CNWRA 94-014

SEISM 1.1 TEST ANALYSIS

Prepared for

Nuclear Regulatory Commission
Contract NRC-02-93-005

Prepared by

Center for Nuclear Waste Regulatory Analyses
San Antonio, Texas

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Renner B. Hofmann

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PREVIOUS REPORTS IN SERIES

Number	Name	Date Issued
1	Identification of Pertinent Regulatory Requirements for Systematic Regulatory Analysis of Issues Related to Probabilistic Fault Displacement and Seismic Hazard Analysis in 10 CFR Part 60	February 1991
2	Probabilistic Fault Displacement and Seismic Hazard Analysis Literature Review (CNWRA 91-013)	November 1991
3	Assessment of Requirements for Exercising the SEISM Code on Computer Systems Available to the CNWRA	May 1992
4	Selection of Alternate Acceleration Attenuation Functions for the Basin and Range	August 1992
5	SEISM 1 Code Modifications and Application: Assessment of Needed Effort	August 1992
6	Regulatory History and Intent for Probabilistic Fault Displacement and Seismic Hazard Analysis (PFD&SHA)	September 1992
7	Probabilistic Fault Displacement and Seismic Hazard Analysis Literature Assessment. (CNWRA 91-013, Rev. 1)	February 1993
8	SEISM 1 Code: Adaptations for Use in the Western U.S.	May 1993

ABSTRACT

SEISM 1, the U.S. Nuclear Regulatory Commission (NRC) Office of Nuclear Reactor Regulation (NRR) Probabilistic Seismic Hazard Analysis Code, was developed by the Lawrence Livermore National Laboratory (LLNL) to determine seismic risk for nuclear power plants in the eastern United States. This code has been modified by the Center for Nuclear Waste Regulatory Analyses (CNWRA) to function for sites in the western U.S. and on CNWRA SUN workstations (Hofmann, 1992b; Hofmann and Bangs, 1993). The purpose of the test analyses described in this report was to provide error-message free calculations of seismic and fault displacement hazards using data from the Yucca Mountain (YM) region. The analyses were not intended to provide a benchmark of probabilistic seismic or fault hazard for YM.

A preliminary test analysis comprised the Shearon-Harris nuclear power plant (NPP) test problem provided by LLNL, with all site and source zone longitudes shifted 35° to the west. A more comprehensive test analysis using data from the YM area was also devised to test the functionality of the code with western United States attenuation functions and narrow source zones to approximate faults. A high-level nuclear waste (HLW) repository currently is required to have performance assessed for a period of 10,000 yr. Earthquake history in the United States is too recent to provide a reliable estimate for such an extended period based on historical earthquake recurrence intervals. Consequently, published interpretations or opinions of paleofault offsets were used as a basis for long-term seismicity in the test analysis for the YM area. Published rates of fault displacement were usually generalized from large data sets or geomorphic information. The code requires multiple expert opinions regarding seismic source zones, earthquake recurrence, and vibratory-ground-motion attenuation functions. Expert opinion inputs are also required for a self appraisal of the likelihood that the estimate or alternate estimate is correct. For this test analysis, source zones (faults thought to have Quaternary activity) were taken from the literature. Maximum magnitudes and earthquake recurrences were estimated by different means or from various sources as though they were differing expert opinions. The "experts," whose opinions comprise the published information are termed "pseudo-participants" in this report because they were not directly elicited. Sources of information were Coppersmith et al. (1993), U.S. Department of Energy (1988), Somerville et al. (1987), Rogers et al., (1977), Campbell (1987), Douglas and Ryall (1975), Joyner and Boore (1981), Atkinson (1982), and Schnabel and Seed (1973). The differences in times of publication provided some insight into the assumption that the addition of new information will not greatly perturb a probabilistic analysis.

SEISM 1.1 output is a hazard curve that depicts the annual probabilities of various ground accelerations anticipated at a site. Probabilistic design spectra may also be expressed in hazard curve form by using other attenuation functions. The data and interpretations used in this analysis suggest that a 1 in 10,000 yr event could produce a 0.6 g acceleration at the center of the repository (50th percentile or mean of the probability distribution function) or 0.9 g based on the best estimates for input data supplied by the pseudo-participants. As more and better data become available, this value is likely to change. Proper elicitation of contemporary experts with currently available or soon to become available data will also be likely to change this value, perhaps by a significant factor. The test computation suggests that the SEISM 1.1 code functions appropriately for use with data derived from published sources regarding the area around YM, Nevada. However, the code has not been quality assured at this time.

A procedure to use SEISM 1.1 to provide an estimate of the hazard (annual probability) of various amounts of displacement on a specified fault is implemented. The method uses relationships between earthquake magnitude, rupture area, and fault displacement.

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This report was prepared to document work performed by the CNWRA for the NRC under contract NRC-02-93-005. Activities reported here were performed for the NRC Office of Nuclear Material Safety and Safeguards, Division of Waste Management (DWM). This report is an independent product of the CNWRA and does not necessarily reflect the views or regulatory position of the NRC. Opinions expressed are intended to apply only to the application of probabilistic seismic hazard analysis (PSHA) codes to a high-level nuclear waste (HLW) repository.

QUALITY OF DATA, ANALYSES AND CODE DEVELOPMENT

DATA: Data used in this report was obtained from published literature or provided by the LLNL with the SEISM 1 code. These data have not been quality assured by the CNWRA. Sources for the data should be consulted for determining the level of quality for those data.

ANALYSES AND CODES: The SEISM 1.1 computer code and the commercially available MATLAB program were used in this analysis. This report describes development of version 1.1 of the SEISM code, however, the code has not been sufficiently developed to be placed under the CNWRA Configuration Management System. MATLAB and other incidental plotting programs used in the preparation of this report are commercial programs whose source code is not available, and therefore, are not under CNWRA's Configuration control.

LIST OF ACRONYMS, SYMBOLS, AND NON-STANDARD TERMS

3D	Three dimensional
A	Acceleration
a	The "intercept" term for an earthquake recurrence function
ave.	Average
ACNW	Advisory Committee on Nuclear Waste, an oversight committee for NRC HLW matters
AMHC	Arithmetic Mean of Hazards Curve
ARC/INFO	A proprietary commercial computer program for the archival and retrieval of geographic information using arcs and nodes
ASLB	Atomic Safety and Licensing Board of the NRC
b	The slope term for an earthquake recurrence function
BE	Best Estimate
BEHC	Best Estimate Hazard Curve
CDRZ	Closest Distance to an earthquake Rupture Zone
CDS	Compliance Determination Strategy
CFR	Code of Federal Regulations
cm	Centimeter
CNWRA	Center for Nuclear Waste Regulatory Analyses
CP	Constant Percentile
CPHC	Constant Percentile Hazard Curve
DWM	NRC Division of Waste Management
DOD	Department of Defense
DOE	Department of Energy
EPA	Environmental Protection Agency

LIST OF ACRONYMS, SYMBOLS, AND NON-STANDARD TERMS (Cont'd)

Epicentral Distance	Distance to the point on the earth directly above the initiation of an earthquake
EPRI	Electric Power Research Institute
g	Unit of gravitational attraction, equivalent to 980 cm/s^2
GM	Ground Motion
GS	Geologic Setting Element, an administrative subdivision of the CNWRA
GUI	Graphical User Interface
G-XPRT	Ground motion expert — also equivalent to an acceleration attenuation function as used in this report and as displayed in SEISM code output
HLW	High-Level Nuclear Waste
Hypocentral Distance	Distance to the underground initiation point of an earthquake
IMSL	International Mathematical and Scientific Library of functions
ISB	Intermountain Seismic Belt
km	Kilometer
KTU	Key Technical Uncertainty
LANL	Los Alamos National Laboratory
LARP	License Application Review Plan for a HLW repository
LLNL	Lawrence Livermore National Laboratory
m	meters
M	Richter magnitude
M_O	Seismic moment
M_L	Richter local magnitude
M_{Max}	Maximum magnitude

LIST OF ACRONYMS, SYMBOLS, AND NON-STANDARD TERMS (Cont'd)

MMI	Modified Mercalli damage Intensity
M_S	20-s surface wave magnitude
M_W	Moment magnitude
N	Number of earthquakes of a specified magnitude
NAS	National Academy of Sciences
N_C	Number of earthquakes equal to or greater than a specified magnitude
near-field	A distance less than a fault dimension
NEHRP	National Earthquake Hazard Reduction Program
NMSS	NRC Office of Nuclear Material Safety and Safeguards
NPP	Nuclear Power Plant
NRC	Nuclear Regulatory Commission
NRR	NRC Office of Nuclear Reactor Regulation
NTS	Nevada Test Site
NV	Nevada
NWTRB	Nuclear Waste Technical Review Board, a Congressional oversight committee for DOE HLW matters
PA	Performance Assessment
PC	Personal Computer
PFD&SHA	Probabilistic fault displacement and seismic hazard analysis
Pseudo-participant	An artificial expert whose opinions are derived from published literature
PSHA	Probabilistic Seismic Hazard Analysis
QA	Quality Assurance

LIST OF ACRONYMS, SYMBOLS, AND NON-STANDARD TERMS (Cont'd)

RES	NRC Office of Nuclear Regulatory Research
RSSF	The Proposed NTS Remote Spent Fuel Storage Facility
R or r	Distance
R_{rp}	SPRZ distance
RV	Random Vibration
s	Second
S	Fault slip area
Saturation	The failure of a particular magnitude scale to increase with increasing earthquake energy
SEISM 1	A PSHA computer code developed for NRR by LLNL for the analysis of seismic hazard at eastern U.S. NPPs
SEISM 1.1	SEISM 1 modified by CNWRA to evaluate seismic and fault displacement hazards for HLW repository sites in the western U.S.
SEISM 1.x	Potential future version of SEISM 1
SEP	NRC's Systematic Evaluation Program
SHC	The LLNL Seismic Hazard Codes. A recent version is SEISM 1.
SPRZ	Closest distance to the surface projection of a fault rupture zone
SSMRP	NRC Seismic Safety Margins Research Program
SSSP	NRC Site Specific Spectra Project
SwRI	Southwest Research Institute
TOP	CNWRA Technical Operating Procedure
UNV/R	University of Nevada at Reno

1 INTRODUCTION

A probabilistic seismic hazard analysis (PSHA) code, SEISM 1, was acquired from the Lawrence Livermore National Laboratory (LLNL). This code was developed by LLNL for the Nuclear Regulatory Commission (NRC) Office of Nuclear Reactor Regulation (NRR) to assess probabilistic seismic risk for nuclear power plants (NPP) in the eastern United States. The Center for Nuclear Waste Regulatory Analyses (CNWRA) was assigned the task of adapting the code to its computers and modifying the code to evaluate effects of proposed seismic and tectonic models on seismic and fault displacement hazards at the potential high level nuclear waste (HLW) repository at Yucca Mountain (YM) Nevada. This report is one in a series describing the process of adapting the SEISM 1 code for use in analyses of the potential YM HLW site. Test calculations to affirm that the adaptations implemented by the CNWRA are performing correctly and recommendations for further development are described.

1.1 PURPOSE

The purpose of this project was modification of the SEISM 1 code to permit its use in the analyses of seismic and fault displacement hazard for a western United States site. This code would contribute to quantification and possible reduction of key technical uncertainties (KTUs) associated with several earthquake related potentially adverse conditions designated in 10 CFR Part 60, the NRC Federal Regulation applicable to HLW repositories. The KTUs are specific to the YM, Nevada site.

Concern with Section 60.122(c)(12-14) (Nuclear Regulatory Commission, 1992a, b), that is, siting criteria, potentially adverse conditions, and specific references to earthquakes, respectively, were the primary motivations for initiation of this project. Other sections of Part 60 that also relate to or allude to seismic and related concerns are:

- Content of Application, Safety Analysis Report, Description and assessment of the site [60.21(c)(1)(i)(A) and (B), and (ii)(A) and (C)];
- Permanent Closure [60.51(a)(3)];
- General design criteria, Protection against natural phenomena [60.131(b)(1)];
- Additional design criteria for the underground facility [60.133(a)(2), (b), and (g)(2)];
- Performance Confirmation and Processes Pertaining to the Geologic Setting, General requirements, parameters and processes pertaining to the geologic setting; [60.140(d)(2)];
- Confirmation of geotechnical and design parameters, rock deformations and displacement [60.141(c)].

Hofmann (1992c) has more thorough discussion of the applicable sections of Part 60 that were of concern upon initiation of this project by the NRC Division of Waste Management (DWM).

The U.S. Department of Energy (1988) stated that probabilistic methods would be used to develop faulting and seismic design criteria for the proposed YM project. Environmental Protection Agency (EPA) requirements for radionuclide releases are in probabilistic terms in the EPA currently remanded regulation and in proposed revisions. The NRC 10 CFR Part 60 and the DOE 10 CFR Part 960 regulations include the EPA regulation by reference. By inference, the probabilities of exceeding design criteria and consequent effects on radionuclide release must be known. Probabilistic fault displacement and seismic hazard analysis (PFD&SHA) methodologies provide a means of estimating the first of these probabilities. Seismic risk and probabilities of fault displacement presented in a license application or in hearings must be analyzed by regulatory staff. The SEISM 1.x codes, after adaptation to HLW repository requirements, provide a means of expeditiously performing such analyses. The efforts reported here are intended to provide a version of the SEISM code that can be used for this purpose in conducting prelicensing reviews.

An exploration of the concept of PFD&SHA as it applies to the much longer times of performance concern for a HLW repository was deemed prudent, if not critical, to meet the limited 3-yr license review time required of the NRC for a HLW repository.

Compliance Determination Strategies (CDSs) (Nuclear Regulatory Commission 1992b and 1993a, b) were developed by the NRC and the CNWRA for earthquake-related adverse conditions. KTUs were found for several of the earthquake-related potentially adverse conditions. Where such uncertainties existed, NRC research and independent analyses are anticipated to be required to resolve related licensing issues before submission of the license application if the 3-yr schedule for licensing is to be met.

The CDSs corresponding to 60.122(c)(12-14) address (i) Historical Earthquakes, (ii) More-Frequent/Higher Magnitude Earthquakes, and (iii) Correlation of Earthquakes with Tectonic Processes. KTUs as described in these CDSs are:

- "The inability to predict the likelihood of earthquake occurrence over the next 10,000 years."

- "Paleofaulting data indicates that seismic activity has migrated randomly from one major range front fault system to another in the Basin and Range tectonic province. Therefore there is considerable uncertainty that the relatively low seismicity at YM will continue over a 10,000 year period."

- "Many fault plane solutions from the historical seismic record do not agree with the fault movement indicated by striae (slickensides) on exposed fault planes, therefore fault movement, earthquake strong motions and their radiation patterns, which will be used in tectonic models are uncertain."

- "Correlation of earthquakes with tectonic features" (*the lack thereof*).

Other KTUs, applicable to a broad range of CDSs, whose uncertainty may be at least partially quantified through PFD&SHA are:

- "Predicting long-term performance of seals for the underground test boreholes"

- "Variability (temporal, spacial, etc.) in model parametric values"

- "Prediction of future system states (i.e., disruptive scenarios)"

The reasons for research and independent analysis to reduce or quantify uncertainties in the KTUs are summarized in the CDS for correlation of earthquakes with tectonic processes:

(1) Quantitative knowledge about tectonic processes, including the ability to predict the occurrence of earthquakes for the next 10,000-yr or the ability to correlate earthquakes with known structures, in the YM area is, and will most likely remain, uncertain;

(2) Alternative conceptual models for tectonic processes will remain at the time of licensing;

(3) The alternative models for addressing both the probability of tectonic activity and potential effects from this activity may span several orders of magnitude;

(4) No proven method currently exists for extrapolating relatively short-term seismic data and experience to the long performance periods (i.e., 10,000 yr) required for a geologic repository; and

(5) The effects of tectonic activity on the ability to demonstrate compliance with the overall system and subsystem performance objectives will be highly contentious during licensing.

These items all lie at the cutting edge of current technology, yet they are critical to the resolution of licensing the nation's first HLW repository. It is expected that the DOE, which is in the process of developing its license application, will address these issues. However, because these issues are at the state-of-the-art in their resolution and are controversial among well-qualified investigators, the NRC must be cognizant of and capable in these technical areas. Methods and tools (e.g., computer codes) capable of assessing arguments presented by the licensee and those in opposition, are of great potential benefit. A method of quantifying such uncertainties is through probabilistic methods with input from well qualified experts in appropriate academic or technical fields. This method requires the input of expert opinions regarding the interpretation of available or reasonably obtainable data and its application in a probabilistic analysis system that is known to function properly. Without a probabilistic seismic and fault displacement analysis (PFD&SHA) tool, and experience in using it to analyze the considerable data being developed by the DOE, presentation of regulatory staff findings may be less effective. In addition to the Atomic Safety and Licensing Board (ASLB), staff may also be required to defend their findings before the Advisory Committee on Nuclear Waste (ACNW) and possibly the Nuclear Waste Technical Review Board (NWTRB), which oversees DOE activities. Recent involvement of the National Academy of Sciences in probabilistic seismic hazard analysis (PSHA) methodologies may require a defense before that body as well as the occasional Congressional subcommittee hearing convened to consider nuclear matters.

A thorough investigation of probabilistic methods is vital to a timely resolution of geoscience licensing activities. A concerted effort is required to ensure that probabilistic methodologies are properly framed and developed for the unique problems that are encountered by a long term development of a HLW repository with a 10,000-yr period of performance concern. Current research regarding PSHA for the NRC/NRR, the DOE and the Department of Defense (DOD) should be followed to assure that applicable developments are available to the repository licensing activity and that their impact on potential licensability is assessed. These efforts must begin early to identify those uncertainties that are particularly large and that cannot be reduced by analytical methods without concerted research efforts. The PSHA tools (computer codes and elicitation methodologies) are presently in a formative stage of development. They have been applied primarily to estimating hazards at facilities with expected lifetimes of only a few decades. Application of PFD&SHA to a HLW repository presents new problems that require technical effort to resolve.

The efforts described in this report are preliminary attempts to apply and investigate these initial probabilistic tools in their application to much longer term nuclear hazards. The entire spectrum of probabilistic tools, geoscientific data including seismology, and computer modeling of tectonic and dynamic earthquake-generating processes must be approached from the standpoint of a long term (e.g. 10,000 yr) hazard to the public. This effort cannot be performed only by the license applicant. Because of its state-of-the art content, it must be understood by the regulator, who must anticipate how to resolve such issues from the point-of-view of all parties at a licensing hearing.

1.2 BACKGROUND

Elements of the SEISM 1 code, designed only for use in the eastern United States, were modified to accommodate sites in the western United States and to adapt the program for use on CNWRA SUN system computers. A series of modifications and tests have been performed and are reported in Hofmann (1992a, b) and Hofmann and Bangs (1993). Subsequent modification to the code are in Appendix A. The eastern U.S. test example, provided with the code, yields correct output values when used with the revised code. The eastern U.S. test example, when translated to western U.S. coordinates, also provides correct test results. Spot checks of attenuation function performance were made as a consequence of the test analyses. Some of these spot checks involved hand calculations, while others were performed by the use of several different equation solver computer programs. Each element or subroutine requiring longitude as input data was tested after modification and found to be functional.

A test of the entire code, with input data for a western U.S. site, remained as a final exercise to demonstrate the functionality of the revised code. A site in the YM, Nevada, area was chosen for the test calculation because it is being currently considered as a potential site for a HLW repository. Code changes necessary to perform a western United States PFD&SHA are in Appendix A.

Input data for the SEISM codes are normally derived from the elicitation of expert opinion. Elicitations, however, are costly, and the purpose of this report is to show that the revised code worked properly rather than to provide a formal PSHA for a western U.S. site. Therefore, expert opinions were derived from the literature. The models generated from published papers are termed pseudo-participants throughout the report. Use of this term indicates that a properly conducted elicitation was not employed to develop all the input data required for the SEISM 1.1 test calculation. Self assessments of uncertainty are also required inputs to the code. When not given in the literature, these assessments were estimated by the author of this report from a comparable range of such assessments provided for the eastern U.S. studies, for example Bernreuter et al. (1989). Self estimates of an expert's expertise in the geographic region of the site (another required code input) were all deemed to be high because the information was derived from articles published on the Basin and Range tectonic province or, more specifically, YM or the Nevada Test Site (NTS). The fact that the authors published earthquake or fault offset information in this region is taken to indicate a high level of expertise.

Some uncertainty estimates were partially based on a test elicitation of fault and earthquake matters for YM to be used with a different PSHA or PFD analysis procedure. These data were published by Coppersmith et al. (1993) for the Electric Power Research Institute (EPRI).

Input data for the test analysis conducted by the CNWRA include source zones and vibratory ground motion attenuation functions. Input files for the western U.S. test analysis are in Appendix B. The attenuation functions were selected from published literature and were appropriate for the western United States. The accelerations they predict for various magnitude earthquakes were compared with 1992 Little Skull Mountain earthquake strong motion data published by Lum and Honda (1993). A preliminary analysis of these data was performed in Hofmann and Bangs (1993). Additional analyses are made in this report to clarify the complications caused by various definitions of source to site distance and peak acceleration. These test calculations evaluated hazards only in terms of peak accelerations. Other formulae for pseudo-velocity design spectra, however, could also be used.

1.3 SUMMARY

Results from test runs, whose inputs comprised various subsets of the input data in this report, indicate a well-functioning code. Previously made code modifications were shown to perform well in calculations of the test problem provided with the code. Code modifications or refinements to them that were made later than Hofmann and Bangs (1993) are in Appendix A of this report.

Regions, for example, northeast (NE), southeast (SE), north-central (NC), and south-central (SC), were defined for the eastern United States in SEISM 1. For the western United States, YM is indicated to be in the SC region. Regions are addressed in the code to permit associating an expert's weighting of his relative experience in each region. The pseudo-participants developed for this test analysis were all assumed to be fully weighted for the region in which the site was located. The use of the SC region is only to provide a required input to the code for this test. It has no other implication here.

Computations were then made with all pseudo-elicitation input. Output files from the western U.S. test analysis computations are summarized in this report. Calculations with input from all pseudo-participants had the largest uncertainties. Computations limiting the number of pseudo-participants, however, also had large uncertainties for certain combinations of pseudo-participant opinions. The use of multiple pseudo-participants produced higher aggregated design accelerations than the use of a single pseudo-participant, particularly at larger negative exponential values of risk, for example 10^{-4} to 10^{-5} per year. This effect is not pronounced, however. Design accelerations for these rare occurrences were influenced by nearby faults even though they had low probabilities of rupture. The use of more recent pseudo-participant opinions significantly increased design values over the earliest study by Rogers et al. (1977). The Rogers et al. (1977) analysis conjectured that there was sufficient uncertainty that much higher estimates were possible. The Ghost Dance fault, considered by most other published experts, had not been discovered in 1977. The test calculation used opinions expressed in the literature published over a span of years. An elicitation that employs expert opinion with the current state of knowledge would be expected to produce results that differ from these calculations. Where only opinions largely based on expert opinions in Coppersmith et al. (1993) are used, results are less divergent. However, the best estimate hazards for a 10,000-yr return period ranged from about 0.7 g to about 1.2 g. Had the experts in Coppersmith et al. (1993) supplied all the information required by this analysis rather than this author drawing some of it from other sources, results may have differed significantly.

2 CODE FUNCTIONALITY TEST

Test input provided with the SEISM 1 code (for the Shearon Harris NPP) was modified to test the functionality of the code after it was extended to accept western U.S. data. The Shearon Harris site was translated to a location in Nevada and all source zone longitudes were also moved west an equivalent amount by subtracting 35°. Figure 2-1 depicts the original test case with one expert's source zones as an example. Figure 2-2 depicts the test case translated 35° to the west. These plots were in rectilinear coordinates from a screen display file. Consequently, western boundaries of some eastern U.S. seismic source zones extend beyond the U.S. map defined for screen display and do not plot on the figure. Hazard computations, however, were not affected. Latitudes and longitudes are indicated for the margins of the map projections of Figures 2-1 and 2-2.

Results from the test calculation with shifted coordinates should be the same or very nearly the same as when the problem was calculated for the eastern United States. Results may vary a little for each calculation on a SUN workstation when identical inputs are used. This effect is described in Hofmann (1992b). The minor differences between calculations using identical inputs can be reduced below plotting resolution but with significantly longer calculation times.

Final aggregated risks calculated in the two tests appear to be virtually identical, as illustrated in Figures 2-3 and 2-4. This test provides assurance that the code is functioning properly and that there are no undiscovered variables that are not declared over the whole range of longitude desired. This test provided identical or nearly identical results for approximately 50 pages of output. A minor problem with the test input when used for western U.S. longitudes was found and corrected.

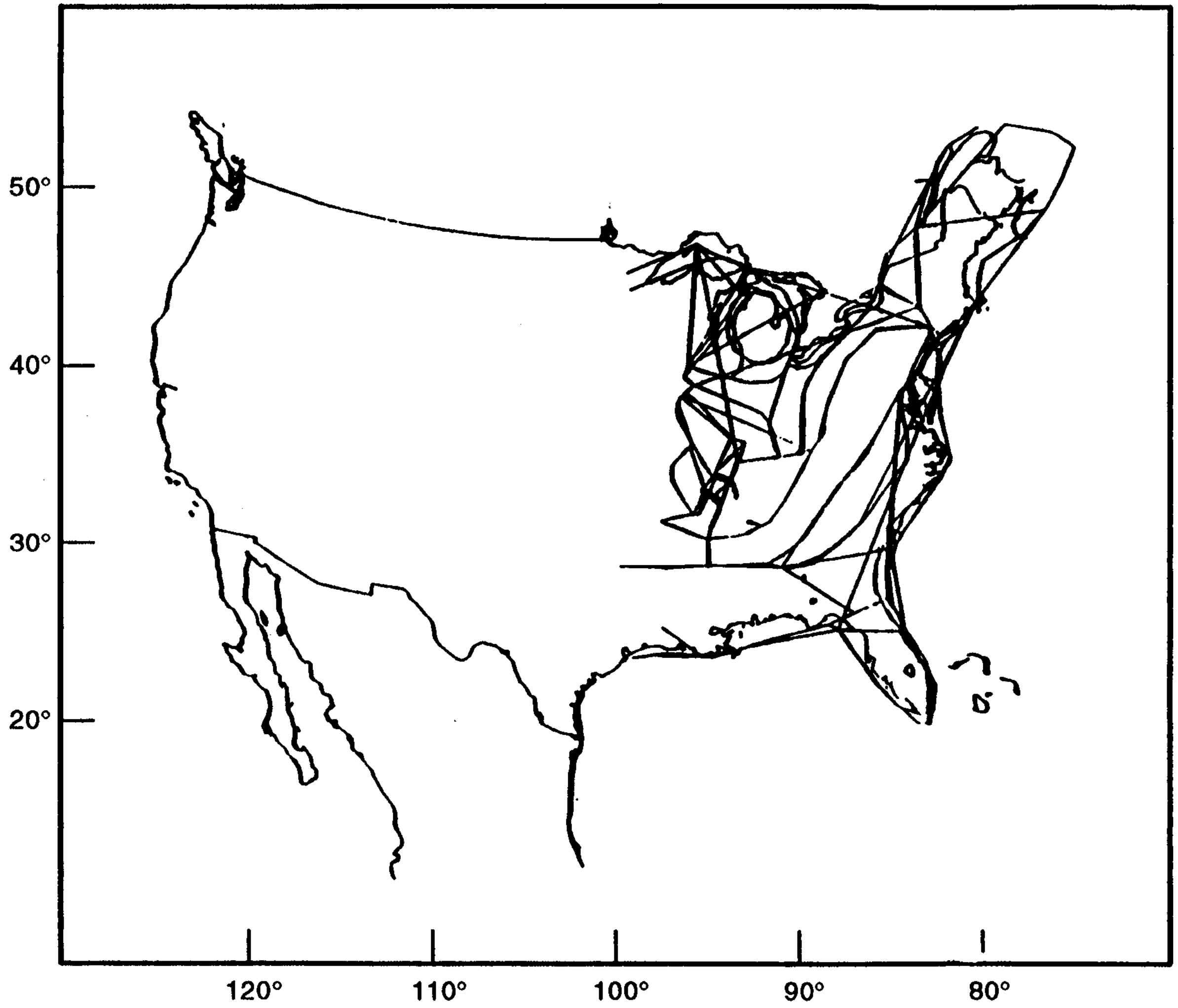


Figure 2-1. Shearon Harris nuclear power plant test problem

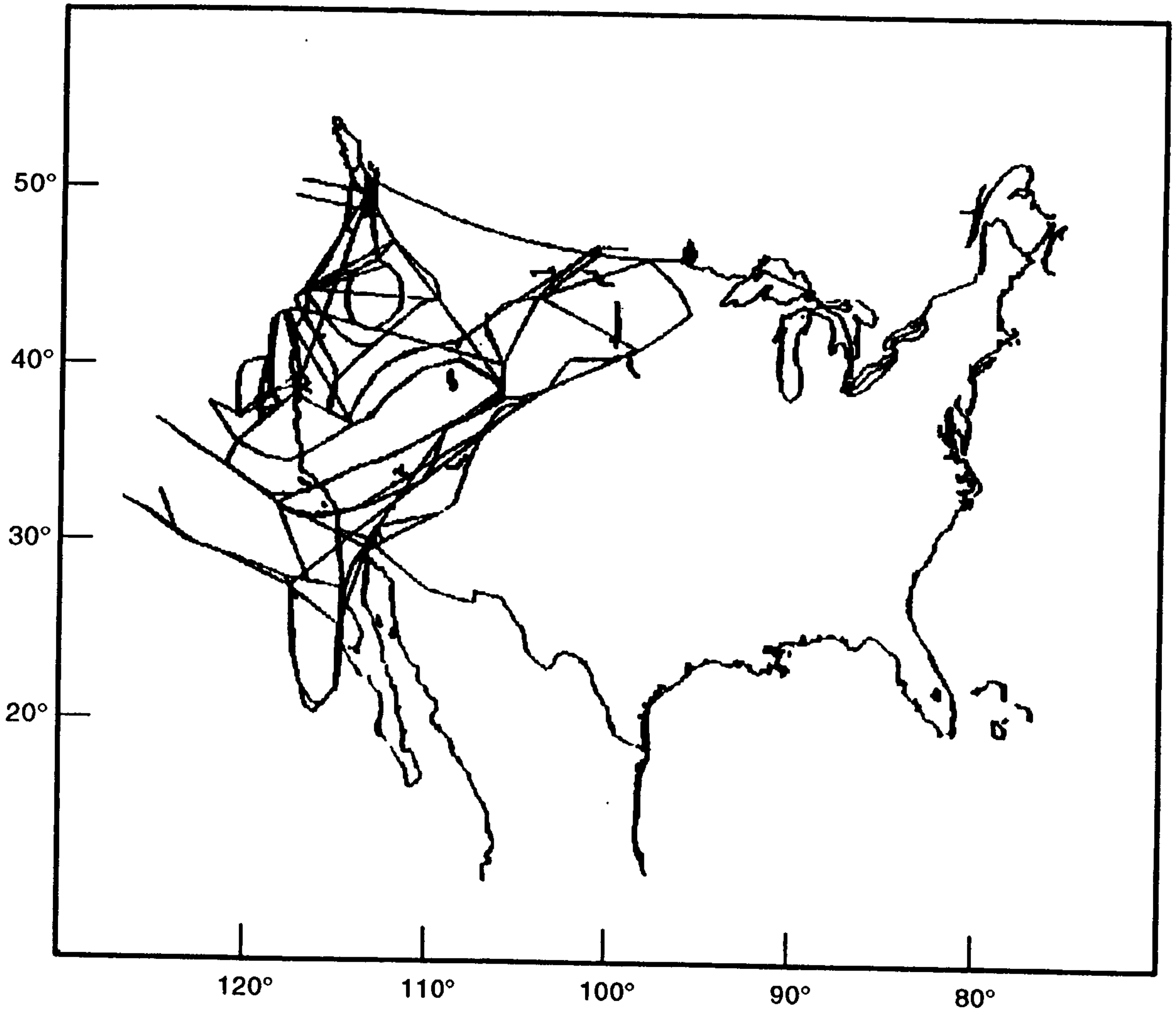


Figure 2-2. Shearon Harris nuclear power plant test problem translated to western U.S. coordinates

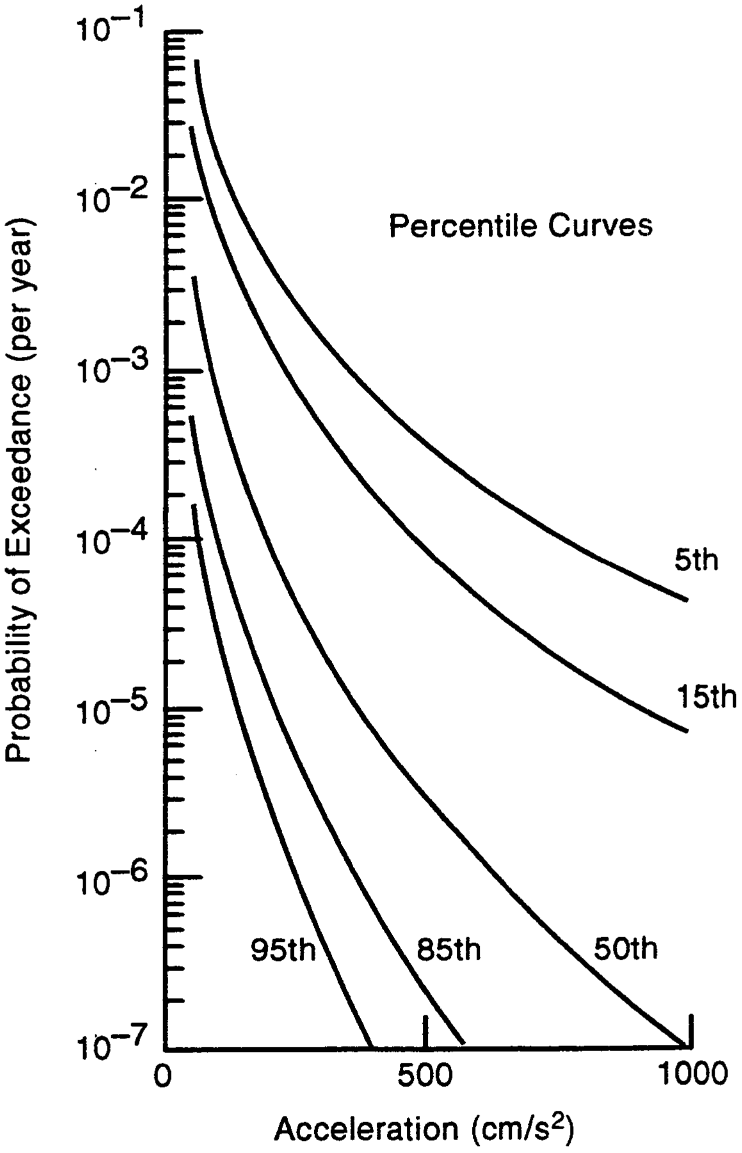


Figure 2-3. Shearon Harris aggregated risk—Eastern U.S. problem results

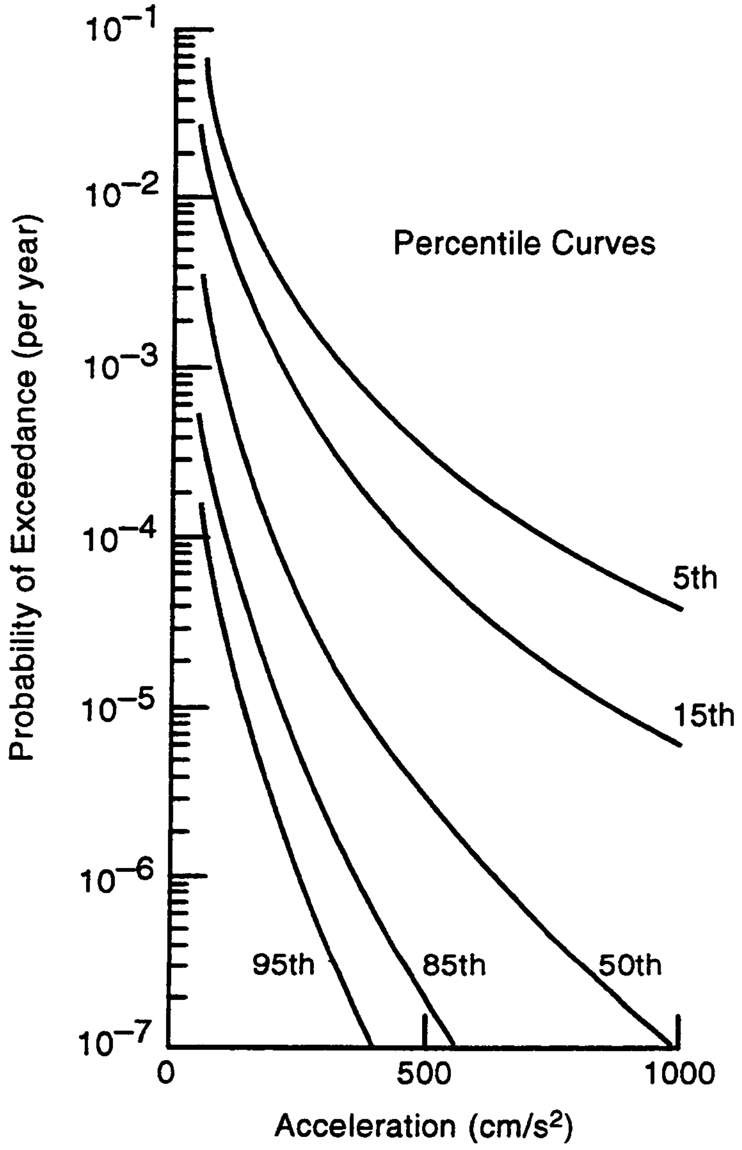


Figure 2-4. Shearon Harris aggregated risk—Translated problem results

3 YUCCA MOUNTAIN REGION TEST

A test of SEISM 1 for the YM area would not be complete without addressing, to some degree, the conditions involved in such a hazard analysis. There are two principal concerns. The first concern is that the relatively short historical record of seismic activity cannot be used to define maximum magnitudes (M_{max}) or recurrence formulae. These formulae predict the relative numbers of maximum and smaller magnitude earthquakes that will occur over a specified time interval. Instead, the level of seismicity must be inferred from the much longer Quaternary geological record. Relative numbers of earthquakes of various magnitudes in the Western United States appear to be reasonably stable (Abercrombie and Brune, 1994) and are assumed in this analysis to be similar to modern seismicity. The second concern is that earthquake strong motion attenuation relationships for the eastern United States, which are programmed into the code, are unsuitable for the YM area. The effectiveness of code changes to address these concerns needs to be determined. The way in which inputs are derived for an analysis of hazard over 10,000-yr needs exploration to define future efforts and to develop possible new input variables, appropriate for a HLW repository, which maybe subjects of expert opinions. It is emphasized that this test analysis is an exploration of code functionality and not a benchmarking or initial estimate of seismic hazard at the YM site. Input files developed for this test are in Appendix B. Data from the publications cited were not collected under the CNWRA Quality Assurance Program.

Because the SEISM 1 code was originally developed for re-evaluating, in a probabilistic manner, the seismic hazard at a number of eastern U.S. NPPs, little effort was put into the code to make it more versatile for use in solving other problems. An example is that computer directory and file paths (environment variables) for certain input data must be hard coded into several subroutine source code files. These files, then must be recompiled to machine language. If this code is to be used for new sites or the analysis of alternative interpretations of input data, and used on a variety of computers, then changes in the basic coding to make the program more versatile and user friendly, and to limit requirements for recompiling, would be worthwhile.

3.1 DATA SOURCES

Seismic source zones in this area are primarily faults with known or suspected Quaternary movement. Some published opinions would include a background seismic zone as well, which permits a random earthquake to occur anywhere in the site region. For this test, a random earthquake or background zone was not included. The effect of such a zone is an anticipated topic for future sensitivity analyses. SEISM 1.1 requires that faults be described as thin narrow quadrilateral source zones, or combinations of such quadrilaterals, that follow irregularities in fault strike. Such irregularities are common in the normal dip-slip or oblique-slip faults of the Basin and Range tectonic province.

SEISM 1 requires considerable input. Input files for 69 eastern U.S. NPPs are designed so that changes in source zones, recurrence formulae, or attenuation functions can be applied to all the plant sites in one calculation. There are about 200 pages of input files. Many input files do not relate to site parameters. Consequently, a substantial amount of input also must be prepared for a test calculation at a YM, Nevada site. Changes in site, computer, operating system or compiler, however, may require that the code be recompiled to make a calculation. This necessity to recompile is an artifact of the original goal of creating the program. Its use for other sites or computers was not a primary consideration.

3.1.1 Faults as Seismic Source Zones

The comprehensive compilation of faults and fault data provided by Somerville et al. (1987), was used as the basic source for faults and their locations. However, the fact that more recent and precise fault maps are being prepared is recognized. Most literature concerning the seismic hazard in the NTS/YM region considers only a subset of the faults plotted by Somerville et al. (1987) to be of concern in hazard analysis. Several opinions published by EPRI, (Coppersmith et al., 1993), considered that surface faulting may be caused by underlying strike-slip faulting and that these underlying faults (only generally described) are also capable of generating earthquakes, sometimes substantial ones. Locations for these presumed faults were not estimated or used in this test analysis. That other faulting models have been proposed, for example pull-apart basins between the offset ends of long strike-slip faults, is recognized, e.g. Young et al. (1992) and Ferrill et al. (1994). Such models may be incorporated in more formal risk analyses in the future.

Many small earthquakes in the Basin and Range tectonic province do not correlate well with mapped faults. For example, Rogers et al. (1987), state with regard to the southern Great Basin:

> ". . . microseismicity in this region is largely uncorrelated with range front faults in spite of the likelihood that some of these faults, particularly in the Walker Lane Belt, may be of late Quaternary age . . . . This lack of correlation suggests that these earthquakes reflect effects of deformation processes other than those directly related to the basin and range topography."

This observation may support Wesnousky et al. (1982), who conclude that faults may only rupture at their M_{max} except for aftershock sequences. The microearthquakes reported by Rogers et al. (1987) are mostly of strike-slip origin. Larger earthquakes in the Basin and Range tectonic province have ruptured existing faults at the surface. Faults on which Quaternary movement is observed, including historical movements, appear to be largely but not entirely dip-slip. Reaveley (1985) states that:

> "Normal slip faults are the predominant type of fault in the basin and range of Nevada, Utah, and southern Idaho, and the basin and range of eastern Idaho and southwestern Montana. Past displacements of these faults has produced the various mountain ranges and valleys in these regions."

Smith and Arabasz (1991) state, with regard to the Intermountain Seismic Belt (ISB), at the eastern margin of the Basin and Range tectonic province:

> "Forty-nine moderate to large earthquakes ($5.5 \leq M_s \leq 7.5$) since 1900 and spectacular late Quaternary faulting with a predominance of normal to oblique-normal slip make the Intermountain region a classic study area for interplate extensional tectonics."

Rogers et al. (1991) review seismic fault plane solutions and geologic studies, e.g. that of Slemmons (1967), suggesting a substantial component of strike-slip fault motion for some Basin and Range faults and historic earthquakes. Doser's (1988) extensive review and reanalysis of seismic data from Nevada earthquakes results in similar conclusions. These observations have led to the hypothesis that damaging-level earthquakes have been associated with known faults on which Quaternary movement has been observed and that future large earthquakes may also be expected on these faults. Smaller faults that can support only small M_{max} may not be easily detectable.

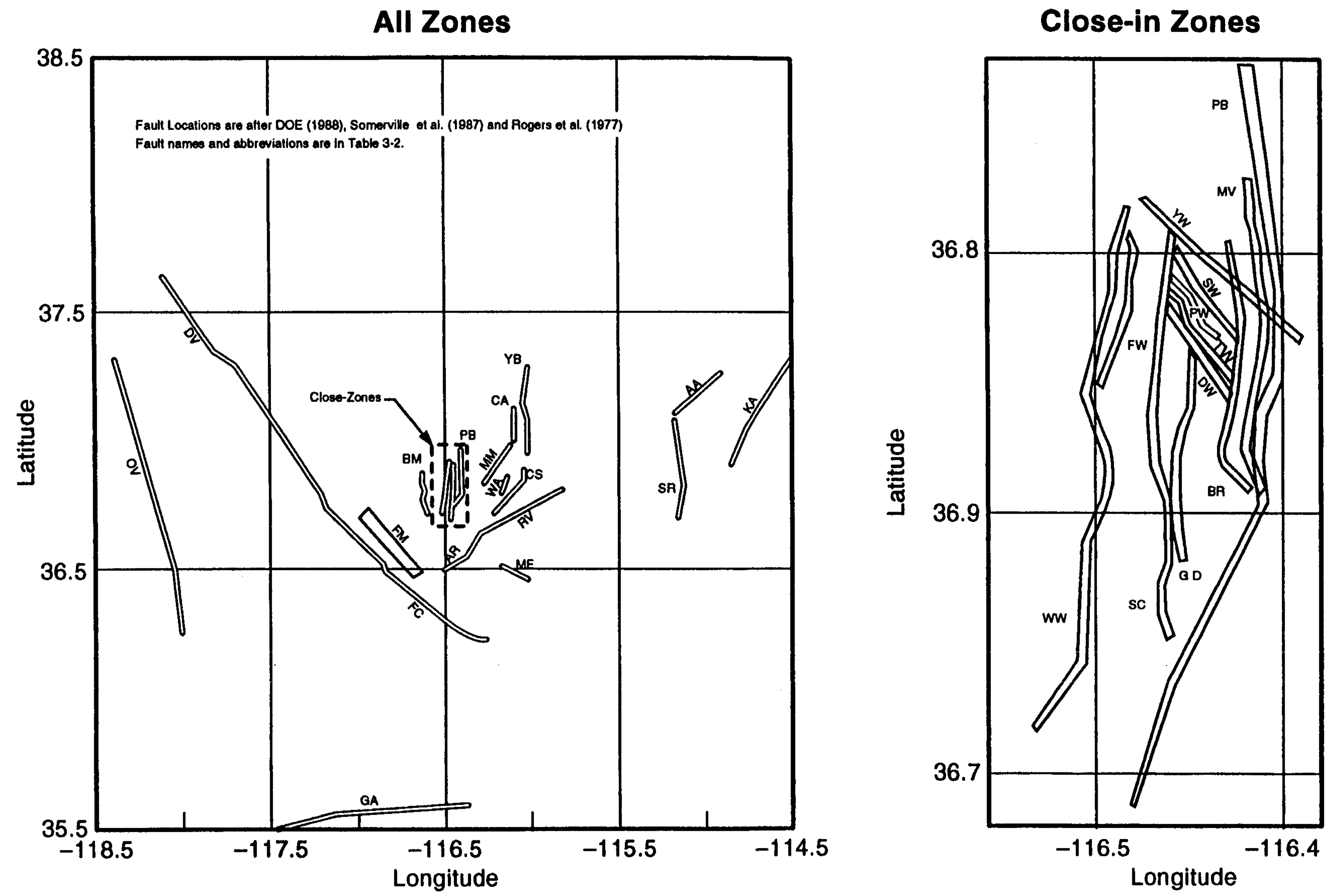
Initiation of fault rupture may be strike-slip, but total fault movement may be almost entirely dip-slip according to a fault plane solution based on short- and long-period seismograms (Vetter and Ryall, 1983). This phenomena may be caused by the state of the stress tensor with initiation of rupture starting at depth, where shear stress may be relatively higher than at the surface. Tajima and Célérier (1989) point out that fault rupture mechanisms may change during the rupture process.

A set of fault data from the analysis of Rogers et al. (1977), for a facility within the NTS, was also used to compare the perceived risks from various faults over a period of several years and to note potential effects on resulting computed risks.

A list of sets of faults used by various publications (or expert opinions summarized in Coppersmith et al., 1993) is in Section 3.2.1. Faults used in the analysis are plotted on Figure 3-1. Characteristics of these faults, as estimated by the respective experts or by this author, are also in Section 3.2.1. M_{max} were not estimated in the literature for some of the faults considered active. Consequently, following the procedure of Somerville et al. (1987), estimates were usually made with a relationship of fault length to M_{max} that is an average of the estimates by Slemmons (1977) and by Bonilla and Buchanan (1970) (Figure 3-2), for North America. Other such relationships are in the literature, for example, Wells and Coppersmith (1994), and they may be incorporated in future studies.

Richter magnitudes, used throughout this report, are defined as M_L up to 6.5 and M_S for higher magnitudes to M=8. At this time, M_W, the moment magnitude is considered to apply to magnitudes higher than M=8. This accepted convention is described in Nuttli and Herrmann (1978). Maximum magnitudes for faults considered to be of concern at YM by Slemmons in Coppersmith et al. (1993) are derived from Slemmons (1977), Figure 3-2. The assumption that an entire fault may rupture at one time can be used with these curves to assign a particular magnitude earthquake to a fault. In Coppersmith et al. (1993), several maximum magnitudes are often elicited with accompanying estimates of their probability. For this test run, however, where two maximum magnitudes are given in Coppersmith et al. (1993), they are assumed to bracket the most likely value. Where many maximum magnitudes are given with varying likelihoods of being correct, two with a significant likelihood are selected to bracket the most likely value. These arbitrary modifications are made to simplify and standardize input for the test computation. SEISM 1 does not have the capability of using time- or strain-dependent probability distributions, which may give rise to characteristic fault slip episodes or characteristic magnitudes. Therefore, the multiple estimates with accompanying likelihoods for maximum magnitude are not currently utilizable in this version of SEISM. Actual elicitations are costly and when they are performed, all details should be preserved. Under those circumstances, attempts should be made to include as much expert elicitation detail as practicable, provided the level of detail is credible.

There are two principal hypotheses concerning the recurrence of earthquakes on a fault or faults. One hypothesis holds that the Gutenberg and Richter (e.g., 1944 and 1954) recurrence formula for earthquakes, $N_c=a-bM$, applies to each fault where N_c represents the number of earthquakes of M and larger. An alternative formula is $LogN=a+b(8-M)$ where N represents the number of earthquakes of magnitude M and a and b are constants for a particular seismically active fault or zone. These constants are referenced in the literature and in this report as a-values and b-values.



Fault Locations are after DOE (1988), Somerville et al. (1987) and Rogers et al. (1977)
Fault names and abbreviations are in Table 3-2.

Figure 3-1. Faults as seismic source zones

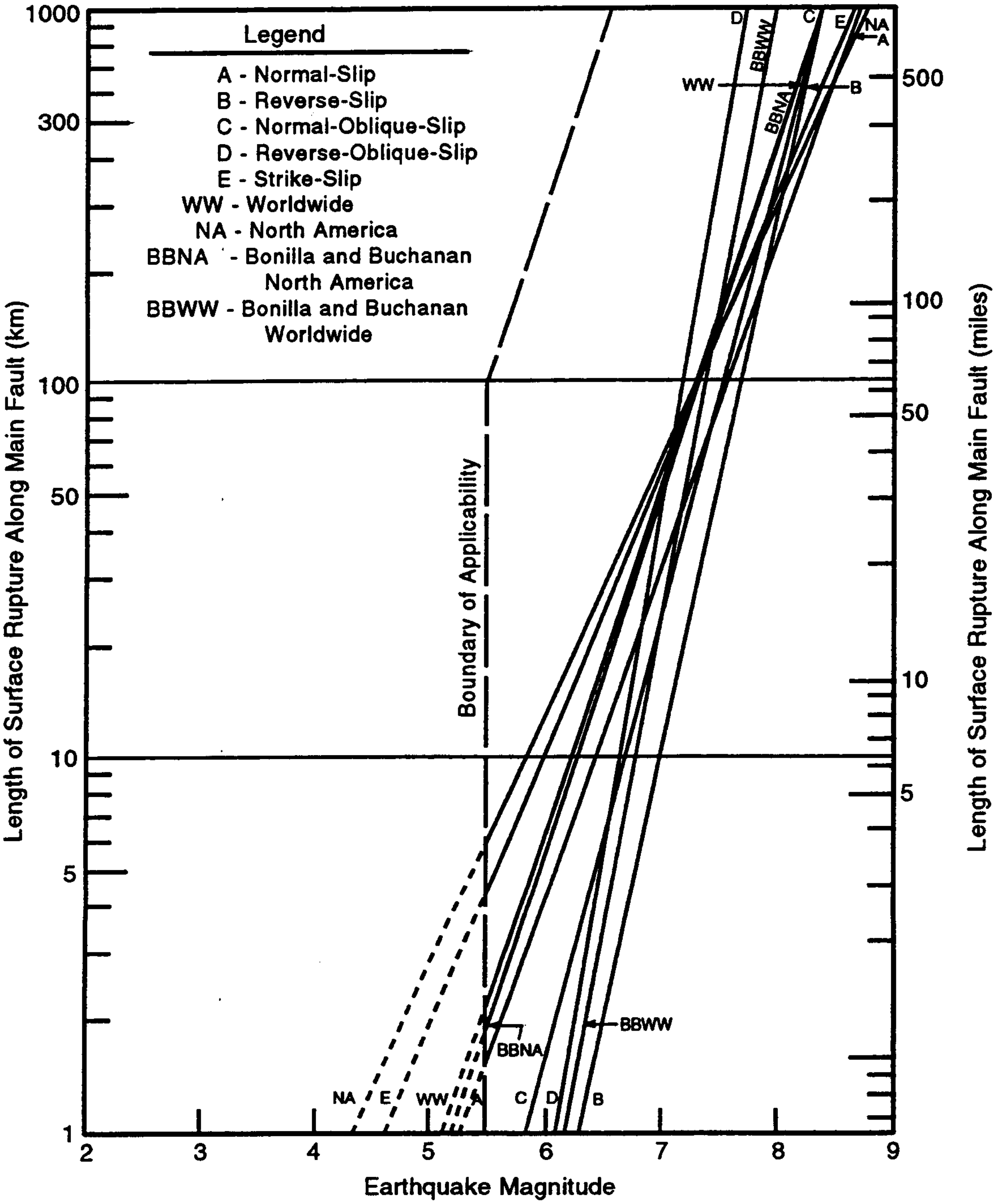
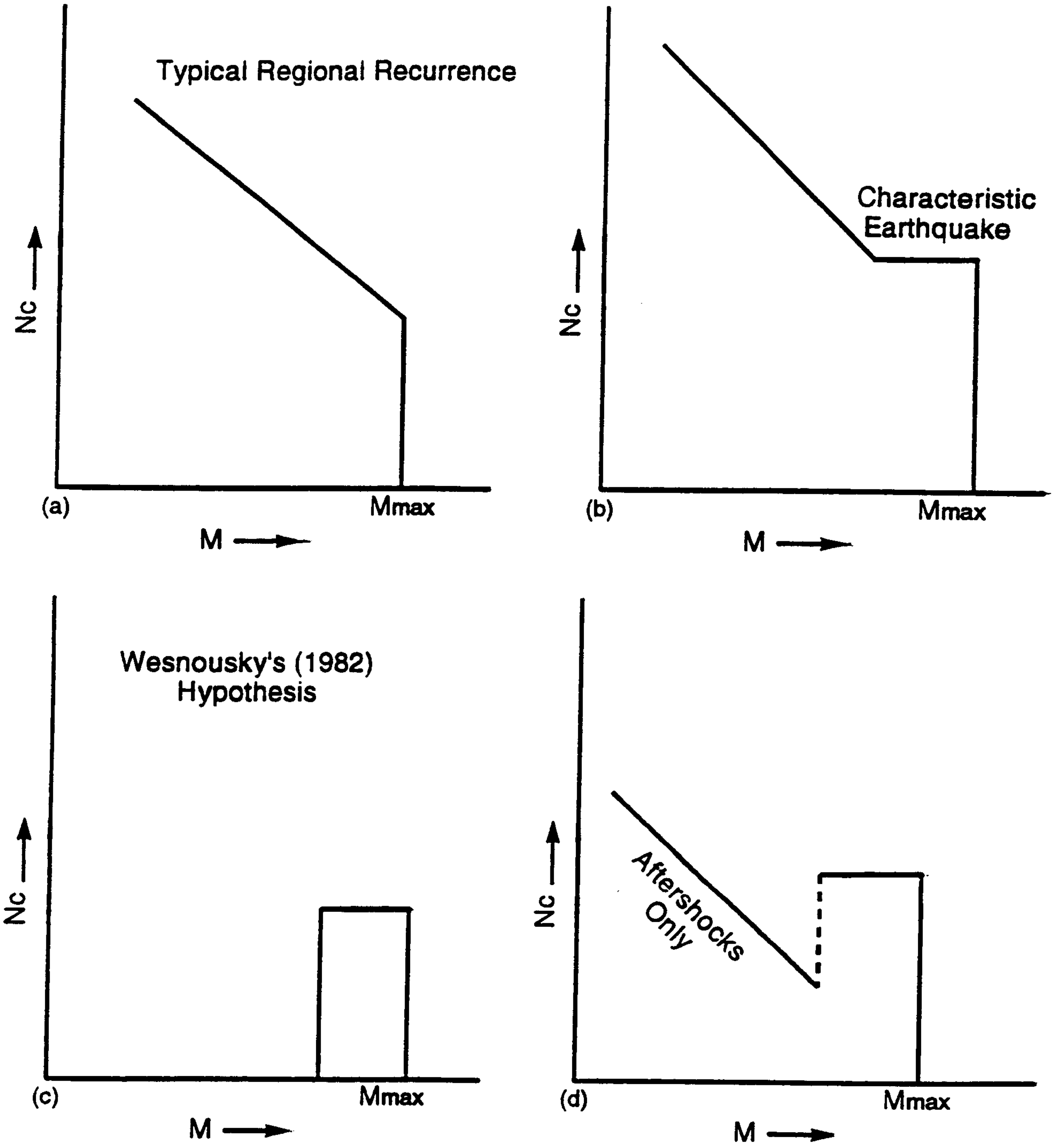


Figure 3-2. Fault lengths and maximum magnitude from Slemmons (1977)

Another hypothesis is that faults have a preponderance of earthquakes that correlate with their individual total length, and that few or no earthquakes are smaller (Wesnousky et al., 1982). This hypothesis assumes that a collection of faults of various lengths produce earthquakes of various magnitudes in accordance with the Gutenberg and Richter recurrence formula, but each fault in the collection produces only the maximum magnitude that the fault can support. Wesnousky et al. (1982) studied earthquakes in the western part of Japan's Honshu Island, where historical seismicity is known to some degree for about a 400-y period. This area, like the Basin and Range tectonic province, is characterized by many parallel faults on which earthquakes are restricted to a 15-km crustal depth. Unlike the Basin and Range tectonic province dip-slip and oblique-slip earthquakes, however, the Japanese source mechanisms studied were usually reverse faulting or thrusting. Krinitzsky (1993b) supports the view that individual faults do not generate earthquakes with a recurrence that follows a regionally determined slope and that recurrence for a given fault becomes highly unstable above magnitudes 5 to 6. However, Wesnousky's et al. (1992) study is for an island arc which is a different tectonic setting than the Basin and Range tectonic province. Recent earthquake catalogues in Nevada, since network expansion has occurred, are more complete for small earthquakes than those used by the authors cited in this report. Recalculation of the *b*-value based on N_c normalized to annual occurrences per unit area will improve accuracy. Because of the critical importance of the *b*-value for PFD&SHA (e.g. see Krinitzsky, 1993b) acquisition of recent seismic catalogues from the University of Nevada and use of recent U.S. Geological Survey catalogues, (e.g. Harmsen, 1994) is recommended to determine if Abercrombie and Brune's (1994) hypothesis that $b \approx 1$, derived from California data, also applies to Nevada. Narrowing the range of *b*-values in SEISM 1.1, if justifiable, should reduce uncertainties significantly.

Sketches of possible shapes of recurrence curves for individual faults are shown on Figure 3-3. Figure 3-3a represents a regional recurrence slope with the *a*-value adjusted to uniformly apportion regional seismicity to a fault. Paleoseismicity is derived by trenching and age dating. An M_{max} cutoff is dictated by fault length. Figure 3-3b represents a characteristic earthquake (e.g., Schwartz and Coppersmith, 1984) where there is a disproportionately larger number of earthquakes with magnitudes near M_{max}. Figure 3-3c represents a recurrence that would result from Wesnousky's et al. findings for western Honshu Island, Japan where only earthquakes near the maximum supportable by the fault occur except for aftershock sequences. Aftershocks are usually removed before recurrence is estimated. Figure 3-3d is essentially the same as Figure 3-3c assuming that aftershocks of large earthquakes could not be separated from other earthquakes. This curve may be indistinguishable from Figure 3-3b unless historical seismicity can be used to determine recurrence and the fault is sufficiently seismically active to provide a statistically significant earthquake data set.

In the analysis presented here, regional recurrence slopes from contemporary seismicity are assumed to apply to individual faults for this test of SEISM 1.1 primarily because this assumption is part of the present code. If alternative assumptions are to be tested, coding changes will be required. The author recognizes that Basin and Range tectonic province seismic history is probably not long enough to distinguish between the hypotheses that each fault supports seismicity with the same recurrence slope as regional seismicity or that faults only generate earthquakes near their maximum potential magnitude as dictated by fault length. The number of earthquakes in a source zone for magnitudes of 4 or greater are obtained from the literature or estimated based on fault length relationships. Somerville et al. (1987) lists $N_{M=4+}$ estimates for many faults. Where N is not given, averages from other published estimates for the fault are used. The formula $Log\ N_c=a-bM$ is used to estimate the recurrence intercept, *a*-value, assuming the average value of the recurrence slope, *b*-value, to be 0.91 and M=4. The *b*-value is allowed to range ± 0.5 units from the average value in this analysis. See the c/j/sis file under Seismic Hazard in Appendix B for additional information.



Nc = Cumulative Number of Earthquakes of M or Greater
Vertical Axis is Logarithmic

Figure 3-3. Possible recurrence relationships for individual faults

For the purposes of this test calculation, M_{max} based on fault length is assumed to have caused observed fault offsets. The rationales for this assumption are:

(1) Only the largest magnitudes seen in the Basin and Range consistently produce visible surface offset.

(2) Fault traces for larger magnitudes are several or tens of miles long and the likelihood of a trench being at the point of maximum offset is low (therefore small offsets are also likely to have been caused by large earthquakes).

(3) The graph of displacement versus magnitude for normal faults of Slemmons (1977) indicates that, for each succeeding smaller magnitude, the displacement is reduced by approximately half of an order of magnitude. Therefore, small earthquake offsets are not likely to be seen.

The *a*-values are estimated from the number of offsets observed in trenched faults divided by the time span over which the offsets are observed to occur or from estimates in the literature, particularly from the rates published by Slemmons (1977) if no other source is available.

A correction may be necessary to account for the possible contribution of smaller earthquakes to the total offset observed in a trench. There is uncertainty in this correction. It can be argued that smaller earthquakes may occur anywhere on a large rupture plane and that their rupture dimensions are a fraction of the total fault length. Therefore, they do not contribute significantly to the offset observed. Somerville et al. (1987) use the average of empirical relationships developed by Slemmons 1982 (similar to Slemmons 1977) and Bonilla et al. (1984). For recurrence slopes (*b*-values) near 0.9, there are about 8 times as many of each succeedingly whole magnitude smaller earthquake. Not all smaller earthquakes are likely to occur in the same place on the fault plane as the maximum offset of the next larger magnitude. Further, magnitudes less than $M=6$ are rarely observed to rupture the surface in the Basin and Range tectonic province. The fault slip area for $M=6$, if assumed to be square, is about one half the fault plane down-dip extent (width), and for faults capable of producing $M=7$ earthquakes, their length is only a fraction (less than 1/6) of total fault length. Therefore, only about one half of such events are likely to disrupt the surface and only 1/6 of their offsets are likely to be seen in any particular trench across the fault. On the average, only about $8 \times 1/2 \times 1/6 = 2/3$ of an $M=6$ offset is likely to have increased an $M=7$ offset observed in any particular trench. Because the offset of $M=6$ earthquake is about 1/6 the offset of an $M=7$ earthquake, the potential increase from $M=6$ earthquakes is on the order of only 10 percent. In only a few cases are M_{max} larger than 7 indicated for a particular fault. On this basis, *a*-values were roughly estimated. They are regarded as adequate to test the code at YM but not regarded as adequately developed for a baseline risk study. These values, and consequently the risk, could vary substantially depending on the assumptions made. For this test analysis, the roughly estimated *a*-values are given a substantial range in the SEISM 1.1 input. Potential effects of uncertainty in recurrence slopes on seismic risk analyses are discussed by Krinitzsky (1993a, b, c). In a re-elicitation for the eastern U.S. seismicity study, LLNL asked the experts for the number of earthquakes that they would expect, in each seismic source zone they used, for M_{min}, M_{max}, and an intermediate magnitude. From this data, *a*- and *b*-values were computed. Uncertainties for the resulting risks were less than those from prior elicitations of *a*- and *b*-values directly, Savy et al. (1993) and Sobel (1993).

Rupture areas for small earthquakes may occupy any convenient place on the total rupture plane available on a fault. Figure 3-4 is a rupture area versus M plot from Wyss (1979) and a sketch of an M=7.4 potential M_{max} for the Basin and Range with numbers of rupture areas for smaller magnitudes also plotted in a random fashion. Similar alternative relationships to Wyss (1979) are Kanamori and Anderson (1975) and Wells and Coppersmith (1994). Only if these smaller rupture areas occur along the top boundary of the larger fault-rupture plane will they be observed in the paleoseismic record. Consequently, only earthquakes slightly smaller than suggested by the displacements observed in surface trenches are likely to contribute to the observed offsets. Rogers et al. (1987) observe that hypocenters of small earthquakes often appear to occur within cylinders slanting with depth. A speculation might be that these cylinders represent a series of spheres of hypocentral resolution and that the earthquakes are following zones of weakness at the intersection of two faults. If resolution of hypocenters was better, the hypocenters might have followed lines, rather than cylinders. Metcalf (1983) states: "Present seismic and tectonic activity in the NTS region is concentrated along the intersections of the shear zones and in areas of deep basin formation, such as Frenchman Flat." This observation lends credence to the conjecture that the plunging cylinders of hypocenters observed by Rogers et al. (1987) may represent intersections of fault planes.

In the absence of observations of fault offsets in the Quaternary, calculation of *a*-values requires the offset for M_{max}, a recurrence slope, and a strain rate. A recurrence based on strain rate can be obtained directly from Slemmons (1977). However, there are other strain rate estimates for many of the faults listed by various pseudo-participants, and those strain rates would be preferred to accompany their expert opinions. In several cases, the values used were from an average of Slemmons and Bonilla's data. The number of years between maximum magnitudes may be estimated from Slemmons' (1977) displacement versus magnitude graph for normal faults using an average of these rates. If a pseudo-participant is assumed to adhere to the Wesnousky et al. (1982) hypothesis, risk could be halved. This form of estimation can also be employed in reverse to estimate fault offset from seismicity. This procedure is not offered here as a final one, but as a convenience for estimating how this alternative interpretation might affect results produced by this test calculation.

Krinitzsky (1993b) summarizes evidence that suggests earthquake recurrence curves derived from regional data cannot be applied to individual faults. He shows that individual faults may have different activity levels that only in the aggregate over a large area look anything like a regional recurrence relationship. Because there are many more earthquakes of each succeedingly smaller magnitude and serious damage to well engineered structures begins at about M=6 from earthquakes at relatively short distances (e.g. 50 km or less) only those faults within this, or a corresponding larger radii for faults with greater M_{max}, are of a high level of concern. At M=7, most western U.S. acceleration attenuation curves would predict 0.1 g or less on rock at 100 km. Rock sites are defined as those with no soil to a few meters of soil over bedrock. Therefore, the assumption of a regional recurrence relationship on each fault within a radius this small is unlikely to provide a correct evaluation of risk. Data are too few in the Basin and Range area to resolve this problem. Krinitzsky (1993a) points out several probabilistic risk analysis predictions that were obviously not in accord with historical seismicity. He attributes this failure of PSHA to accurately predict risk on the nature of regional recurrence relationships and the impossibility (except possibly in regions of very high seismicity) of using these relationships for individual faults or small source regions.

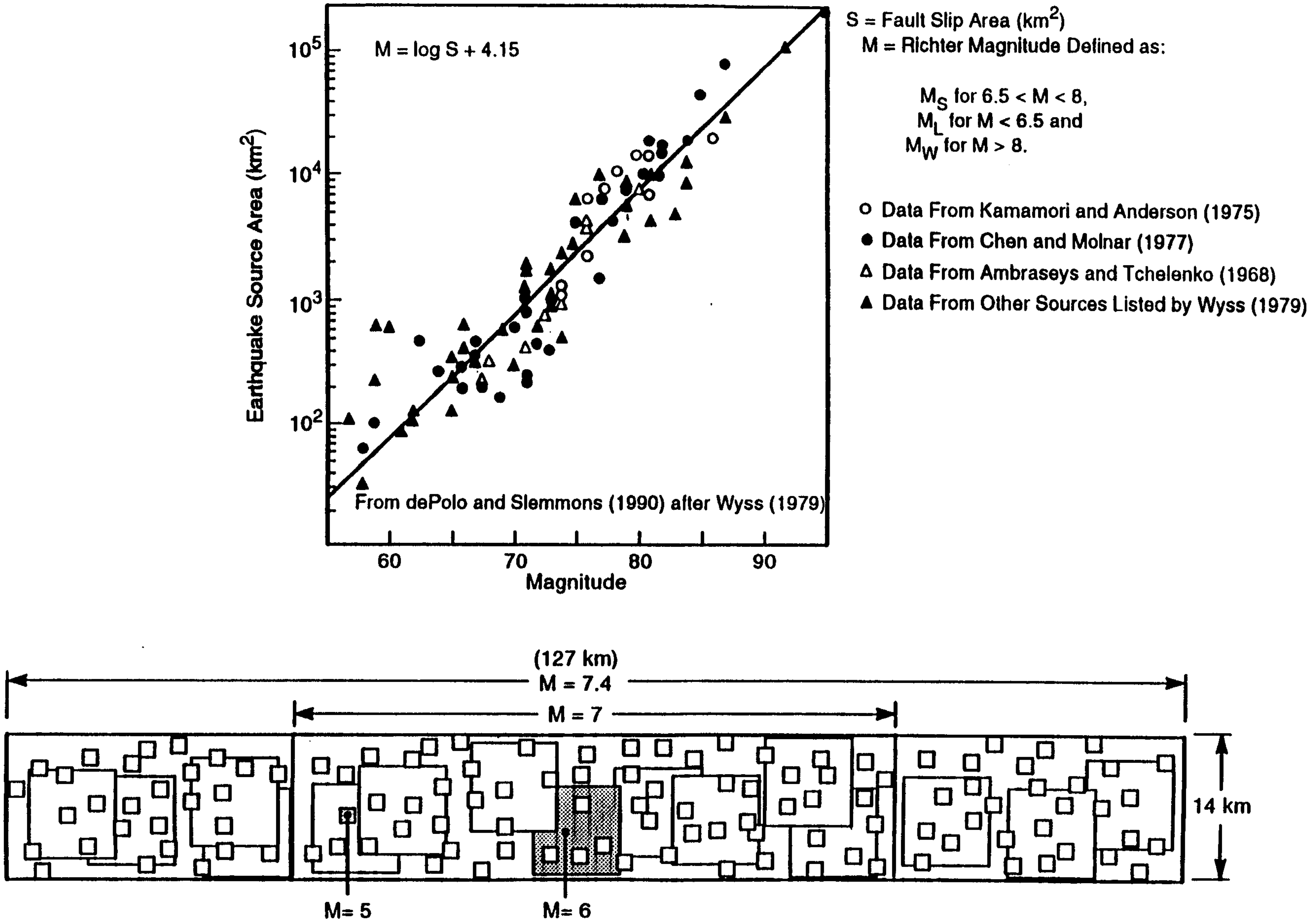


Figure 3-4. Fault rupture areas

3.1.2 Ground Motion Attenuation

Acceleration attenuation functions used in this analysis are plotted to the same scale and format, in Appendix C. In Figure 3-5 several attenuation functions for M-5.6 are plotted using the distance measures and acceleration amplitude definitions proposed by the authors of the functions. In Figure 3-6, the curves are plotted to a common site to surface-projection-of-the-rupture-plane distance and for peak acceleration. Acceleration data are from the magnitude 5.6 1992 Little Skull Mountain earthquake. Little Skull Mountain earthquake accelerations and site to fault-slip-zone distances for stations 1, 2 and 3 as plotted by Lum and Honda, (Figure 3-7) are indicated on Figures 3-5 and 3-6. The range of distances was estimated from the aftershock distributions published by University of Nevada at Reno and U.S. Geological Survey (1992), Figure 3-8. A sketch of an interpretation of fault slip area is simplified in Figure 3-9. Strong motion seismograph stations at greater distances than stations 1, 2 and 3, are not sensitive to differences in definition of source-to-site distances. Larger epicentral distances are the same, within the plotting resolution, as other distances based on various interpretations of fault slip area. The differences between curves in Figures 3-5 and 3-6 are substantial in the near-field. For earthquake sources near a facility site, a common distance measure and definition for peak acceleration become necessary for an accurate hazard calculation using several different attenuation functions that may be preferred by various experts. Modeling fault slip areas for near-field locations in a probabilistic analysis, however, adds complications that should be eventually treated statistically. These complications will add to uncertainty in results. Near-field is defined for this report as a site-to-source distance less than a fault dimension. Formulae for attenuation shown in Figures 3-5 and 3-6 are adapted to the rupture plane geometry of the Little Skull Mountain earthquake as indicated on Figure 3-9 and as implied by the data of Figure 3-8. Future earthquakes here may differ, but a geometry must be selected to predict acceleration with a common distance measure.

In this test analysis, near-field distances are treated as the shortest-distance-to-the-surface-projection-of-the-rupture-zone (SPRZ) (see Figure 3-10). Fault slip planes from earthquake magnitudes less than 6 are assumed to extend to within 4 km of the surface. Although slip planes for larger earthquakes rupture to the surface, effective stress is arbitrarily assumed to be lower at shallow depths. Peak accelerations are assumed not to be generated above 4 km for these shocks. An example of somewhat similar reasoning is in Joyner and Boore (1981), who determined an effective depth to the top of a slip plane to be 7.3 km based on a statistical analysis of California data. Joyner and Boore (1993) suggested about 4 km based on velocity data. Future test calculations should explore assumptions regarding effective depth of fault rupture planes. It is possible that some depth other than 0 or 4 km may be more appropriate for earthquakes in the 6 to 7+ magnitude range. The 4 km number was arbitrarily selected based on University of Nevada at Reno and U.S. Geological Survey (1992) preliminary aftershock plots for the 1992 Little Skull Mountain earthquake. This number may change as additional aftershock data and analyses are published or when strong motions from future Basin and Range earthquakes are recorded.

The modified formulae assume vertical fault dip. If the dip is 70°, for example, and the rupture surface is assumed to be 4 km down dip, only a 1.4-km distance error results. This error does not significantly affect the final aggregated hazard, but could be further refined. The effect of fault dip on seismic hazard from smaller earthquakes (magnitude 5 range) distributed over the fault plane may be significant.

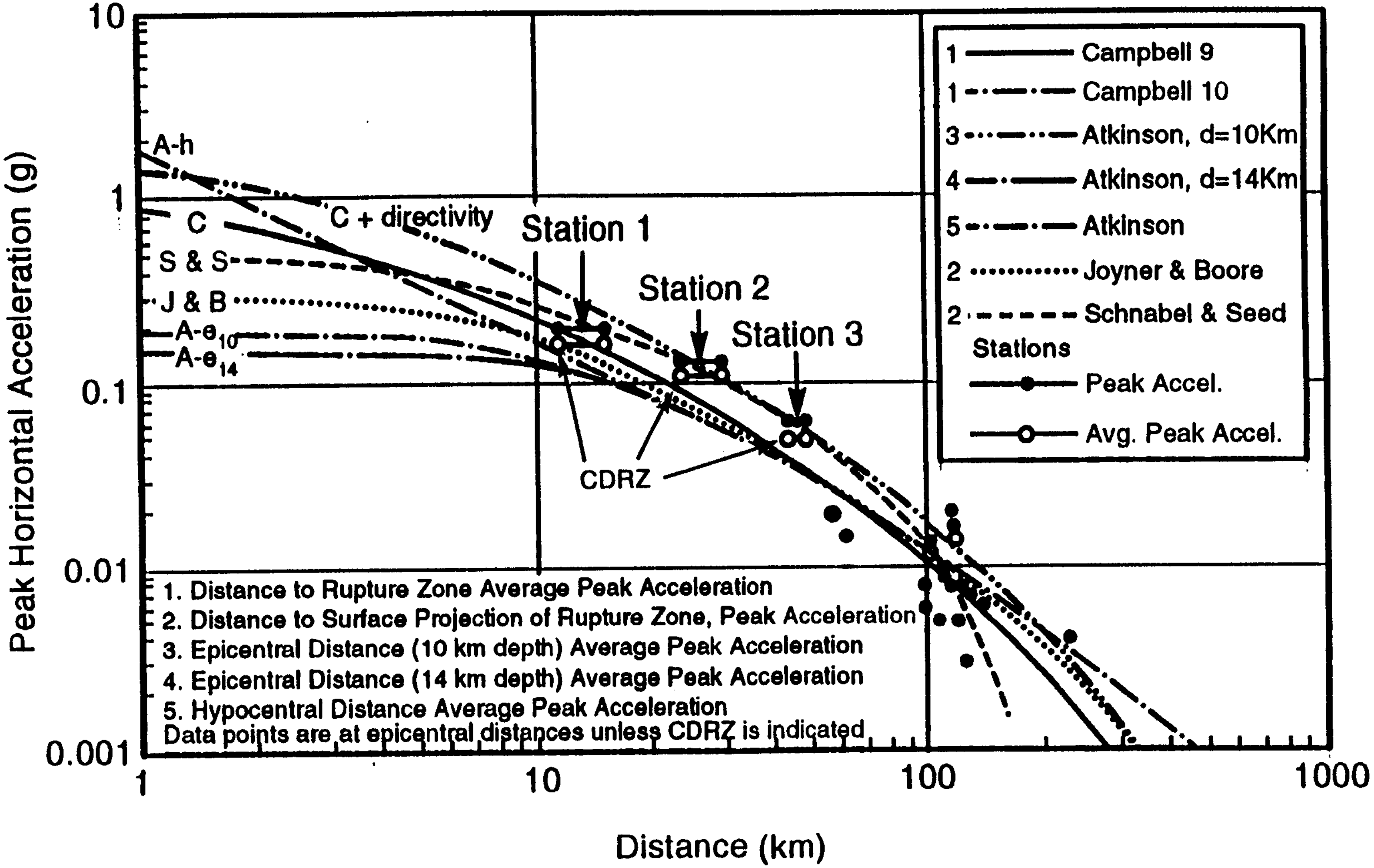


Figure 3-5. Selected acceleration attenuation curves for M=5.6 and Little Skull Mountain strong motion

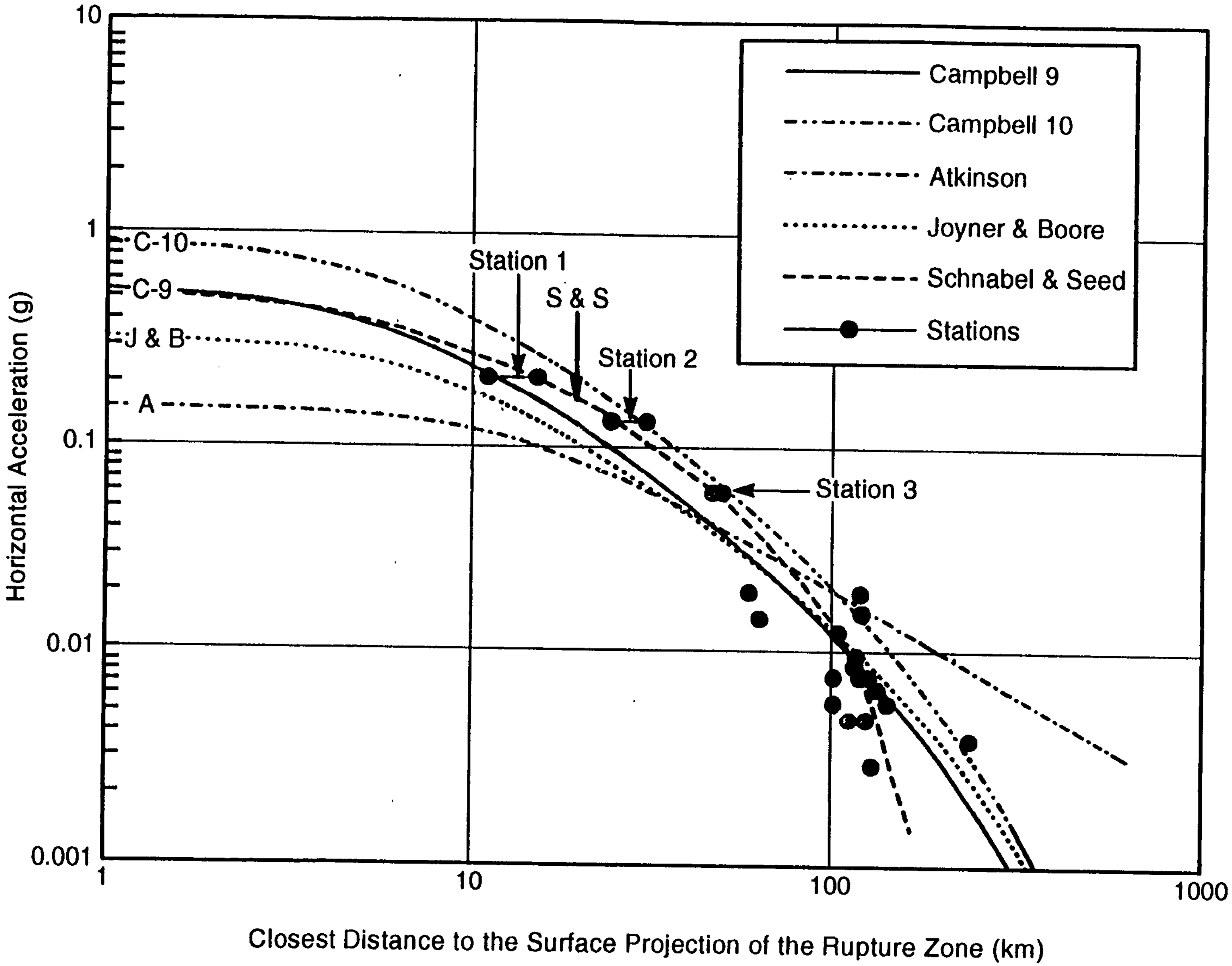


Figure 3-6. Selected peak acceleration attenuation curves with a common distance definition for M=5.6 and Little Skull Mountain strong motion

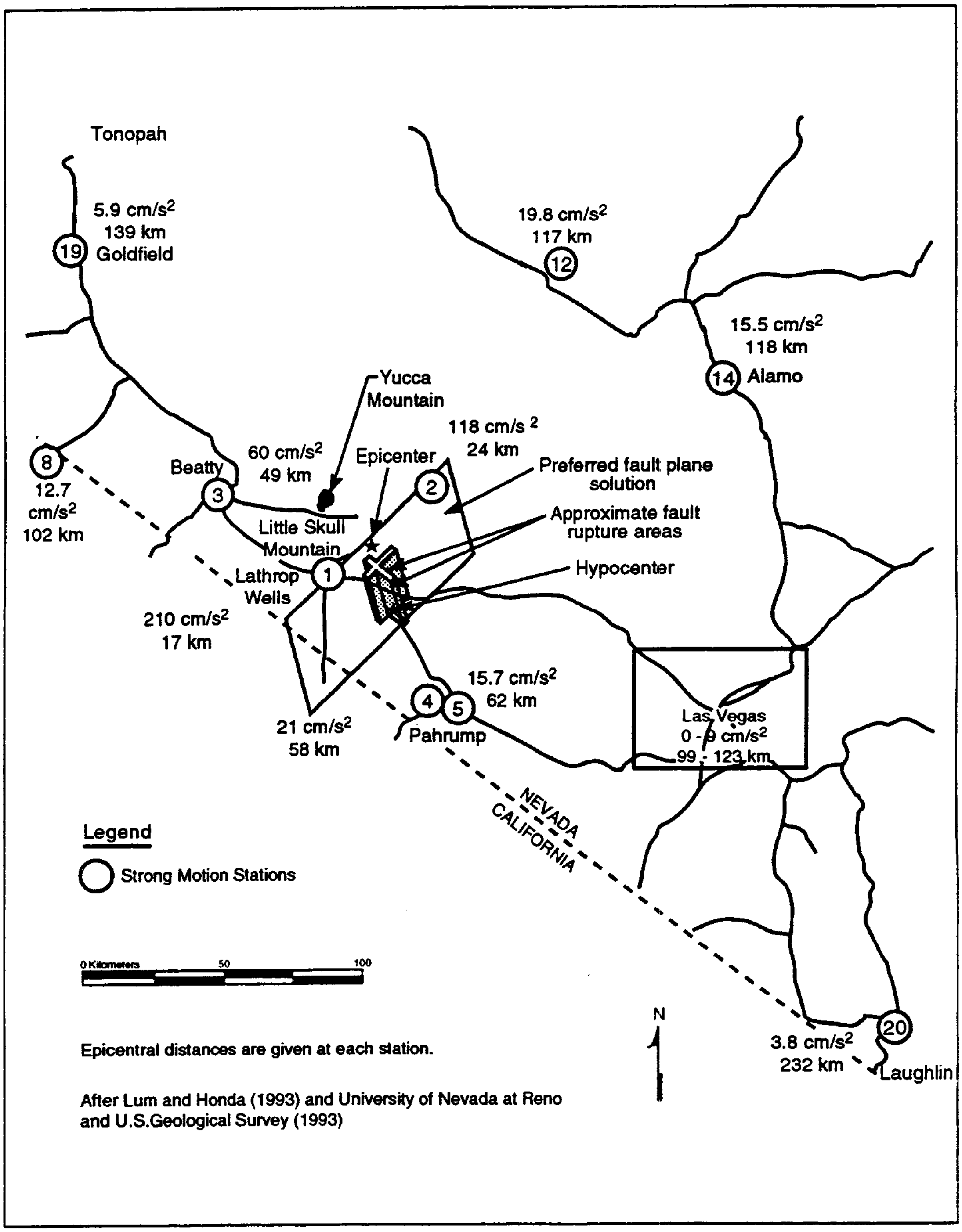
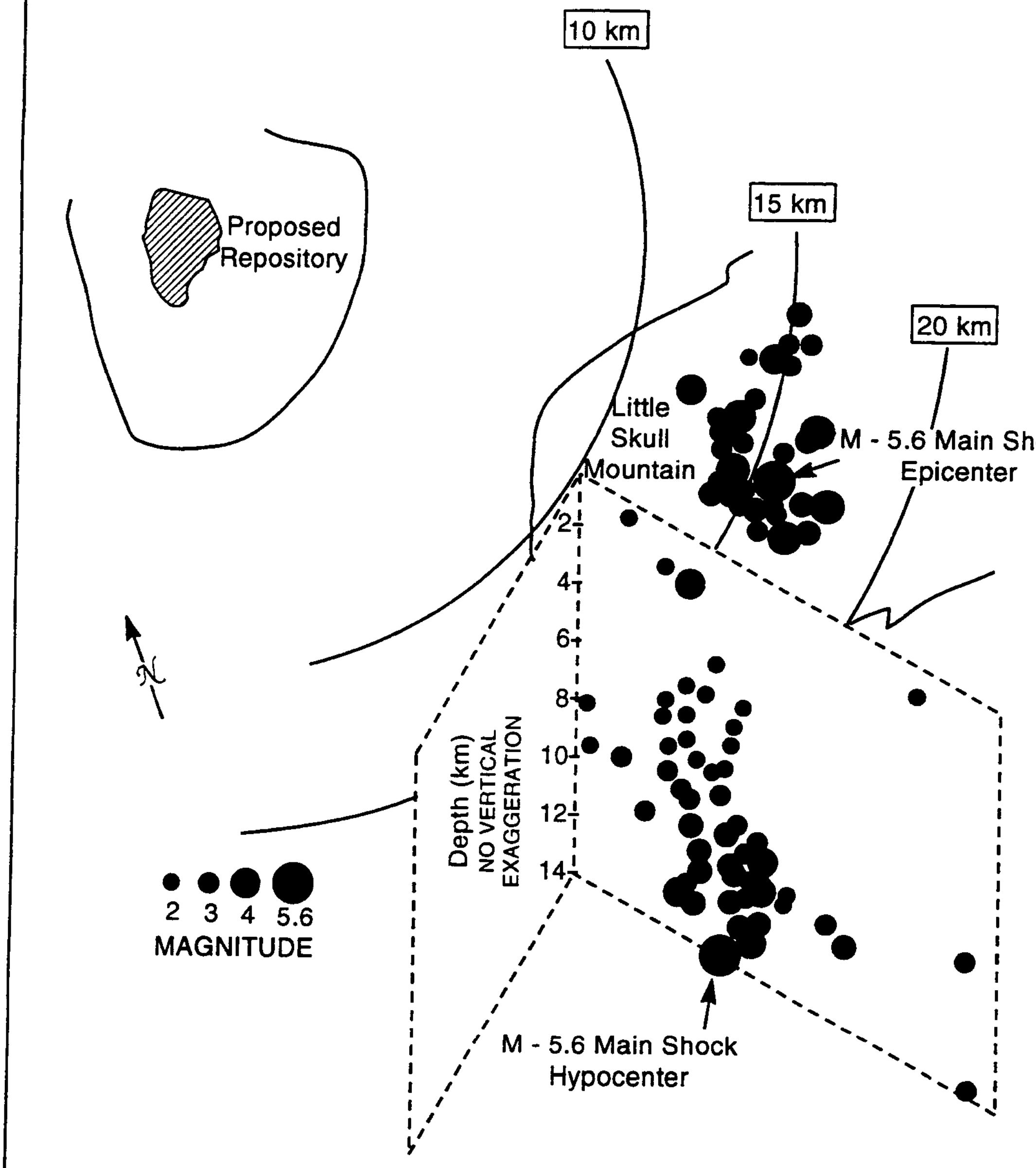


Figure 3-7. Southern Nevada stations which recorded 1992 Little Skull Mountain earthquake strong motion



After University of Nevada at Reno and U.S. Geological Survey (1993)

Figure 3-8. Epicenters and hypocenters of the 1992 Little Skull Mountain earthquake and aftershocks

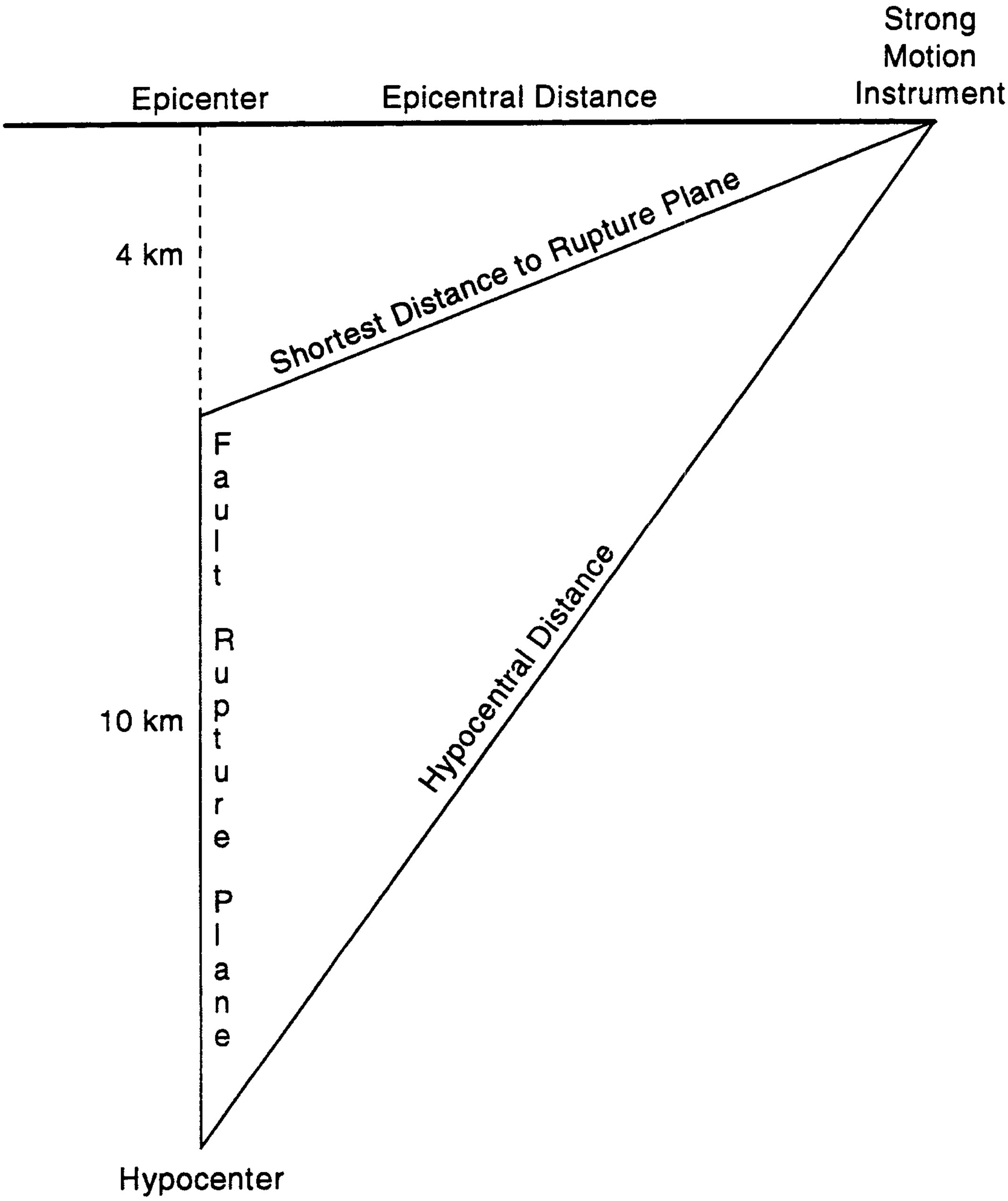


Figure 3-9. Sketch of 1992 Little Skull Mountain earthquake principal slip plane

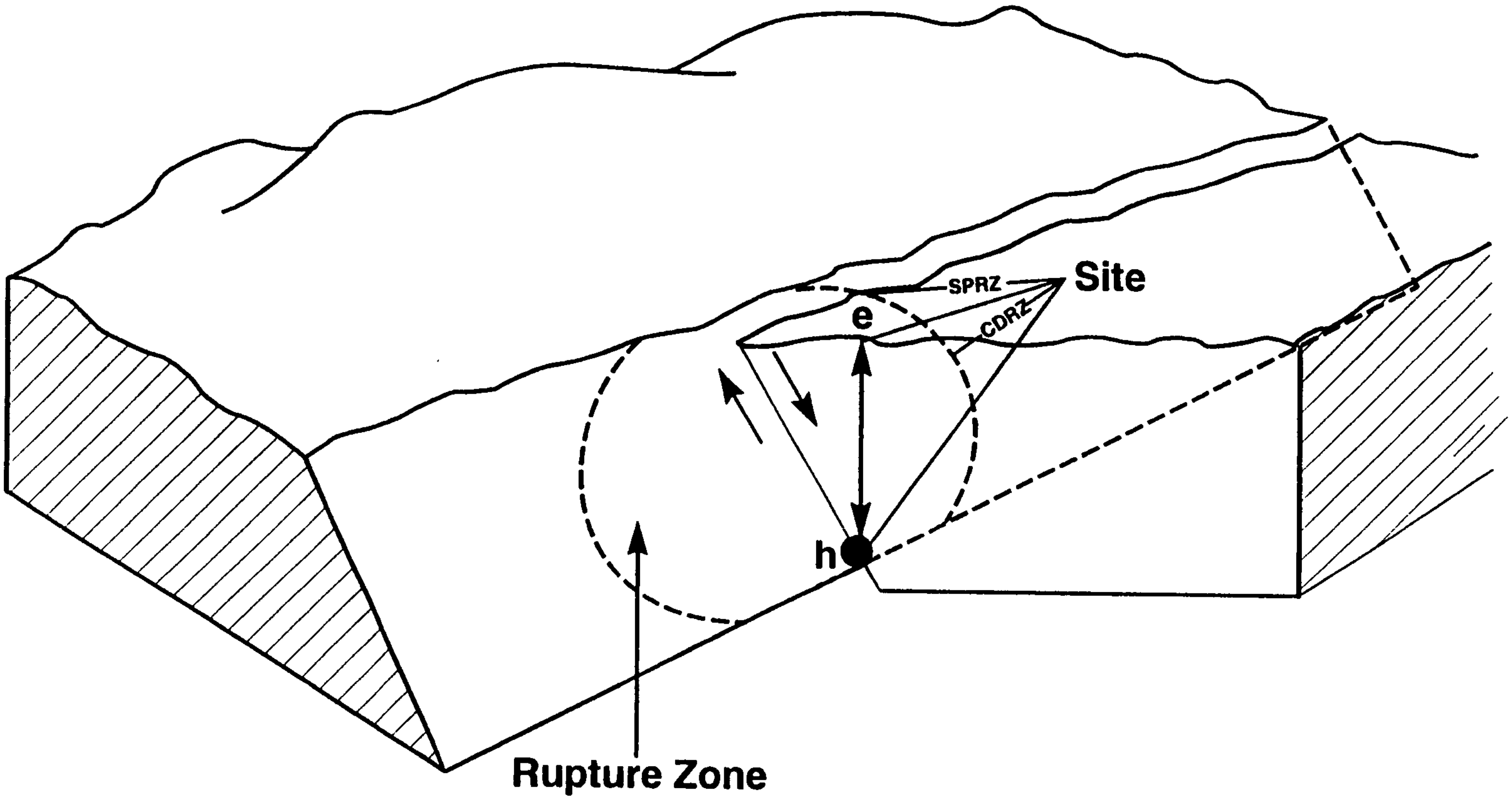


Figure 3-10. Sketch of distance measures

Near-field strong motion is not likely to be accurately represented by empirical attenuation curves because there is a limited number of near-field strong motion records for large earthquakes. Quasi-theoretical methods such as those based on Hanks and McGuire (1981), which were developed from teleseismic recordings, are also not likely to represent near-field ground motion because the methods are derived from teleseismic recordings that are insensitive to near-field phenomena. Where design acceleration is controlled by near-field earthquake sources, additional theoretical model studies will probably be necessary. If several such studies are made, results could be treated statistically as variations in expert opinion. The Little Skull Mountain earthquake has produced a valuable and unique set of strong motion records from a Basin and Range tectonic province earthquake. However, there are generally large differences between strong motion records from individual earthquakes of the same magnitude. The Little Skull Mountain strong motion records may or may not have produced accelerations that would be near the mean of those from several Basin and Range earthquakes, were such records available.

Attenuation curves labeled Campbell 9 (Figure 3-6), from Campbell (1987), fit average peak acceleration data well. "Average peak" acceleration is defined as the average of the highest accelerations recorded on each of two horizontal accelerograph components. The peaks need not occur at the same time on the two horizontal components. This curve, for sediments less than 10 m thick, is constrained by far-field data, and is for a strike-slip source earthquake. Campbell (1987) does not provide a curve for normal dip-slip source earthquakes. McGarr's (1984) analysis, for example, suggests that stress drops for strike-slip and dip-slip sources are more similar to each other than for thrust or reverse faults. This author, therefore, assumes that a strike-slip source is more like a normal dip-slip source than is Campbell's (1987) alternative, a thrust or reverse fault. Campbell's attenuation functions for strike-slip sources are assumed to be adequately representative of Basin and Range tectonic province earthquakes. Most published attenuation functions do not distinguish between fault source types.

The curve for Atkinson (1984), Figures 3-5 and 3-6 (see also Appendix C), is computed from the published formula for distances less than 20 km. Atkinson (1984) prefers the use of the Joyner and Boore (1981) curve (Appendix C) at distances beyond 20 km. The combined curve is stated to be valid for hypocentral distances. Hypocentral distances are larger than the closest distance to the rupture zone (CDRZ) unless the earthquake has a very shallow focus. Attenuation curves plotted in Atkinson (1984) are for the epicentral distance equivalent of a nominal 10-km hypocentral depth, which gives them a different appearance than Atkinson's formula plotted for a 14 km hypocentral depth or Atkinson's curve plotted for hypocentral distance. The three Atkinson curves are plotted on Figure 3-5 for comparison. Data points on these figures are for the Little Skull Mountain earthquake with a preliminary hypocentral depth of 14 km as reported by University of Nevada in Reno and U.S. Geological Survey (1992). Smith et al. (1993) propose that two intersecting fault planes ruptured during the Little Skull Mountain of 1992. The Atkinson curve as plotted on Figures 3-5 and 3-6 was reformulated assuming a hypocentral distance of 14 km, but plotted against epicentral distance which is a special case of SPRZ. SPRZ, CDRZ, epicentral, and hypocentral distances are illustrated in Figure 3-10.

The Schnabel and Seed (1973) curves (Figures 3-5 and 3-6 and Appendix C) match the Little Skull Mountain near-field peak acceleration well. "Peak" acceleration is defined as the highest acceleration recorded on a horizontal accelerograph component. Curves published more recently than Schnabel and Seed (1973) are based on much larger data sets, which include the larger variability present between individual earthquakes. Campbell's (1987) attenuation function for soil <10 m thick and constrained by far-field data, labeled Campbell 9, and multiplied by 1.12, provides a good fit for both near- and far-field Little Skull Mountain earthquake peak acceleration data. The 1.12 factor adjusts the average-of-the-peak accelerations recorded by each horizontal component to the peak horizontal acceleration recorded by a horizontal component of a strong motion accelerograph. This factor is based upon Campbell's estimate that peak accelerations are about 12 percent higher than average peak accelerations. All the curves are largely dependent upon California data. If Little Skull Mountain data are representative of Basin and Range earthquakes, there appears to be little justification for reducing stress drop from 100 to 36 bars (reported by Stark and Silva, 1992), as suggested by Hofmann and Bangs (1993), in the quasi-empirical (RV) methods, for example Atkinson (1984), to tailor them for the stress regime at YM.

3.2 PSEUDO-PARTICIPANTS

Pseudo-participants are required for source zones and for attenuation functions. A variety of strong motion attenuation functions are applicable to the western United States. Two summaries of attenuation functions are Donovan (1982) and Campbell (1985). With the exception of Schnabel and Seed (1973), only the more recent functions are recommended for use in the Basin and Range tectonic province. The Schnabel and Seed curves have been widely used and have continued to predict accelerations reliably except for the very-near- and extremely-far-fields where the curves were not defined. Interest in the proposed NTS Retrievable Surface Storage Facility (RSSF) for high level nuclear waste (e.g. see Hannon and McKague, 1975) prompted publication of Rogers' et al. (1977) deterministic/probabilistic analysis of a site about 20 km east of YM. Subsequent analyses directed at YM include Coppersmith et al. (1993), Perkins et al. (1987), Somerville et al. (1987) and the U.S. Department of Energy (1988). From these sources, a range of published opinions were collected and assigned to pseudo-participants. These ranges of opinion provide the input to this SEISM 1.1 test analysis.

3.2.1 Fault Source Pseudo-Participant Models

Estimates of fault and earthquake data are generated for eight pseudo-participants. The data required are:

- Location, length, and configuration of faults to be used as seismic source zones.
- M_{max} for each fault.
- *a*- and *b*-values for the Gutenberg and Richter [e.g., (1954)] recurrence formula for each fault.

Estimates of fault parameters were partially based on the elicitation of five experts who reported opinions on earthquakes in Coppersmith et al. (1993), on data in Somerville et al. (1987), Rogers et al. (1977) and U.S. Department of Energy (1988). The pseudo-participants are identified by numbers 1 through 8. Most of the publications cited did not include estimates of all the parameters needed by SEISM 1. Missing parameters were obtained from published fault length versus parameter curves or from other experts who published at about the same time. Therefore, some of the data attributed to a pseudo-participant in this analysis may not represent the opinions of the author who provided most of the data. The choice of which faults are of concern is consequential information in every case. Table 3-1 lists sources of the fault and earthquake parameters used in this test analysis.

The Gutenberg and Richter (e.g., 1954) recurrence formula *b*-value is assumed to be 0.91 for this study, as used by Somerville et al. (1987). Ryall et al. (1966) obtained a value of about 0.9 for earthquakes occurring in the Ventura-Winnemucca seismic zone. Douglas and Ryall (1975) found the recurrence slope to be 0.91 for all active areas in western Nevada and list their regional recurrence

Table 3-1. Sources of pseudo-participant data

1	Coppersmith et al. (1993)
2	Somerville et al. (1987)
3	Rogers et al. (1977)
4	U.S. Department of Energy (1988)
5	Bernreuter et al. (1989)
6	Ryall et al. (1966)
7	Douglas and Ryall (1975)
8	Slemmons (1977)
9	Bonilla and Buchanan (1970)

Note that most of the publications cited did not provide all the data required (source-zones, attenuation-functions, recurrence-parameters and self-evaluations of uncertainties) for a SEISM 1.1 test analysis computation were derived, follow: for a SEISM 1.1 hazard calculation, and that data from more than more publication were used for each pseudo-participant.

formula as Log $N=6.48-0.91M$. Other values have been found by other investigators, e.g. Perkins et al. (1987) found $b=1.03$ for the NTS area and Frohlich and Davis (1993) found $b=1.06$ for normal faults worldwide. Rogers et al. (1977) found $b=0.83$ for a region about the NTS. Abercrombie and Brune (1994) determine $b=0.96$ for California earthquakes with a wide range of magnitudes. They therefore, believe that $b \approx 1.0$ for large complete data sets. The range of b-values used in this analysis includes $b=0.96$. Recurrence slopes of less than 0.9 (but some times more than 0.9) are often found with older data or with sparse data sets. There are several possible causes. First, the number and sensitivity of seismic stations have increased through time. Therefore, older lists are likely to be deficient in smaller undetected earthquakes. Second, the relationship between modified Mercalli damage intensities (MMI) and magnitudes has a high level of uncertainty. Many older shocks were not adequately recorded by seismographs so their magnitudes were estimated from a relationship between MMI and magnitude. Finally, even though there may be a relatively long seismic history, it may not be long enough to establish a statistically significant sample for larger earthquakes.

Therefore, estimates of *b*-values from sparse or old data may be in error. Sparse data can produce almost any recurrence slope. A list of earthquakes should cover a sufficiently long period of time to yield a statistically significant sample because of the many variables and clustering effects observed in earthquake occurrence. Ideally, the seismic history should be several times longer than the recurrence between earthquakes of the maximum magnitude expected. Aftershocks are not easily separated from lists of earthquakes. Foreshocks and aftershock sequences may have a shallower recurrence slope (but not always) than ambient seismicity. If seismic history is short, these effects on recurrence may be significant. Krinitzsky (1993b) discusses these variabilities and provides an extensive reference list.

Aftershocks of larger earthquakes (e.g., M=7+) may perturb recurrence slopes for decades after their occurrence. The building of strain decades after a major earthquake may also perturb recurrence relationships. This problem is generally recognized. In support of recent effort by the Coalition of Professional and Scientific Associations in Support of the National Earthquake Hazard Reduction Program (NEHRP), Swain (1994) states:

> "Hand-in-hand with identifying the locations of magnitude 6-7 earthquakes is the problem of determining their frequency. The real significance of the Northridge earthquake for establishing seismic risks is that it questions the fundamental paradigm of earthquake risk assessment: That past earthquake rates of activity are a good indicator of future rates and hence probability of occurrence. The Northridge earthquake occurred only a few miles from the epicenter of the 1971 San Fernando earthquake, on a fault previously unidentified for earthquake hazard investigations, and the nature of faulting was much different. We must assume that many such fault structures exist, and if earthquake rates are increasing compared to the first part of this century, as recent earthquake activity seems to indicate, the earthquake risk in California may be much higher than has previously been indicated. The real risk can only be understood by a concentrated research effort to understand how typical is the occurrence of Northridge-type earthquakes in other parts of Southern California, Northern California and elsewhere in the 38 of our states which are at risk for earthquakes."

The NEHRP Coalition-supporting organizations that contributed to this statement are: The American Geophysical Union, American Institute of Architects, American Society of Civil Engineers, American Society of Public Administration, Association of Engineering Geologists, Earthquake Engineering Research Institute, Seismological Society of America and the Structural Engineers Association of California. Therefore, there is substantial support for concern over the stability of *a*- and *b*-values in recurrence relationships as currently used in risk analyses. The 1992 Little Skull Mountain earthquake, a few miles from YM, is clearly associated with and may have occurred in response to stress changes brought about by the larger 1992 Landers, CA earthquake. The Little Skull Mountain earthquake occurred on a fault previously unidentified for earthquake hazard investigations. Also of note are the large Holocene displacements discovered by geologists on the Death Valley fault several tens of kilometers from YM. Because there is no historic record of seismic activity on this fault, there has been a presumption that these movements are the result of aseismic slip. It is also possible that this fault is currently inactive but has, during the Holocene prior to our limited period of knowledge of seismic activity, produced a series of great earthquakes. It is possible that strain changes prior to and following such events could influence seismic activity at YM to a greater extent than the more distant Landers event. It, therefore, seems prudent that special efforts be taken to unequivocally date the movement of faults within, and in the vicinity of, YM. Potential temporal variations in recurrence relationships in the YM area should be assessed and incorporated in risk calculations.

Following Wesnousky et al. (1982) and Somerville et al. (1987), regional *a*-values are used with fault length dictating the magnitude that any particular fault may generate. Only faults with a potential to generate earthquakes with magnitudes between 6.2 and 7.2 appear to be adequately identified. The number of faults in the range that can support an average of M=6.7 is considered adequately defined to determine the Gutenberg and Richter recurrence relation. Three presumptions could be made to formulate a method for determining *a*-values. The first is that only faults within a small area, about 6,000 km^2, need be of concern in determining the level of seismic activity (the *a*-value of the recurrence formula). The second is that the number of faults in such a small area is not adequate to define the relationship, and that therefore a much larger area, about 100,000 km^2, must be considered to develop the recurrence curve. A third possible presumption is that paleoseismicity through the Quaternary does not adequately represent the future seismicity at the YM site because of the potential for change in such rates. Hofmann and Bangs (1993) estimate that there is a 10 percent chance that during a 10,000-yr period, seismicity at YM may increase to the maximum levels observed in the Basin and Range. This higher level of activity would be expected to last for about 1,000-yr. A case could also be made that current seismicity may continue or that current seismicity is higher than Quaternary seismicity. Other assumptions may be preferred by various experts.

Fault source zones for the YM area used in this analysis are given in Table 3-2 and on Figure 3-1. SEISM 1.1 code input files are in Appendix B of this report. Table 3-2 contains estimates of *a*-values based on published opinions that are often different for each of the pseudo-participants. However, because of difficulties in debugging input for this initial test computation, all *a*-values are set to those of pseudo-participant 6 (loosely based on Somerville et al., 1987) unless no *a*-value is given by pseudo-participant 6 for a particular fault. The effect on hazard of using a wider range of *a*-values will be investigated in future sensitivity studies.

The listed *a*-values, other than for pseudo-participant 6, were estimated with the assumption that N_c for $M=4$ is related to M_{max} as listed in Table 3-2 on the basis that there are about eight times as many earthquakes of each whole magnitude less than M_{max}. If N for M_{max} is known and the *b*-value is assumed to be 0.91, the *a*-value for $M=4$ may be calculated from the recurrence relation. For pseudo-participant 7, this process was used to apportion regional seismicity to *a*-values on each fault as indicated by the principal source of data for this expert. These values are higher than those of other authors, probably because much of the regional seismicity occurs on unknown smaller faults in addition to those identified by the principal source of data. If an assumed background source zone was used with this pseudo-participant, and some of the regional seismicity assigned to it, the remainder could be apportioned to the faults identified and the *a*-values would be more similar to others. This process, however, was not the intent of the principal source of data for this pseudo-participant.

Methods to determine *a*-values from paleofault offsets are not well discussed in the literature. This topic should be researched in the literature as a future task. Another approach to determining *a*-values involves the use of strain rates where such data are presented in the literature. Initial attempts to use this procedure provided a broader range of *a*-values than expected, so it was not used to derive the *a*-values in Table 3-2.

3.2.2 Ground Motion Pseudo-Participant Models

An examination of several suites of strong motion acceleration attenuation functions and the Little Skull Mountain earthquake strong motion records suggested that several published functions fit the recorded strong motions within expected error bands. The attenuation functions examined are plotted in Appendix C. This author, therefore, chose several of these functions to represent pseudo-participant opinions regarding appropriate attenuation functions for use in the YM region. There are many other published attenuation functions, and it is likely that an elicitation of ground motion experts would indicate a preference for functions other than those chosen here. However, the chosen functions are reasonable and provide input for a test calculation with SEISM 1.1. Table 3-3 lists the author, basic published formulae, and formulae modified to provide a uniform measure of distance and of peak acceleration using the attenuation functions denoted in Figure 3-3. It may be preferable to ultimately alter the code itself to adapt to the different distance measures proposed by authors of attenuation functions rather than to modify the functions. The uniform distance measure used for the modified formulae is epicentral distance for Atkinson's attenuation function and distance to the surface projection of the rupture zone (SPRZ) for the other attenuation functions. For earthquakes occurring randomly over a fault zone, epicentral distance and the distance to the surface projection of the fault slip plane could result in roughly equivalent average risk, particularly when the random nature of rupture plane symmetry, or displacement asymmetry about the slip plane center is considered in a probabilistic analysis. In calculating the modified formulae, fault-slip-plane-deviation from vertical is ignored because it is usually not accurately known and would contribute only a small correction for most Basin and Range faults if it was considered. For a deterministic analysis, or consideration of very-near-field faulting, detailed geometry may merit further analysis. The modified formulae all yield peak acceleration in cm/s^2 as required by SEISM 1 according to Bernreuter et al. (1989) and Davis (1991). Where formulae produce accelerations in g's, they are multiplied by 980 cm/s^2/g. If the formulae are given in average peak acceleration, they are multiplied by 1.12 to correct them to peak acceleration. Where hypocentral distance or CDRZ are defined, geometric corrections are made so that the distance definition is given as distance to the surface projection of the fault slip plane.

Initial calculations with these units did not produce expected results. The output of eastern U.S. attenuation functions was plotted to verify that the version of SEISM 1 used in this analysis produces cm/s^2. An average value of about 3,000 cm/s^2 is indicated at 10 km from Magnitude 7.5 and 8 earthquakes, a value that seemed too large and raised concerns about our plotting procedure and perhaps coding. However, LLNL provided a printout of the eastern U.S. attenuation function output using a computer program developed to test such functions when installed in SEISM 1. The routine verified a maximum of about 3,000 cm/sec^2 for these magnitudes.[1] Further, the eastern attenuation function curve fits in the code were not made to an expert's function, but to the data set from which it was derived.[2] This procedure was used because ground motion amplitudes for a standard set of spectral bands, for spectral attenuation functions, were desired and the spectral bands proposed by the experts were not uniform. The curve-fit formulae may extrapolate differently from the original functions.

Several test calculations were made by CNWRA to locate possible sources of errors. A final calculation with the functions as listed in Table 3-3 provided results within the expected range of values. The attenuation functions in Table 3-3 were weighted equally for each source zone pseudo-participant. Output from SEISM 1.1 calculations, however, include results for each attenuation function used.

Attenuation functions of Campbell (1987) were developed from strong motion records at very short distances. Campbell calls these functions "unconstrained." Far-field records were added, and the curves recalculated. These records are called "constrained" by Campbell. The complete Little Skull Mountain earthquake strong motion data set fit two of Campbell's (1987) constrained curves best, so two

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[1] B. Davis, personal communication, March 7, 1994.

[2] D. Bernreuter, personal communication, March 7, 1994.

constrained curves were selected for this test computation. For larger earthquakes whose rupture zones breach the surface, it is possible that very near-field records may be better fit by the unconstrained curves. This possibility remains as an uncertainty at this time.

Table 3-2. Pseudo-participant opinions regarding faults of concern at Yucca Mountain

Participant	M_{max}	Length (km)	Symbol	Name	N	Offset of M_{max} (cm)	Strain Rate (cm/yr)	*a*-Value
The bases for these estimates were not provided in the data sources for pseudo-participants 1-5. Some of these data are assumed to have been derived from recently measured paleofault offsets. N is the annual number of earthquakes in the M=4 range.								
1	6.0 - 7.7	25	SC	Solitario Canyon	1.25×10^{-5}	64	0.0008	1.4
	6.2	8	GD	Ghost Dance/ Abandoned Wash	5.833×10^{-6}	12	0.00007	0.47
	6.9	32	PB	Paintbrush Canyon/ Stagecoach Road	8.411×10^{-6}	107	0.0009	1.28
	6.3	14	BR	Bow Ridge	1.091×10^{-5}	27.5	0.0003	0.84
	5.6	5	PW	Pagany Wash (South of and parallel to Yucca Wash)	1.111×10^{-5}	9	0.0001	0.20
	5.6	5	DW	Drillhole Wash	1.111×10^{-5}	9	0.0001	0.20
	6.0	6	FW	Fatigue Wash	1.191×10^{-5}	42	0.0005	0.80
	6.8	24	WW	Windy Wash	2.800×10^{-5}	50	0.0014	1.703
2	6.8 - 7.0	20	SC	Solitario Canyon			0.0002	1.275
	6.2	8	GD	Ghost Dance/ Abandoned Wash	5.0×10^{-5}		0.0001	0.470
	6.9	32	PB	Paintbrush Canyon/ Stagecoach Road			0.0002	1.275
	6.3	14	BR	Bow Ridge	5.0×10^{-5}		0.002	0.84
	7.1	24	WW	Windy Wash			0.002	0.80
	6.0	5	FW	Fatigue Wash			0.002	0.84
3	6.0 - 7.0	20	SC	Solitario Canyon	1.25×10^{-5}		0.0008	0.174
	5.7 - 6.0	5.5	GD	Ghost Dance/ Abandoned Wash	1.33×10^{-5}		0.00004	0.337

Table 3-2. Pseudo-participant opinions regarding faults of concern at Yucca Mountain (Cont'd)

Participant	M_{max}	Length (km)	Symbol	Name	N	Offset of M_{max} (cm)	Strain Rate (cm/yr)	*a*-Value
3	6.8	39	PB	Paintbrush Canyon/ Stagecoach Road	1.33×10^{-5}		0.0008	0.194
4	6.5 - 7.4	25	SC	Solitario Canyon	1.33×10^{-5}	80		0.164
	6.4	8	GD	Ghost Dance/ Abandoned Wash	1.33×10^{-5}		0.251	
	6.8	24	WW	Windy Wash	1.33×10^{-5}	27		0.194
	6.8	39	PB	Paintbrush Canyon/ Stagecoach Road	1.33×10^{-5}	50	0.0008	0.194
	6.3	14	BR	Bow Ridge	1.33×10^{-5}	20		0.266
5	6.2 - 6.5	16	SC	Solitario Canyon	5.00×10^{-3}	50	0.0005	0.460
	4.7 - 5.3	4	GD	Ghost Dance	5.00×10^{-5}	10	0.00005	0.642
	6.1 - 6.3	12	BR	Bow Ridge	2.0×10^{-5}	25	0.0003	0.291
	>7	?	RS	Random Source	(1.25×10^{-4}/ 10,000 km/yr)			
6	M_{max} and recurrence information are all derived from fault lengths.							
	6.5	17	SC	Solitario Canyon	1.206×10^{-5}	68	0.00082	0.233
	6.0	9	GD	Ghost Dance/ Abandoned Wash	7.188×10^{-5}	32	0.00023	0.300
	7.0	33	PB	Paintbrush Canyon/ Stagecoach Road	2.088×10^{-5}	147	0.0037	0.162
	6.1	11	BR	Bow Ridge	1.111×10^{-5}	39	0.0002	0.294
	5.6	5	PW	Pagany Wash	2.778×10^{-6}	18	0.00005	0.337
	6.8	25	CS	Cane Spring (West of and parallel to Rock Valley)	1.517×10^{-5}	116	0.0018	0.196
6	6.7	23	MM	Mine Mountain	1.490×10^{-5}	100	0.0015	0.226

Table 3-2. Pseudo-participant opinions regarding faults of concern at Yucca Mountain (Cont'd)

Participant	M_{max}	Length (km)	Symbol	Name	N	Offset of M_{max} (cm)	Strain Rate (cm/yr)	*a*-Value
	6.5	17	BM	Bare Mountain	1.206×10^{-5}	68	0.00082	0.220
	7.4	53	RV	Rock Valley	2.022×10^{-5}	277	0.0056	0.097
	5.7	6	SW	Sever Wash (S of and parallel to Yucca Wash)	3.044×10^{-6}	23	0.00007	0.325
	6.1	10	YW	Yucca Wash (North of YM Site)	5.128×10^{-6}	39	0.0002	0.278
	6.4	15	MV	Midway Valley (West of and parallel to Paintbrush Canyon)	1.016×10^{-5}	62	0.00063	0.246
	5.6	5	TW	Tea Cup Wash (Parallel and merges w/Pagany Wash)	2.778×10^{-6}	18	0.00005	0.348
	6.1	10	WA	Wahmonie	5.128×10^{-6}	39	0.0002	0.277
	6.2	12	AR	Amargosa Valley	6.383×10^{-6}	47	0.003	0.267
	6.5	17	CA	Carpet Bag	1.206×10^{-5}	68	0.00082	0.596
	7.2	41	YB	Yucca Boundary	2.217×10^{-5}	212	0.0047	0.120
	8.5	50 - 165	DV	Death Valley/Fish Lake Valley	1.00×10^{-4}	2000	0.1	−0.115
	8.5	190	FC	Furnace Creek	1.250×10^{-5}	2000	0.025	−0.078
	7.2	45	SR	Sheep Range	1.906×10^{-5}	212	0.004	0.118
	7.0	34	KA	Kane Springs	4.898×10^{-5}	147	0.00072	0.161
	8.0	150 - 300	GA	Garlock	1.00×10^{-3}	685	7	0.0
	8.5	120 - 300	OV	Owens Valley	6.00×10^{-4}	2000	1.1	−0.143
	6.7	27	WW	Windy Wash	1.150×10^{-5}	100	0.0012	0.20

Table 3-2. Pseudo-participant opinions regarding faults of concern at Yucca Mountain (Cont'd)

Participant	M_{max}	Length (km)	Symbol	Name	N	Offset of M_{max} (cm)	Strain Rate (cm/yr)	*a*-Value
7	The primary source for this pseudo-participant provided no fault information other than M_{max} and length. A regional recurrence based on historical seismicity was suggested as appropriate, but *a* and *b*-values were not presented. Additional efforts will be required to more accurately incorporate this opinion. The M=4.7 for Mercury Valley is not used. Most of the data for this pseudo-participant were derived from an older publication. Douglas and Ryall's (1975) formula LogN=6.48-0.91M was assumed with the constant term divided by 14 and apportioned among the various faults. The areas encompassing the faults and for which the recurrence formula was determined, are about the same. However, they are overlapping rather than coincident, which would have been preferable. That the various faults do not each have the same level of activity is recognized by the author of this Test Analysis Report. However, this approach is a possible approximation of the published opinion for this pseudo-participant.							
	6.7	25	CS	Cane Spring				0.46
	4.7	4	ME	Mercury Valley				0.46
	6.9	29	MM	Mine Mountain				0.46
	6.5	17	BM	Bare Mountain				0.46
	7.2	36	RV	Rock Valley				0.46
	6.4	15	MV	Midway Valley				0.46
	6.8	25	YB	Yucca Boundary				0.46
	7.2	38	FM	Funeral Mountains				0.46
	8.5	200	DV	Death Valley/Fish Lake Valley				0.46
	8.5	200	FC	Furnace Creek				0.46
	6.5	20	SR	Sheep Range				0.46
	7.0	32	AA	Alamo Area				0.46
	8.5	200	GA	Garlock				0.46
	8.5	150	OV	Owens Valley				0.46
8	The primary source for this pseudo-participant also provided no fault information other than M_{max} and length. Recent publications were referenced. The primary utility of this data set is the list of faults of concern. An average of *a*-values from pseudo-participants 1-6 was used.							
	6.8	16	SC	Solitario Canyon				0.19

Table 3-2. Pseudo-participant opinions regarding faults of concern at Yucca Mountain (Cont'd)

Participant	M_{max}	Length (km)	Symbol	Name	N	Offset of M_{max} (cm)	Strain Rate (cm/yr)	*a*-Value
8	6.9	24	PB	Paintbrush Canyon/ Stage Coach Road				0.19
	6.7	14.5	BR	Bow Ridge				0.28
	6.6	17	MM	Mine Mountain				0.23
	6.8	18.5	BM	Bare Mountain				0.23
	6.7	12	RV	Rock Valley				0.10
	6.6	10	WA	Wahmonie				0.29
	6.6	12	AR	Amargosa Valley				0.27
	6.6	12	CA	Carpet Bag				0.60
	7.1	38	YB	Yucca Boundary				0.13
	7.9	175	DV	Death Valley				0.12
	7.2	42	FC	Furnace Creek				0.08
	7.1	35	SR	Sheep Range				0.12
	6.7	12.5	WW	Windy Wash				0.20

Table 3-3. Selected western United States attenuation functions

Expert 1	
Author	Campbell (1987) for soils < 10 m thick, constrained by far-field recordings.
Basic Formula	Units are average peak acceleration in g and CDRZ distance in km. $\ln A = -2.893+0.85M-1.25\ln[R+0.0872\ e^{0.678M}]-0.0059R$ (9th figure of Appx. C.)
Modified Formula	Units are peak acceleration in cm/sec^2 and distance in km. $\ln A = -2.771+0.85M-1.25\ln[(R_{rp}{}^2+16)^{½}+0.0872\ e^{0.678M}] -0.0059R+\ln 980 = 4.11655 +0.85M -1.25\ln[(R_{rp}{}^2 + 16)^{½} + 0.0872e^{0.678M}]-0.0059R$ Note that the last term is not corrected for epicentral distance because its value is significant only at large distances where distance definition differences are small. This formula is for peak acceleration.
Expert 2	
Author	Campbell (1987) for soils < 10 m thick, constrained by far-field recordings plus fault directivity.
Basic Formula	Units are average peak acceleration in g and CDRZ distance in km. $\ln A=-2.370+0.85M-1.25\ln[R+0.0872\ e^{0.678M}]-0.0059R$ (10th figure of Appx. C.)
Modified Formula	Units are peak acceleration, SPRZ distance (km) and cm/sec^2. $\ln A=-2.251+0.85M-1.25\ln[(R_{rp}{}^2+16)^{½}+0.0872e^{0.678M}]-0.0059R + \ln 980=+0.85M-1.25\ln[(R_{rp}{}^2+16)^{½}+0.0872e^{0.678M}]-0.0059R$ See note for the previous modified formula above. This formula is intended for use with faults whose strike to fault-to-site-line angle is less than 10 arc degrees. This formula is for peak acceleration.
Expert 3	
Author	Atkinson (1984) for hypocentral distance with acceleration given in cm/s^2. Hypocentral depth for the Basin and Range tectonic province is assumed to be 14 km in the modified formula. The basic formula is stated to be for rock sites. This formula is based on stochastic theory, e.g. see Hanks and McGuire (1981). Beyond 20 km this curve merges with that of Joyner and Boore (1981), also described in this section. Atkinson prefers that the Joyner and Boore curves be used beyond 20 km. Atkinson's version of the Joyner and Boore formula is for average peak acceleration in cm/s^2 and hypocentral distance.

Table 3-3. Selected western U.S. attenuation functions (Cont'd)

Basic Formula	Units are hypocentral distance in km and average peak acceleration in cm/s^2. For distance $\leq$ 20km, $A=34.9\ e^{(0.575M)}R^{-1}(1.15M\ -2.35)^{1/2}$ (2nd figure of Appx. C.) Units are hypocentral distance in km and average peak acceleration in cm/sec^2. For distance $>$20km, Atkinson's version of Joyner and Boore's formula $A=82.4\ e^{(0.573M)}R^{-1}e^{(-0.00587R)}$
Modified Formula	Units are epicentral distance in km (assuming a 14 km depth of focus) and acceleration in cm/s^2. For distances $\leq$ 20 km, $\ln A=\ln 34.9+0.575M-\ln(R_{rp}{}^2+196)^{1/2}+1/2\ \ln(1.15M\ -2.35)+\ln 1.13=3.6747+0.575M-\ln(R_{rp}{}^2+196)^{1/2}+1/2\ln(1.15M\ -2.35)$ for (3rd figure of Appx. C.) For distance $>$20 km, Atkinson's version of the Joyner and Boore formula are in units of km for epicentral distance and cm/s^2 for acceleration. $\ln A=\ln 82.4+0.573M-\ln R\ -0.00587R+\ln 1.13$ $= 4.5338+0.573M-\ln(R_{rp}{}^2+196)^{1/2}-0.00587(R_{rp}{}^2+196)^{1/2}$ for The equation assumes a hypocentral depth of 14 km.
Expert 4	
Author	Joyner and Boore (1981). This is an empirical equation. Distance is measured to the surface projection of the fault slip area assuming that the effective fault slip area is 7.3 km below the earth's surface for magnitudes of 5.3 to 7.4.
Basic Formula	Units are SPRZ distance in km and acceleration in g. $\text{Log } A=-1.02+0.249M-\text{Log } r-0.00255r+0.26P$ (1st Figure of Appx. C) Where $r=(d^2+7.3^2)^{1/2}$, and r=CDRZ Note that if P=1 in the last term, the formula is for the 84th percentile. If P=0, the formula is for the 50th percentile. Separate formulae are not provided for rock and soil sites. Log is to the base 10.

Table 3-3. Selected western U.S. attenuation functions (Cont'd)

Modified Formula	Units are SPRZ distance in km, assuming a depth to the top of the rupture zone of 4 km, and acceleration in cm/sec^2. $\text{Log } A = -1.02+0.249M-\text{Log }(R_{rp}{}^2+53.29)^{1/2}-0.00255R_{rp}+\text{Log } 980$ $=5.8676+0.249M-\text{Log }(R_{rp}{}^2+53.29)^{1/2}-0.00255R_{rp}$ Note that the last term is not modified for distance measures because it is significant only at distances where the correction is small. For peak acceleration. The assumed depth to the fault rupture zone is decreased from 7.3 to 4 km. Log is converted to ln in the coded formula.
Expert 5	
Author	Schnabel and Seed (1973). These curves are empirical and are difficult to fit with formulae. A table lookup scheme is used to represent the curves with a series of short straight lines. Distance is to the surface projection of the causative fault, which is assumed here to be equivalent to SPRZ.
Basic Curves	Units are distance to the surface projection of the causative fault in miles and acceleration is in g.
Modified Curves	Units are equivalent to SPRZ in km and acceleration in cm/s^2. (4th figure of Appx. C), ln cm/s^2 is provided by the coded table.
Definition of Terms	
M =	Richter magnitude defined as M_L to M=6.5 and M_S for M > 6.5, where M_L is the Richter Local magnitude (Richter, 1935 and Gutenberg and Richter, 1942), and M_S is the 20 s surface wave magnitude (e.g., Gutenberg, 1945, and Gutenberg and Richter, 1942 and 1956). M_w (e.g., Kanamori, 1977) is now accepted for magnitudes greater than 8.
R or r =	Distance in km as defined by various authors.
R_{rp} =	SPRZ. Note that this distance is difficult to define prior to an earthquake. Estimates are developed as discussed in Section 3.1.2 and on Figure 3-9.
A =	Acceleration in cm/s^2.
e =	2.7183

4 FAULT DISPLACEMENT ANALYSIS

4.1 BACKGROUND

Most probabilistic fault displacement analyses in the literature are of the fault tree type in which alternative probabilities regarding activity or nonactivity are branches. Other branches indicate peak magnitude, possible selections of *a*- and *b*-values to define earthquake recurrence, recurrence of fault offsets, possible lengths of faults, whether faults are connected, etc. Experts will assign probabilities or uncertainties to each branch to arrive at a risk value. For example see Somerville et al. (1987) or Coppersmith and Youngs (1990), who use trees for both fault displacement and seismic hazard analysis.

However, the use of the SEISM 1 code as a tool for development of probabilistic fault displacement hazards appears feasible. An approach is suggested here. The code requires input variables and produces outputs in terms of earthquakes and their recurrence. These outputs, in turn, are related to fault offsets and fault slip areas. There are several such formulae in the literature. Examples are Wyss (1979) for fault slip area, S in km:

$$M_S = \log S + 4.15 \tag{4-1}$$

and Slemmons (1977) for normal - oblique faults offset:

$$M = 6.75 + 1.260 \log D \tag{4-2}$$

These relationships are useful in predicting fault offset hazards by exploiting the statistical processes programmed into SEISM 1. A part of the SEISM 1 code's capability is related to the attenuation of wave propagation. This part of the code is not required in fault displacement analysis and is not used. Each fault is considered alone, with input from several experts to provide a range of information regarding the fault. Magnitude is converted to fault displacement. This relationship is substituted for one of the earthquake attenuation functions (f-models) in the SEISM 1 code. Several published relationships could be used in future calculations. All variables and associated uncertainties, except for distance, are used to generate the fault displacement hazard, which is the inverse of earthquake or fault-displacement return-period.

4.2 IMPLEMENTATION OF FAULT HAZARD ANALYSIS

Fault displacement (*D*), or offset, is expressed in centimeters in the formula as programmed into SEISM 1 to provide a range of numbers compatible with the range of accelerations in cm/s^2 generated by the SEISM 1 seismic hazard routines. SEISM 1 requires attenuation function output to be in the form of a natural logarithm, consequently the formula for "*D*" in cm is:

$$\ln (D) = 1.82745 \, (M - 4.23) \tag{4-3}$$

The plotting functions require less alteration in the code when *D* is in cm. Additional decades are added to the x and y axes and the scales are both made logarithmic. The variable, *D*, is expressed in the code as if it were an acceleration, *A*. Resulting hazards are for the entire fault zone throughout its down-dip extent (width). Figures 4-1 and 4-2 are examples of fault displacement output. Figure 4-1 is plotted to a log-log scale to display the wide range of fault offset data that may be of interest. These

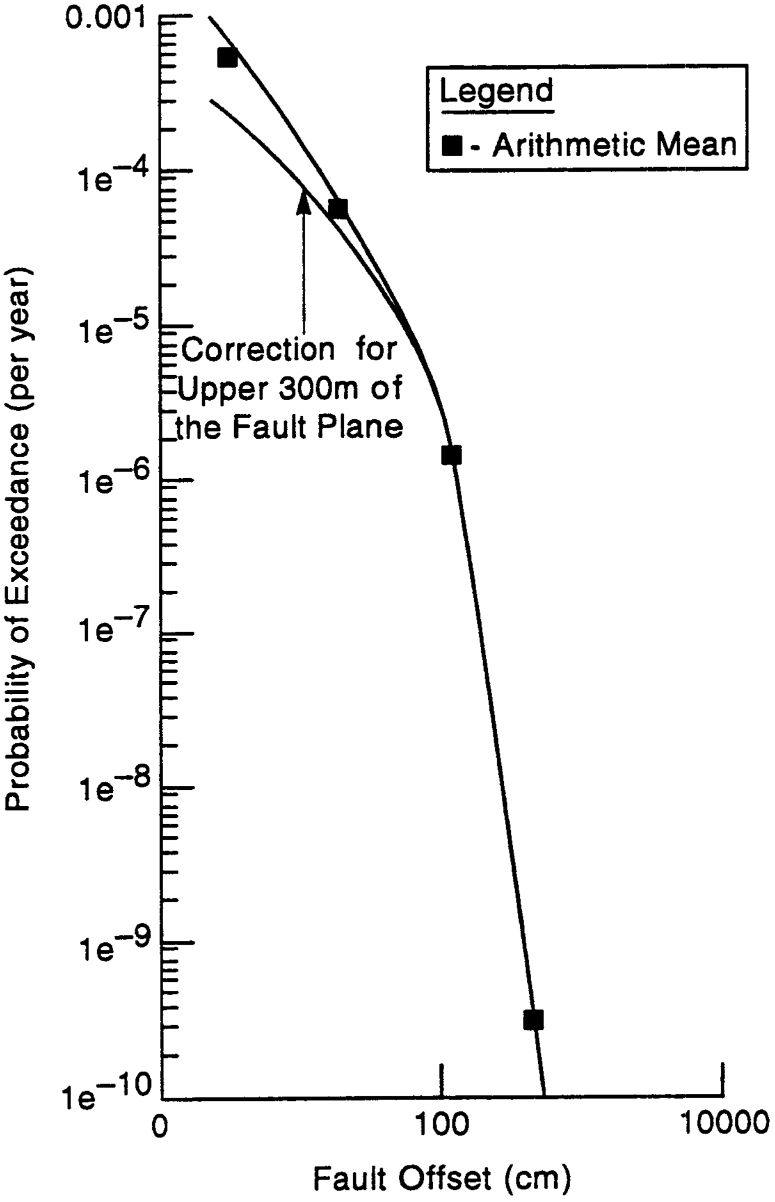

Figure 4-1. Fault displacement hazard for the Paintbrush Canyon Fault

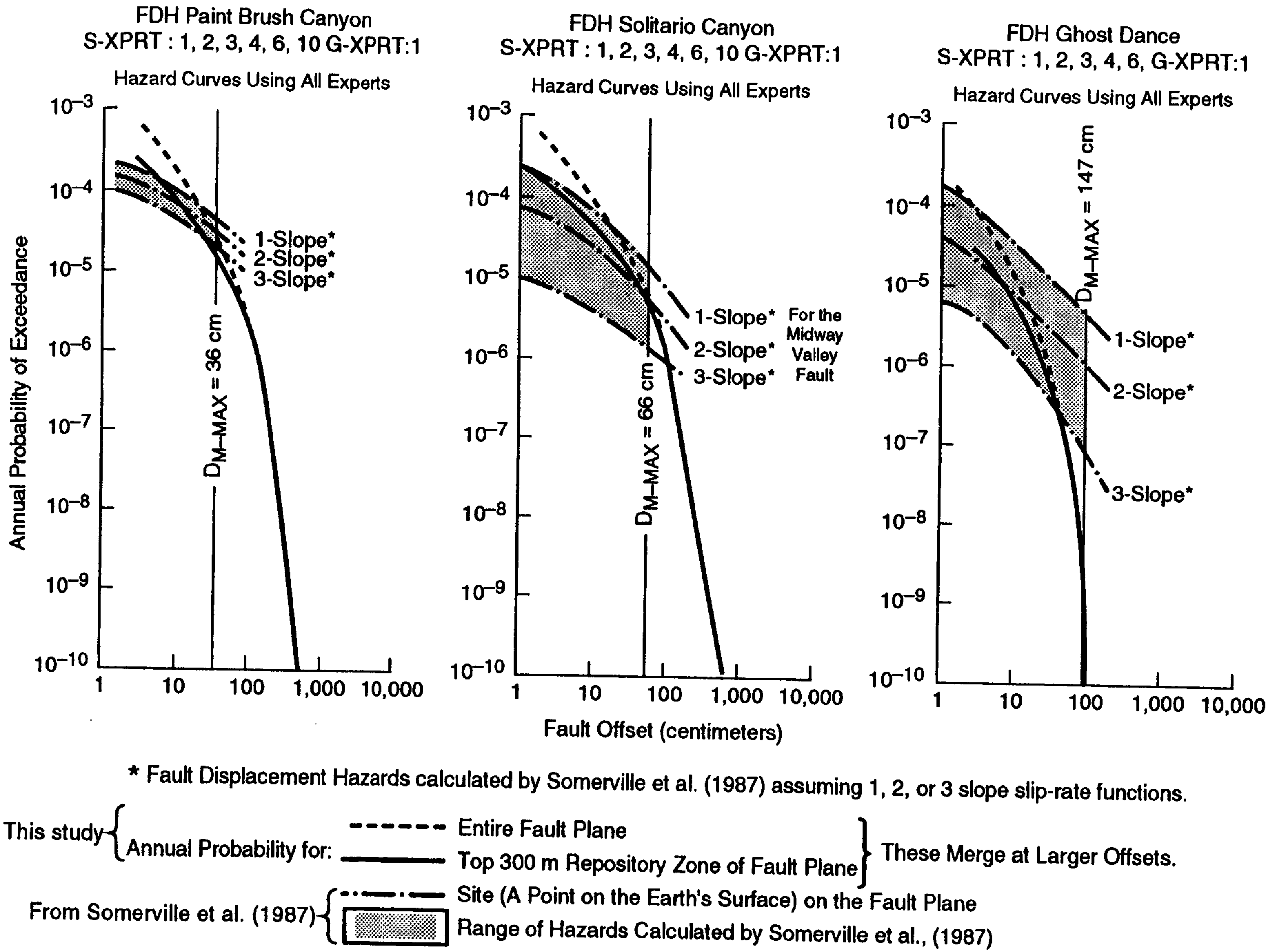

Figure 4-2. Arithmetic average hazard for several faults

initial calculations assume that the Gutenberg-Richter recurrence relation applies to individual faults over a long period of time. The hazard of a fault displacement occurring within 300 m of the earth's surface (the repository horizon) is a function of the slip area for a given magnitude earthquake, total fault area, and fault geometry. For smaller earthquakes whose rupture dimensions do not fill the 14-km down dip width of the fault, only a few may intersect the surface or extend into the repository horizon. The curves of Slemmons (1977) indicate that M=6.4 has a rupture area equivalent to a square 14 km on a side, which would fill the down-dip extend of the fault and always cause displacement of the top 300 m repository zone.

4.3 FAULT DISPLACEMENT HAZARD CORRECTIONS FOR THE REPOSITORY HORIZON

Corrections may be made for the fact that not all rupture areas of earthquakes smaller than about 6.4 will intersect the repository horizon. Even though there are many more M=5 earthquakes than M=6.4 earthquakes, their rupture areas are relatively small, and only a small fraction of them will intersect the top 300-m of the fault plane where the repository would be directly affected.

The proposed analysis would produce accurate hazards for earthquakes whose fault area extends from the 300-m depth to the full down dip dimension of the fault plane. Magnitude 6.4 and larger earthquakes have such fault areas. For smaller earthquakes, a slip dimension may be a fraction of the full down-dip extent of the fault but there will be more of them. For example, using the recurrence relation with a=0.3 and b=0.91 (see section 3 of this report), if a M=5 earthquake and square slip areas are assumed, about 25 such areas will fill a 13.7 by 13.7 km area. This size area fits between the 300 meter depth of repository workings to an assumed maximum 14 km depth. Therefore, only about one-fifth of the M=5 earthquakes may rupture the 300-m zone at the surface. However, there are about 19 times as many M=5 earthquakes as there are M=6.4 earthquakes assuming the b-value for recurrence value used in this analysis. This value suggests that there are about four times as many M=5 size ruptures that reach the 300-m surface zone, as there are M=6.4 ruptures. The hazard value reported by the displacement equation to be installed in SEISM 1.1 would be roughly five times too high for M=5. This correction for M=5 and similar ones for each succeedingly higher magnitude would permit a more accurate estimate of rupture displacement occurrence in the 300-m surface zone of a fault. Each scenario for fault displacement hazard requires its own logic. If the analysis is for the Ghost Dance fault through the repository, only the approximately 3-km lateral extent of the repository workings might be considered. This fact would further reduce the hazard from M=5 earthquakes by the ratio of 3-km to the length of the fault.

The real dimensions of fault rupture areas are not necessarily square as depicted on Figure 3-4. Earthquakes of various magnitudes generated by a Monte Carlo process and that appear in the upper 300 meters of the fault plane are counted. This approach also permits investigating the effect of fault slip area aspect ratios. Results for a MatLab-generated Monte Carlo process for the rupture area of a M=5 earthquake (from Figure 3-4) are provided in Figure 4-3.

The effect of changing the aspect ratio of rectangular faults from square (1 to 1) to rectangular (9 to 1 and 1 to 9) is graphed. If the very small fault-slip area of an M=5 earthquake was within a very narrow vertical rectangle, it could intersect the top 300-m of the fault plane for every occurrence. Fault rupture areas associated with earthquakes, however, are not very narrow and deep. Therefore, these small rupture areas will only occasionally occur within or adjacient to the 300-m thick repository horizon at

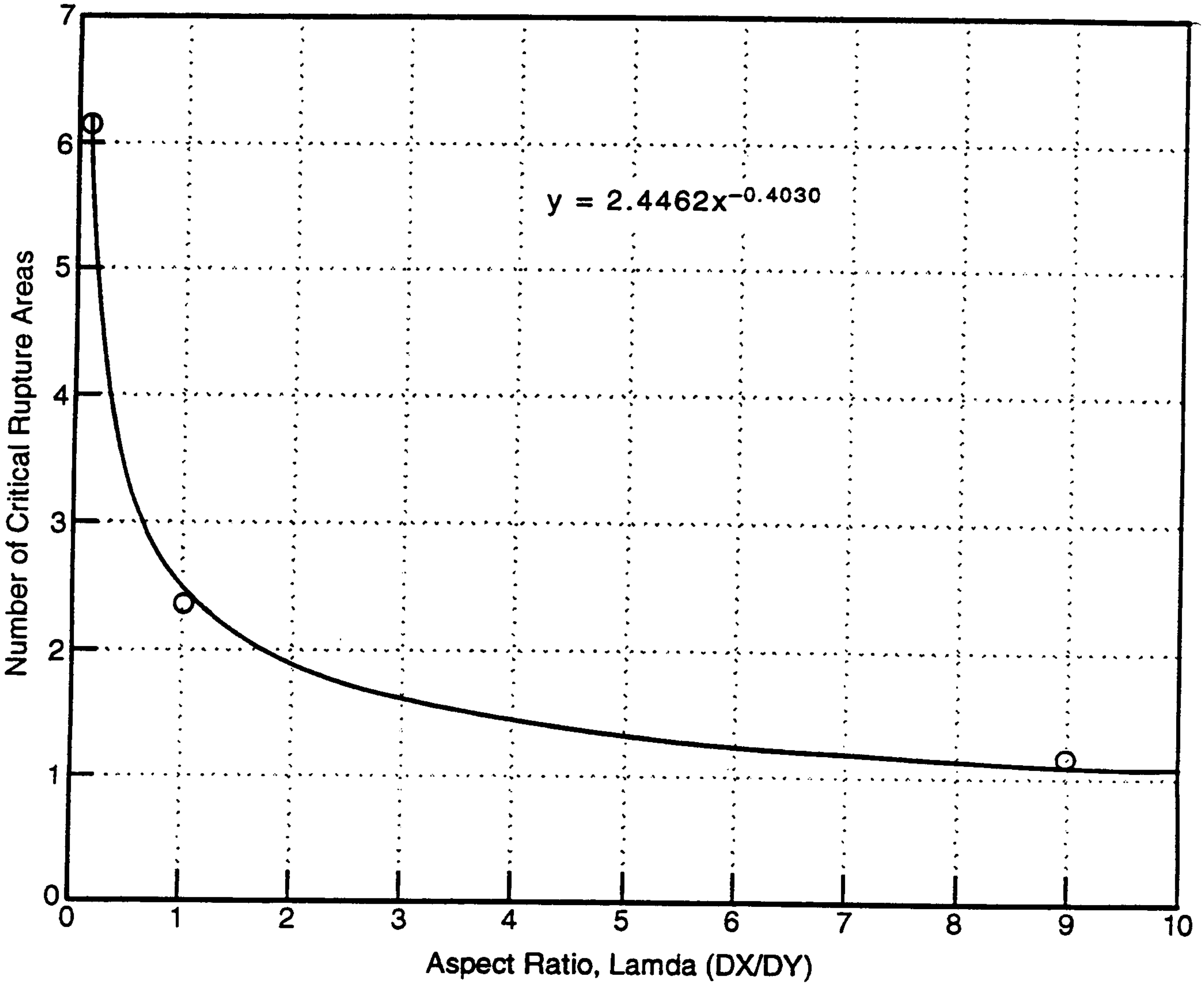

Figure 4-3. Sketch of the effect of fault slip aspect ratio on fault offset hazard correction for the top 300-m of the fault plane

the surface. The number of rupture zone intersections of the top 300-m thick repository horizon by M=5 earthquakes for each equivalent M=6.4 earthquake (which will rupture the entire down-depth extent of the fault) is plotted on the y axis. This data plotted on a log-log graph is a straight line. The best-fit line on a log-log plot was converted to the linear curve and formula on Figure 4-3. The data indicate that the number of earthquake rupture areas which intersect the 300-m zone is sensitive to fault rupture area shape. Plots of width and length of normal dip-slip fault-rupture areas by Wells and Coppersmith (1994), largely derived from California data, suggest a width to length ratio of 1 to 1 for M=5, 1 to 1.2 for M=6 and 1 to 2.3 for M=7. If an average ratio of 1 to 1 is assumed, the correction is about a 2.3 times reduction in hazard for M=5, based on the Monte Carlo calculation, compared to M=6.4 (see Figures 4-3 and 3-4). If the curve fit to the Monte Carlo calculation on Figure 4-3 is used, the reduction is about 2.4. The Little Skull Mountain earthquake slip zone as outlined by preliminary aftershock data suggests an aspect ratio between 2 to 1 and 3 to 1 for this earthquake. A fault plane with displacement areas is sketched in Figure 3-4. The number of fault slip areas for the entire fault plane, which is the basis for the hazard graph on Figure 4-1, would have to be modified by a factor of 2.3 to 2.4, for M=5 earthquakes. Similar modifications are required for all magnitudes between M=6.4 (the magnitude earthquake whose slip zone, if square, fills the depth of the fault plane to 14 km) and M=5 (the lowest magnitude used in the analysis). These smaller offsets (less than 50 cm) may be of importance depending on repository waste emplacement designs. Fault slip area aspect ratios are a variable that is subject to differences in expert opinion.

Our version of SEISM 1 integrates over source zones in such a way that a less precise hazard estimate for individual faults is produced than would be obtained by an integration scheme designed for fault sources. A version of SEISM 1 being prepared for NRR may have an improved integration scheme for use with fault sources. The SEISM 1 code was developed using large areas as source zones. If it is assumed that smaller than maximum earthquakes and associated fault displacements are likely to occur on smaller currently undefined faults, the fault displacement hazard would be distributed over an area about the fault. Larger offsets would be restricted to the mapped faults used as source zones in the program. For this test analysis, an external MATLAB Monte Carlo routine was used to develop corrections to the fault displacement hazard calculated for the whole fault zone to estimate hazard for only the upper portion of the zone. Programming revisions to SEISM 1.1 could be made to calculate various scenarios directly. However, the level of effort would not be trivial.

If the Wesnousky et al. (1982) relationship is assumed, smaller presently unknown randomly distributed faults associated with a large fault, for example as proposed by Bonilla (1970), would have to be considered. The problem becomes three dimensional. It is no longer confined to a single fault plane, but is distributed over many smaller fault planes throughout a volume of rock.

Displacement hazards for several example faults are shown in Figure 4-2. Each desired scenario for fault displacement hazard will require some modification of logic or corrections, similar to those described above, to determine the likelihood of a certain amount of fault offset on a fault plane, a specific part of the fault plane, or in a volume of rock surrounding a part of a fault plane. If the hazard from random fault offsets in a volume of rock is desired, the dispersal of smaller offsets throughout the rock mass could be based on the Wesnousky et al. (1982) proposal: only the maximum magnitude that a fault can support will occur on that fault (plus aftershocks). Smaller earthquakes will occur on smaller probably unrecognized faults. Another scenario is that fault offset is distributed among branches of the main fault as well as on the main fault. The branches may be roughly parallel structures with various dips from the surface that join with the main fault at depth. A suite of such scenarios could be calculated, but each new analysis will require additional programming. Only the basic process of determining fault offset hazard for an entire fault plane is presently programmed in SEISM 1.1.

4.4 EXAMPLE COMPUTATIONS OF FAULT DISPLACEMENT HAZARD

Example computations are summarized in Figures 4-1 and 4-2. Displacement hazard for each fault requires a separate SEISM 1 computation because each fault has different parameters (location, geometry, size and slip history). This computation results in substantial output. An example of complete output is at the end of Appendix D. Selected summary plots for three faults are shown in Figure 4-2. Pseudo-participant 6 is roughly based on data from Somerville et al. (1987), who provides annual displacement exceedances for several faults. One of several examples from Somerville et al. (1987) is reproduced in Figure 4-4. Values from Figure 4-4 are plotted on Figure 4-2 as dot-dashed lines. Results from this study on Figure 4-2 are plotted as dotted lines for comparison. Analyses for the Ghost Dance, Paintbrush Canyon, and Solitario Canyon faults were made in this study. They were selected because most of the pseudo-participants derived from the literature named these faults as important considerations for the YM or NTS areas. Calculating offset hazards of faults for which several pseudo-participants provided data, permitted exercising the statistical routines in SEISM 1.1. Other faults were selected by only one or a few of the pseudo-participants and would not have provided much input for the statistical routines.

4.5 COMPARISON OF CALCULATIONS WITH PUBLISHED VALUES

The principal publication for comparison of fault rupture hazards available at the time of this study was Somerville et al. (1987). Much of the input data for the SEISM 1.1 analysis was derived from that report. Our methods differ from Somerville et al. in several respects. Figure 4-2 illustrates the fault displacement hazard for the entire fault and for the 300-m repository horizon from this study, and the range of values calculated in the Somerville et al. (1987) for the repository represented by a point on the earth's surface. Results from the three faults investigated in this study are largely within the range of values developed by the Somerville et al. (1987) study for offsets less than those equivalent to the maximum magnitude associated with fault length. Results from this study are consistent with the range of Somerville et al., (1987) except that a lower hazard is calculated for offsets near that associated with the maximum magnitude for the fault. Estimates of hazard for offsets larger than the average maximum expected, for example, for a 200-cm offset, may differ by over an order of magnitude between the Somerville et al. (1987) report and this study.

Somerville et al. (1987) did not calculate a fault displacement hazard for the Solitario Canyon fault. Their results for the Midway Valley fault of similar length, maximum magnitude, and recurrence are illustrated for comparison with the Solitario Canyon fault displacement hazard developed in this study.

Hazard curve slopes for this study are steeper than those for the Somerville et al. (1987) study. Hazard values are identical where the curves cross. Reasons for the differences appear to be:

- Somerville et al. (1987) chose a site on the surface. Consequently, the correction for small offsets will be larger than for the 300-m deep repository horizon used in this study. The use of a point as a site would be a major contributor to flattening (lowering) of their curves for small offsets compared to the 300-m repository horizon hazard of this study.

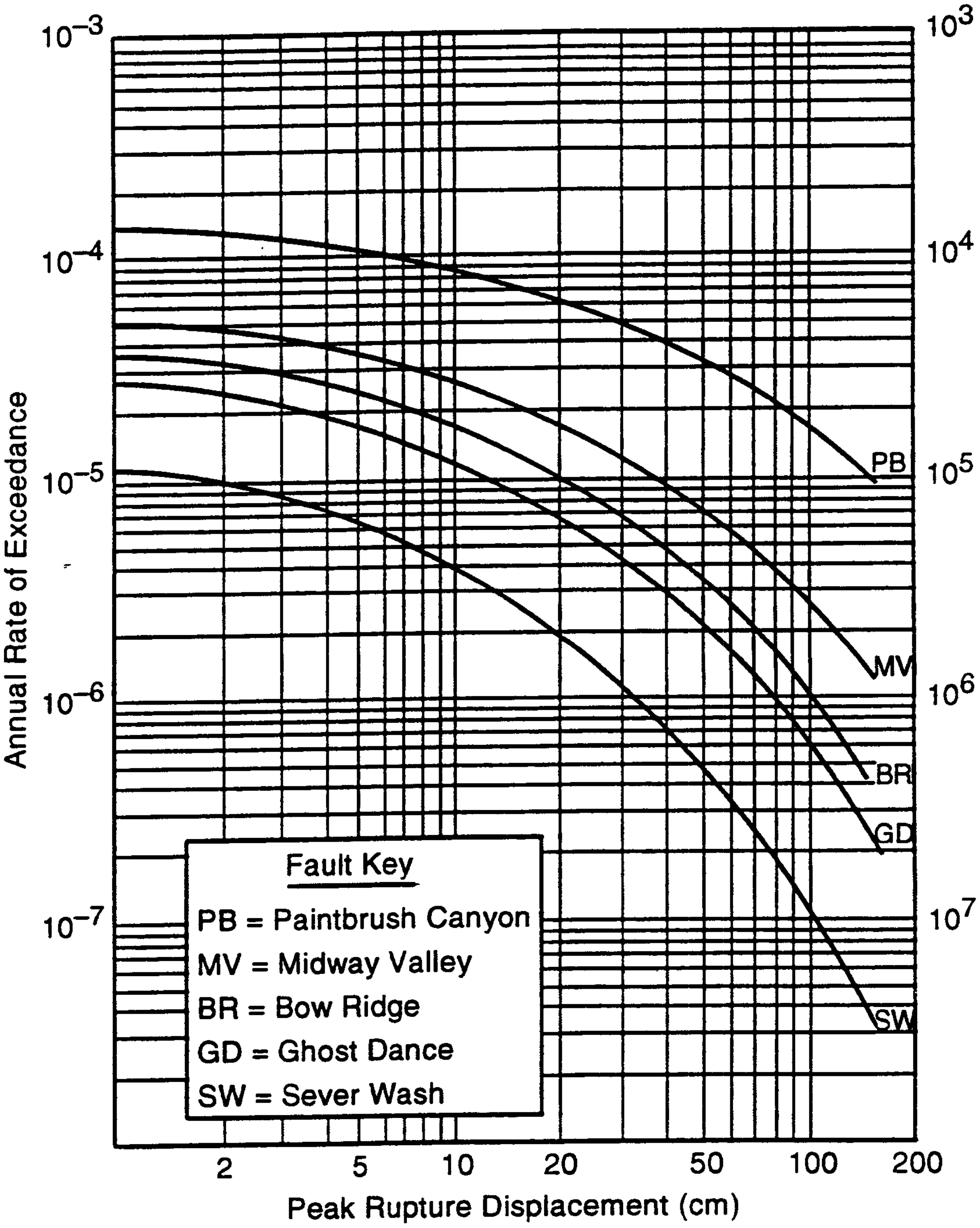

Figure 4-4. Two-slope slip rate function for selected Yucca Mountain area faults. (From Somerville et al., 1987). Note: Other assumed slip rate functions increase annual rate of exceedance by an order of magnitude.

- Somerville et al. (1987) appear to use a circular rupture and define its radius in the probability calculations. In this study, a rectangular slip surface is used. The effect of this difference has not been analyzed in detail, but it would be expected to influence results.

- Somerville et al. (1987) use the fault offset versus magnitude and fault length versus maximum magnitude relationships of Bonilla et al. (1984). In this study, the calculations employed the relationship of Slemmons (1977). The values, however, are not greatly different.

- In some relationships, the type of assumed probability distribution, normal or log normal, were different in the two studies. Further, the Somerville et al. (1987) standard deviations for the Bonilla et al. (1984) relationships may have been larger than those used in this study. This variation may tend to increase their hazard for large offsets. If several relationships had been used as though they were differing expert opinions in this study, a similar effect would be expected. Such an effect could be explored in future sensitivity studies.

- Tapering of fault displacement over the rupture surface was employed by Somerville et al. (1987). No tapering was employed in this study.

It is difficult to track the exact calculations made in the Somerville et al. (1987) study. Example calculations are not provided. In this study, an attempt was made to simplify the statistical process to illustrate where corrections might be needed for various scenarios. Considering the differences in detail between the two studies, the level of agreement in results is reasonable.

5 SEISMIC HAZARD RESULTS

Two tests of the SEISM 1 code were made. One was to determine if the test problem provided with SEISM 1 could be calculated when the problem was shifted to western coordinates. The other was to exercise simulated fault source zones and western ground motion attenuation functions entered into the code for use at a YM, Nevada region site. A printout of hazard calculations for each expert and the aggregated final hazard is provided for the YM calculation. There are three probabilistic measures of hazard produced by the SEISM 1 code. They are:

1. Best Estimate Hazard Curve (BEHC)

   This curve is based only on best estimate (BE) input parameters provided by the experts, for example, M_{max}, and the *a*- and *b*-values of the recurrence relationship. See Page C-23 of Volume 2 of Bernreuter et al. (1989) for a more detailed list and discussion. The statistical uncertainty estimates provided by the experts are not used in this estimate of hazard.

2. Constant Percentile Hazard Curve (CPHC)

   Estimated variability in input parameters is included in these estimates that are often made for the 15th, 50th, and 85th percentiles of input parameters. The Monte Carlo simulations (hazard calculations based on various source zones and distances to the site) are plotted for various percentile variations in the parameters. Bernreuter et al. (1989) state that the 50th constant percentile (CP) hazard curve is a relatively stable measure of hazard. It appears to be the preferred measure because it includes estimates of uncertainty. For this YM area test calculation, the 50th percentile hazard curve predicts lower design accelerations than the best estimate hazard curve, about 0.6 g versus 0.9 g.

3. Arithmetic Mean Hazards Curve (AMHC)

   This statistical measure is also referenced as the arithmetic weighted average of hazards curve or the arithmetic average curve. Expert self-weights by region are included in these estimates. Because of the simplified nature of this initial test calculation in which all experts were assumed to have the same self weight for the YM region, there is little difference between the best estimate and the arithmetic average hazard curves.

Results from the YM calculation, (Table 5-1) suggest a 10,000-yr recurrence best estimate of about 0.9 g and a 50th constant percentile hazard of about 0.6 g for the pseudo-participant opinions used. Complete hazard analysis computation results are in Appendix D. Input files used to generate hazard calculations are in Appendix B. Future refinements should include more detailed consideration of near field calculation of accelerations, diminution of acceleration with depth for earthquake sources that are distant from the site, inclusion of a background seismicity zone, and treatment of faulting in three dimensions. The latter problem may also influence probabilistic hazard calculations for fault offset. Planned sensitivity studies using the revised SEISM 1 code would test effects of these variables.

Figure 5-1 contains summary curves representing the 50th constant percentile hazard and the arithmetic average hazard for this test analysis computation.

Table 5-1. Summary of test calculations

Mean Recurrence Interval, yr	Peak Acceleration (g)				
	This Study		Rogers et al. (1977)[1]	Somerville et al. (1987)[2]	Perkins et al. (1987)[3]
	BE and Ave.	50th CP			
100	0.08	0.07	0.20	0.09	0.04
456	0.14	0.18	0.30	0.13	0.10
1,000	0.38	0.31	N/A	N/A	N/A
10,000	0.95	0.61	0.70	0.62	0.30

[1] From faults within a 400 km radius of the RSSF site at NTS
[2] From faults within a 200 km radius of the YM site
[3] For NTS about at the RSSF site

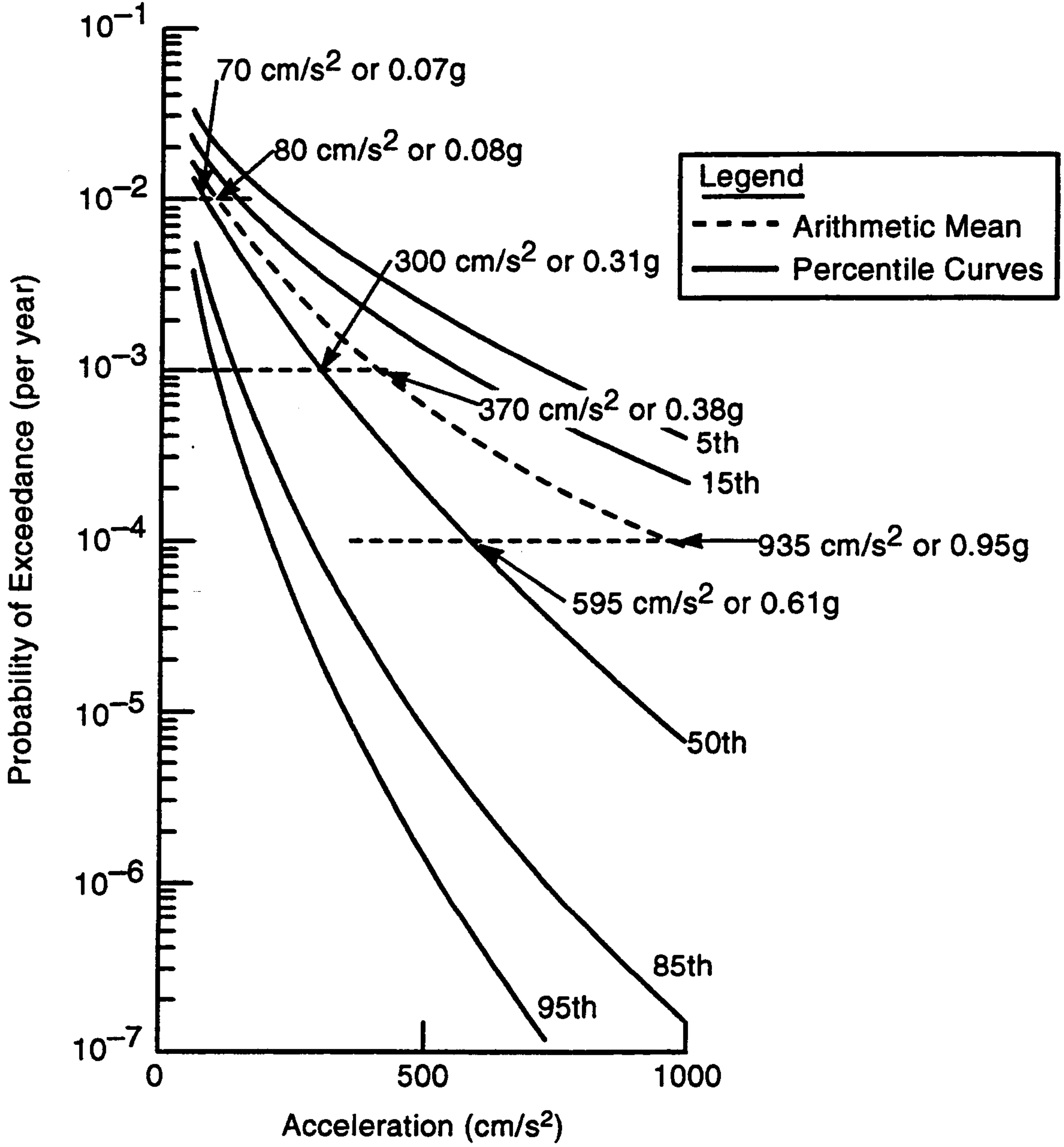

Figure 5-1. Aggregated risk curves for the center of the Yucca Mountain Site

Pseudo-participants 7 and 8 (labeled 10 on the printouts because the use of 8 and 9 in this field of input is reserved for other information by SEISM 1) did not consider the Ghost Dance fault. The hazard curves for pseudo-participant 7 are lower than those for the other pseudo-participants who included the Ghost Dance as an active fault. The hazard curves of pseudo-participant 8 are very near the average for the other pseudo-participants. However, pseudo-participant 8 assigns generally higher M_{max} to nearby faults that are considered important to the analysis. Recent data by Whitney (presented at the March 8th and 9th, 1994 Nuclear Waste Technical Review Board (NWTRB) meeting in San Francisco) should probably be used to revise the input estimates this pseudo-participant. Sensitivity analyses may determine the effect of this revision.

6 PROBLEMS WITH CODE DEVELOPMENT AND USE

Several problems were encountered with the SEISM 1.1 code and its use in making calculations over long time periods.

First, the use of library functions in executable form inhibits the use of the SEISM 1 code on newer computers or on existing computers when operating system or compiler updates are made. Substantial effort was expended in trying to make calculations after system upgrades had been installed. Executable library functions are sold for a particular machine, operating system, and compiler. Library source codes may also be purchased for a particular machine that allows recompiling when operating system or compiler updates are provided. Both of these options are expensive. The latter is on the order of $20,000 for the International Mathematic and Scientific Library (IMSL). Many changes are currently taking place in PCs, workstations, and their software. A subtle change in the compiler or operating system can cause hours or days of delay and frustration. Public domain source code for the library functions used in SEISM 1 can be substituted for the IMSL functions but at a cost of some effort. The public domain functions may not be as efficient as the IMSL routines resulting in either more cumbersome code, longer calculation times or both. There are not many IMSL function calls, however, so this concern may not be serious. Source code for LLNL library functions used in SEISM 1 is probably available. Some of the LLNL functions could be replaced by calls to X-Windows or Motif functions.

Second, the present form of the code does not define fault sources such that accurate source to site distances, as variously defined for western United States attenuation functions, can be determined. The accuracy deterioration occurs in the near-field of faulting, which is defined for this report as a fault dimension. NRC/NRR has contracted with LLNL to incorporate faults as 3D source zones in the SEISM code. Completion of this effort is anticipated in 1994. This code version will also be primarily for use at eastern United States sites. Consequently, accommodation for the various definitions of site to source distance given in western United States ground motion attenuation functions may not be incorporated. Those portions of the new code that could advantageously be used for repository evaluation could be incorporated in SEISM 1.1. If this new code version is not available, modifications should be made to SEISM 1.1 to incorporate the effects of near-field dipping faults. If dipping faults are incorporated in SEISM 1.1, the attenuation-function's distance-measure would be revised from site-to-surface-projection-of-the-fault, to site-to-closest-distance-to-the-rupture-zone. The latter will vary as a function of magnitude for magnitudes whose fault slip area does not occupy the entire down-dip extent of the fault plane.

Third, the use of circular distance bands (a hold-over from Cornell, 1968) in the current version of the code tends to smear out the effect of individual faults and could deteriorate the precision of hazard calculations. The proposed revision of the code for NRR may correct this problem. It is most severe in the near-field of fault sources.

Fourth, the code is not completely documented. The SEISM 1 users manual (Davis, 1991) remains in draft form at the time of preparation of this report. Attempts to make calculations with western U.S. data have revealed several undocumented requirements or undocumented input definitions:

- The inner and outer circle are not well defined. They are distance radii at which the equivalent of angular integration increments, in the code version available to us, may be changed. However, other entries defined as inner and outer circles are not defined. The input for inner and outer circles however, consists of eight numbers in each of two rows of input that represent a coarse and a fine digitization of distance. Results from each are compared and an error flag is created if they do not agree. The occurrence of a flag is usually indicative of an error in the input listing of source zone digitized quadrilaterals.[6]

- The best estimate, lower and upper bounds following the entry for "occurrence rate magnitude," are not clearly defined. These entries are for the number of earthquakes in the particular source zone for which the entry is made, at the occurrence rate magnitude or higher, per year. The occurrence rate magnitude is that magnitude for which the *a*-value is determined. It is often M=4.

- Dummy source zones with low maximum magnitudes and low *a*-values are required for distance bands defined by either the inner or outer circles series of radii if no source zones exist between the bands as defined.

Fifth, the basis on which *a*-values are determined appears to be a subject for expert opinion. These values can have a strong influence on the resulting hazard curves. A methodology for developing *a*-values needs to be carefully considered and consistently applied. It may be a topic for consideration by the CNWRA PFD&SHA advisors. There may be other undocumented requirements. Parts of the code have been analyzed using "write statements" to track data flow. Analysis of the whole code with CASE tools is under way. Some of these problems may be relieved by current work for NRR and additional documentation being prepared by LLNL. However, those who are to pass judgments on hazard calculations made by this code would benefit from understanding its operation in detail.

Sixth, there are a number of problems in associating regional earthquake recurrence intervals and consequent fault slips to particular faults. Krinitzsky (1993b) discusses many of these problems in detail. One problem is the skipping of higher levels of seismic activity from one range-bounding fault system to another on a random basis throughout the Quaternary. This phenomenon was reported by Wallace (1981, 1984, 1985 and 1987), Ryall and VanWormer (1981), and by VanWormer and Ryall (1981). Krinitzsky (1993b) discusses variations in earthquake recurrence slope with time on a world-wide basis, which may imply that this phenomenon is common for earthquakes everywhere. Another concern is that of seismicity induced by large events, sometimes at great distances. An example is the recent Landers, California, earthquake, which apparently induced the Little Skull Mountain earthquake 270 km distant and 20 km from the proposed YM repository. The band of high seismicity representing the Ventura-Winnemucca seismic zone (Ryall et al., 1966) is only a few miles from YM (Figure 6-1). The Ventura-Winnemucca seismic zone encompasses the more narrowly defined Walker Lane seismic zone. A change in regional stress brought on by a large earthquake in the Ventura-Winnemucca seismic zone could enlarge this zone to engulf the adjacent YM area for a significant period of time. Concerns about seismicity induced by large earthquakes were expressed by several of the Fault Displacement and Seismic Hazard Analysis advisors to the CNWRA (see Hofmann 1993).

Seventh, there is uncertainty regarding whether faults produce only earthquakes of the maximum magnitude that they can support or whether each fault has sequences of earthquakes that follow a recurrence pattern similar to that of Gutenberg and Richter (e.g. Gutenberg and Richter, 1954). According to Wesnousky et al. (1982), seismic risk results will change by about a factor of 2, depending on which hypothesis is used.

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[6] B. Davis, personal communication, February 10, 1994.

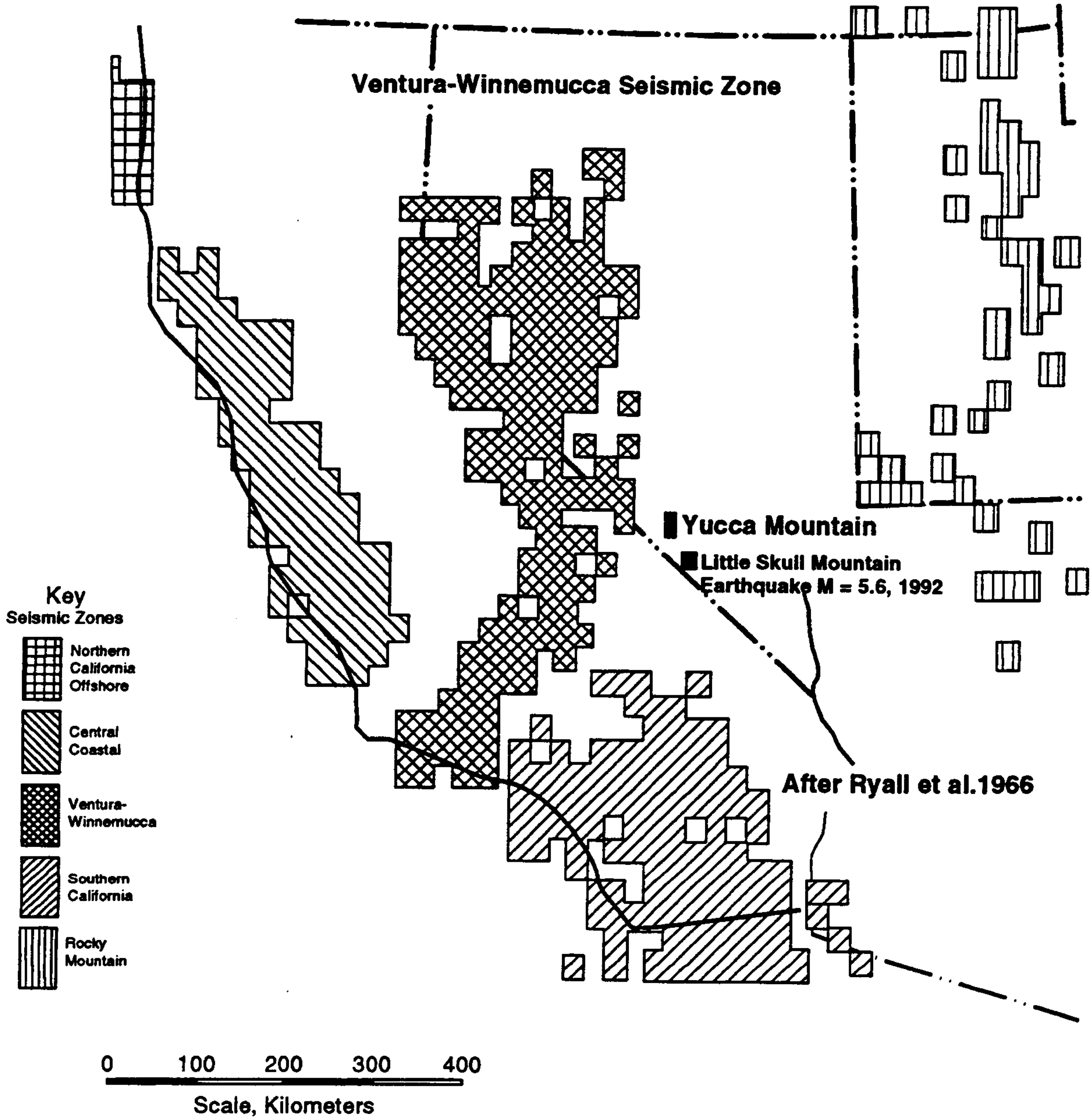

Figure 6-1. The Ventura-Winnemucca seismic zone

Eighth, CNWRA configuration control of this code is not possible at this time because of its lack of portability and the requirement for full documentation and verification of the test cases provided with the code. Considerable effort will be required to comply with the CNWRA TOP-018 requirements.

7 CONCLUSIONS AND RECOMMENDATIONS

The SEISM 1 code may be used to obtain estimates of seismic hazard in the YM area. This conclusion is based upon a test calculation using information from the literature assembled as pseudo-participant opinions and using western strong ground motion attenuation functions. The test problem was simplified as much as possible to reduce the large amount of input required. The simplifications include elimination of source zones (faults) that cross or overlap, use of published attenuation functions without change for diminution of ground motion with depth, no consideration of a background seismicity zone, and no consideration of conceptual models for large deep master faults that may control observable surface faulting. The dip of near-field faults was not considered in this calculation, although it is likely to influence results significantly. These issues require some background study before adding code and input to accommodate them in an analysis. The purpose of the test analysis was to provide an error-message free calculation with data from the YM region and not necessarily to provide a final or benchmark analysis of probabilistic seismic and fault displacement hazard.

7.1 CONCLUSIONS

SEISM 1 modified for western U.S. sites functions properly with the five new western U.S. attenuation functions. However, the code is cumbersome to use for the purpose of testing different tectonic and seismic hypotheses because input data must be entered on a precise row and column basis for most input files and multiple entries for the same data are often required for several input files.

7.2 RECOMMENDATIONS

Recommendations are of three types. They concern possible modifications to the SEISM 1 code, matters that should be addressed to reduce input uncertainties, and programmatic concerns.

7.2.1 Coding

Rapid changes occurring in workstation technology suggest that changes or upgrades will be increasingly frequent. Although the changes may implement faster computational technology, the code will not be operable on the improved workstations without considerable added expense and delays to replace or update its library functions. IMSL routines in SEISM 1 should be replaced by public domain source code. Source code for LLNL library routines in SEISM 1 should be sought. This source code is necessary to preclude having to use the code on only one machine-compiler-operating system combination. CNWRA TOP-018 requires that codes in use at CNWRA be portable. If all requirements of TOP-018 are not met, the code may be accepted "as-is" but calculations cannot be certified to any higher degree by CNWRA.

New coding should be employed to more exactly depict faults as 3D seismic source zones. If the NRC/NRR version of the code with fault source coding is available, it could be used. However, additional changes may be needed for application in the YM area.

Documentation of SEISM 1 is sometimes dated and incomplete. The material is distributed throughout several reports for example, Davis (1991) and Bernreuter et al. (1984, 1985, 1987, 1989). This distributed documentation may be a consequence of development of code to assist in the solution of one complex problem and then extended for use on another similar problem. SEISM 1 is not a code initially developed for a broader market. Initiation of development of a methodology to analyze seismic risk at NPPs began in 1977 (Bernreuter and Minichino, 1982). These initial efforts were associated with the NRC Systematic Evaluation Program (SEP) and the Seismic Safety Margins Research Program (SSMRP). Input to the method was also developed under the NRC Task Action Plan A-40 in the LLNL Site Specific Spectra Project (SSSP). The first LLNL PSHA code inputs were completed in 1982. Updates were made in 1985 and 1987 (Bernreuter et al., 1989). Obviously, the Seismic Hazard Codes (SHC), later named SEISM, codes have evolved considerably through the 1980s and 1990s. Completion of revised code by LLNL for NRR may improve documentation. If not, substantial efforts at documenting inputs to the code in a manner that is easily understood by a broader user group is likely to be required. The present form of the code and its documentation are cumbersome for geoscience staff to use in testing the effect on risk of various tectonic or seismic models proposed by the applicant or other litigants in a HLW repository hearing.

Path descriptions for the locations of files should be declared outside of the source code to preclude having to recompile the code for use on different computers. This procedure is considered good coding practice. Unfortunately, it is not a trivial effort to revise the code to avoid frequent recompilations.

Entering data and source zones into the code is also cumbersome and sometimes requires assistance of a programmer. Consequently, the development of a graphical user interface (GUI), or extension of the SHC interactive executive routine of SEISM 1 is recommended. The interface would ask questions and provide a limited space for a response with suggested defaults if appropriate. An improved user interface is anticipated for the revised code being prepared for NRR. If available to DWM, the improved interface could reduce the proposed effort to facilitate analysis of a HLW repository with its longer period of performance concern. Development of a GUI is recommended. Source regions or faults could be entered on a map with a mouse or light pen. The interface could be designed to accept ARC/INFO or other map files. A staged development of the GUI is recommended to permit interfacing with data file standards that are evolving at DOE and NRC.

7.2.2 Matters to be Addressed to Reduce Uncertainty

Problems associated with paleofault displacements as surrogates for earthquake information appear more serious and plenteous than anticipated. This topic should be investigated in detail. Advice from a panel of experts to review the conclusions of a literature search and initial attempts to use this process might help formulate new research directions and provide a more solid basis for accepting or rejecting this process as a part of PFD&SHA for facilities with a long (e.g., 10,000 yr) period of performance.

PFD&SHA processes are methods by which geoscience data may be analyzed to develop potential hazard assessments. However, in this early attempt to use the SEISM 1 code with data suitable for a HLW repository, it is apparent that research is needed to reduce input uncertainties. Input parameters with substantial uncertainty and that require further study include:

- Earthquake recurrence slopes for individual faults, the apportionment of regional recurrence relationships among faults, or the substitution of other assumptions regarding recurrence and magnitude limits on individual faults. Calculations with SEISM 1.1 are recommended to evaluate the effect on risk of different recurrence models for individual faults using paleodata from recent DOE trenching, rather than fault length inferences as used in most published studies. A study of recent very complete catalogs of seismic data, for example, Harmsen (1994), is recommended to reassess the *b*-value for Basin and Range tectonic province sites.

- Earthquake recurrence intercepts, *a*-values, derived from paleofault offset parameters. (see pages 3-20, 21, and 6-2.)

- Changes in recurrence parameters, *a*- and *b*-values, caused by a potential enlargement of a zone of seismic activity immediately preceding or following a large earthquake within that zone may influence seismic hazard estimates for YM. The Ventura-Winnemucca, or the Walker Lane Seismic Zone within it, are close enough that they may envelope the YM area for periods of time.

- The time duration for a zone of seismicity to remain larger (e.g. the Ventura-Winnemucca zone of Figure 6-1) and possibly acquire changed *a*- or *b*-values following a large earthquake is needed to assess seismic or fault displacement hazard over a 10,000 yr period. This quantification would help determine what proportion of a 10,000-y period may have higher seismic risks than historical seismicity implies.

- Attenuation of ground motion at depth. A detailed formula for how strong ground motion may diminish with depth and the probability of this diminishment given the material properties and geologic configuration at YM is needed.

- Near-field strong ground motion, peak acceleration, spectra or time-functions (real or synthetic). Formulae to represent these inputs will be required.

7.2.3 Programmatic Concerns

7.2.3.1 Quality Assurance Requirements of CNWRA TOP-018

Quality assurance (QA) efforts for computer codes maintained, developed or modified by CNWRA are subject to NRC and Southwest Research Institute (SwRI) QA audits. Quality assured code is required if results from the code are to be used in compliance determinations. To bring a code under configuration control, the version of the code being used must be submitted with a users manual for that version of the code, a detailed technical description of the code, a test case that has been analyzed and verified, and a benchmark calculation. The code must be portable. The documentation available with SEISM 1 as received from LLNL does not meet these requirements nor does the version as modified by CNWRA for use in the western United States. An independent verification of the test case provided by LLNL will be required. Usually such verification is made by hand calculations, the use of quality assured commercial code for certain portions of the calculation, and, at times, by simple easily verified coded subroutines. The Shearon-Harris test case provided by LLNL is complex. The verification task is not trivial. The technical description of the code in available LLNL reports and the draft users manual do not appear to provide sufficient detail for a full understanding of the workings of the code. Constructing such a technical description and preparation of a more detailed users manual are also not trivial tasks.

The degree to which CNWRA and DWM should accept responsibility for QA of the LLNL code is a policy decision. This burden could be shifted to the applicant or to others who use it for the purpose of generating evidence at a hearing, where appropriate. To the extent that the code is modified for use by NRC in evaluating the effect on hazard at YM from alternative tectonic or seismic hypotheses, the QA requirements appear to be the responsibility of the user. Alternative hypotheses may be presented by the applicant in the License Application (LA) or by NRC staff in their evaluation of the LA. Alternative hypotheses are also likely to be produced and supported by other parties to licensing hearings. NRC staff may need to evaluate them, too. An extension of the SEISM 1 code for use with a long-lived HLW repository in the western United States is a tool that could be employed for these purposes.

Consideration of the level of QA efforts to be applied to the SEISM codes, and the degree to which the CNWRA or the NRC should be responsible for them, appears to be a significant item for planning future efforts.

Tentative recommendations for compliance with CNWRA TOP-018 are:

1. Prepare a Users Manual and a Technical Code Description based on Davis (1991), references by Bernreuter et al. (various years 1982–1989), and coding changes made to date.
2. Conduct manual calculations to verify the Shearon-Harris Test Case supplied by LLNL with SEISM 1.
3. Prepare a benchmark calculation to satisfy the requirements of SwRI QA auditors.
4. Modify the code to make it portable between computers and operating systems.
5. Investigate the feasibility of contracting to use LLNL's data base to facilitate (1) above. If this use is feasible and reasonable in cost, implementation of a contract is recommended.

7.2.3.2 Updating of Coding

Based on the difficulties we have had in determining various functions of the code and the fact that the code has evolved over several years through the efforts of ten or more programmers, it is our opinion that the code should be evaluated and modified to conform with currently recommended coding practices. This effort may be significant in terms of budget and manpower, but is anticipated to reduce future efforts in use, maintenance, and modification of the code.

7.2.3.3 Schedule

Bringing the code to its present state has required a considerable expenditure of effort beyond our initial estimates. Future efforts could take several forms:

- Continue the CNWRA effort to add functionality, to document, and to test the code.
- Wait for LLNL to complete the current revision of the code which is being jointly funded by NRC/RES and DOE. The proposed added functionality may reduce the efforts required by CNWRA to add 3D fault capabilities and improve the user interface. Currently, the revision is expected before the end of FY94.

- Abandon further efforts to develop the code because of higher priorities for other activities. Future efforts by the DOE to use this or a similar code for its hazard work may eventually become available for NRC use as well.

- Develop a new code. The effort expended to date in adding functions to the existing SEISM 1, could have resulted in considerable progress toward developing and documenting a new code designed specifically for DWM requirements. It is a difficult decision to make at this point whether initiation of new code development or continuing with SEISM 1 would be most cost effective. Recommendations by the National Academy of Science (NAS) study regarding SEISM 1 and the EPRI code EQHAZARD, may have an impact on the further use of these codes and the direction of their further development.

There are positive and negative aspects to each choice. Maintenance of SEISM 1 will clearly be more costly than initially thought. Although more costly than anticipated, continued working with the code provides an independent capability that may be desirable. Waiting for the DOE or the NRC/RES to improve the code may preclude some duplication of effort and conserve resources. However, a consequence is that independent analyses of proposed geoscience model effects on seismic or fault displacement hazards, dependent on the use of this code may have to be postponed until later in the licensing process. This delay could impact the 3-yr time period in which the LA is to be evaluated by NRC. Present estimates of LA submission, however, suggest that there may be enough time in the future for such efforts. Development of new code would ensure that all functions are adequately documented and that modern coding practices are used uniformly throughout. If code work is abandoned for a time, some relearning time would be expected if the work is resumed later.

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APPENDIX A

CODE MODIFICATIONS

Files Modified:

- sia.f
- prds.f
- amodel.f through emodel.f
- rdatex

Input File Path Modifications

- bdir.f
- initial.f
- nsitecor.f
- rsitecor.f
- selsite.f
- shc

Modifications to Use When Plotting Fault Displacement Hazards

- comb.f
- plotter.f
- raleas.f

Modifications to Create a File of Diagnostics

- newloc.f

Appendix Computer Files are attached in Microfiche

Many comments, write statements and diagnostics were added to the code to aid in determining the functioning of subroutines and to track data flow in the process of debugging code and input files. These additions do not affect code functioning so are not documented here. The write statements and diagnostics will be removed from the code when a new version is completed and placed under configuration control. Paths to input files differ in each version of the code installed on a different computer. Changes required to insert proper paths for a particular work station are described in the CNWRA report to NRC, "SEISM1 Code: Adaptations for use in the Western U.S.," [Hofmann and Bangs (1993)]. Changed lines of code sometimes have a different format line number in the new than in the old version. This different number is caused by the insertion of comment lines, write statements, and diagnostics. The change in format line number does not change the functioning of the code. Changed lines of code are commented. They are identified with surrounding black lines or underlines in this Appendix.

APPENDIX B

SEISM 1.1 TEST ANALYSIS INPUT FILES

- Seismic Hazard
- Fault Displacement Hazard Example

Appendix Input files are attached in Microfiche

SEISM 1 often requires input that are for Modified Mercalli Intensities (MMI). These values are not called by the program when data are flagged as being associated with magnitudes rather than damage intensities. However, the code will require that there be an entry for MMI. Therefore, some blocks of data in the input files are from the eastern U.S. studies. They are not called by the code. Not all of these entries may be required for the code to assess if its entries are complete. There is no documentation regarding this issue, so all the unused entries are allowed to remain from the Shearon Harris example problem. When more is learned about undocumented code input requirements, recognizable dummy values can be inserted, and some of the unused input may be eliminated.

The SEISM 1 code requires dummy source zones to exist, if no real zone is present, within each distance integration band defined by either the set of coarse integration circles (outer circles) or the set of fine integration circles (inner circles). Therefore, zones identified as BZ (bogus zones), followed by the distance of the nearest integration circle, are added to some of the expert's list of sources zones. In each case, the maximum magnitude is listed as 5.1 and the *a*-value is 0.1. The best estimate *b*-value remains at 0.91 for BZs. The values used will permit a calculation to be made, but it should have little influence on hazard. As more is learned about this undocumented requirement, the *a*-value and M_{max} for BZs may be reduced further.

APPENDIX C

ATTENUATION

Appendix Attenuation Curves are attached on Microfiche

LIST OF ATTENUATION FUNCTIONS

The following plots are attenuation functions from the literature that were considered for use in this analysis. These plots are at the same scale with distance and peak acceleration definitions preserved as indicated by the authors of the functions. Because of a need for common definitions of peak acceleration and measures of distance, the formulae representing these functions are coded for the test analysis in a modified form as discussed in Section 3 of this report. Curves 1, 3, 4, 9, and 10 were used in this test calculation. Other more recently derived curves may be considered for future calculations.

1. **Attenuation Curves of Joyner and Boore (1981)**
2. **Attenuation Curves of Atkinson (1984) for Hypocentral Distance**
3. **Attenuation Curves of Atkinson (1984) for Epicentral Distance (assuming a 14 km depth)**
4. **Attenuation Curves of Schnabel and Seed (1973) - 4a original, 4b, log plot.**
5. **Attenuation Curves of Campbell (1987) for Soil <10 m thick (unconstrained)**
6. **Attenuation curve of Campbell (1987) for Soil <10 m thick (unconstrained) + Directivity**
7. **Attenuation Curves of Campbell (1987) for Soil >10 m thick (unconstrained)**
8. **Attenuation Curves of Campbell (1987) for Soil >10 m thick (unconstrained) + Directivity**
9. **Attenuation Curves of Campbell 1987) for Soil <10 m thick (constrained)**
10. **Attenuation Curves of Campbell (1987) for Soil <10 m thick (constrained) + Directivity**
11. **Attenuation Curves of Campbell (1987) for Soil >10 m thick (constrained)**
12. **Attenuation Curves of Campbell (1987) for Soil >10 m thick (constrained) + Directivity**

APPENDIX D

YUCCA MOUNTAIN REGION TEST CALCULATION OUTPUT

- **Seismic Hazard Analysis Output**
- **Fault Displacement Hazard Analysis Example-Output**

Appendix Output Files are attached on Microfiche