BIOGRAPHIES
MEMBERS OF THE EXPERT PANEL
PROBABILISTIC VOLCANIC HAZARD ANALYSIS PROJECT

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

APPENDIX B

REFERENCES
DISTRIBUTED TO EXPERT PANEL MEMBERS

REFERENCES
DISTRIBUTED TO EXPERT PANEL MEMBERS
PROBABILISTIC VOLCANIC HAZARD ANALYSIS PROJECT

Bogue, S.W., and Coe, R.S., 1981, Paleomagnetic correlation of Columbia River basalt flows using secular variation: Journal of Geophysical Research, v. 86, no. B12, p. 11,883-11,897.

Byers, F.M., Jr., Carr, W.J., and Orkild, P.P., 1989, Volcanic centers of southwestern Nevada: Evolution of understanding, 1960-1988: Journal of Geophysical Research, v. 94, no. B5, p. 5908-5924.

Carr, W.J., 1990, Styles of extension in the Nevada Test Site region, southern Walker Lane Belt; an integration of volcano-tectonic and detachment fault models, *in* B.P. Wernicke (ed.), Basin and Range Extensional Tectonics near the Latitude of Las Vegas, Nevada: Geological Society of America Memoir 176, p. 283-303.

Carr, M.D., and Yount, J.C. (eds.), 1988, Geologic and hydrologic investigations of a potential nuclear waste disposal site at Yucca Mountain, southern Nevada: U.S. Geological Survey Bulletin 1790, 152 p.

Christiansen, R.L., and Yeats, R.S., 1992, Post-Laramide geology of the U.S. Cordilleran region, *in* Burchfiel, B.C., Lipman, P.W., and Zoback, M.L., (eds.), the Cordilleran Orogen: Conterminous U.S.: Boulder, Colorado, Geological Society of America, The Geology of North America, v. G-3, p. 261-406.

Connor, C.B., and Hill, B.E., 1994, Strategy for the evaluation and use of probability models for volcanic disruptive scenarios: prepared for the Nuclear Regulatory Commission by the Center for Nuclear Waste Regulatory Analyses, San Antonio, Texas (CNWRA 94-015).

Connor, C.B., and Hill, B.E., 1994, Estimating the probability of volcanic disruption of the candidate Yucca Mountain Repository using spatially and temporally nonhomogeneous Poisson models: American Nuclear Society Focus '93.

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

Connor, C.B., and Sanders, C.O., 1994, Geophysics review topical report: application of seismic tomographic and magnetic methods to issues in basaltic volcanism: prepared for the Nuclear Regulatory Commission by the Center for Nuelear Wast Regulatory Analyses, San Antonio, Texas (CNWRA 94-013).

Cornwall, H.R., 1972, Geology and mineral deposits of southern Nye Coutny, Nevada: Nevada Bureau of Mines and Geology Bulletin 77, scale 1:250,000.

Crowe, B.M., Harrington, C., McFadden, L., Perry, F., Wells, S., Turrin, B., and Champion, D., 1988, Preliminary geologic map of the Lathrop Wells volcanic center: Los Alamos National Laboratory Report LA-UR-88-4155, 7 p.

Crowe, B.M., Morely, R., Wells, S., Geissman, J., McDonald, E., McFadden, L., Perry, F., Murrell, M., Poths, J., and Forman, S., 1992, The Lathrop Wells volcanic center: Status of field and geochronology studies: Proceedings, Third International Conference, High Level Radioactive Waste Management, Las Vegas, Nevada, April 12-16, v. 2, p. 1997-2013.

Crowe, B.M., and Perry, F.V., 1989, Volcanic probability calculations for the Yucca Mountain site; Estimation of volcanic rates: Proceedings, Nuclear Waste Isolation in the Unsaturated Zone, Focus '89, American Nuclear Society, p. 326-334.

Crowe, B.M., and Perry, F.V., 1991, Preliminary map of the Sleeping Butte volcanic centers: Los Alamos National Laboratory Report LA-12101-MS, 11 p.

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

Crowe, B.M., Perry, F.V., Valentine, G.A., Wallmann, P.C., and Kossik, R., 1994, Simulation modeling of the probability of magmatic disruption of the potential repository Yucca Mountain site: Focus '93 Symposium Volume, American Nuclear Society.

Crowe, B.M., Picard, M., Valentine, G., and Perry, F.V., 1992, Recurrence models of volcanic events; applications to volcanic risk assessment: Proceedings, Third International Conference, High Level Radioactive Waste Management, Las Vegas, Nevada, April 12-16, v. 2, p. 2344-2355.

Crowe, B.M., Turrin, B., Wells, S., Perry, F., McFadden, L., Renault, C., Champion, D., and Harrington, C., 1989, Volcanic hazard studies for the Yucca Mountain Project: Waste Management '89, v. 1, p. 485-492.

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

Evans, J.R., and Smith III, M., 1992, Teleseismic tomography of the Yucca Mountain region; volcanism and tectonism: Proceedings, Third International Conference, High Level Radioactive Waste Management, Las Vegas, Nevada, April 12-16, v. 2, p. 2371-2380.

Faulds, J.E., Bell, J.W., Feuerbach, D.L., and Ramelli, A.R., 1994, Geologic map of the Crater Flats area, Nevada, (with 3 cross-sections): Nevada Bureau of Mines and Geology Map 101, scale 1:24,000.

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

Fox, K.F., Jr., and Carr, M.D., 1989, Neotectonics and volcanism at Yucca Mountain and vicinity, Nevada: Radioactive Waste Management and the Nuclear Fuel Cycle, v. 13(1-4), p. 37-50.

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

Fridrich, C.J., Crowe, B.M., Hudson, M.R., Langenheim, V.E., and Thompson, G.A., 1994, Structural control of basaltic volcanism in a region of oblique extension, southwest Nevada volcanic field: Eos, Transactions, American Geophysical Union, v. 75, no. 44, p. 603.

Frizzel, V.A. Jr., and Shulters, J., 1990, Geologic map of the Nevada Test Site, southern Nevada: U.S. Geological Survey Miscellaneous Investigations Series Map I-2046, scale 1:100,000.

Geissman, J.W., Brown, L., Turrin, B.D., McFadden, L.D., and Harlan, S.S., 1990, Brunhes chron excursion/polarity episode recorded during the late Pleistocene, Albuquerque volcanoes, New Mexico, USA: Geophysical Journal International, v. 102, p. 73-88.

Hackett, W.R., and Smith, R.P., 1994, Volcanic hazards of the Idaho National Engineering Laboratory and adjacent areas: prepared for the U.S. Department of Energy, Idaho National Engineering Laboratory Report INEL-94/0276, issued December, 1994.

Hagstrum, J.T., and Champion. D.E., 1994, Paleomagnetic correlation of late Quaternary lava flows in the lower east rift zone of Kilauea volcano, Hawaii: Journal of Geophysical Research, v. 99, no. B11, p. 21,679-21,690.

Healey, D.L., Harris, R.N., Ponce, D.A., and Oliver, H.W., 1987, Complete bouguer gravity map of the Nevada Test Site and vicinity, Nevada: U.S. Geological Survey Open-File Report 87-506, scale 1:100,000.

Hildenbrand, T.G., and Kucks, R.P., 1988, Total intensity magnetic anomaly map of Nevada: Nevada Bureau of Mines and Geology Map 93A, scale 1:750,000.

Hill, B.E., Leslie, B.W., and Connor, C.B., 1993, A review and analyses of dating techniques for Neogene and Quaternary volcanic rocks: prepared for the Nuclear Regulatory Commission by the Center for Nuclear Waste Regulatory Analyses, San Antonio, Texas, (CNWRA 93-018).

Ho, C.-H., 1990, Bayesian analysis of basaltic volcanic eruptions: Journal of Volcanology and Geothermal Research, v. 43, p. 91-98.

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

Ho, C.-H., 1992, Risk assessment for the Yucca Mountain high-level nuclear waste repository site: Estimation of volcanic disruption: Mathematical Geology, v. 24, no. 4, p. 347-364.

Ho, C.-H., Smith, E.I., Feuerbach, D.L., and Naumann, T.R., 1991, Eruptive probability calculation for the Yucca Mountain site, USA: statistical estimation of recurrence rates: Bulletin of Volcanology, v. 54, p. 50-56.

Langenheim, V.E., Kirchoff-Stein, K.S., and Oliver, H.W., 1993, Geophysical investigations of buried volcanic centers near Yucca Mountain, southwest Nevada: Proceedings, Fourth International Conference, High Level Radioactive Waste Management, Las Vegas, Nevada, v. 2, p. 1840-1846.

Luedke, R.G., and Smith, R.L., 1981, Map showing distribution, composition, and age of late Cenozoic volcanic centers in California and Nevada: U.S. Geological Survey Miscellaneous Investigations Series Map I-1091-C, scale 1:1,000,000.

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

McBirney, A.R., 1992, Volcanology, *in* R.L. Hunter and C.J. Mann (eds.), Techniques for Determining Probabilities of Geologic Events and Processes: Oxford University Press, p. 167-184.

Minor, S.A., Sawyer, D.A., Wahl, R.R., Frizzel, V.A., Schilling, S.P., Warren, R.G., Orkild, P.P., Coe, F.A., Hudson, M.R., Fleck, R.J., Lanphere, M.A., Swadley, W.C., and Cole, J.C., 1993, Preliminary geologic map of the Pahute Mesa 30' x 60' Quadrangle, Nevada: U.S. Geological Survey Open-File Report 93-299, scale 1:100,000.

O'Leary, D.W., and Weisenberg, C.W., 1995 (draft), Current evaluation of tectonic models for the Yucca Mountain region: U.S. Geological Survey Administrative Report. (Final report due in 1996.)

Perry, F.V., and Crowe, B.M., 1992, Geochemical evidence for waning magmatism and polycyclic volcanism at Crater Flat, Nevada: Proceedings, Third International Conference, High Level Radioactive Waste Management, Las Vegas, Nevada, April 12-16, v. 2, p. 2344-2355.

Ponce, D.A., Harris, R.N., and Oliver, H.W., 1988, Isostatic gravity map of the Nevada Test Site and vicinity, Nevada: U.S. Geological Survey Open-File Report 88-664, scale 1:100,000.

Ratcliff, C.D., Geissman, J.W., Perry, F.V., Crowe, B.M., and Zeitler, P.K., 1994, Paleomagnetic record of a geomagnetic field reversal from late Miocene mafic intrusions, southern Nevada: Science, v. 266, p. 412-416.

Rosenbaum, J.G., Hudson, M.R., and Scott, R.B., 1991, Paleomagnetic constraints on the geometry and timing of deformation at Yucca Mountain, Nevada: Journal of Geophysical Research, v. 96, no. B2, p. 1963-1980.

Schweickert, R.A., 1989, Evidence for a concealed dextral strike-slip fault beneath Crater Flat, Nevada: Abstracts with Programs - Geological Society of America, v. 21, no. 6.

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

Sheridan, M.F., 1992, A Monte Carlo technique to estimate the probability of volcanic dikes: Proceedings, High Level Radioactive Waste Management, v. 2, p. 2033-2038.

Smith, E.I., Feuerbach, D.L., Nauman, T.R., and Faulds, J.E., 1990, The area of most recent volcanism near Yucca Mountain, Nevada: implications for volcanic risk assessment: Proceedings, High Level Radioactive Waste Management, v. 1. p. 81-90.

Stewart, J.H., 1992, Walker Lane Belt, Nevada and California - An overview, *in* S.D. Craig (ed.), Structure, Tectonics, and Mineralization of the Walker Lane: Reno, Nevada, Geological Society of Nevada, Proceedings Volume, Walker Lane Symposium, p. 1-16.

Turrin, B.D., and Champion, D.E., 1991, $^{40}Ar/^{39}Ar$ laser fusion and K-Ar ages from Lathrop Wells, Nevada, and Cima, California; the age of the latest volcanic activity in the Yucca Mountain area: Proceedings, High Level Radioactive Waste Management, v. 2, p. 68-75.

Turrin, B.D., Champion, D.E., and Fleck, R.J., 1991, $^{40}Ar/^{39}Ar$ age of the Lathrop Wells volcanic center, Yucca Mountain, Nevada: Science, v. 253, no. 5020, p. 654-657.

Turrin, B.D., Champion, D.E., and Fleck, R.J., 1992, Response to "Measuring the age of the Lathrop Wells volcanic center at Yucca Mountain": Science, v. 257, p. 556-558.

Tversky, A., and Kahneman, D., 1974, Judgment under uncertainty: Heuristics and biases: Science, v. 185, p. 1124-1131.

U.S. Geological Survey, 1986, Beatty 30'x 60' Quadrangle, scale 1:100,000.

U.S. Geological Survey, 1979, Pahute Mesa 30'x 60' Quadrangle, scale 1:100,000.

Wallmann, P.C., 1993, A technique for calculation of the probability of dikes intersecting a repository: Proceedings, Focus '93 Symposium, American Nuclear Society, p. 192-199.

Wallmann, P.C., Miller, I., and Kossik, R., 1994, Assessment of volcanic and tectonic hazards to high level radioactive waste repositories: Proceedings, High Level Radioactive Waste Management, v. 4, p. 188-195.

Wells, S.G., Crowe, B.M., McFadden, L.D., Turrin, B.D., Champion, D.E., and Fleck, R.J., 1992, Measuring the age of the Lathrop Wells volcanic center at Yucca Mountain: Science, v. 257, p. 555-558.

Wells, S.G., McFadden, L.D., Renault, C.E., and Crowe, B.M., 1990, Geomorphic assessment of late Quaternary volcanism in the Yucca Mountain area, southern Nevada: Implications for the proposed high level radioactive waste repository: Geology, v. 18, p. 549-553.

Wells, S.G., McFadden, L.D., Renault, C.E., and Crowe, B.M., 1991, Reply to "Geomorphic assessment of late Quaternary volcanism in the Yucca Mountain area, southern Nevada: Implications for the proposed high level radioactive waste repository": Geology, v. 19, p. 661-662.

Whitney, J.W., and Shroba, R.R., 1991, Comment on "Geomorphic assessment of late Quaternary volcanism in the Yucca Mountain area, southern Nevada: Implications for the proposed high level radioactive waste repository": Geology, v. 19, p. 661-662

APPENDIX C

SUMMARIES
PVHA WORKSHOPS

APPENDIX C

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

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

February 22 and 23, 1995
Phoenix, Arizona

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

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

DAY 1 - WEDNESDAY, FEBRUARY 22

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

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

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

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

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

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

DAY 2 - THURSDAY, FEBRUARY 23

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

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

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

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

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

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

TABLE 2
DATA NEEDS FOR TECHNICAL ISSUES
WORKSHOP ON DATA NEEDS

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

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

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

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

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

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

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

DAY 1 - THURSDAY, MARCH 30

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

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

Four speakers gave presentations in the session on "Methods for Characterizing the Recurrence Rate of Future Volcanism." Bill Hackett (WRH Associates) gave a presentation entitled "Event Counts," which was based on the volcanic geology of the Eastern Snake River Plain (ESRP), Idaho. He described the character of basalt flows in the ESRP and the structural features associated with emplacement of basaltic dikes therein. Mel Kuntz (US Geological Survey [USGS]) gave the final talk of the morning session. He also drew on examples from the ESRP, discussing recurrence intervals, magma-output rates, effusion rates, and eruption durations.
The afternoon session began with a presentation by George Thompson (Stanford University) entitled "Coupling of Basaltic Dike Injection to Stress and Strain in Extending Regions: Prediction Capability at Yucca Mountain?" He discussed the relationship between normal faulting and volcanism as a means of accommodating crustal strain in extending regions. Chih-Hsiang Ho (University of Nevada, Las Vegas [UNLV]) gave the final presentation of the day, entitled "Volcanic Hazard Analysis at the Yucca Mountain Nuclear Waste Repository Site." He discussed the applications of his Bayesian approach to modeling the future hazard at Yucca Mountain.

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

DAY 2 - FRIDAY, MARCH 31

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

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

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

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

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

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

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

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

DAY 1 - TUESDAY, MAY 16

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

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

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

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

DAY 2 - WEDNESDAY, MAY 17

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

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

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

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

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

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

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

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

DAY 1 - TUESDAY, DECEMBER 5

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

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

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

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

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

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

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

DAY 2 - WEDNESDAY, DECEMBER 6

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

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

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

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

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

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

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

APPENDIX D

SUMMARIES
PVHA FIELD TRIPS

APPENDIX D

SUMMARY
CRATER FLAT FIELD TRIP
PROBABILISTIC VOLCANIC HAZARD ANALYSIS PROJECT
YUCCA MOUNTAIN, NEVADA

March 29, 1995

The field trip to Crater Flat was organized at the request of the expert panel members, who wanted to observe first hand the volcanic geology and structural elements of the Crater Flat basin. The primary goal of the field trip was to provide the expert panel members an opportunity to form their own interpretations regarding the spatial, temporal, and physical aspects of the Crater Flat volcanic centers. The field trip was led by several earth scientists who have carried out extensive mapping and/or research of the geology in the Crater Flat area. The field trip stops and presentations were made at locations where key outcrops of the local geology could be observed. The presentations given by the field trip leaders focused on their interpretations of the spatial, temporal, and structural aspects of the local and/or regional geology of the Crater Flat basin. A copy of the field trip itinerary is included with this summary. This itinerary was modified slightly during the course of the day.

A meeting was held the evening before the field trip to review the geologic setting of the region, and to discuss the field trip itinerary.

Stop 1: I-95 (near the southern end of Bare Mountain)
Chris Fridrich (U.S. Geological Survey [USGS]) presented an overview of Basin and Range extensional tectonics. He discussed the Cenozoic tectonic evolution of the Yucca Mountain region, and the implications for structural controls on volcanism in the Crater Flat basin.
Frank Perry (Los Alamos National Laboratory [LANL]) then gave a brief presentation on the late Cenozoic basalt chronology of the region.

Stop 2: Steve's Pass
Chris Fridrich presented an overview of his tectonic pull-apart model of the Crater Flat basin. George Thompson (Stanford University) then reviewed the USGS seismic line across the Crater Flat basin. He discussed the structural character of the basin based on his interpretation of the seismic line, and he also discussed the significance of the Bare Mountain fault.

Stop 3: Red Cone
Gene Smith (University of Nevada, Las Vegas) presented his geologic mapping of Red Cone. He led the field trip participants to a number of outcrops on and adjacent to the cone, and discussed his geologic interpretations at each. Included in the discussions was his interpretation of vents, and vent alignments on the cone. Frank Perry then presented and discussed $^{40}Ar/^{39}Ar$ age dates and geochemical data from the cone. Chuck Connor (Center for Nuclear Waste Regulatory

Analyses [CNWRA]) gave a brief presentation on the results of a ground magnetometer experiment by the CNWRA to explore the existence of subsurface dike connecting Red and Black cones. He stated that the resolution of their data did not allow an interpretation for or against the presence of a dike.

Stop 4: Black Cone

Gene Smith presented his geologic mapping and interpretations of Black Cone. He also presented geochemical data that he interprets as evidence that Black Cone and Red Cone were derived from different magma sources. Frank Perry presented and discussed the $^{40}Ar/^{39}Ar$ age dates and geochemical data from Black Cone.

Stop 5: Trench 8 (Solitario Canyon fault)

Chris Menges (USGS) gave an overview of the stratigraphy and structures exposed in the exploratory trench excavated across the Solitario Canyon fault. His discussion focused on the significance of an ash deposit that was discovered in a fissure adjacent to the main fault in the trench exposure, and the temporal relationship between faulting events and volcanic activity in the region. Frank Perry, along with Chris Menges, discussed the age and chemistry of the ash, and its correlation with the volcanic centers in Crater Flat.

Stop 6: Southeast (3.7 Ma) Crater Flat

Frank Perry and Bruce Crowe (LANL) gave an overview of the basalts in southeast Crater Flat. Frank Perry discussed the geochemistry and how it differs from the younger centers in Crater Flat. Bruce Crowe discussed dike geometry and orientations of the 3.7 Ma area.

CRATER FLAT
MARCH 29, 1995 FIELD TRIP PARTICIPANTS

NAME	AFFILIATION
Lynn Bowker	Los Alamos National Laboratory
Richard W. Carlson	Carnegie Institution of Washington
Karen Carter	Los Alamos National Laboratory
Chuck B. Connor	Center for Nuclear Waste Regulatory Analyses
Kevin Coppersmith	Geomatrix
Todd Crampton	Geomatrix
Bruce Crowe	Los Alamos National Laboratory
Terry Crump	TRW
Wendell A. Duffield	U.S. Geological Survey
Kean Finnegan	Los Alamos National Laboratory
Richard V. Fisher	University of California
Chris Fridrich	U.S. Geological Survey
Sandra Green	Eureka County Information Center
William R. Hackett	WRH Associates
Brittain E. Hill	Center for Nuclear Waste Regulatory Analyses
William J. Hinze	ACNW/Nuclear Regulatory Commission
Mel A. Kuntz	U.S. Geological Survey
Alexander R. McBirney	University of Oregon (Emeritus)
Chris Menges	U.S. Geological Survey
Peter A. Morris	Applied Decision Analysis
Stephen T. Nelson	Woodward-Clyde Federal Services
Jeanne C. Nesbit	U.S. Department of Energy
Roseanne C. Perman	Geomatrix
Frank Perry	Los Alamos National Laboratory
John Perry	Nye County
Michael F. Sheridan	State University of New York, Buffalo
Eugene I. Smith	University of Nevada
Richard P. Smith	Idaho National Engineering Laboratory
J. Carl Stepp	Woodward-Clyde Federal Services
George A. Thompson	Stanford University
John Trapp	U.S. Nuclear Regulatory Commission
George P.L. Walker	University of Hawaii
Gene Yogodzinski	University of Nevada

SUMMARY
SLEEPING BUTTE/LATHROP WELLS FIELD TRIP
PROBABILISTIC VOLCANIC HAZARD ANALYSIS PROJECT
YUCCA MOUNTAIN, NEVADA

April 25 and 26, 1995

A two day field trip to the Sleeping Butte and Lathrop Wells volcanoes was organized at the request of the expert panel members, who wanted to observe first hand the volcanic geology at each of the volcanic centers, particularly at the Lathrop Wells cone. The primary goal of the field trip was to provide the expert panel members an opportunity to form their own interpretations regarding the spatial, temporal, and physical aspects of the Sleeping Butte and Lathrop Wells volcanic centers. The Lathrop Wells volcano was visited on the first day of the trip and the Sleeping Butte volcanoes on the second day. The field trip was led by several earth scientists who have carried out extensive mapping and/or research of the geology of the two areas. The field trip stops and presentations were made at locations where key outcrops of the local geology could be observed. The presentations given by the field trip leaders focused on their interpretations of the spatial, temporal, and physical aspects of the local and/or regional geology of the Sleeping Butte or Lathrop Wells area. A copy of the Lathrop Wells scheduled field itinerary is included with this summary; a printed itinerary for the Sleeping Butte field trip was not prepared.

A meeting was held the evening before the Lathrop Wells field trip to review the geologic investigations conducted at the Lathrop Wells volcanic center. Several short presentations were made in preparation for the field visit.

DAY 1 - LATHROP WELLS VOLCANIC CENTER

Stop 1: East Quarry

Bruce Crowe and Frank Perry (Los Alamos National Laboratory) gave an overview of the chemical and physical properties of their Qs3 and Qs4 tephra units exposed in a bulldozer cut. The two units are separated by soil horizons, which were identified and described by Les McFadden (University of New Mexico) and Steve Wells (University of California). They described the degree of development and structure of the various soil horizons, and the estimated relative age of the soils based on their physical properties.

Stop 2: South Quarry

Frank Perry briefly described the vent deposits (Qs1) draped by fall sheet deposits (Qs2) mapped and interpreted by Crowe and Perry (1988) at this location.

Stop 3: Southern Margin of Main Cone
Frank Perry briefly described the Qs2 fall sheet remnant mapped and interpreted by Crowe and Perry (1988) overlying the local Miocene bedrock. He also briefly discussed the flow/vent relationships of the Ql1d deposit in the area.

Stop 4: West of Main Cone
Les McFadden and Steve Wells discussed the geomorphology of the main cone and the alluvial fan blanketing the northwest margin of the cone. Of particular interest was an erosional geomorphic surface at the base of the main cone that is draped by a relatively thin apron, or fan of alluvial deposits. Also discussed was the lack of rilling, or erosion of the main cone itself, and the estimated age of the cone based on the geomorphic relationships and features present.

Stop 5: North of Main Cone
Les McFadden and Steve Wells continued their discussion of the geomorphology of the main cone and adjacent alluvial fan.

Stop 6: Trench Exposure of Scoria Flow Relationships and Soils
Bruce Crowe and Frank Perry discussed the stratigraphy of the volcanic deposits exposed in the trench. Les McFadden and Steve Wells described the soil horizons between the volcanic units, and discussed their relative ages based on their degree of development and structure.

Stop 7: Scoria Vents East of Main Cone
Bruce Crowe gave a brief overview of his interpretation of the vent/scoria flow relationships on the east side of the main cone.

Stop 8: Main Cone Summit
Frank Perry gave an overview of the volcanic geology at Lathrop Wells. The field trip participants then engaged in an open discussion of the day's field observations.

DAY 2 - SLEEPING BUTTE

The Sleeping Butte visit was led by Scott Minor, Robert Fleck, Duane Champion, and Paul Orkild, all of the U.S. Geological Survey. Scott Minor began the trip by presenting an overview of the preliminary geologic mapping of the Pahute Mesa 30'x 60' quadrangle. The first stop was at the summit of Thirsty Mountain, from which Scott Minor pointed out the edge of the Timber Mountain - Oasis Valley caldera complex. Robert Fleck then presented some of his age dates for the Thirsty Mountain basalt. The next stop was at Hidden Cone, where various volcanic features along the southeast side of the cone were examined. Scott Minor described the geologic mapping of the surrounding area, noting that a fault occurs at the south end of the cone. Robert Fleck presented age dates for the Hidden Cone basalts, and Duane Champion presented paleomagnetic data for the basalt flows at the northern end of the cone. The final stop of the day was at Little Black Peak, where several outcrops were examined.

LATHROP WELLS AND SLEEPING BUTTE AREA APRIL 25-26, 1995 FIELD TRIP PARTICIPANTS

NAME	AFFILIATION
Duane Champion	U.S. Geological Survey
Chuck Connor	Center for Nuclear Waste Regulatory Analyses
Kevin J. Coppersmith	Geomatrix
Todd Crampton	Geomatrix
Bruce Crowe	Los Alamos National Laboratory
Terry Crump	TRW
Wendell A. Duffield	U.S. Geological Survey
Richard V. Fisher	University of California, Santa Barbara
Robert Fleck	U.S. Geological Survey
Sandra Green	Eureka County
William R. Hackett	WRH Associates
Brittain E. Hill	Center for Nuclear Waste Regulatory Analyses
Mel A. Kuntz	U.S. Geological Survey
Alexander R. McBirney	University of Oregon
Steve McDuffie	Nuclear Regulatory Commission
Les McFadden	University of New Mexico
Scott Minor	U.S. Geological Survey
Stephen T. Nelson	Woodward-Clyde Federal Services
Paul Orkild	U.S. Geological Survey
Roseanne C. Perman	Geomatrix
Frank Perry	Los Alamos National Laboratory
John Perry	Nye County
Leon Reiter	Nuclear Regulatory Commission
Michael F. Sheridan	State University of New York, Buffalo
Eugene I. Smith	University of Nevada, Las Vegas
Richard P. Smith	Idaho National Engineering Laboratory
Engelbrecht von Tiesenhausen	Clark County
George P.L. Walker	University of Hawaii
Steve Wells	University of California, Riverside
John Whitney	U.S. Geological Survey
Gene Yogodzinski	University of Nevada, Las Vegas

APPENDIX E

ELICITATION INTERVIEW SUMMARIES

APPENDIX E

RICHARD W. CARLSON
ELICITATION INTERVIEW FOR PVHA PROJECT

VOLCANIC/TECTONIC SETTING

In the broadest sense, volcanism in the Yucca Mountain region (YMR) (for the purposes of this elicitation "Yucca Mountain region" is defined as the circular area 50 km in radius centered on the proposed repository site) is an expression of the same volcanic/tectonic process occurring throughout the Basin and Range/western U.S. Miocene and younger volcanism and extension in the Basin and Range most likely represents the reaction of the western part of continental North America to the change from subduction along its western margin to the overriding of the various oceanic spreading centers (Atwater, 1970; Christiansen and Lipman, 1972; Cross and Pilger, 1978; Eaton, 1982). This led to a considerably different temperature structure in the mantle beneath the western U.S. (Severinghaus and Atwater, 1990), which is expressed by the changing character of volcanism. During the pre-Miocene subduction interval, the lithospheric mantle beneath the western U.S. was cooled by the cold subducting oceanic slab, but also was charged with volatiles by fluids rising from the dehydrating subducting plate. When subduction ceased, the overridden oceanic spreading center brought hot asthenospheric mantle directly beneath the volatile-charged lithosphere. This gave rise to the first burst of volcanism, manifest in the YMR by early caldera-forming silicic volcanism and associated basaltic activity beginning roughly at 15 Ma (Christiansen et al., 1977). The large volumes associated with this early volcanism probably reflect the diapiric ascent of asthenosphere that filled in the void as the subducting slabs detached and sank into the deeper mantle, with an additional contribution from the easily melted, hydrous mantle beneath the area formed as a result of the long history of subduction-induced metasomatism (Carlson and Hart, 1987). Volcanism following this initial burst is expressed differently, both compositionally and volumetrically, in various parts of the Basin and Range (Jones et al., 1992). In the YMR, the volume erupted decreases dramatically with time and the volcanism becomes more alkalic, reflecting increasingly smaller degrees of partial melting (Crowe et al., 1995).

In the author's opinion, the continuing volcanism in the YMR reflects conductive heating of the lithospheric mantle by the underlying asthenosphere, perhaps assisted by mantle ascent accompanying lithosphere extension. In the geological, geophysical, and volcanological data reviewed during the course of the PVHA project, the author does not see a clear connection between the tectonic history of post-Miocene extension in the YMR and the post-8 Ma volcanism.

suggesting that melting is primarily accomplished by conductive heating of the lithosphere rather than by diapiric ascent. Isotopic compositions of Sr and Nd in the Yucca Mountain basalts are extreme for Basin and Range lavas and point strongly to a magma source in Proterozoic lithospheric mantle (G. Yogodzinski presentation at PVHA Workshop 3). Thus, the YMR has much less potential to generate partial melts compared to most of the Basin and Range, where hot asthenospheric mantle appears to have displaced whatever lithospheric mantle was present prior to inception of Basin and Range activity.

REGION OF INTEREST

The main cause of Miocene and younger volcanism in the Basin and Range appears to be replacement of cold subducting slabs with hot asthenospheric mantle beneath the western North American lithosphere (Atwater, 1970). This represents a broad and more-or-less constant "flame," capable of causing melting and volcanism across the entire Cordilleran U.S. Clearly, however, all of the Basin and Range has not responded similarly to this "flame" (Christiansen and Lipman, 1972; Jones et al., 1992). In the Basin and Range, Yucca Mountain sits in a heat flow low, has minimal signs of present-day extensional stress, and lies at the northern boundary of the so-called "amagmatic gap," distinguished by the absence of Mesozoic and Cenozoic magmatic activity (Christiansen and Lipman, 1972; Farmer et al., 1989; Jones et al., 1992). The explanation for this may be indicated by the extreme isotopic composition (G. Yogodzinski presentation at PVHA Workshop 3) of the magmas of the YMR: the YMR is underlain by an unusually thick/persistent/non-extended section of Proterozoic lithospheric mantle (this author's extension of the concepts and data presented by G. Yogodzinski at PVHA Workshop 3). Trace element characteristics of the post-5 Ma YMR basalts (Crowe et al., 1995; Vaniman et al., 1982; F.V. Perry, pers. comm., 1995) indicate a source that contained garnet (garnet is stable in a peridotitic assemblage only at depths greater than approximately 60 km) and possibly a hydrous phase, such as amphibole and/or phlogopite, the presence of which would constrain the maximum depth of magma generation to on the order of 100-150 km because these phases are not stable at higher pressures. Nd isotopic compositions of YMR basalts provide minimum depleted mantle model ages of 1-1.5 Ga (calculated from data provided by F.V. Perry, pers. comm., 1995), suggesting that the source of these lavas is Proterozoic lithospheric mantle of an age approaching that of the continental basement in this area (Bennett and DePaolo, 1987; Farmer and DePaolo, 1983; Farmer et al., 1989). The constancy of Sr and Nd isotopic compositions of post-8 Ma basalts from the YMR and some nearby areas (G. Yogodzinski presentation at PVHA Workshop 3) indicate that this 100-150+ km thick section of Proterozoic lithospheric mantle has not been displaced or thinned significantly by Basin and Range extension, as appears to have occurred in many other areas of the Basin and Range (Carlson and Hart, 1987; Leeman and Fitton, 1989; Perry et al., 1987).

Assuming that this feature of the YMR has influenced its volcanic history, the relevant region of interest for calculating volcanic probabilities in the YMR should include nearby areas that have the same isotopic signature of Proterozoic lithosphere: the area within the Amargosa Valley Isotopic Province (AVIP) proposed by G. Yogodzinski (presentation at PVHA Workshop 3). The AVIP includes the area of Yucca Mountain volcanism (northern border to include Sleeping Butte, Thirsty Mesa, and Buckboard Mesa extending south to Crater Flat and Lathrop Wells), and then extends south to include the buried Amargosa Valley centers and the volcanic centers in northern Death Valley that are isotopically similar to the Yucca Mountain basalts. The Death Valley activity is included to increase the number of events from an area whose lithospheric compositional and thermal structure may be similar to the YMR and, hence, may have responded similarly to the broad heat source behind Basin and Range volcanism. Post-Miocene volcanism outside the AVIP is not considered significant by this author in terms of its impact on calculating volcanic event probabilities in the YMR.

The possibility of subdividing the AVIP on the basis of caldera locations and tomography was examined. Tomographic data examined by Evans and Smith (1992) were resolved and interpreted to show high velocities under the Timber Mountain caldera and low velocities (indicating melt) below Crater Flat. (The presence of partial melt is not necessarily correlated with future volcanism, but its absence is a good explanation for why volcanism has not occurred.) The Evans and Smith (1992) map was superimposed on the AVIP, but no clear associations were observed between tomography and the record of young volcanism. The distribution of volcanoes within the AVIP appears to be random. Evidence for clustering of centers is very weak (in part due to the small data set) and the author concludes that there is no good basis for subdividing the area.

EVENT DEFINITION

Temporal Aspects

A volcanic event is defined herein as an eruption or series of eruptions related to the same magmatic conduit system that transfers magma from a diffuse zone of partial melting in the mantle to a volcanic edifice. An event could be an eruption from a single feeder dike at a single time, or it could be related to an en echelon dike set or a branch from a major dike. An event is controlled by the process of magma ascent and crystallization. Thin (thicknesses of a meter or less) dikes filled with magma will be cooled rapidly by the lower temperatures present in surrounding upper crust wall rocks. This cooling will lead to crystallization of the magma in the dike. When the magma has solidified to the point that it reaches a yield strength similar to that of surrounding rock, the "event," as defined here, is over. A new event will be initiated by the next propagation of magma from the mantle source towards the surface. In areas of high magmatic output, this event definition is blurred because individual conduits, and hence volcanoes, may be fed with a more-or-less continuous stream of new, hot, magma. In such situations, "events" may last many thousands of years. The volcanoes and dikes in the YMR are very small, such that an event most likely occurs on the order of tens to hundreds of years.

Spatial Aspects

The expected spatial dimensions of an event are on the order of a basaltic dike: 1 to 5 km (Delaney and Gartner, 1995; Walker, 1987). The maximum might be represented by a set of dikes giving rise to an event having dimensions of 10 to 20 km. A possible example of an event near the maximum size would be the case where the cones in northern Crater Flat are assumed to represent a single event.

Geochemical Affinity

Geochemical affinities need not discriminate individual events because substantial variations can occur in single flows from the same event, but they can provide supporting information to other data that suggest separate events. The volumes of the YMR basaltic volcanoes are low, and they sample a very small region of the mantle (Crowe et al., 1995). Their chemical compositions (Crowe et al., 1995; Vaniman et al., 1982) indicate that the magmas have experienced fractional crystallization since leaving the mantle, but, on the basis of no evidence for crystallization of plagioclase, the magmas do not appear to have undergone storage and fractionation in crustal-depth magma chambers (Crowe et al., 1995). Such magma chambers might be expected to promote mixing and homogenization of magmas prior to eruption. Without such mixing chambers, differences in the degree of partial melting for individual batches of magma extracted from the source rock, the extent of crystallization, and the degree of interaction and incorporation of wall rock by these magmas on route to the surface could lead to chemical variations in magmas erupted at different times during one event.

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

SPATIAL MODELS

The future spatial distribution of volcanoes is modeled using two basic models: a model assuming a uniform distribution of events within the AVIP zone (termed the "uniform" model), and a model of the type proposed by Connor and Hill (1993), where the spatial distribution of observed events is smoothed to represent the probability of future event locations (termed the "spatial smoothing" model). The weights assigned to these models are: uniform (0.4) and spatial smoothing (0.6). The "field shape" approach of Sheridan (1992) was considered but not used in this case because the author is uncomfortable with assigning a "field" shape to individual volcanic centers as sparse as those in the YMR. Nevertheless, guided by the general field shape trends displayed by Basin and Range volcanism (M. Sheridan presentation at PVHA Workshop 3), the author selected "smoothing" kernels that, at the larger of the smoothing distances examined here, cause the "spatial smoothing" model solutions to approach those that would be produced by "field shape" models in terms of the volcanic event contours calculated.

On the basis of his previous studies of volcanic centers in the western U.S. and elsewhere around the world, the author has a strong bias towards believing that the exact location of volcanism is structurally controlled. This bias is reflected in the 60% weight assigned to the spatial smoothing approach, but structural control is poorly supported by volcanism in the YMR, leading to the 40% weight assigned to the uniform model. The Crater Flat cones clearly are aligned, but this may represent a shallow stress condition that was present when the dike feeding these eruptions extended close to the surface. Lathrop Wells does not lie along this alignment, nor do the volcanic centers to the north. In the author's opinion, the strongest evidence for structural control is that the Crater Flat centers, including Lathrop Wells, formed in the area that displays the most evidence for extension in the Quaternary (B. Crowe and G. Thompson presentations at PVHA Workshop 4). Larger-scale alignments, such as along the Walker Lane, were reviewed, but the author does not see a particularly compelling reason to believe that the Walker Lane has had much effect on the YMR volcanic centers.

The spatial control typically observed is that basaltic centers seem to avoid erupting through the center of calderas, presumably because the presence of subsurface silicic magma beneath the caldera impedes ascent of basaltic magma. After the silicic magma crystallizes and cools to the point that it can fracture, basaltic magmas can erupt through calderas. Given the occurrence of Buckboard Mesa, it appears this point has been reached at Yucca Mountain, so there is no longer a good reason to exclude an intra-caldera basaltic center.

In general, there does not appear to be any particular area in the YMR that has either a strongly enhanced or diminished probability of being the site of the next eruptive center. Therefore, spatially homogenous probability models are only slightly less weighted (40% to 60%) compared to structure controlled models such as the spatial smoothing model used here.

The uniform model is implemented by assuming that the probability distribution of future events is uniform within the AVIP (see discussion of AVIP in "Region of Interest" section).

The spatial smoothing approach is implemented using an Epanechnikov smoothing operator that is elliptically shaped, with a 2:1 aspect ratio, and oriented to the northwest parallel to the Crater Flat volcanic zone of Crowe and Perry (1989). Where a single event is represented by multiple cones, the mid-point of the cones is used as the point estimate for the event. The elliptical shape is intended to elongate the probability contours in the northwest direction to reflect this structural trend. This elongation is similar to the "field shape" approach proposed by Sheridan (1992), although the spatial smoothing approach is driven more by the distribution of events than by a parametric form. Two alternative smoothing distances (long dimension of operator) are considered, and their relative weights are: 10 km (0.5), and 20 km (0.5). Smoothing is used for post-5 Ma events within the northern half of the AVIP.

EVENT COUNTS

Based on the definition of volcanic "events" given earlier, the number of events—and their uncertainties—are assessed for each of the centers in the AVIP (Figure RC-2). The event counts and rates of occurrence for various time periods are summarized in Tables RC-1 and RC-2.

Lathrop Wells

The available data at Lathrop Wells suggest that a single event is most likely, but more than 1 event may have occurred (Crowe et al., 1995). Each of the geochronology data sets has its own set of problems and leads to large uncertainties. The paleomagnetic data argue for a single event (Champion, 1991). However, the evidence for a soil horizon, and other observations, lead to problems with the single-event interpretation (Wells et al., 1992; 1990). Although unlikely, it is possible to envision a process where a monogenetic center is reactivated by a second period of activity due to a "random" hit at the same place.

The following event counts and their relative weights are assigned for the Lathrop Wells center: 1 (0.95), and 2 (0.05).

Sleeping Butte

One to 3 events may be represented by the geologic relationships at Sleeping Butte, with 1 event most likely. Little Black Peak and Hidden Cone are closely spaced (3 km apart) and the geochronology would allow for them to be essentially the same age (Crowe et al., 1995). Little Black Peak and Hidden Cone would be considered separate events for the 2-event scenario, which is given much less weight (Champion, 1991; Crowe et al., 1995). For the 3-event scenario, Hidden Cone is interpreted to consist of 2 events, which was suggested at the PVHA Sleeping Butte field trip based on paleomagnetic and geomorphic data.

The event counts and their relative weights for the Sleeping Butte area are: 1 (0.7), 2 (0.2), and 3 (0.1).

Death Valley

The <0.7 Ma Split Cone deposits in Death Valley represent the only post-1 Ma event in this area (informal PVHA memo by B. Crowe).

A single event at Split Cone is assigned a weight of 1.0.

1.0 Ma Crater Flat

The 1.0 Ma basalts in northern Crater Flat represent 1 to 5 events, with 1 event most likely. The single-event scenario is preferred on the basis of age-dating information, although the uncertainties are probably on the order of 50,000 yr (Crowe et al., 1995). Paleomagnetic data indicate the cones are of similar age (Champion, 1991), and available isotopic dates, while less reliable for these relatively young rocks, also allow the interpretation that the cones are of similar age (Crowe et al., 1995). The possible evidence for multiple events at Red Cone reviewed on the PVHA Crater Flat field trip (e.g., scoria mounds, possible dikes, geochemical differences) is not convincing. If the age-dates are not accurate, 3 events could be represented on the basis of geochemical differences between the cones (Red and Black cones formed in a single event, Makani and Little Cones are each separate events) (Crowe et al., 1995). Based on counts of mapped cones, a maximum of 5 events may have occurred (Little Cones consists of two mapped cones).

The following event counts and their relative weights are assigned for northern Crater Flat: 1 (0.6), 3 (0.3), and 5 (0.1).

Buckboard Mesa

Buckboard Mesa basalts appear to be related to a single fissure flow. However, if the two cones are considered separate events, 2 events might be represented (Crowe et al., 1995).

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

3.7 Ma Crater Flat

The 3.7 Ma basalts in southeastern Crater Flat may represent 1 to as many as 6 events, with 1 event most likely (Crowe et al., 1995). Evidence for multiple events is not convincing, and age-dates have overlapping uncertainties that suggest that a single event may have occurred (Crowe et al., 1995). Discontinuities in the outcrops could be related to faulting. Two to 6 events are possible, based on individually mapped dikes and fissures summarized in Crowe et al. (1995).

The following event counts and their relative weights are assigned for the 3.7 Ma area of Crater Flat: 1 (0.8), 2 (0.1), 3 (0.05), 4 (0.02), 5 (0.02), and 6 (0.01).

Amargosa Valley

Three to 6 separate events could be represented by the aeromagnetic anomalies in Amargosa Valley, as discussed and designated by V. Langenheim (presentation at PVHA Workshop 1). Dikes in the 3.7 Ma area of Crater Flat suggest that dike alignments during this general time period should be north-south (Crowe et al., 1995). Anomalies D and C are close together but have different polarities (Langenheim et al., 1993). In the 3-event scenario, anomalies B, C, and D would be separate events, as they are the most believable as buried cones (Langenheim et al., 1993). In the 4-event scenario, anomaly E is also included, which is judged to be a preferred interpretation. Anomalies F and G, which are included in the 5- and 6-event scenarios, have a relatively low probability of representing events, as they have signatures similar to the background noise level (Langenheim et al., 1993). *Note: Anomalies F and G on the aeromagnetic map presented by V. Langenheim at PVHA Workshop 1 correspond to anomaly A in Langenheim et al. (1993).*

The following event counts and their relative weights are assigned to the Amargosa Valley area: 3 (0.3), 4 (0.5), 5 (0.1), and 6 (0.1).

Thirsty Mesa

A single flow sheet appears to be present at Thirsty Mesa that is interpreted to represent simple fissure-fed flows (Crowe et al., 1995). The flow volume is not atypical for the region if it occurred from a single event (Crowe et al., 1995).

The favored number of events at Thirsty Mesa is 1 (0.9), and the possibility of 2 events is included (0.1).

TEMPORAL MODELS AND RATES OF OCCURRENCE

Two temporal models are used: a volume-predictable approach that is applied only to the northern portion of the AVIP, and a homogeneous approach that is applied to the entire AVIP. Because of the small number of events occurring in the northern AVIP, and recognizing the decreasing volume of lava erupted with time throughout this province, a volume predictable approach was developed to estimate the present-day rate of volcanism based on volume estimates for eruptions occurring only over the past 5 my where the data are reasonably complete and accurate. The author considers the volume predictable approach to offer a more reliable estimate of current eruptive rates in the YMR because the very small number of young-(i.e., <1 Ma) vents in the region leads to large uncertainties in both homogeneous (Crowe et al., 1995; Crowe and Perry, 1989) and non-homogenous approaches (Ho, 1991). This volume predictable approach to a time-varying eruptive rate is considered along with a homogeneous approach that averages the event counts over the last 1 my in the YMR. The relative weights assigned to these two models is 70% for the volume-predictable approach and 30% for the 1 my average homogeneous model. The higher weight given to the volume-predictable approach reflects the author's opinion that this approach provides a slightly more reliable "averaging" method to calculate the present day eruptive rate in the YMR, and acknowledges that this rate has not been constant during the history of post-8 Ma volcanism.

The volume predictable approach is designed to recognize that the volume of eruptions has declined over the past 15 my (Crowe et al., 1995) and uses this information to estimate the expected volume of an eruption at the present time and near future. The data for cumulative volume versus time shown in Figure 7.6 of Crowe et al. (1995) were fit by an equation relating volume to the square root of time, as would be expected if magma production were controlled by a diffusion-limited process such as thermal conduction. A simple two-point fit to the data of volume versus time gives the equation:

$$\text{Cumulative Volume (km}^3\text{)} = 3\ (\text{km}^3) + 1.33 * (\text{Time [Ma]})^{1/2}$$

where Time=0 at 4.8 Ma and Time=4.8 Ma today. This equation provides the following eruption rates for the integrated time intervals (Time = 0 today) listed below:

Time Interval (Ma)	Eruptive Volume (m^3/yr)
0 - 0.1	305
0 - 1.0	321
0 - 2.0	344
4.7 - 4.8	4200

To derive event counts and/or repose times from these volumes requires information on the average volume per event and how this has changed with time. The data for volume per event versus time from Figure 7.9 of Crowe et al. (1995) show an exponential fall off with time in the volume per event and were fit with an exponential curve of the following form:

$$\text{Volume per Event (km}^3) = 0.13 * e^{0.65 * \text{Time(Ma)}}$$

where Time=0 today. This curve predicts a current event size of approximately 0.13 km^3 and an event size of 2.9 km^3 at 4.8 Ma. Given the eruptive volume figures quoted above, these event sizes translate into event rates of 2.3 events per million years (426,000 yr repose time) today and 1.4 events per million years (690,000 yr repose time) at 4.8 Ma. Consequently, this approach predicts that although magma production is declining in the Yucca Mountain area, the frequency of eruptions has increased over the past 5 my because the volume per event has decreased more rapidly than the erupted volume with time.

An attempt was made to fit a periodic function to event rate at Yucca Mountain by a cubic spline fit to the data for event count versus time, given as Figure 3.11 in Crowe et al. (1995). This method is considered to have poor accuracy because of the small number of data points included. Nevertheless, the cubic spline fit extrapolates to an event rate of approximately 1.6 events/my at the present time, which is not greatly different from the present-day value calculated from the volume predicable model. Consequently, the author's choice for present-day eruption rate is 2.3 ± 0.7 events per million years.

Undetected Events

The probability that volcanic events (i.e., dikes) would ascend to shallow depths (300 m, which is the depth of the proposed repository) and not erupt at the surface is considered to be low by the author. Dikes ascend by exsolving volatiles in the shallow crust, gaining eruptive pressure with ascent. Unless they encounter some unusually impenetrable strata, the increasing eruptive pressure in the dike should cause the majority of dikes, if they have made it to the upper 0.5 km of the crust, to continue on to surface eruption. To allow for some failed dikes that might make it to 300 m depth, but not to surface eruption, the author estimates that about 10% more events may exist at shallow depth than have been interpreted at the surface (i.e., the event counts should be multiplied by 1.1 to include the undetected events).

EVENT GEOMETRIES

When an event is defined by two or more features (e.g., cones), the mid-point of the features should be used as the point location of the event.

The length of an event is expected to be the length of a basaltic dike, about 1 to 5 km long (Delaney and Gartner, 1995). In some cases, a set of dikes may occur during a single event and extend the total length to as much as 12 km or more (such as the possible event interpreted for northern Crater Flat). The cumulative distribution for event length is the following:

1 km	(0.1)
3 km	(0.5)
5 km	(0.75)
12 km	(0.95)
20-30 km	(1.0)

The maximum dike length lies within the range of 20 to 30 km. Dikes longer than 30 km are given zero probability because this length would exceed the length of most continuous mapped faults in the area (Scott, 1990). The assessed relative weights on maximum lengths are 20 km (0.6), 25 km (0.3)and 30 km (0.1).

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

The width of an event is essentially the width of a dike, estimated to be 0.5 to 1 m (Delaney and Gartner, 1995). In the case of "ballooning" of dikes near the surface, the maximum width is 2 m.

The expected orientation of events is parallel to the alignment of the 1 Ma Crater Flat cones: N25E, with a 90% confidence bound of ±30 degrees.

In modeling the geometry of an event, the eruption locality is considered to be randomly placed relative to the location along the dike, i.e., a dike propagating towards the surface is equally likely to reach the surface at any point along its dimension.

HYDROMAGMATIC ACTIVITY AND TYPE OF ERUPTION

Based both on the nature of eruptive activity in the YMR and in other areas of the Basin and Range (M. Sheridan presentation at PVHA Workshop 3), the most likely event (95% probability) would be another small cinder/scoria cone accompanied by small-volume flows, such as at Crater Flat and Lathrop Wells. Dike injection, of course, would accompany an eruption. The post-caldera activity in the YMR shows no particular tendency towards hydromagmatic eruptions; however, the trend towards a decreasing degree of partial melting increases the likelihood of a volatile, charged eruption. Maar-forming events, however, are rather rare in the Basin and Range (e.g., M. Sheridan presentation at PVHA Workshop 3). The probability of a Plinian event is <5%: 3% of which might be a maar-type eruption (includes hydromagmatic events), 1% large-volume tholeiitic event, and 1% a rhyolitic event.

Richard Carlson
4/12/96

REFERENCES

Atwater, T., 1970, Implications of plate tectonics for the Cenozoic tectonic evolution of western North America: Geological Society of America Bulletin: v. 81, p. 3513-3535.

Bennett, V.C., and DePaolo, D.J., 1987, Proterozoic crustal history of the western United States as determined by neodymium isotopic mapping: Geological Society of America Bulletin: v. 99, p. 674-685.

Carlson, R.W., and Hart, W.K., 1987, Crustal genesis on the Oregon Plateau: Journal of Geophysical Research: v. 92, p. 6191-6206.

Champion, D.E., 1991, Volcanic episodes near Yucca Mountain as determined by paleomagnetic studies at Lathrop Wells, Crater Flat, and Sleeping Butte, Nevada: Proceedings, High-Level Radioactive Waste Management, Las Vegas, Nevada, American Nuclear Society, v. 1, p. 61-67.

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

Christiansen, R.L., Lipman, P.W., Carr, W.J., Jr., Byers, F.M., Orkild, P.P., and Sargent, K.A., 1977, The Timber Mountain-Oasis caldera complex of southern Nevada: Geological Society of America Bulletin, v. 88, p. 943-959.

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

Cross, T.A., and Pilger, R.H., 1978, Constraints on absolute motion and plate interaction inferred from Cenozoic igneous activity in the western United States: American Journal of Science, v. 278, p. 865-902.

Crowe, B., and Perry, F.V., 1989, Volcanic probabilities calculations for the Yucca Mountain site: estimation of volcanic rates: Proceedings, Nuclear Waste Isolation in the Unsaturated Zone, Focus '89, American Nuclear Society, v. 2, p. 326-334.

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

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

Eaton, G.P., 1982, The Basin and Range province: origin and tectonic significance: Annual Reviews of Earth Planetary Science, v. 10, p. 409-440.

Evans, J.R., and Smith, M., III, 1992, Teleseismic tomography of the Yucca Mountain region: volcanism and tectonism: Proceedings, Third International High Level Radioactive Waste Management Conference, American Nuclear Society, v. 2, p. 2371-2380.

Farmer, G.L., and DePaolo, D.J., 1983, Origin of Mesozoic and Tertiary granite in the western United States and implications for pre-Mesozoic crustal structure: Nd and Sr isotopic studies in the geocline of the northern Great Basin: Journal of Geophysical Research, v. 88, p. 3379-3401.

Farmer, G.L., Perry, F.V., Semken, S., Crowe, B., Curtis, D., and DePaolo, D.J., 1989, Isotopic evidence on the structure and origin of subcontinental lithospheric mantle in southern Nevada: Journal of Geophysical Research, v. 94, p. 7885-7898.

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

Jones, J.H., Wernicke, B.P., Farmer, G.L., Walker, J.D., Colman, D.S., McKenna, L.W., and Perry, F.V., 1992, Variations across and along a major continental rift: an interdisciplinary study of the Basin and Range province, western USA: Tectonophysics, v. 213, p. 57-69.

Langenheim, V.E., Kirchoff-Stein, K.S., and Oliver, H.W., 1993, Geophysical investigations of buried volcanic centers near Yucca Mountain, southwest Nevada: Proceedings, High-Level Radioactive Waste Management Conference, Las Vegas, NV, American Nuclear Society, v. 2, p. 1840-1846.

Leeman, W.P., and Fitton, J.G., 1989, Magmatism associated with lithospheric extension: Journal of Geophysical Research, v. 94, p. 7682-7684.

Perry, F.V., Baldridge, W.S., and DePaolo, D.J., 1987, Role of asthenosphere and lithosphere in the genesis of late Cenozoic basaltic rocks from the Rio Grande Rift and adjacent regions of the southwestern United States: Journal of Geophysical Research, v. 92, p. 9193-9213.

Scott, R.B., 1990, Tectonic setting of Yucca Mountain, southwest Nevada, *in* B.P. Wernicke (ed.), Basin and Range Extensional Tectonics Near the Latitude of Las Vegas, Nevada: Geological Society of America Memoir 176, p. 251-282.

Severinghaus, J., and Atwater, T., 1990, Cenozoic geometry and thermal state of the subducting slabs beneath western North America, *in* B.P. Wernicke (ed.), Basin and Range Extensional Tectonics Near the Latitude of Las Vegas, Nevada: Geological Society America Memoir 176, 1022 p.

Sheridan, M.F., 1992, A Monte Carlo technique to estimate the probability of volcanic dikes: Proceedings, High-Level Radioactive Waste Management, Las Vegas, NV, American Nuclear Society, v. 2, p. 2033-2038.

Vaniman, D.T., Crowe, B.M., and Gladney, E.S., 1982, Petrology and geochemistry of hawaiite lavas from Crater Flat, Nevada: Contributions to Mineralogy and Petrology, v. 80, p. 341-357.

Walker, G.P.L., 1987, The dike complex of Koolau volcano, Oahu: internal structure of a Hawaiian rift zone: U.S. Geological Survey Professional Paper 1350, p. 961-993.

Wells, S.G., Crowe, B.M., and McFadden, L.D., 1992, Measuring the age of the Lathrop Wells volcanic center at Yucca Mountain: Science, v. 257, p. 555-558.

Wells, S.G., McFadden, L.D., Renault, C.E., Turrin, B.D., and Crowe, B.M., 1990, A geomorphic assessment of Quaternary volcanism in the Yucca Mountain area, Nevada Test Site, southern Nevada: implications for the proposed high-level radioactive waste repository: Geology, v. 18, p. 549-553.

TABLE RC-1
RICHARD W. CARLSON - EVENT COUNTS

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

TABLE RC-2
RICHARD W. CARLSON - RATES OF OCCURRENCE

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

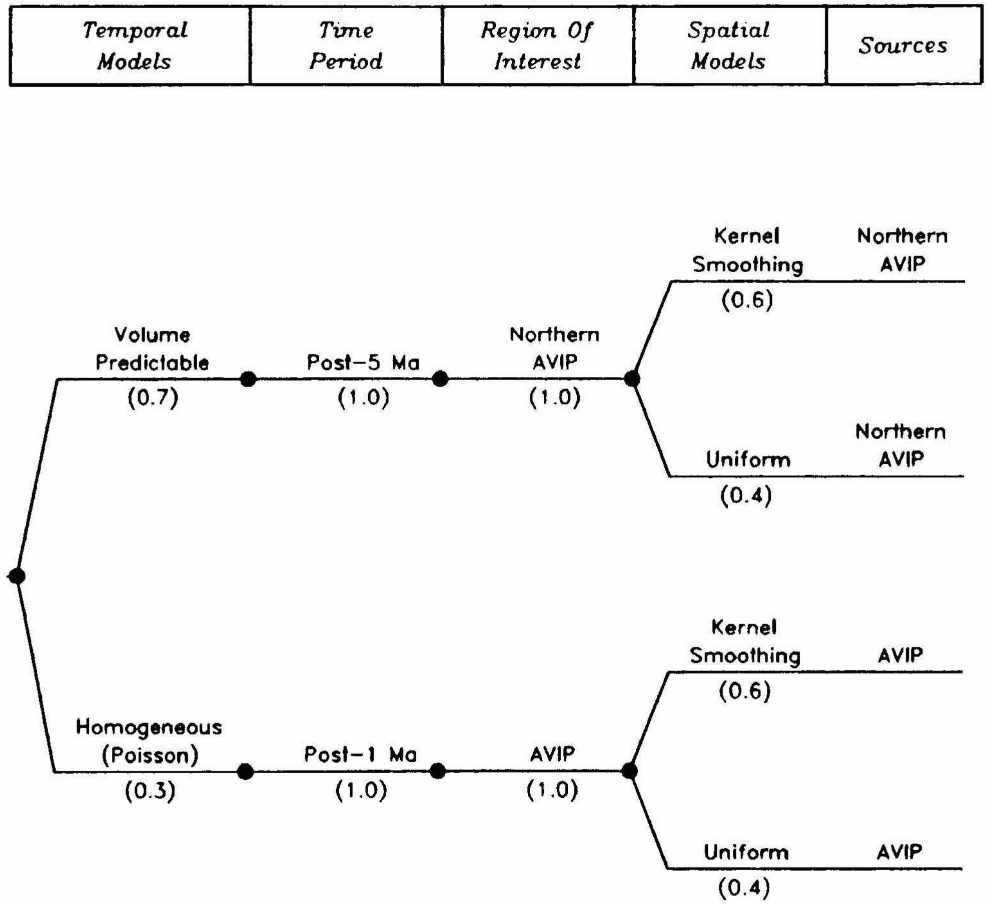
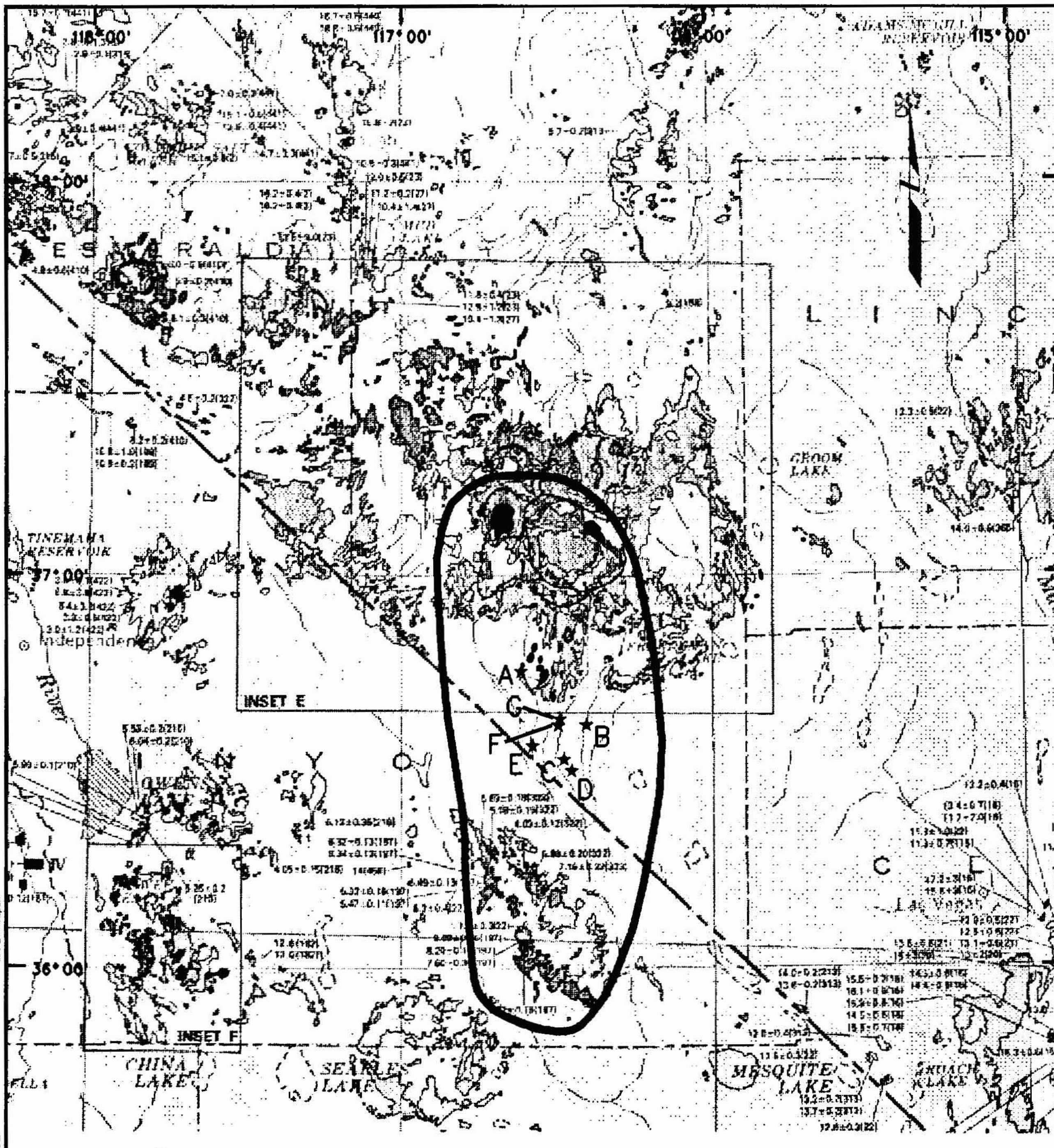


Figure RC-1 PVHA model logic tree developed by Richard W. Carlson.



B★ Aeromagnetic Anomaly

⊘ Proposed Repository

0 25 50
SCALE IN KILOMETERS

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

GEOMATRIX	RICHARD W. CARLSON REGIONAL BACKGROUND ZONE: AVIP	Figure RC-2 PVHA Project

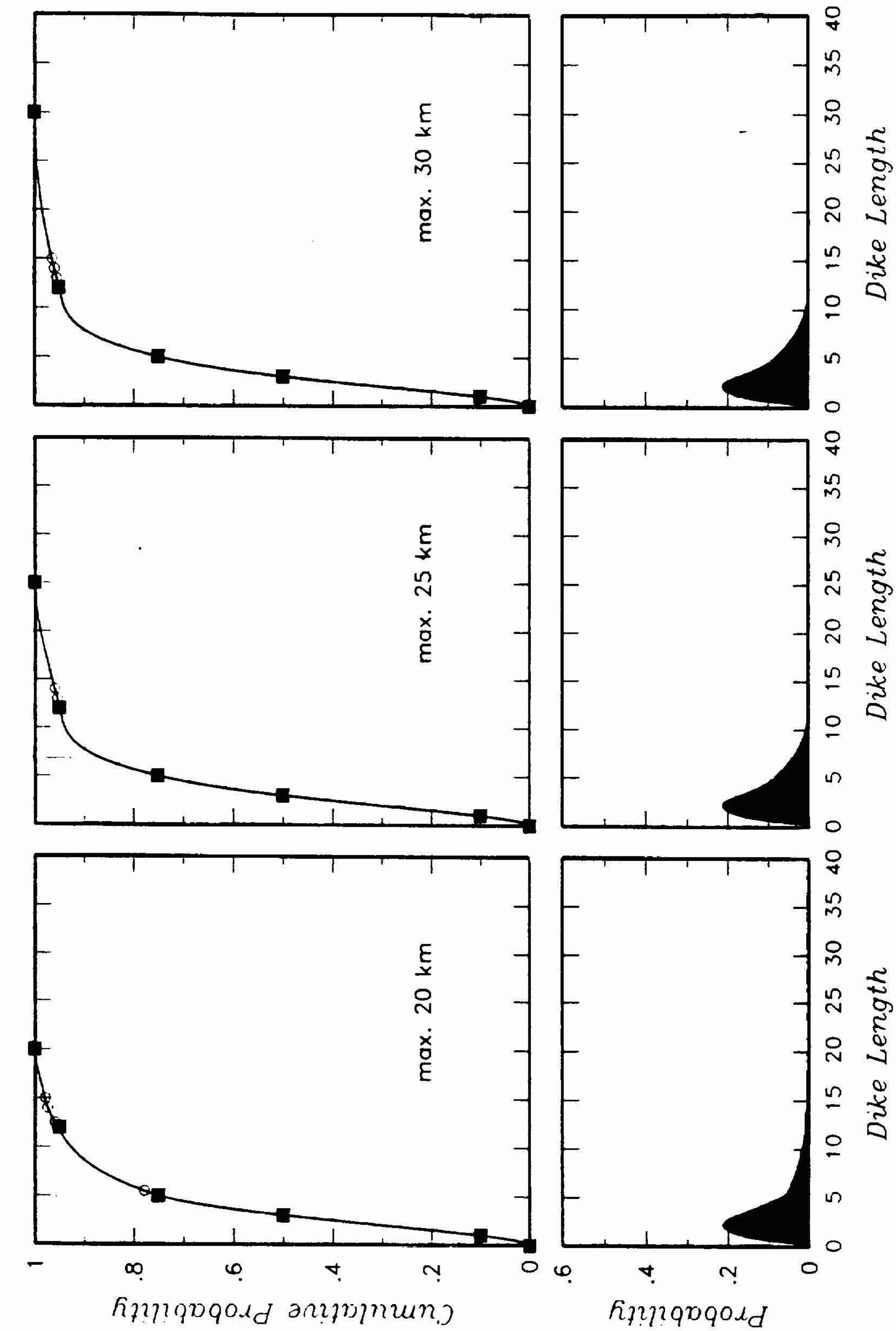


Figure RC-3 Dike length distribution developed by Richard W. Carlson.

BRUCE M. CROWE
ELICITATION INTERVIEW FOR PVHA PROJECT

VOLCANIC/TECTONIC SETTING

The southwest Nevada volcanic field (SWNVF; Christiansen et al., 1977; Byers et al., 1976; 1989) experienced maximum extension and silicic volcanism during the period of about 16 to 11 Ma (Crowe et al., 1995, Chapters 2 and 3). Subsequently, areas of intense tectonism and volcanism migrated outward to the eastern and western edges of the Great Basin. Silicic volcanism ceased in the central and southern part of the SWNVF after eruptive activity of the Black Mountain caldera complex (8-9 Ma; Crowe and Sargent, 1979; Crowe, 1990; Crowe et al., 1995). Voluminous basaltic volcanism accompanied and was probably the driving force (thermally and magmatically) for the generation of the large volume silicic volcanism but basaltic volcanism rarely appeared in the surface eruptions probably because of density trapping beneath the cogenetic silicic magmas. Evidence of cogenetic basaltic and silicic magmas is suggested primarily by the rare occurrences of basalt as very minor components in the strongly compositionally zoned ash-flow sheets (for example as lithic fragments in ash-flow deposits, thin hydrovolcanic layers in the Plinian phases of the ash-flow cycles of the Timber Mountain Tuff). Eruptions of basaltic volcanic rocks became more important volumetrically in the waning phases of activity of the SWNFV (late Miocene) probably as a result of solidification of the silicic magma chambers so that they no longer functioned as density traps for ascending basalt. Subsequent late Miocene and younger volcanic activity was unrelated to the silicic volcanism and consisted of sporadic eruption of small volumes of basalt magma. These eruptions formed volcanic centers and clusters of volcanic centers over widely scattered areas of the Yucca Mountain region (YMR; see Crowe, 1990; Crowe et al., 1995). The YMR, for this elicitation, refers to the area encompassing sites of basaltic volcanism that post-date voluminous silicic volcanism in the central and southern part of the SWNVF. It is identified as the YMR when referencing the distribution area of post-9.15 Ma sites of basaltic volcanism and as the YMR/PQ when referencing the distribution area of post-5.05 Ma sites of basaltic volcanism.

The driving force for the Miocene large volume silicic volcanic activity almost certainly was from upwelling of asthenospheric mantle with generation of basaltic magma from adiabatic decompression and melting of mantle peridotite (Farmer et al., 1991; Perry et al., 1993). The origin of the late Miocene and younger basaltic volcanism in the YMR is less clear but most likely can be attributed to partial melting of a hydrous upper mantle that may or may not be related to low rates of surface extension (Best and Brimhall, 1974; Vaniman et al., 1982; Perry et al., 1987;

1993; Farmer et al., 1989; Perry and Crowe, 1992; see also Crowe, et al., 1995, Chapter 4, and the PVHA Elicitation Interview for R. Carlson, this report).

Two major episodes of Miocene and younger basaltic volcanic activity are recognized in the SWNFV and the YMR following the subdivisions of Crowe (1990). These are basaltic volcanic rocks of the silicic episode (BSE) and postcaldera basalt (PCB). The BSE are judged not to be relevant to probabilistic volcanic hazard assessment (PVHA) because of their Miocene age and their formation during a different tectonic setting than the modern setting for the YMR (Crowe, et al., 1995, Chapter 3). The PCB are divided into two cycles (Crowe, 1990) and include the older postcaldera basalt (OPB) and younger postcaldera basalt (YPB). The OPB are judged to be of limited significance to PVHA for several reasons: (1) they range in age from 9 to 6.5 Ma and because of their age are judged to be at best weak predictors of future rates and/or sites of volcanic activity, (2) they occur primarily in the north and northeast parts of the YMR away from the Yucca Mountain site, and (3) there has been time-space migration of volcanic activity recorded in the patterns of basaltic volcanism associated with the PCB (Crowe et al., 1995; Golder Associates, 1995). The OPB are considered in some aspects of PVHA (see following sections) but their inclusion leads to estimated disruption probabilities that are as low as some regional background estimates (Crowe, 1995). They therefore are assigned small weights in the PVHA. The YPB are judged to be the most important record of basaltic volcanic events for PVHA for the Yucca Mountain site and as used, include all Pliocene and Quaternary (post-5.05 Ma) basaltic volcanic centers and inferred buried volcanic centers identified from aeromagnetic data. Subintervals of the YPB are recognized that correspond to the concept of volcanic cycles (Crowe, 1990; Crowe et al., 1995) and these intervals are emphasized in the PVHA.

Working Assumptions for the PVHA

Several observations concerning the tectonic and volcanic history of the Yucca Mountain region are considered to be especially relevant to the PVHA. These include:

1. The intensity of tectonic activity has waned in the YMR since the Miocene. The detailed history of waning tectonism cannot be established since there is a gap in the preserved record of datable rocks between about 11 Ma and the Pliocene (3.7 Ma basalt of southeastern Crater Flat). However, rates of extension in the Pliocene and Quaternary are dramatically less than extension rates in the Miocene (Carr, 1984; Scott, 1990; Fridrich, 1995).

2. The source region for generation of basaltic magmas during the Miocene, Pliocene, and Quaternary is the lithospheric mantle based on inferences from

isotopic and geochemical data for basaltic volcanic rocks (Vaniman et al., 1982; Farmer et al., 1989; Crowe et al., 1995, Chapter 4).

3. Geophysical data show that the upper mantle in the continental interior including the southern Great Basin is of higher temperature with decreased density compared to coastal areas to the west and cratonal areas to the east (Humphreys and Dueker, 1994). The upper mantle rocks of the southern Great Basin and perhaps many areas of the Basin and Range province probably contain a small degree of partial melt and are capable of generating small volumes of basalt magma (Crowe et al., 1995, Chapters 3 and 4).

4. The YMR is located at the north edge of an amagmatic gap, an area that experienced no or very limited Cenozoic volcanic activity during extensional deformation (Farmer et al., 1989; Jones et al., 1992; Crowe et al., 1995). The amagmatic gap coincides spatially with and may be associated with an area of preserved ancient lithospheric mantle (Farmer et al., 1989).

5. The most active areas of volcanism in the southern Great Basin (recurrence rates, erupted volumes) are at the eastern and western margins of the province (Suppe et al., 1975; Smith and Luedke, 1984). Rates of basaltic volcanic activity in the interior and less active parts of the southern Great Basin are much lower and it is more difficult to relate the location of basalt centers in the less active areas to individual faults or tectonic features (Crowe et al., 1986; 1995).

6. There has been time-space migration of post-9.15 Ma basaltic volcanism in the YMR and this migration is characterized by a southwest stepping or southwest drift of areas of activity (Crowe et al., 1995; Golder Associates, 1995). The region and age of volcanic activity of most relevance to PVHA for the Yucca Mountain site is the area defined by the distribution of basaltic volcanic centers 5.05 Ma and younger. This area can be defined in different ways dependent on geologic interpretations of the volcanic record. Examples of alternative areal definitions include the Crater Flat volcanic zone (CFVZ; Crowe and Perry, 1989), the Area of Most Recent Volcanism (Smith et al., 1990) and the YMR/PQ (defined above, also see Crowe et al., 1995, Chapters 2 and 3).

7. Ascent of basaltic magma in the YMR may follow deeper seated structural features such as buried strike-slip faults of the Walker Lane system (Crowe and Perry, 1989; Schweickert, 1989), or ring-fracture systems of Miocene caldera complexes (Crowe and Carr, 1980).

8. Quaternary basaltic volcanic centers in the YMR/PQ and interior areas of the Basin and Range province tend to occur more commonly in alluvial basins than range interiors. This may be because the alluvial basins represent areas of low