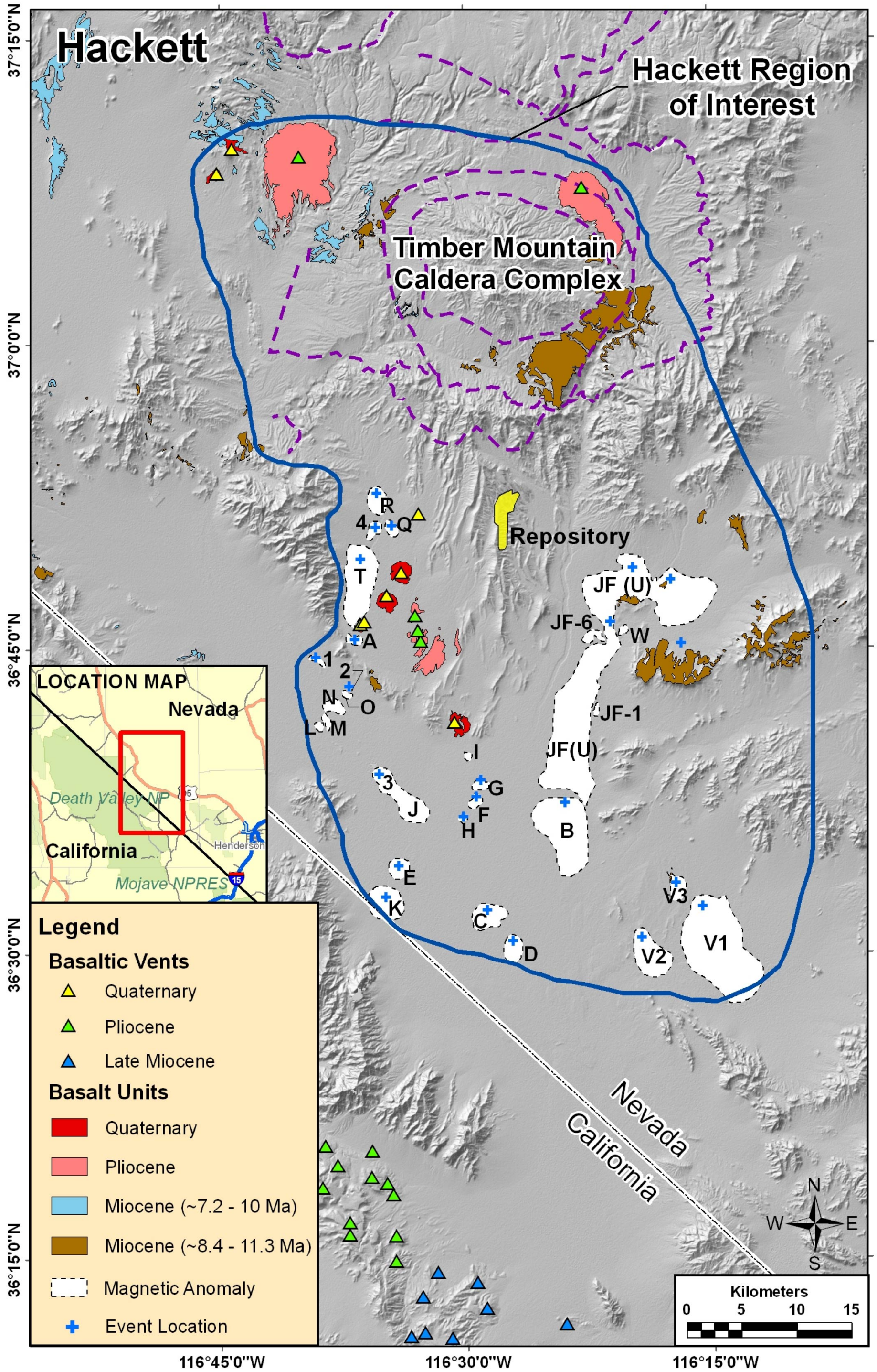
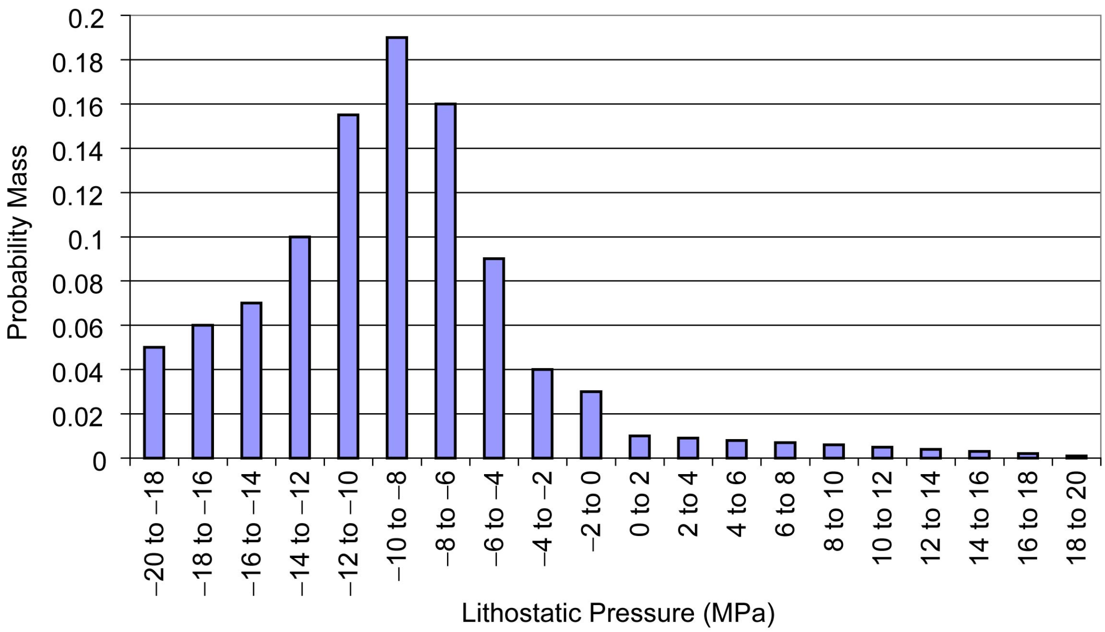
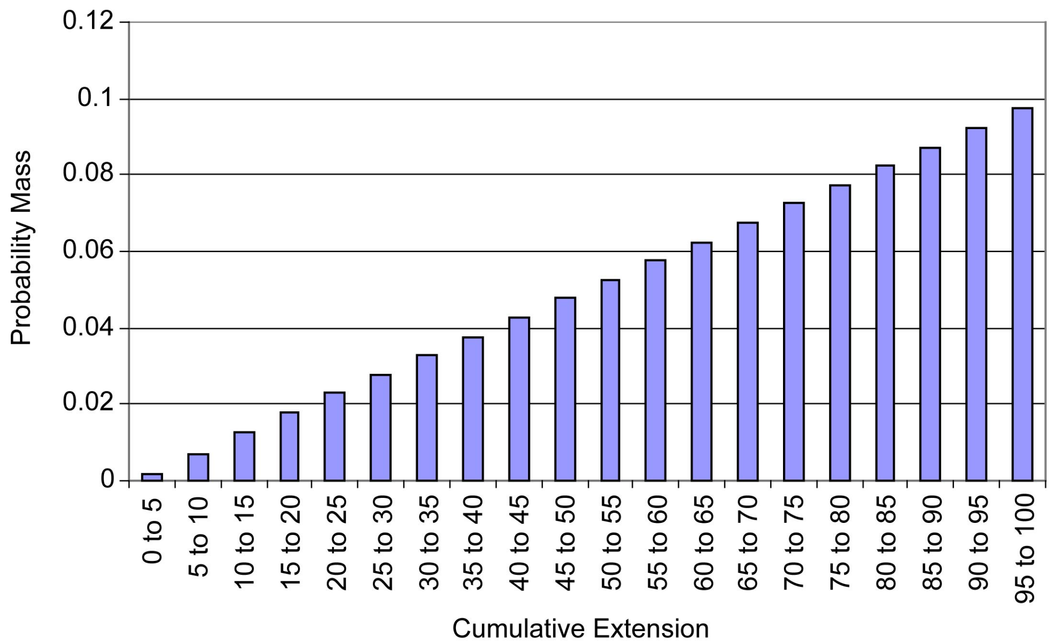


Figure 3.2.3-2. Region of Interest and Locations of Relevant Past Events as Specified by William Hackett



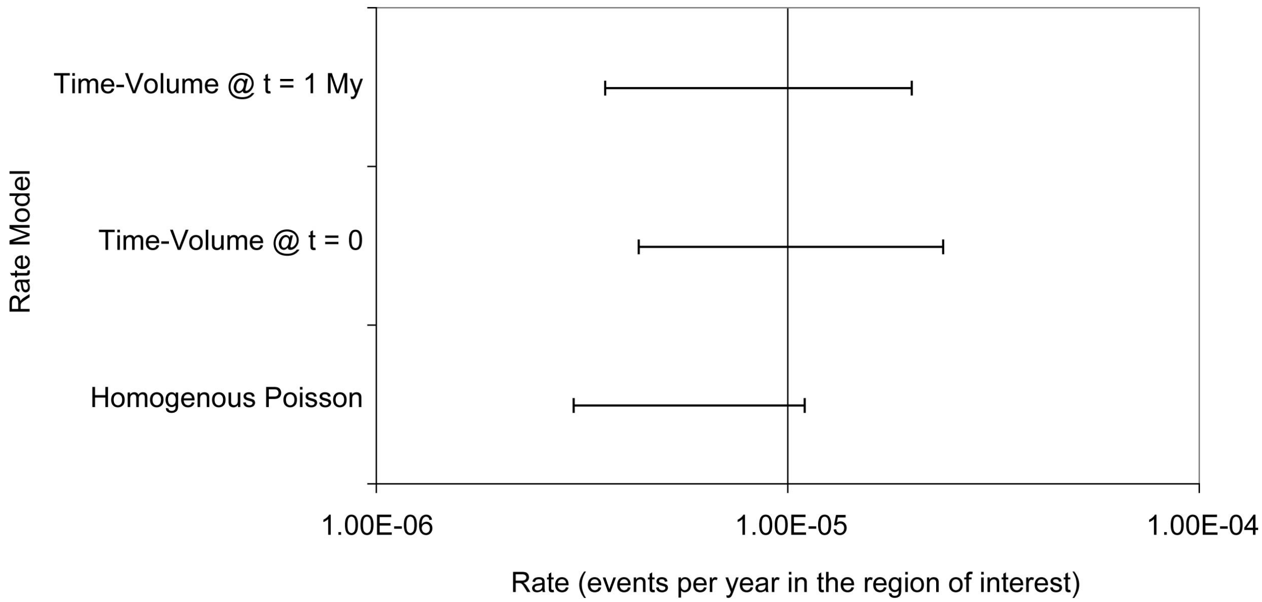
NOTE: Lithostatic pressure in the YMR is one of the data sets provided to the panel and listed in Appendix B. Lithostatic pressure values were calculated from free-air gravity and reflect gravity (mass) excesses (represented as positive lithostatic pressure values) and deficiencies (represented as negative values) relative to a theoretical gravity value at sea level.

Figure 3.2.3-3. Assessment of Probability of Lithostatic Pressure Values at the Location of a Hypothetical Future Event in the Region of Interest, as Specified by William Hackett



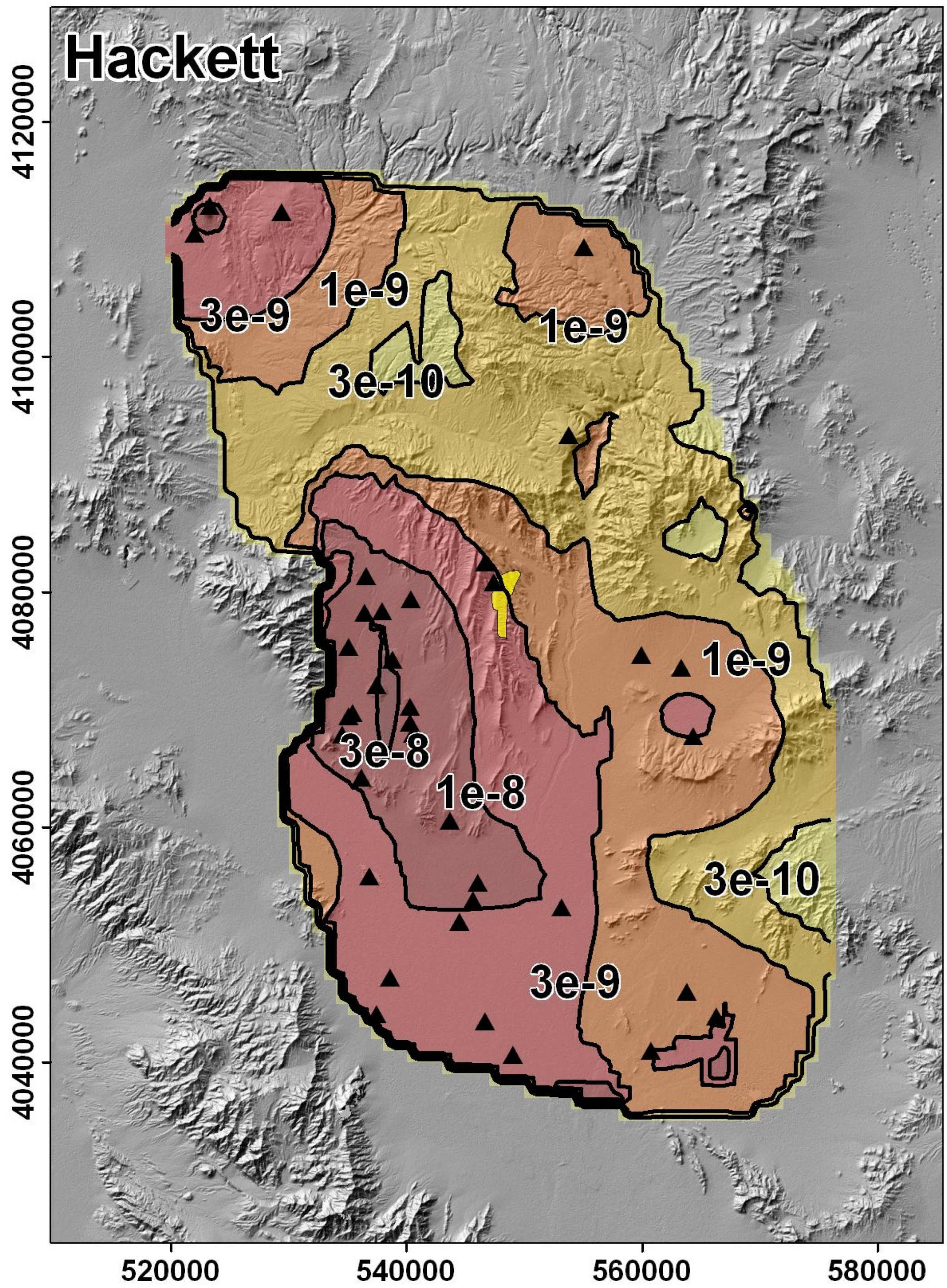
NOTE: Data on cumulative extension is one of the data sets provided to the panel and listed in Appendix B. The values shown on the x-axis are percent extension.

Figure 3.2.3-4. Assessment of Cumulative Crustal Extension at the Location of a Hypothetical Future Event in the Region of Interest, as Specified by William Hackett



NOTES: Bars represent the 5th to 95th percentile of the uncertainty in the rate for each alternative rate model, for estimates based on the most likely event set identified in Table 3.2.3-1. The time-volume rate estimate is time dependent: the distribution at two different future points in time is shown.

Figure 3.2.3-5. Example of Uncertainty in Estimated Rate Based on a Single Interpretation of Past Events for Alternative Temporal Models Specified by William Hackett



NOTE: Contours show the mean rate density in events per year per km^2. Yellow polygon represents the repository footprint; black triangles represent the location of past events (the event set identified as the most likely interpretation of past events by the expert). Map grid ticks are UTM meters; tick intervals are 20 km.

Figure 3.2.3-6. Mean Rate Density for the 10,000-Year Assessment Based on Models Specified by William Hackett

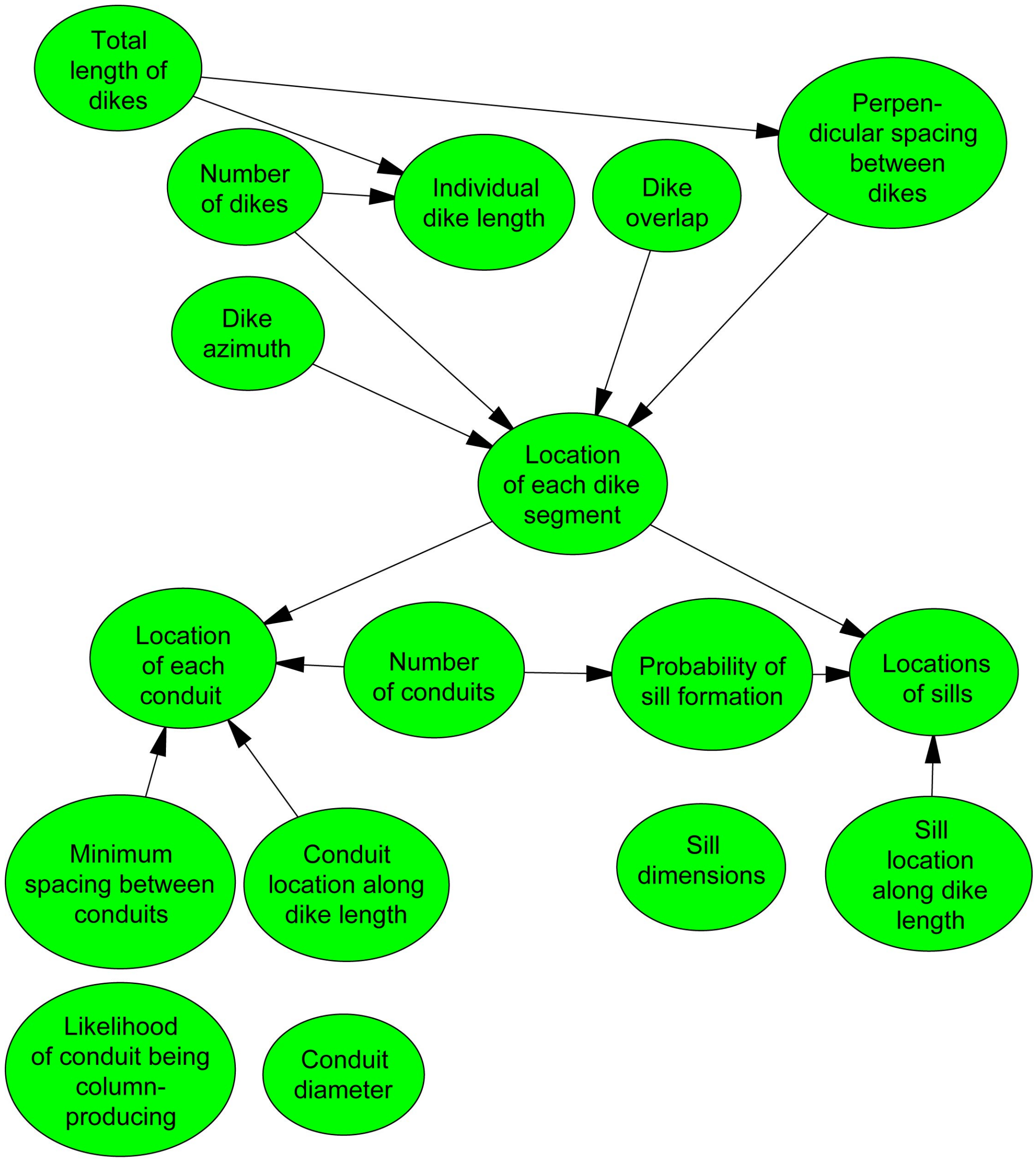
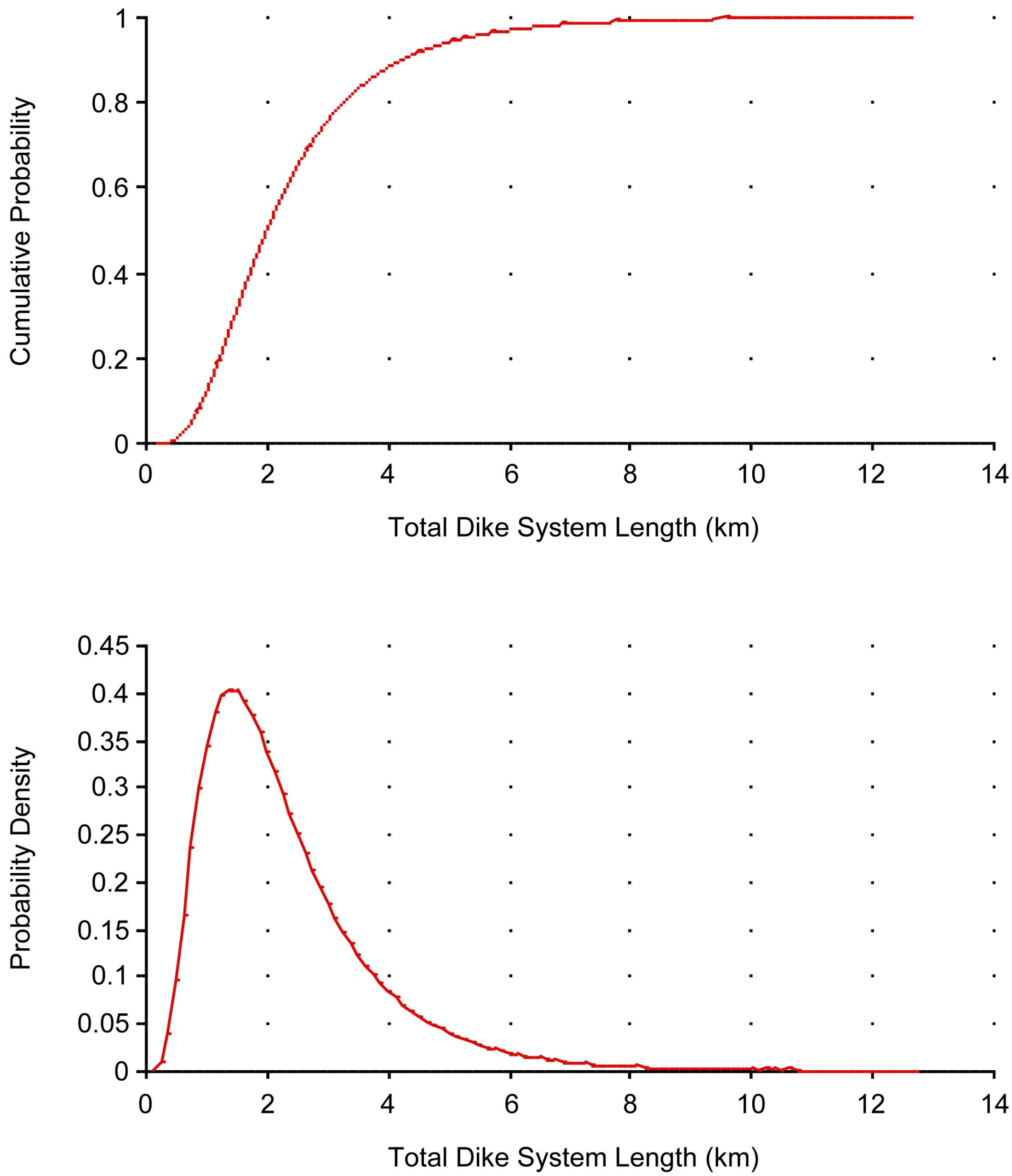
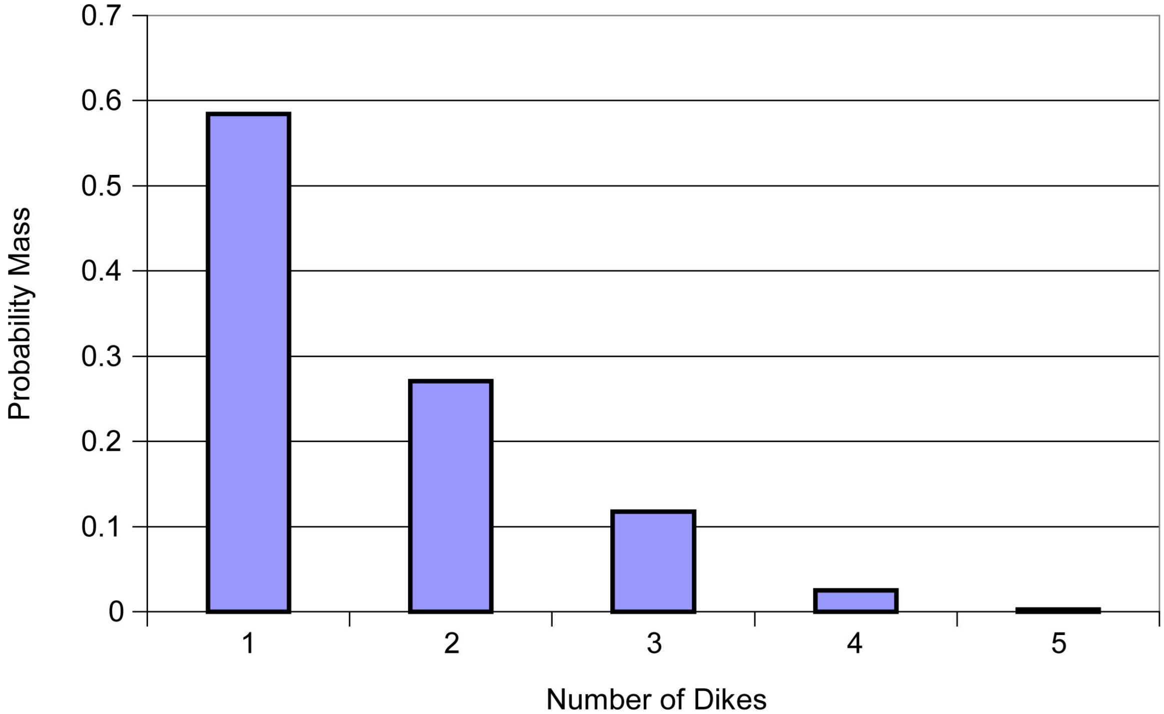


Figure 3.2.3-7. Components of an Event Simulator Based on the Characteristics of Future Events Described by William Hackett



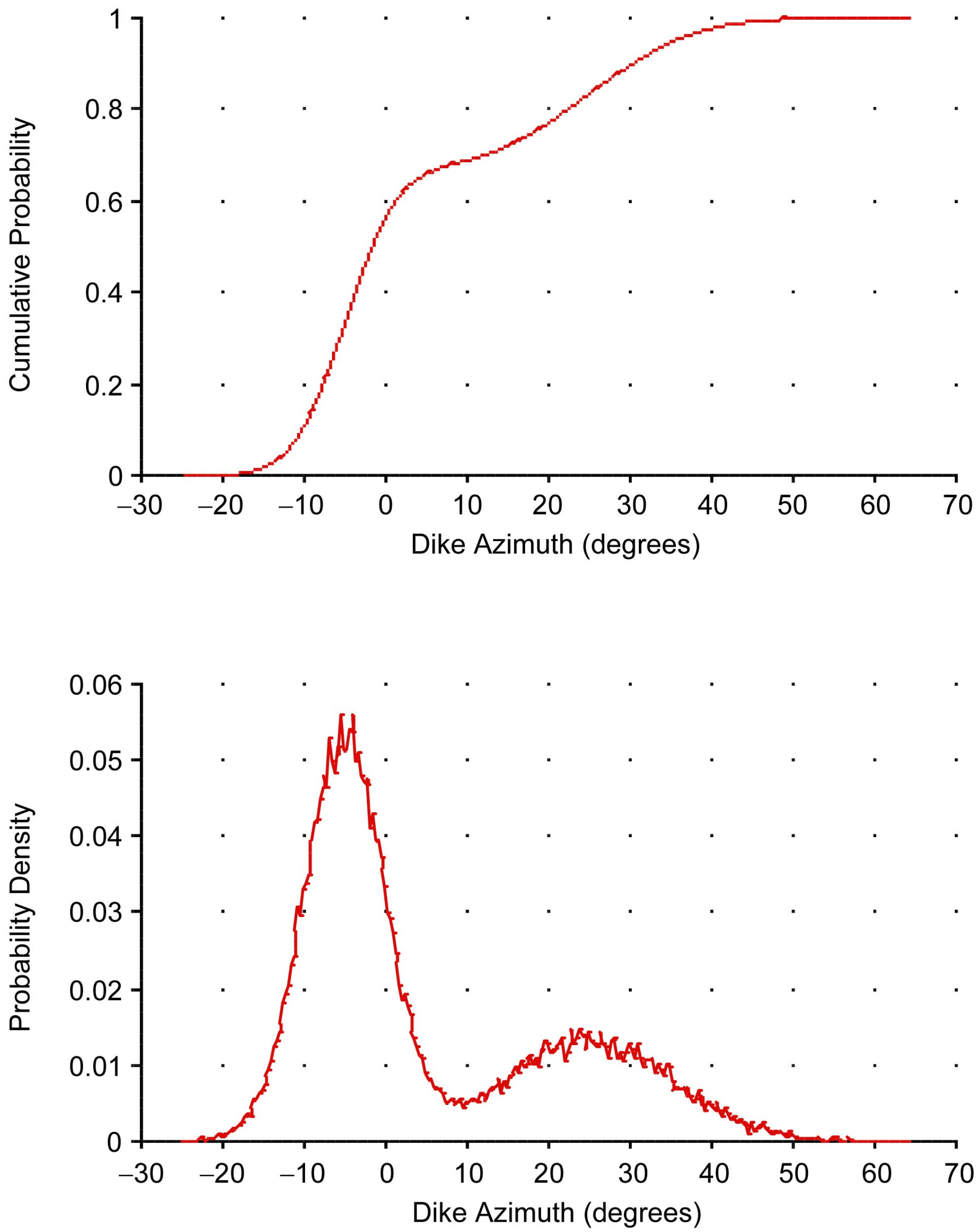
NOTE: Top graph is a cumulative distribution function; bottom graph is a probability density function.

Figure 3.2.3-8. Distribution for the Total Length of Dikes in an Event as Assessed by William Hackett



NOTE: Number of dikes is simulated based on the assessments of the total dike length and the number of dikes associated with various total dike lengths. This graph is based on 30,000 simulations. The probability of 5 dikes in an event is less than 0.3%.

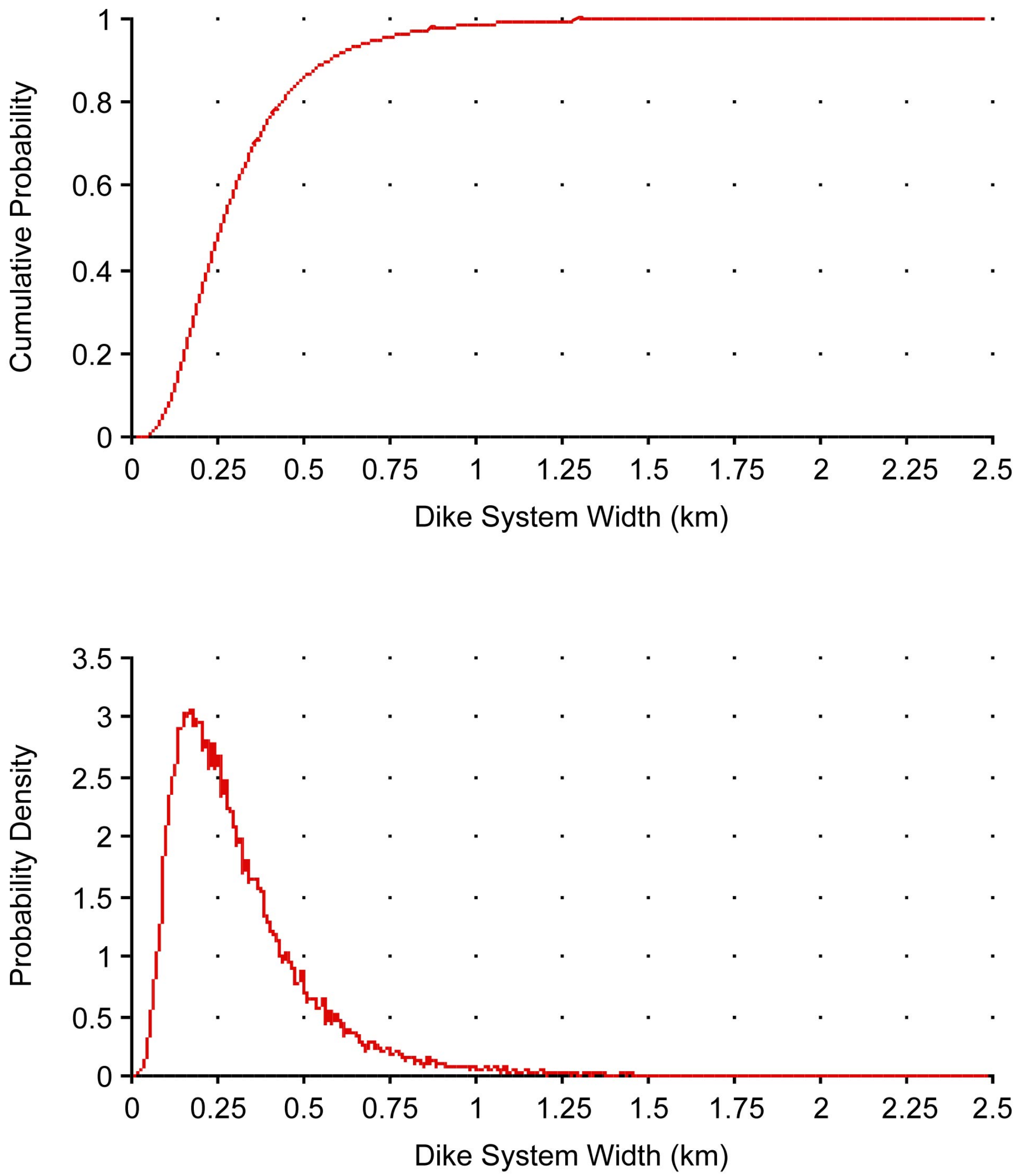
Figure 3.2.3-9. Distribution of the Number of Dikes in an Event, Based on Assessments of William Hackett



NOTES: Top graph is a cumulative distribution function; bottom graph is a probability density function. Results of simulation from a mixture of two normal distributions.

Azimuth of zero represents North.

Figure 3.2.3-10. Distribution for Dike Azimuth Based on Assessments of William Hackett



NOTES: Top graph is a cumulative distribution function; bottom graph is a probability density function.

Dike system width is simulated based on the assessments of the total dike length and the length-to-width ratio of a dike system. This graph is based on 30,000 simulations.

Figure 3.2.3-11. Distribution for the Width of a Dike System, Based on Assessments of William Hackett

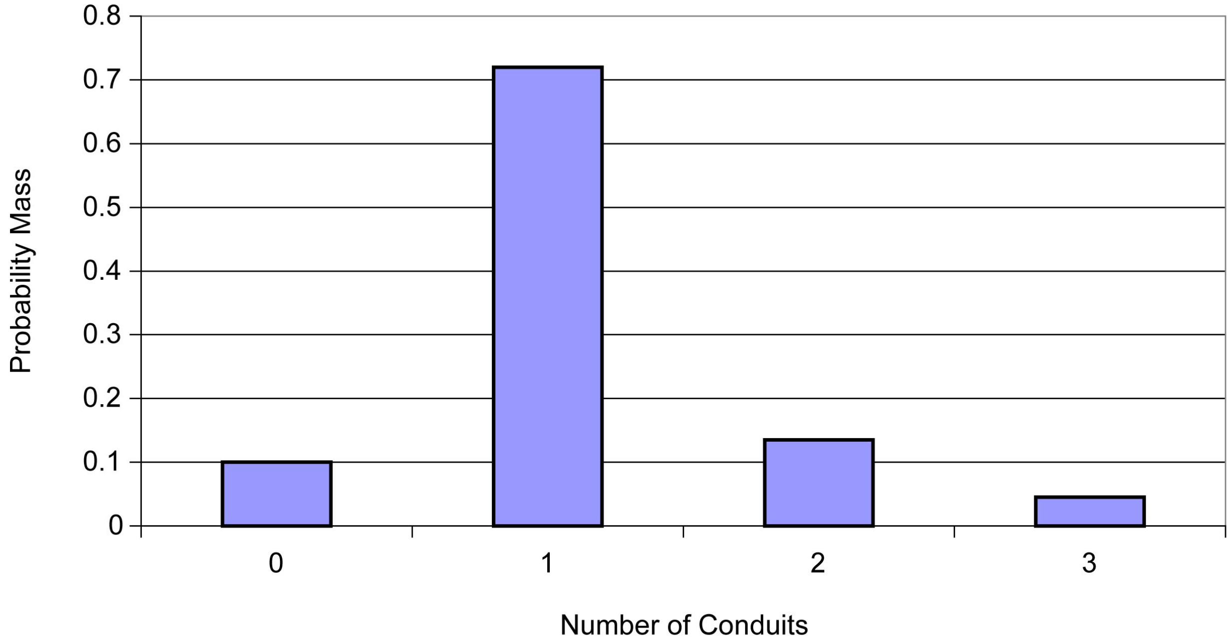
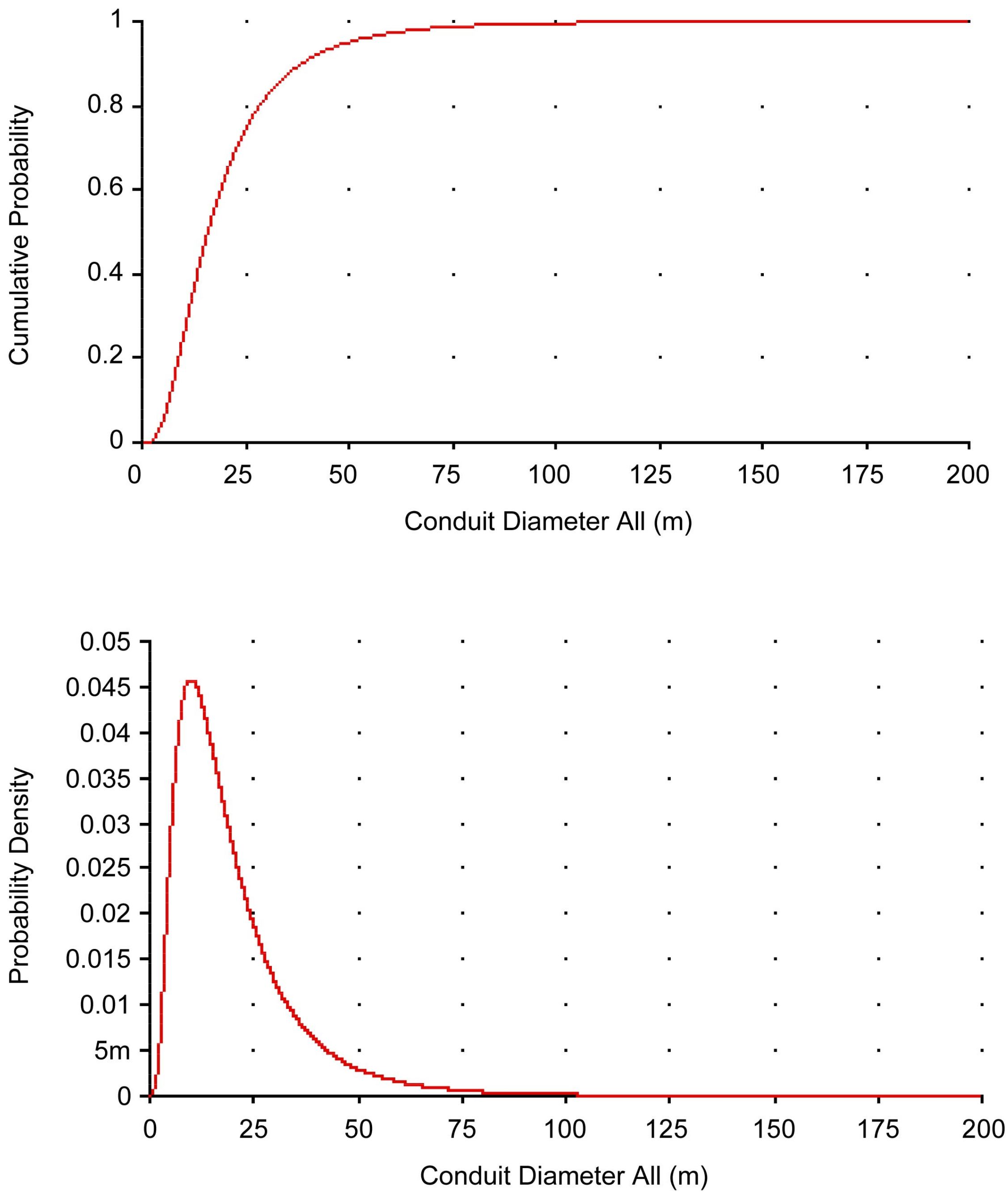
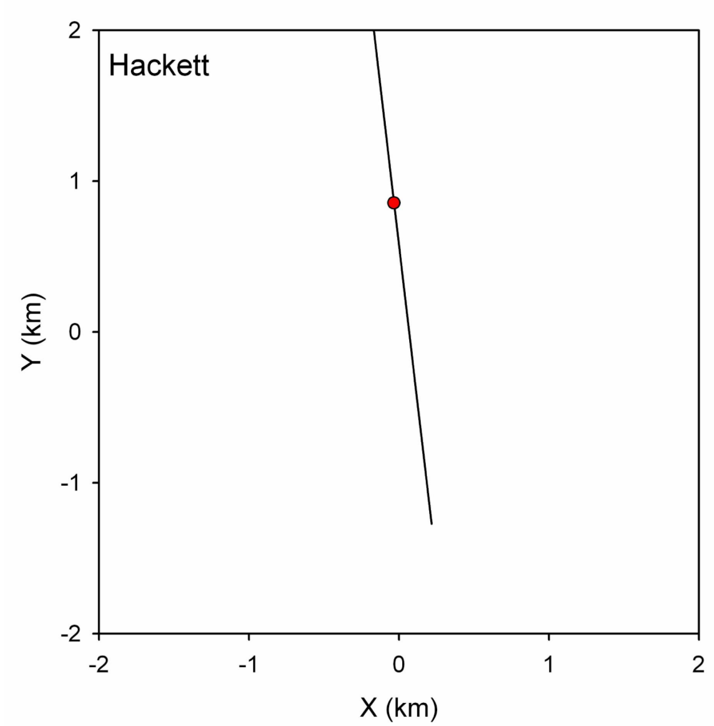


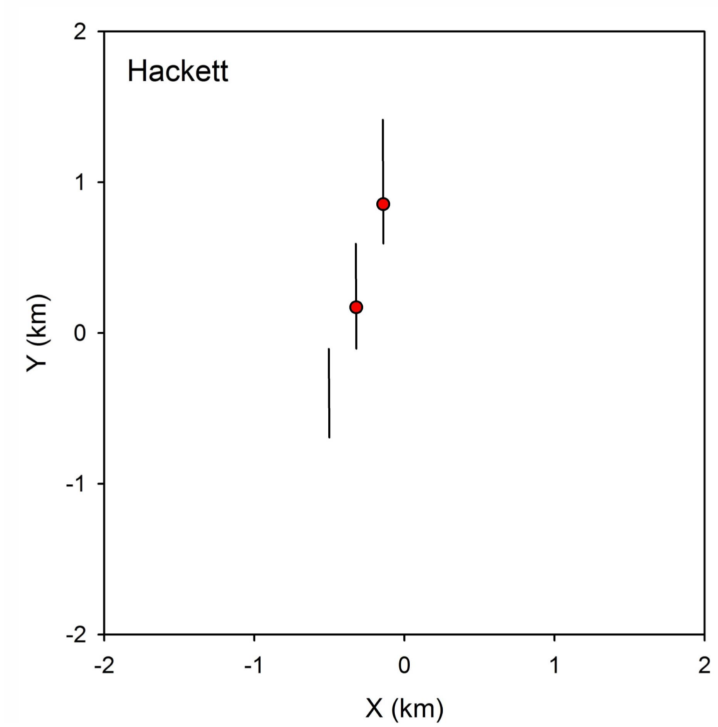
Figure 3.2.3-12. Distribution of the Number of Conduits in an Event as Assessed by William Hackett



NOTE: Top graph is a cumulative distribution function; bottom graph is a probability density function. For values less than 0.01 on the y-axis, suffix notation is used (m = 10^{-3},so 5m = 0.005).

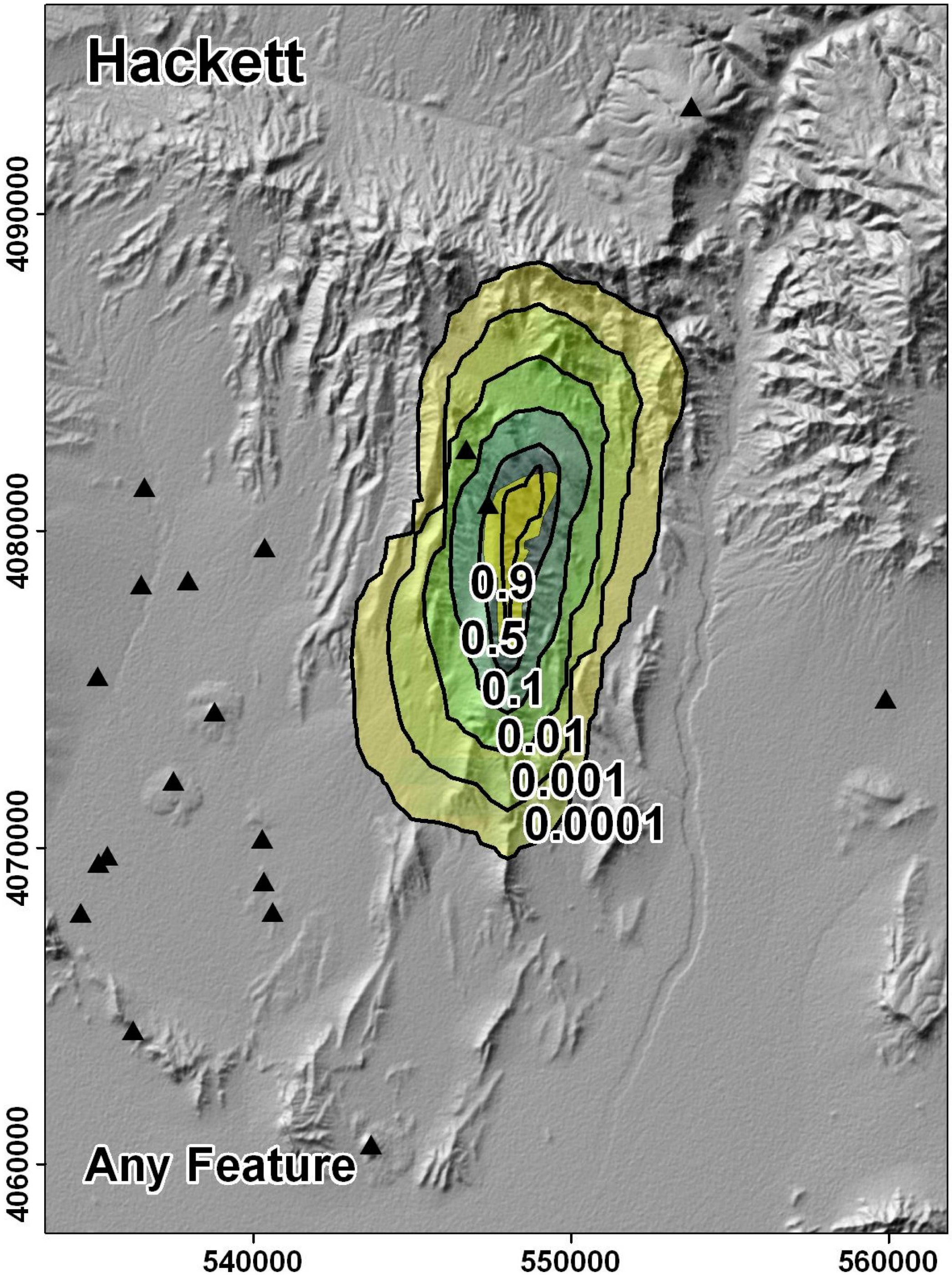
Figure 3.2.3-13. Distribution for Conduit Diameter as Assessed by William Hackett





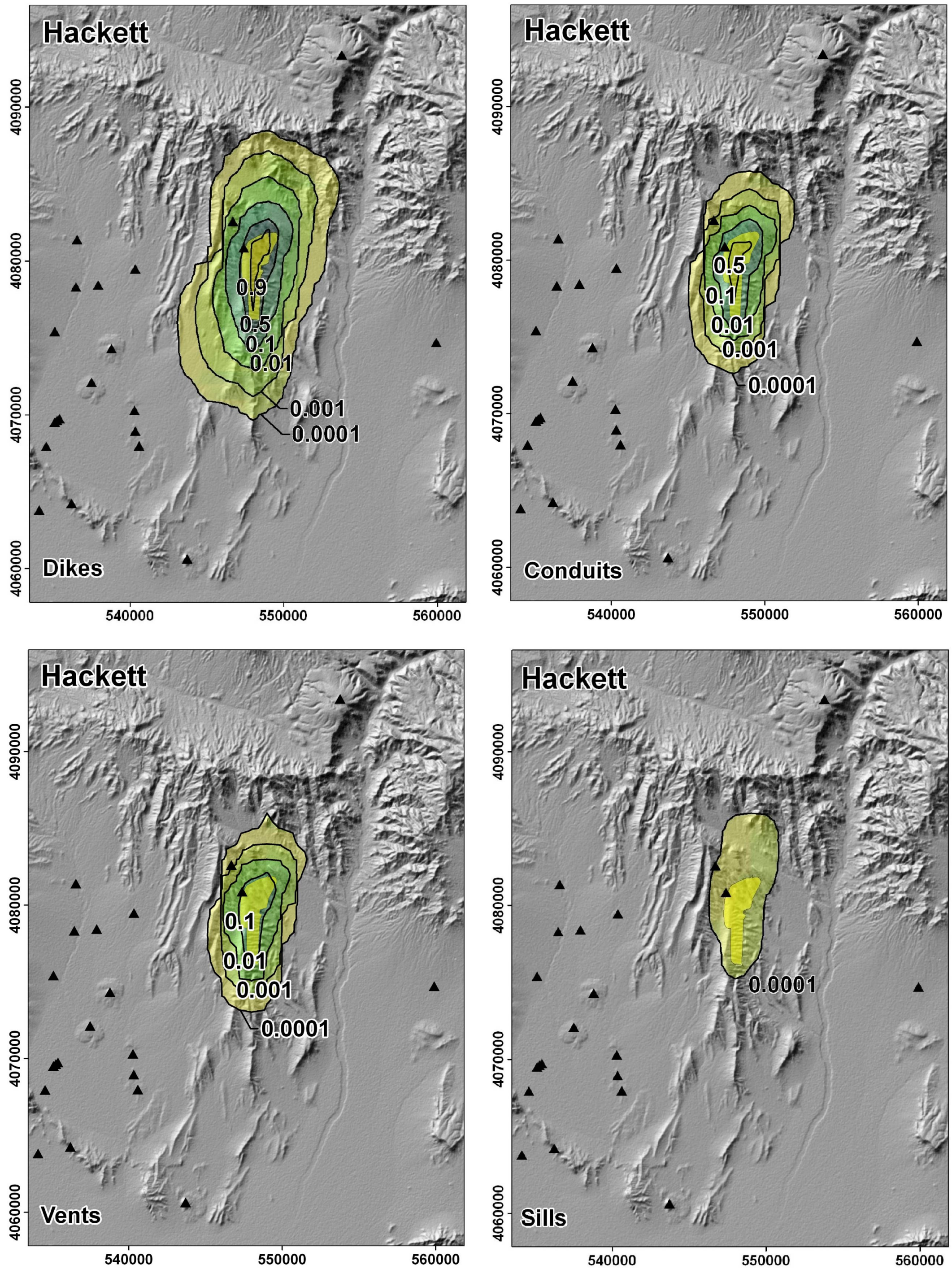
NOTE: Dikes are represented as black lines; their lengths on the figure are the lengths of the simulated dike. Conduits and vents are represented as small red circles; conduits and vents are differentiated from each other, and their diameters are not represented. Sills, if they exist, are represented by light yellow ovals or polygons.

Figure 3.2.3-14. Examples of Simulated Events from the PVHA-U Model for William Hackett



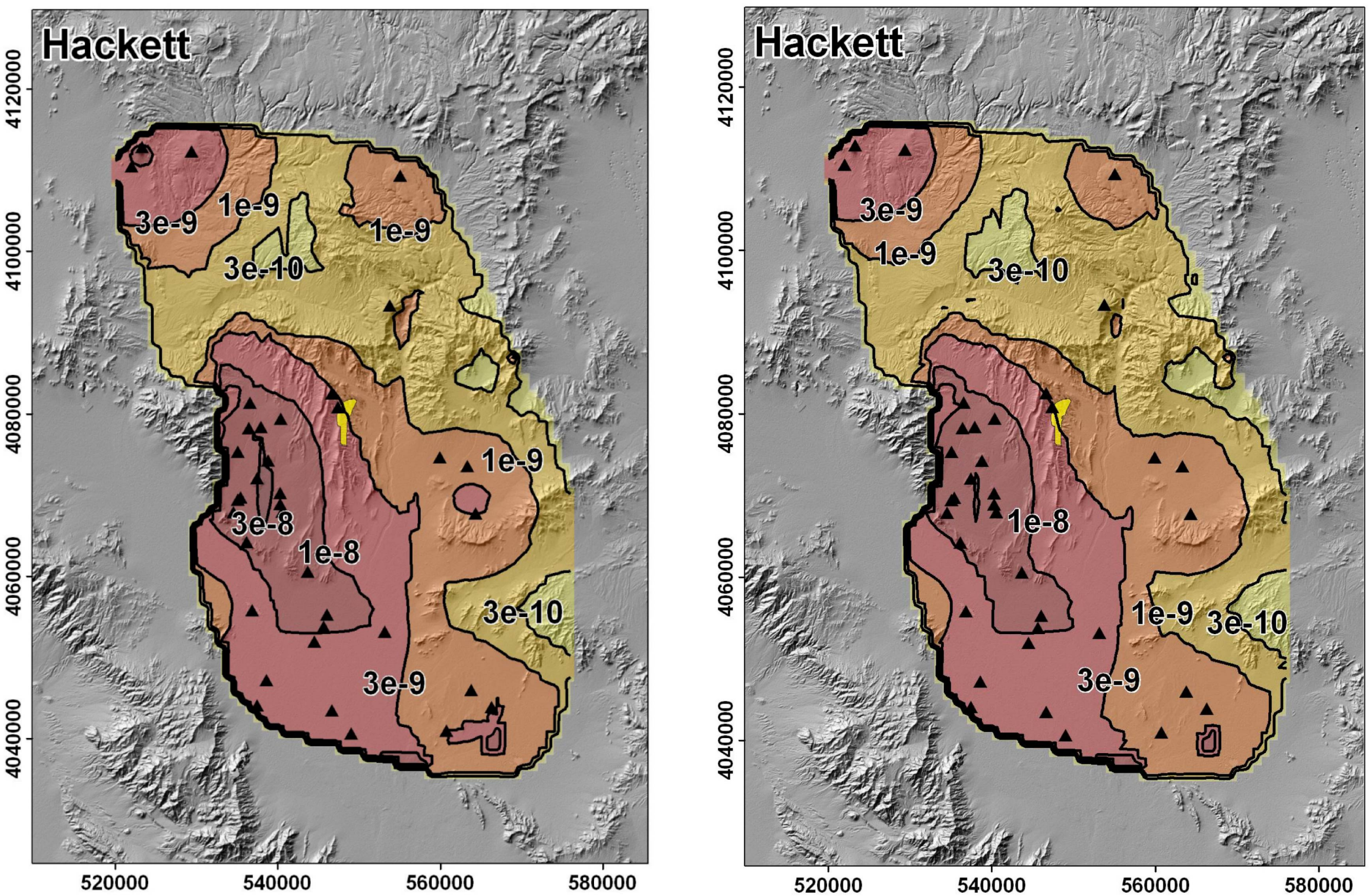
NOTES: Yellow polygon represents the repository footprint. Black triangles represent past events for WH's most likely event set. Map tick intervals are UTM meters; tick intervals are 10 km.

Figure 3.2.3-15. Conditional Probability of Intersection of Any Feature with the Repository Footprint Based on Event Descriptions Developed by William Hackett



NOTES: Yellow polygon represents the repository footprint. Black triangles represent past events for WH's most likely event set. Map tick intervals are UTM meters; tick intervals are 10 km.

Figure 3.2.3-16. Conditional Probability of Intersection of Each Igneous Feature with the Repository Footprint Based on Event Descriptions Developed by William Hackett



NOTE: The left figure is the mean rate density for the 10,000-year assessment, the right figure is the mean rate density for the 1-My assessment. Yellow polygon represents the repository footprint. Map tick intervals are UTM meters; tick intervals are 20 km.

Figure 3.2.3-17. Mean Rate Density for the 10,000-Year Assessment and the 1-My Assessment Based on William Hackett's PVHA-U Models

Table 3.2.3-1. Data Used to Define Spatial Distribution and Event Rates for Future Volcanic Events for William Hackett's PVHA-U Model

Center	Number of Events	Age (Ma)	Volume (km^3)
Lathrop Wells	1	0.08	0.05
Hidden Cone	1	0.35	0.03
Little Black Peak	1	0.35	0.01
Little Cones NE	1 (weight = 0.3)	1.1	0.014
Little Cones SW	2 (weight = 0.7)	1.1	0.012
Makani Cone	1	1.1	0.002
Black Cone	1	1.1	0.06
Red Cone	1	1.1	0.06
Buckboard Mesa	1	2.9	0.84
SE Crater Flat (North Vent, Middle Vent, and South Vent)	3	3.8	0.6 total
Anomaly F	1	3.9	0.03
Anomaly G	1	3.9	0.03
Anomaly H	1	3.9	0.006
Anomaly B	1	3.85	1.28
Thirsty Mountain	1	4.6	2.63
Anomaly C	1	4.8	0.12
Anomaly D	1	4.8	0.07
Borehole V1	1	9.6	0.7
Borehole V2	1	9.6	0.2
Borehole V3	1	9.6	0.1
Jackass Flats	1 (weight = 0.5) 2 (weight = 0.5)	9.5	4.1
Anomaly A	1	10.0	0.06
Dome Mountain	1 (weight = 0.7) 2 (weight = 0.2) 3 (weight = 0.1)	10.0	10
Little Skull Mountain	3 (weight = 0.3) 6 (weight = 0.7)	11.3	2.2
Solitario Canyon Dikes	1 (weight = 0.5) 2 (weight = 0.5)	10.0 (weight = 0.5) or 11.7 (weight = 0.5)	0.001
Anomaly E	1	11.1	0.01
Anomaly 1	0 (weight = 0.8) 1 (weight = 0.2)	11.1	0.001

Table 3.2.3-1. Data Used to Define Spatial Distribution and Event Rates for Future Volcanic Events for William Hackett's PVHA-U Model (Continued)

Center	Number of Events	Age (Ma)	Volume (km^3)
Anomaly 2	0 (weight = 0.8) 1 (weight = 0.2)	11.1	0.001
Anomaly 3 and Anomaly J	0 (weight = 0.5) 1 (weight = 0.5)	11.1	0.2
Anomaly K	0 (weight = 0.4) 1 (weight = 0.6)	11.1	0.2
Western Crater Flat (Anomalies R, Q, 4, T, and T Outcrops)	2, 3, 4, or 5 assigned equal weights	11.2	2.3

NOTE: Table derived from WH's Elicitation Summary in Appendix D.

Table 3.2.3-2. Frequency of the Number of Dikes and Conduits or Vents in Simulated Events Based the Assessments of William Hackett

		Number of Conduits and Vents in an Event			
		0	1	2	3
Number of Dikes in an Event	1	5.9%	**42.5%**	8.0%	2.6%
	2	2.6%	19.1%	3.6%	1.2%
	3	1.2%	8.3%	1.5%	0.5%
	4	0.3%	1.9%	0.3%	0.1%
	5	0.02%	0.2%	0.04%	0.01%