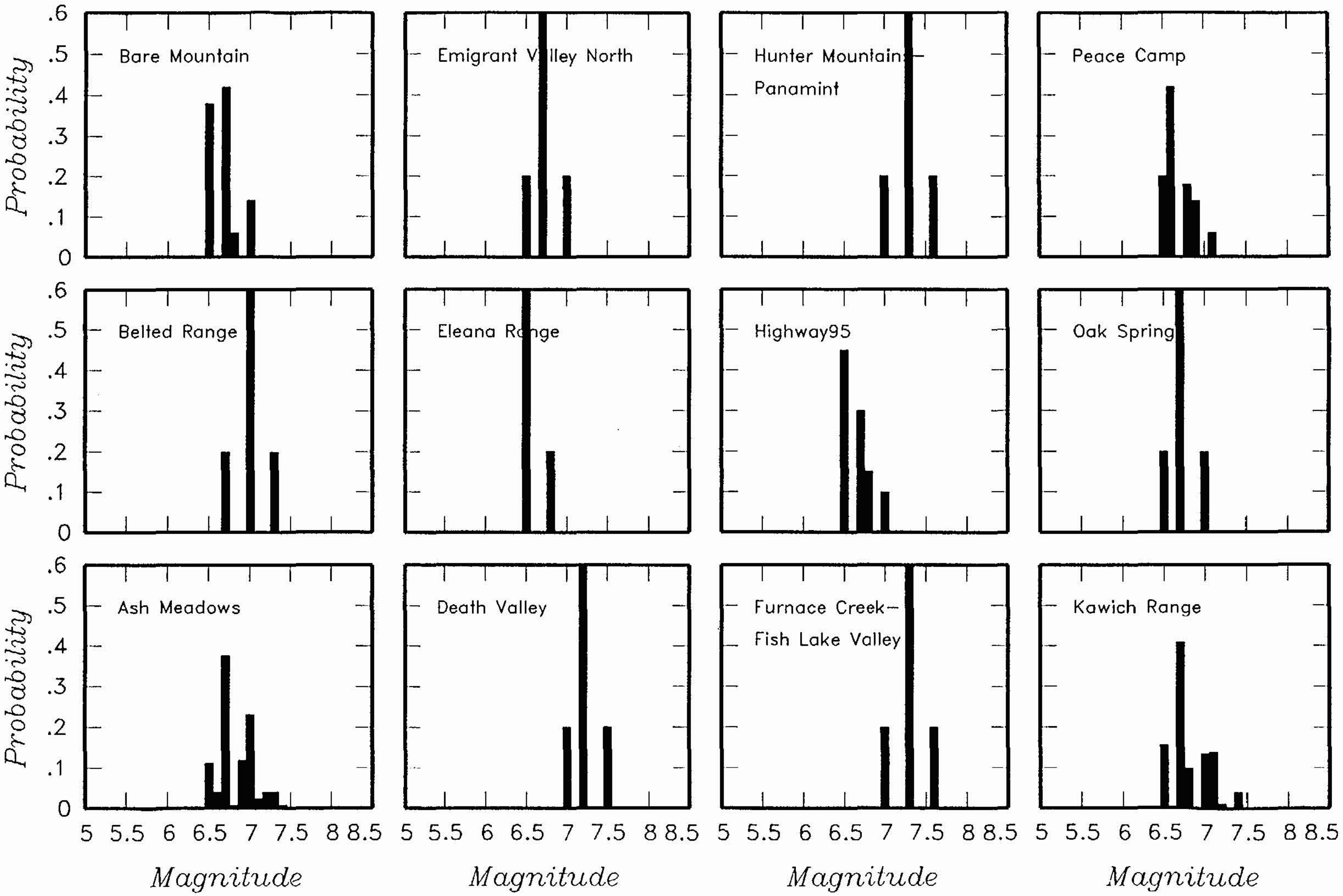


Figure 4-42 Maximum magnitude distributions for DFS team's regional fault sources

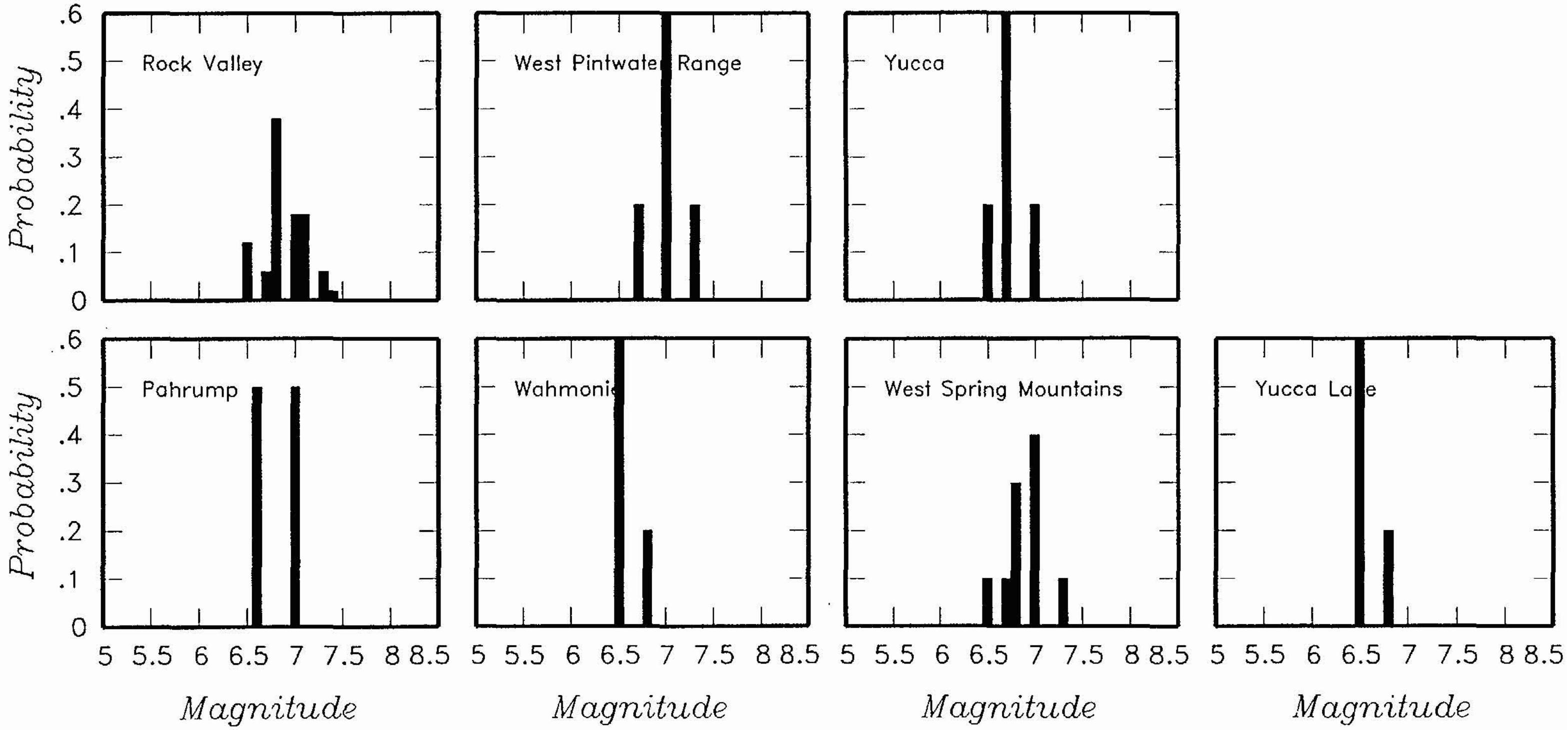


Figure 4-42 (Cont'd.) Maximum magnitude distributions for DFS team's regional fault sources

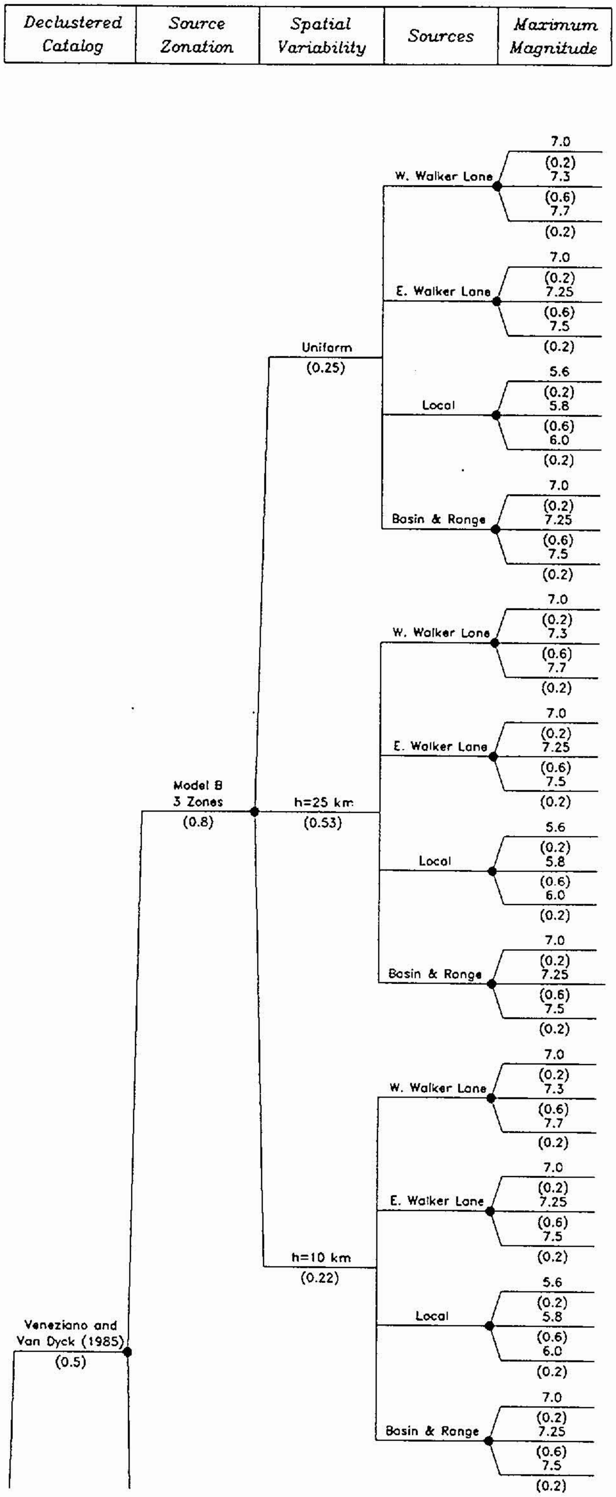


Figure 4-43 Logic tree for regional source zones developed by the DFS team

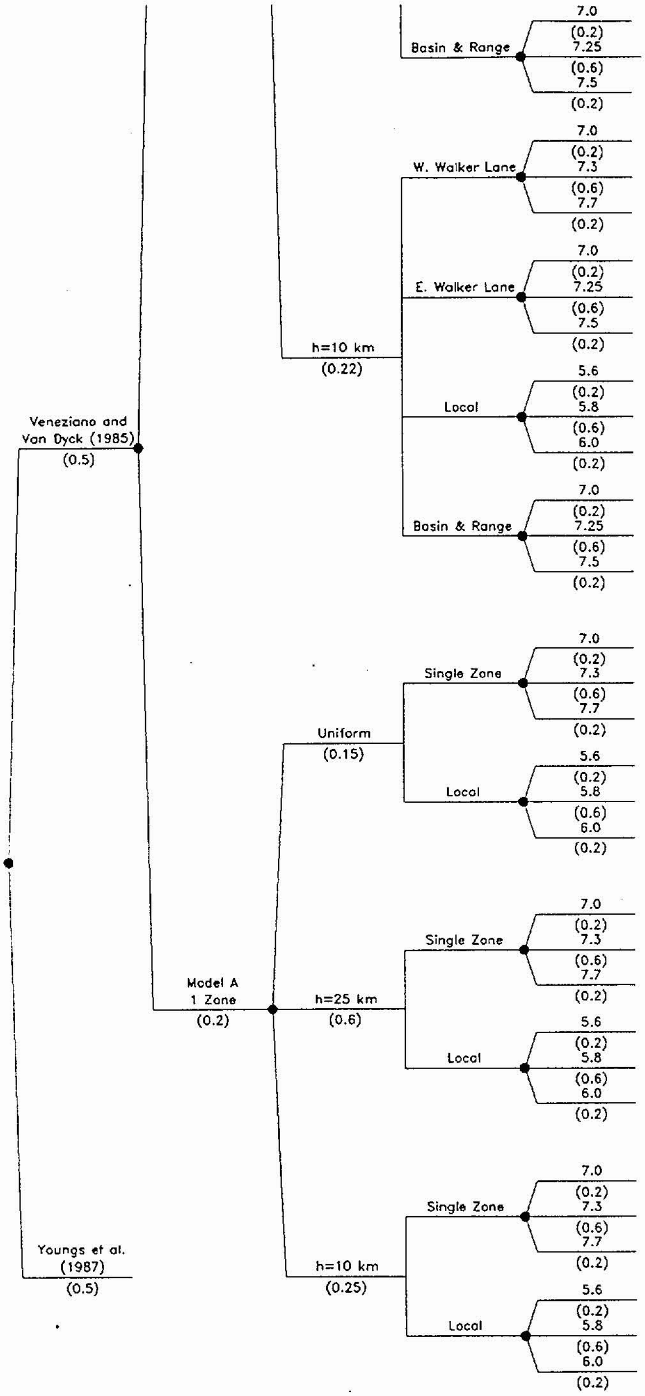


Figure 4-43 (Cont'd.) Logic tree for regional source zones developed by the DFS team

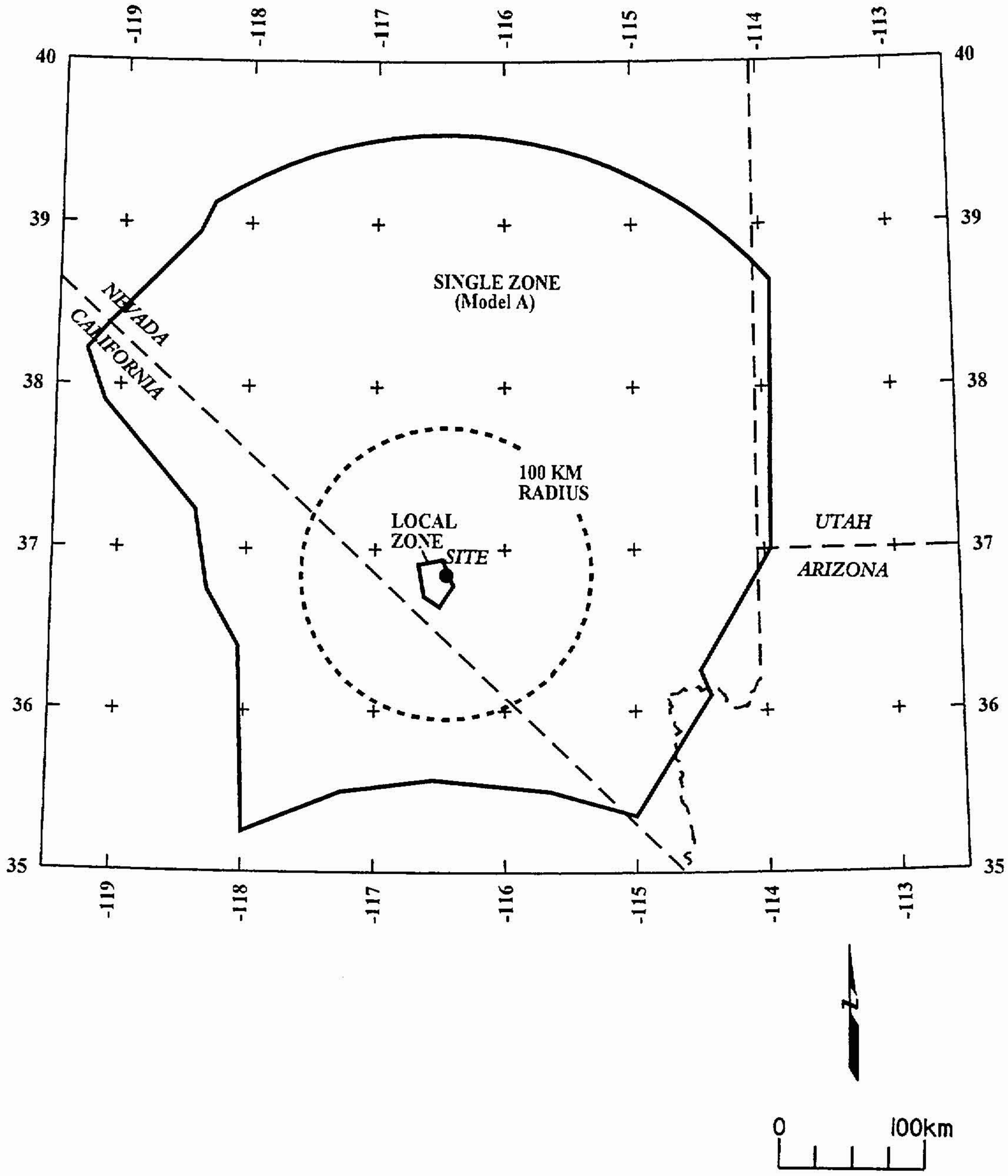


Figure 4-44 Alternative regional source zone models considered by the DFS team

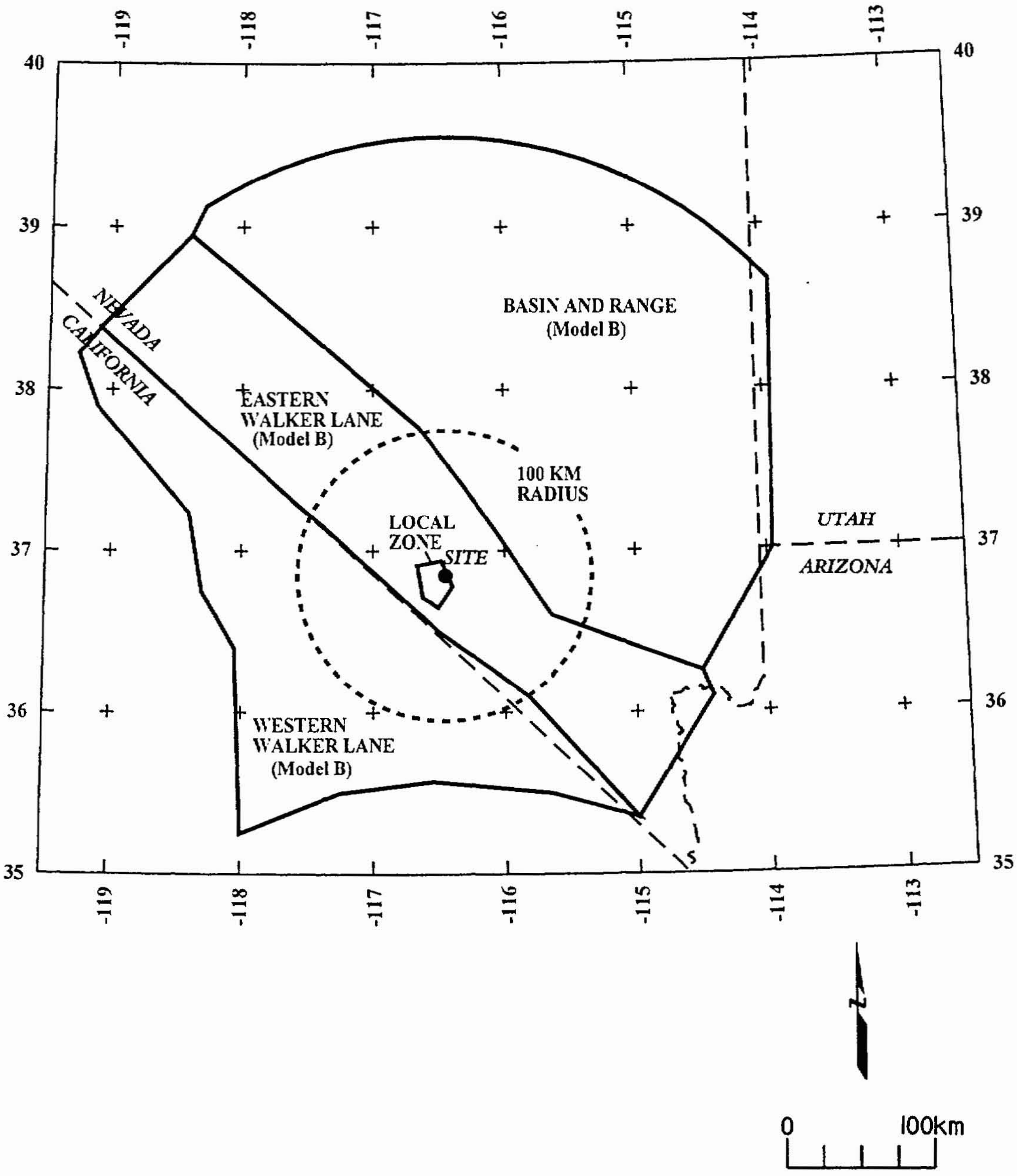


Figure 4-44 (Cont'd.) Alternative regional source zone models considered by the DFS team

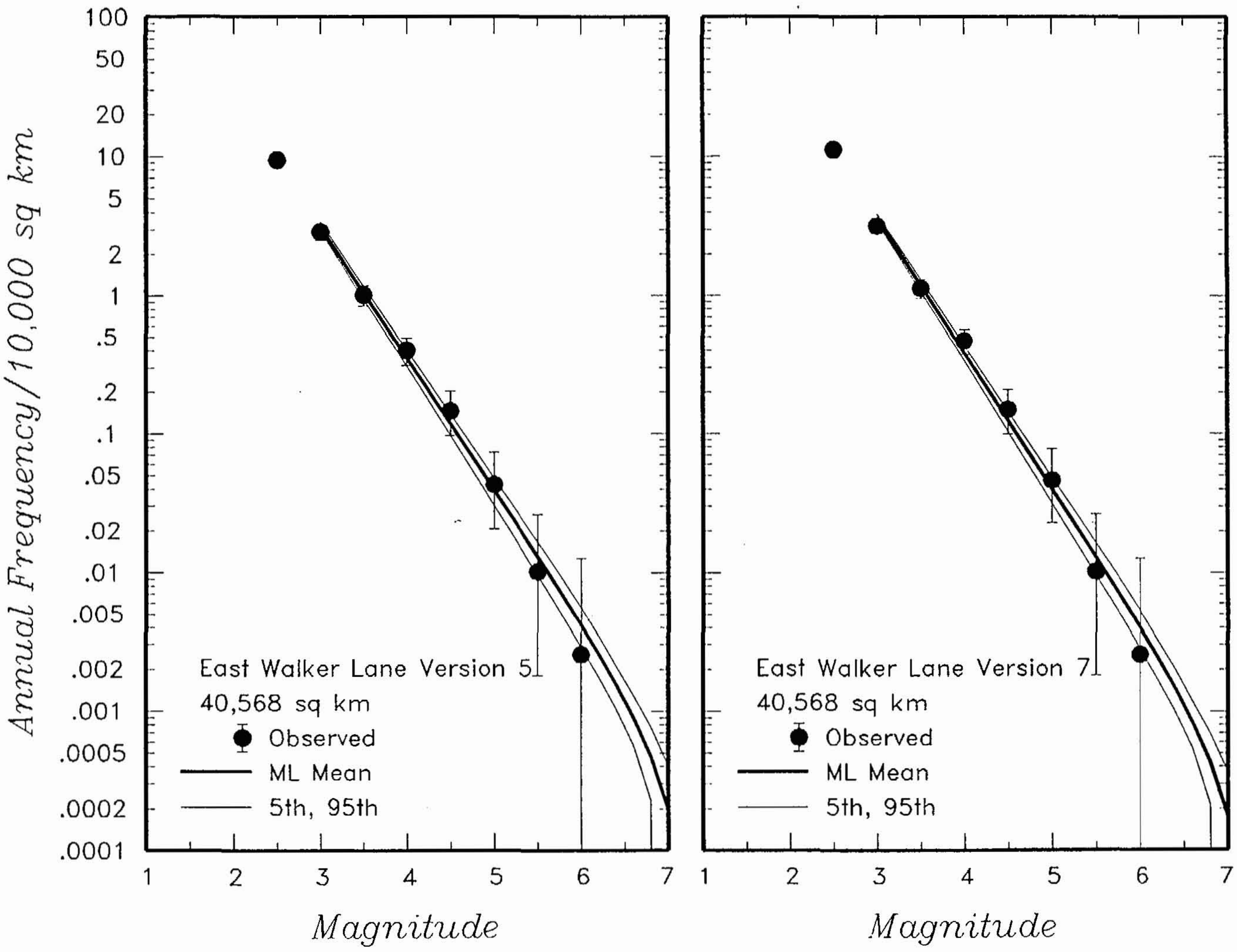


Figure 4-45 Earthquake recurrence relationships for the regional source zones defined by the DFS team. The solid dots with vertical error bars represent the observed data. The thick and thin solid curves are the mean, 5th, and 95th percentiles of the recurrence rates based on the uncertainty in recurrence parameters and maximum magnitude.

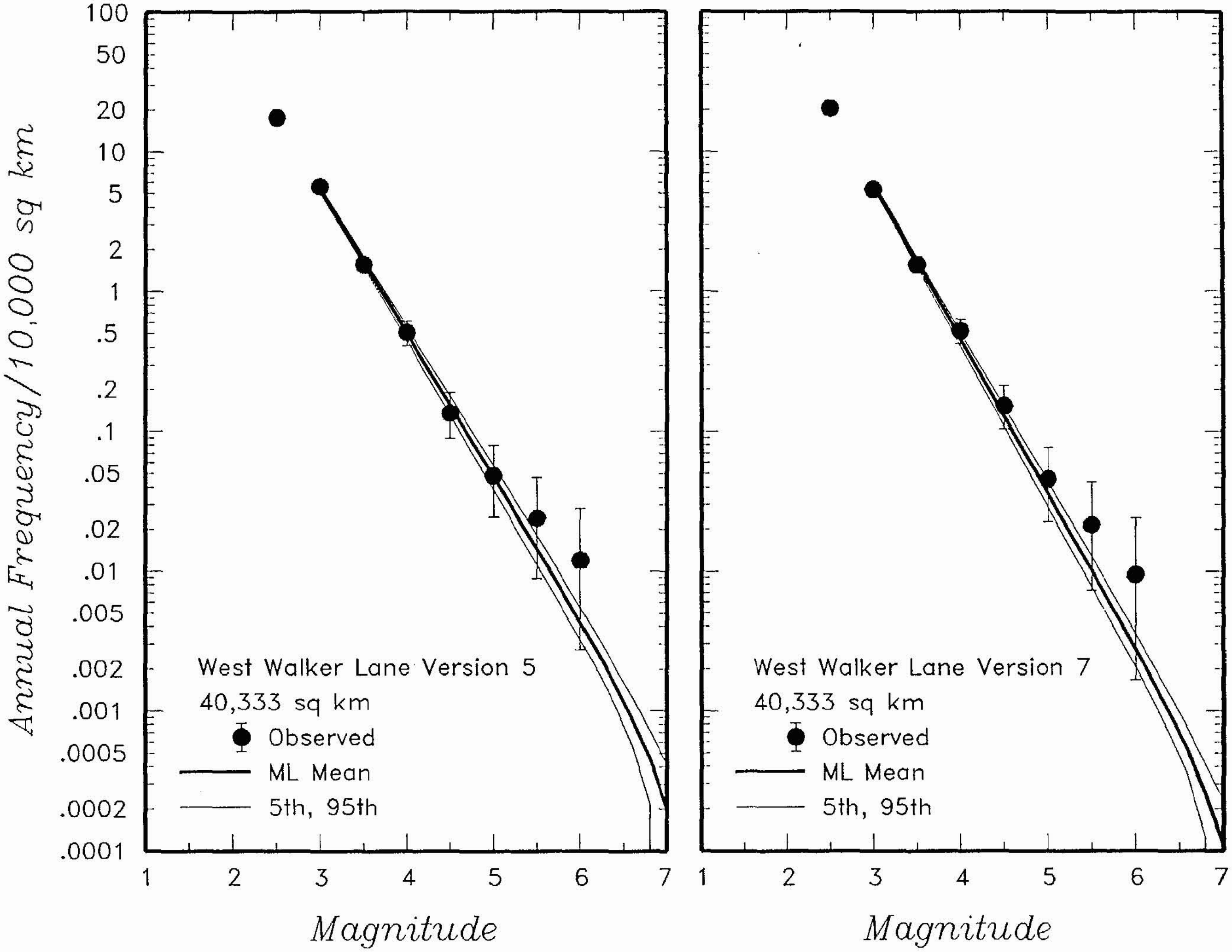


Figure 4-45 (Cont'd.) Earthquake recurrence relationships for the regional source zones defined by the DFS team

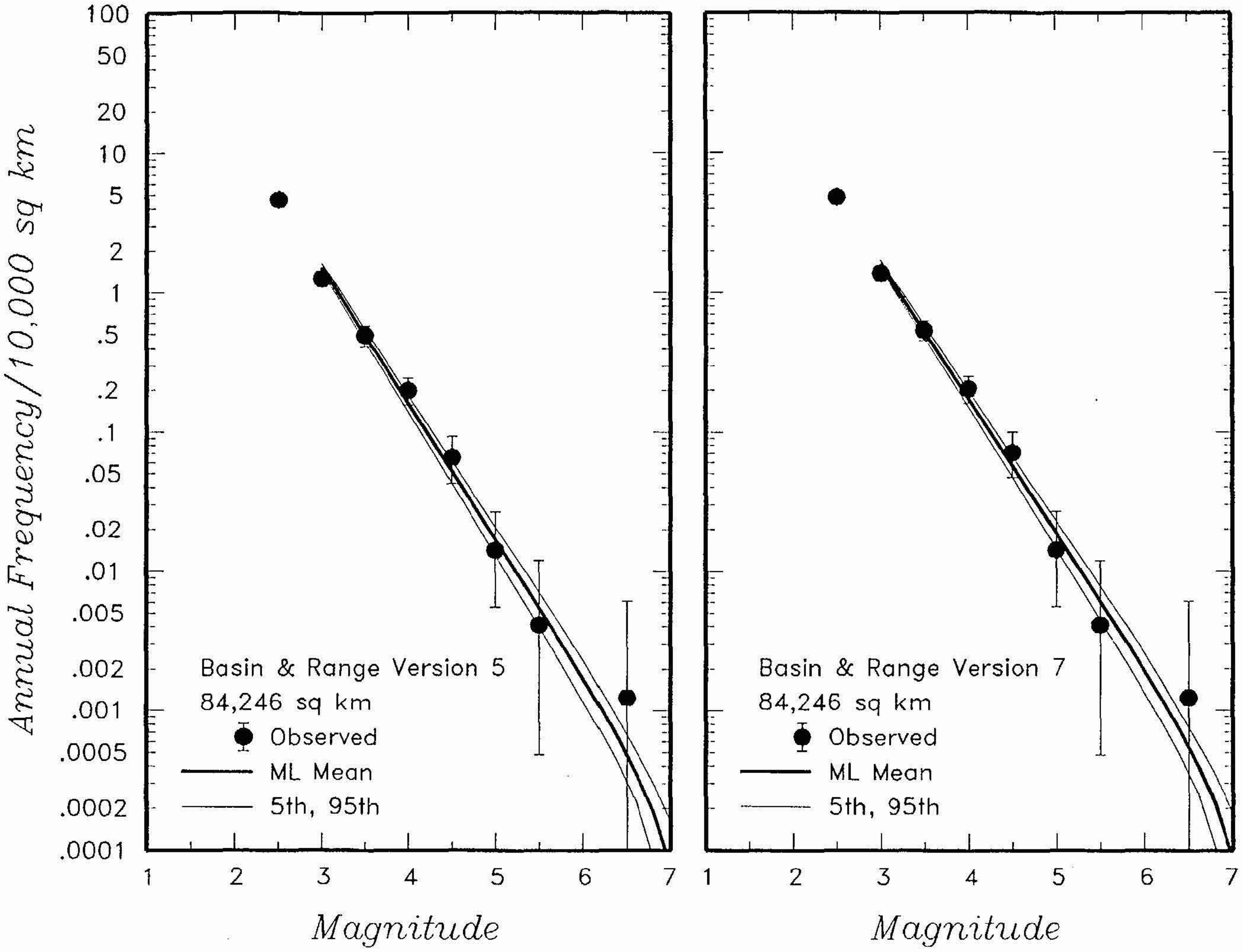


Figure 4-45 (Cont'd.) Earthquake recurrence relationships for the regional source zones defined by the DFS team

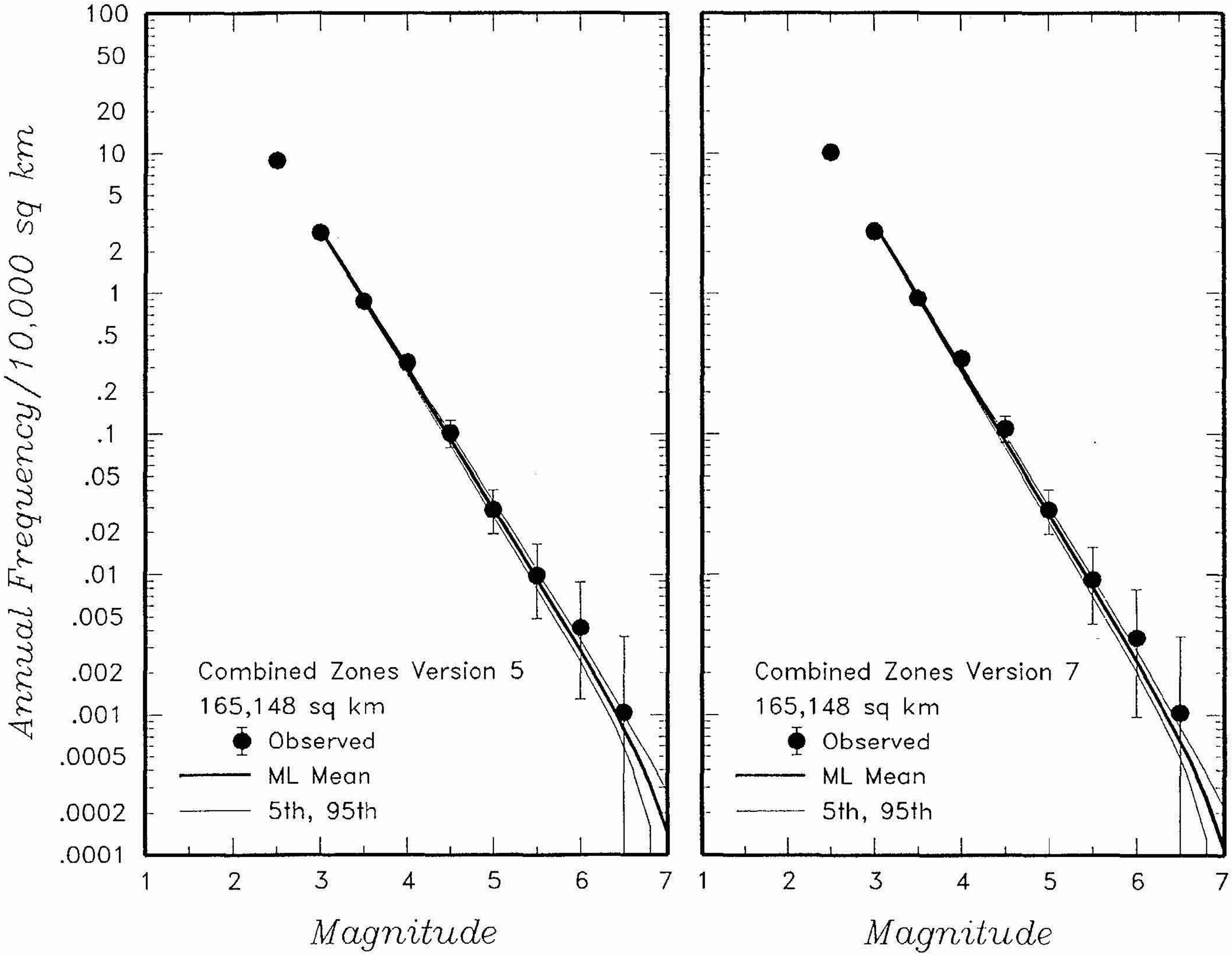


Figure 4-45 (Cont'd.) Earthquake recurrence relationships for the regional source zones defined by the DFS team

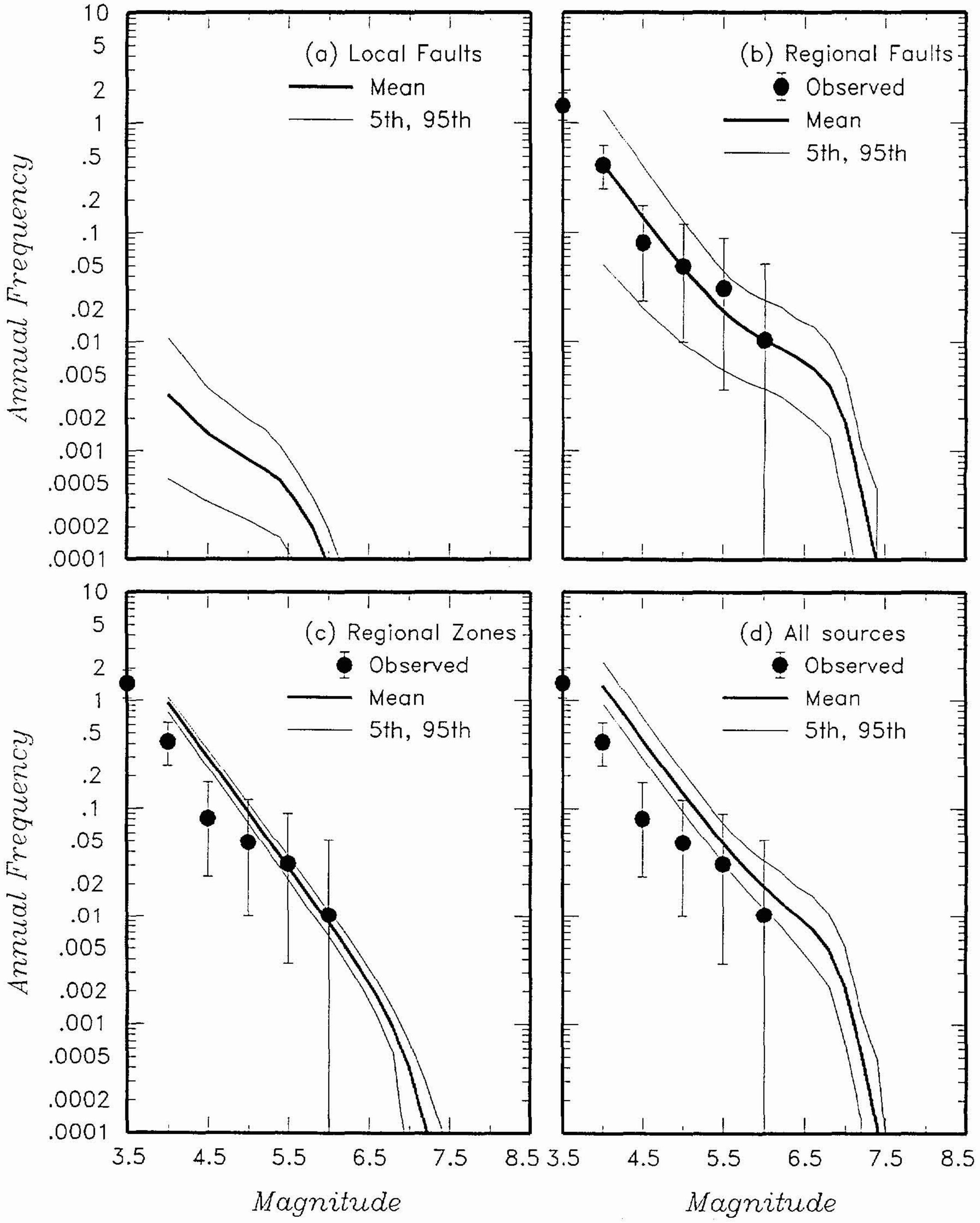


Figure 4-46 Predicted mean, 5th-, and 95th-percentile recurrence rates for (a) local fault sources, (b) regional fault sources, (c) regional source zones, and (d) all sources combined for the DFS team. The solid dots with vertical error bars indicate the observed frequency of earthquakes occurring within 100 km of the Yucca Mountain site.

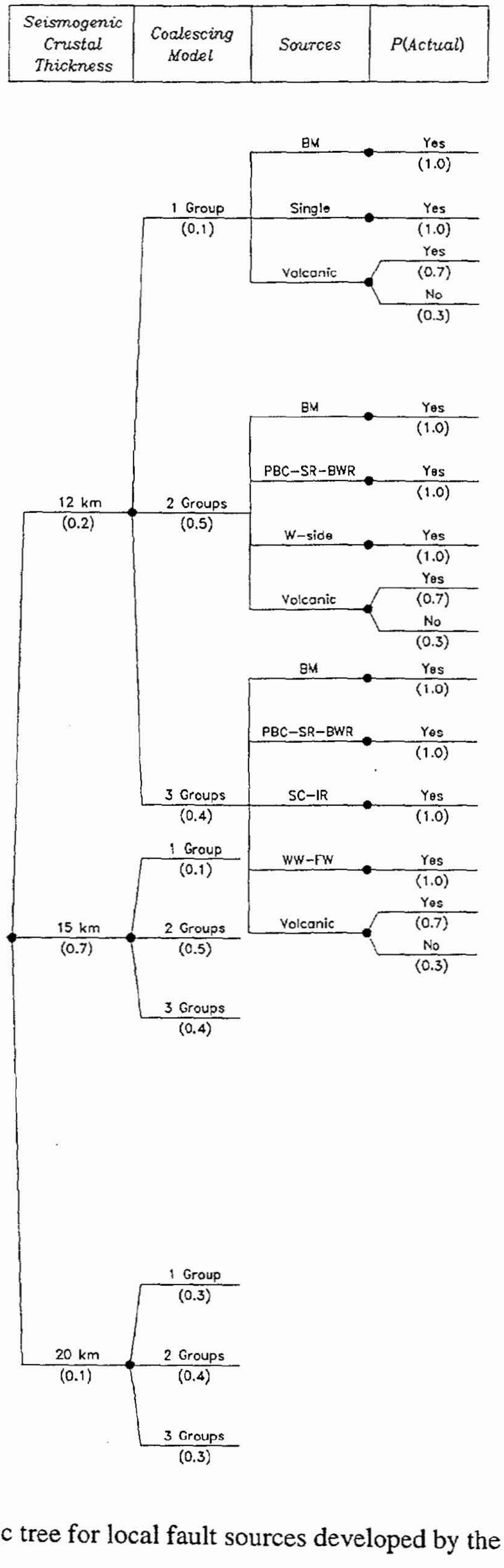
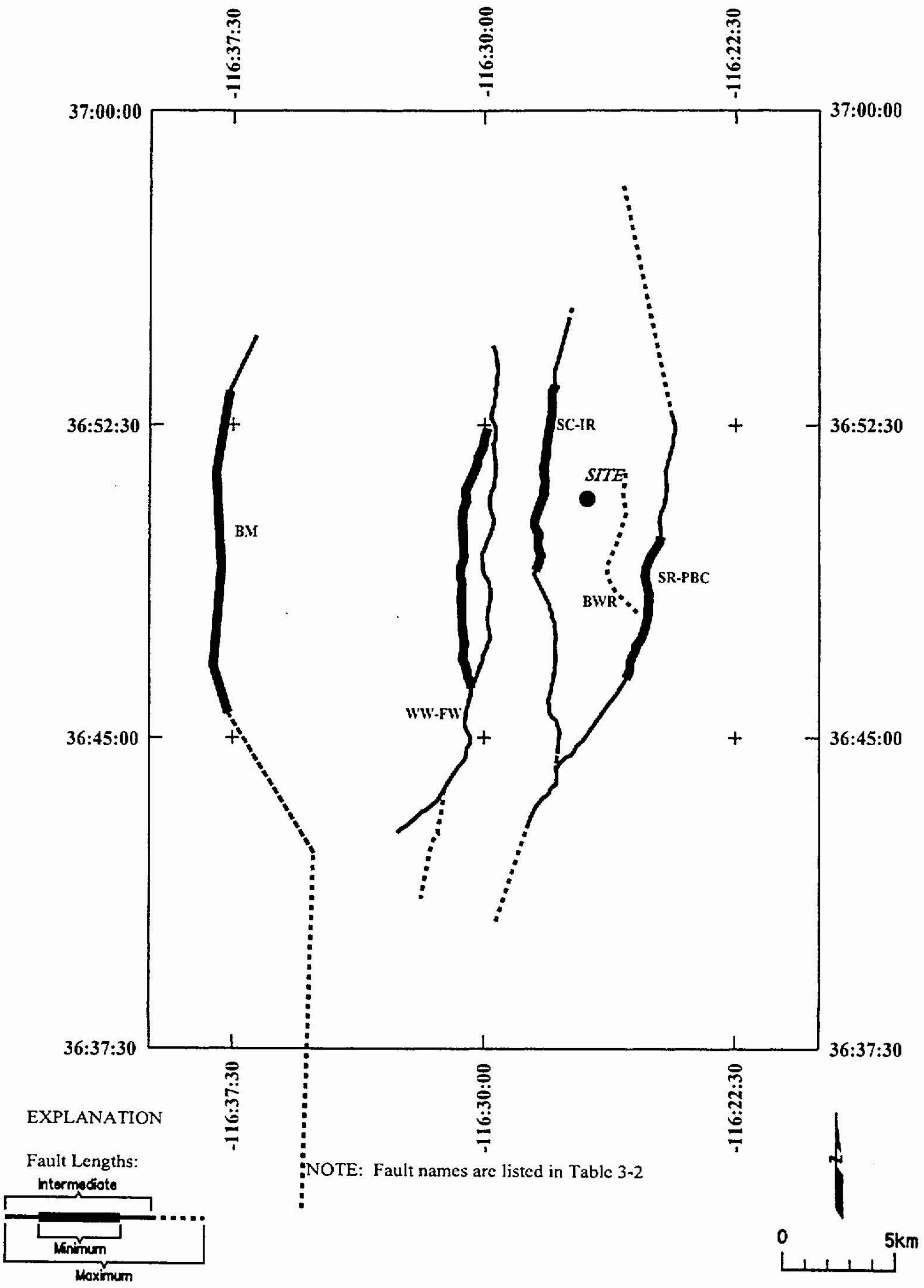


Figure 4-47 Logic tree for local fault sources developed by the RYA team



NOTE: Fault names are listed in Table 3-2

Figure 4-48 Location of local fault sources considered by the RYA team

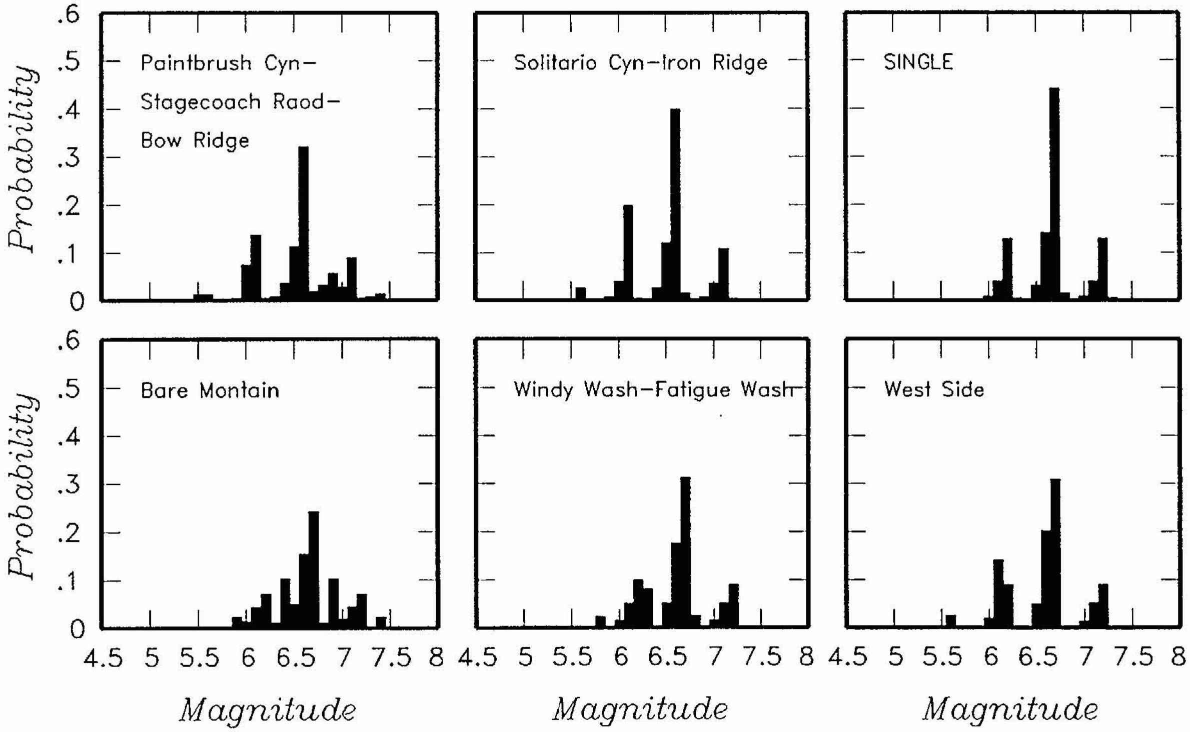


Figure 4-49 Maximum magnitude distributions for RYA team's local fault sources. SINGLE–coalescing source model with single fault system.

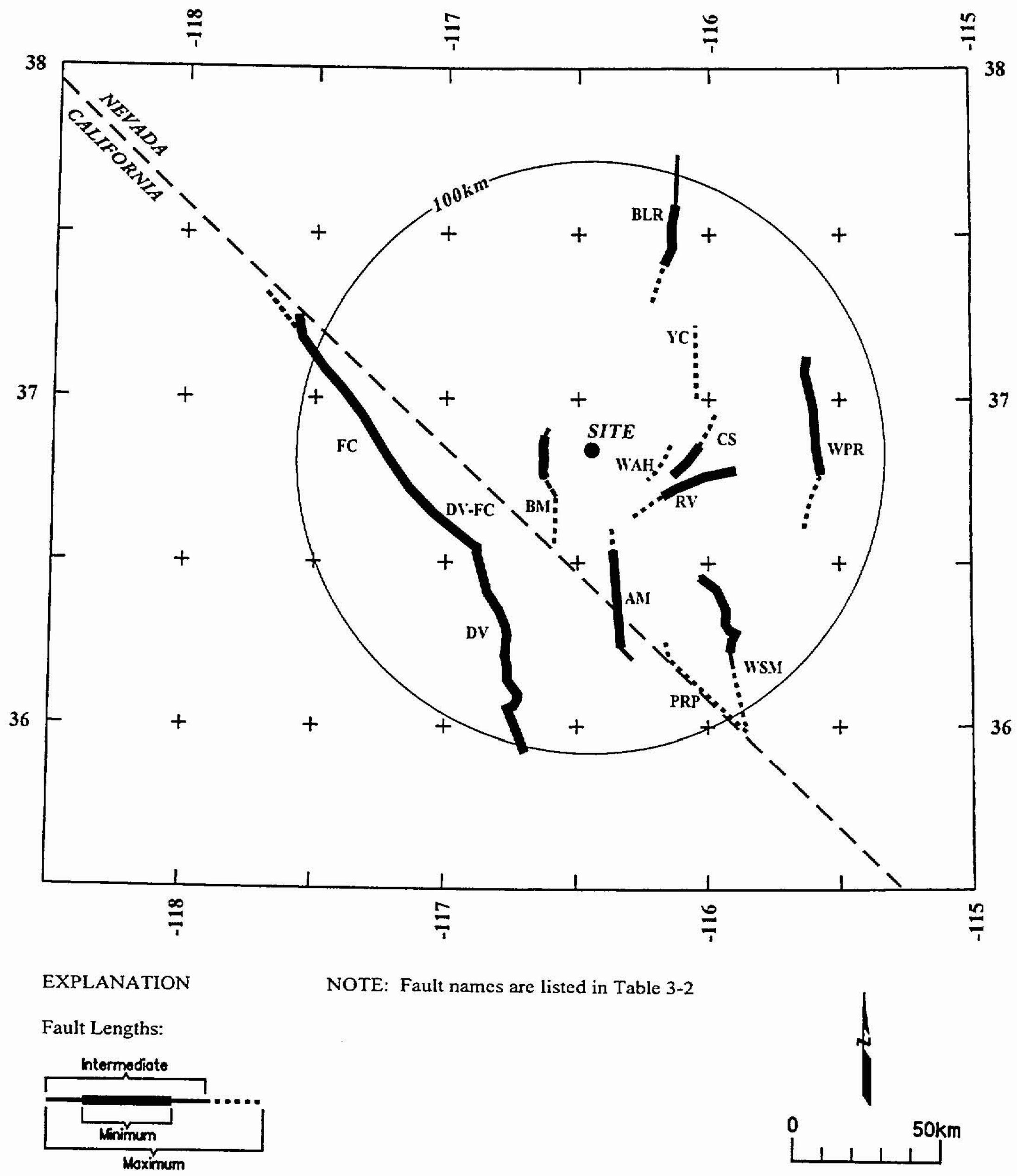


Figure 4-50 Regional fault sources considered by the RYA team

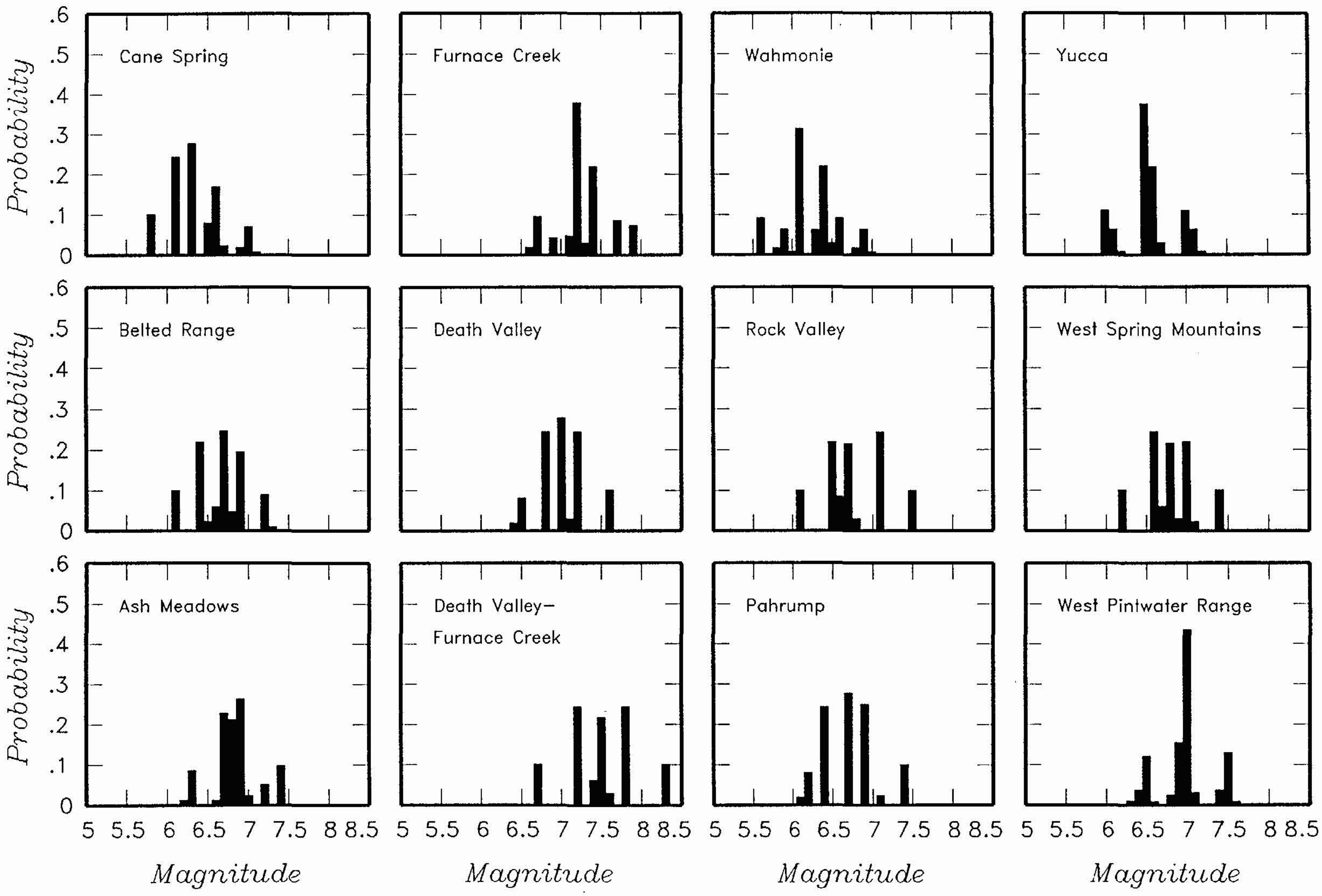


Figure 4-51 Maximum magnitude distributions for RYA team's regional fault sources

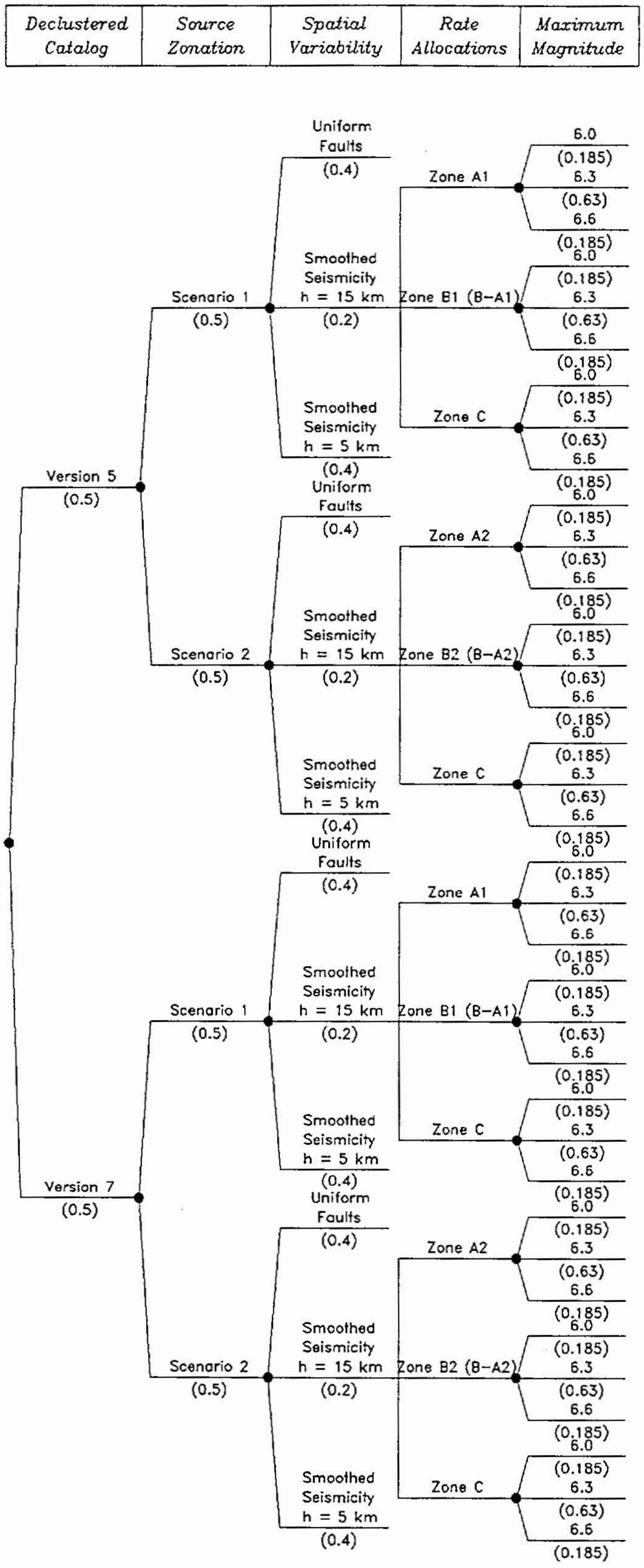


Figure 4-52 Logic tree for regional source zones developed by the RYA team

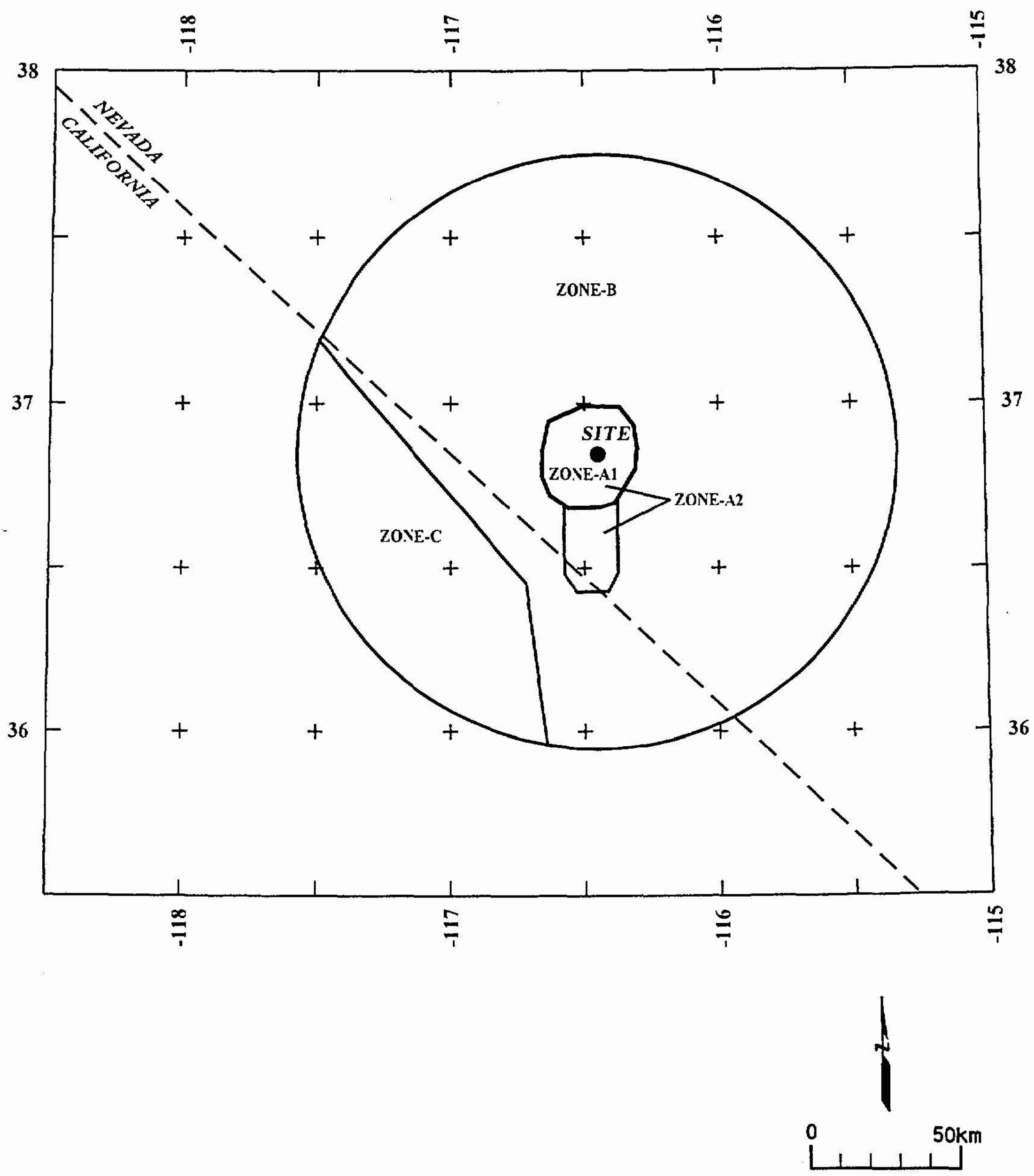


Figure 4-53 Alternative regional source zone models considered by the RYA team

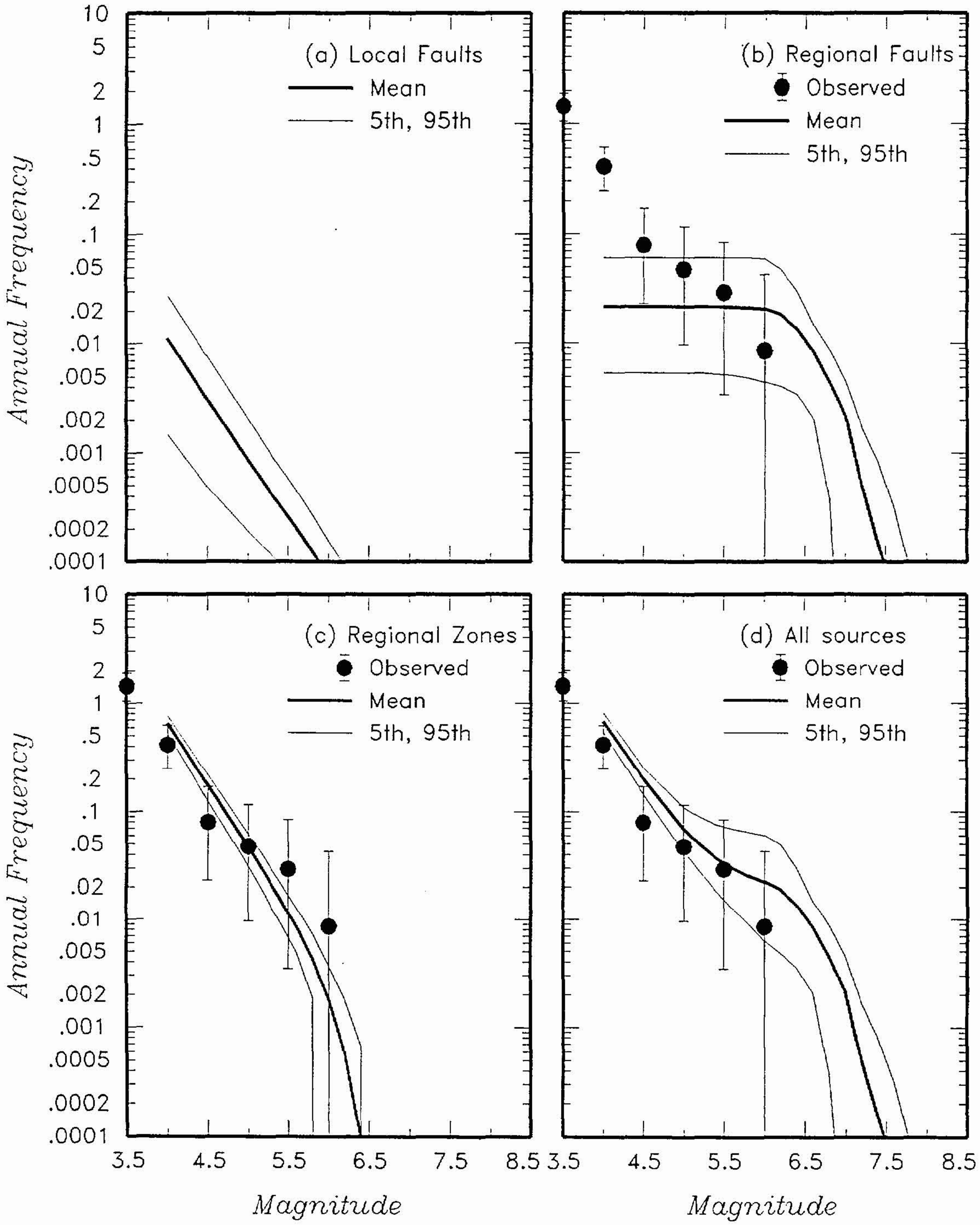


Figure 4-54 Predicted mean, 5th-, and 95th-percentile recurrence rates for (a) local fault sources, (b) regional fault sources, (c) regional source zones, and (d) all sources combined for the RYA team. The solid dots with vertical error bars indicate the observed frequency of earthquakes occurring within 100 km of the Yucca Mountain site.

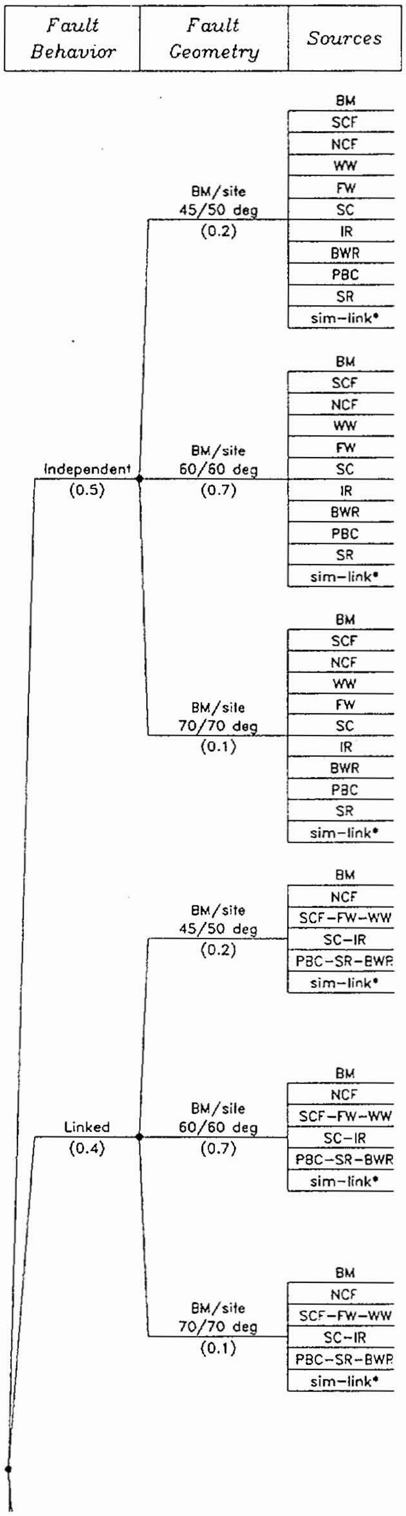
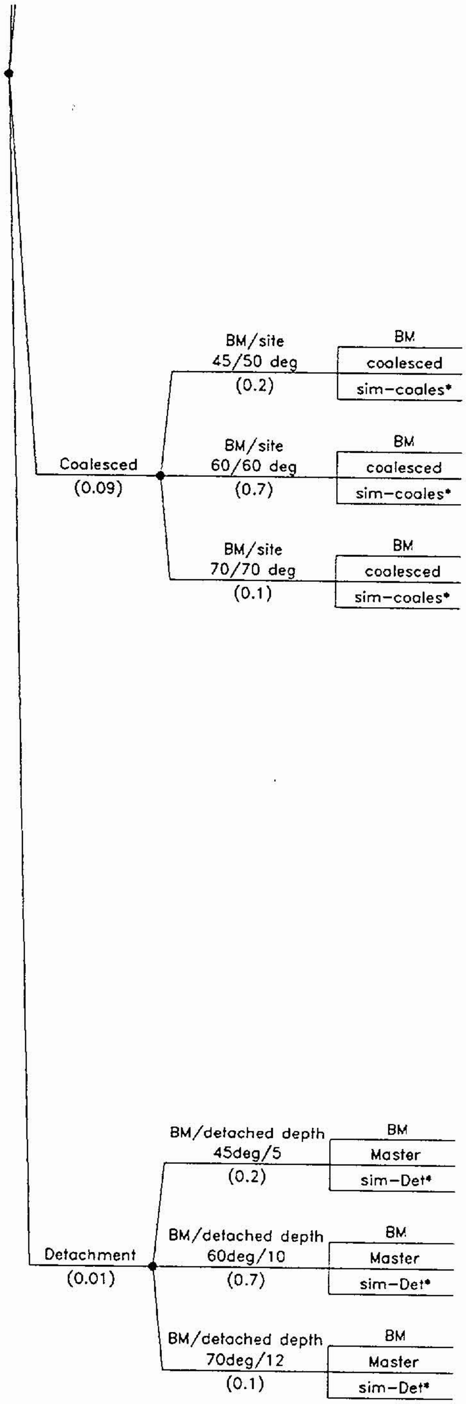
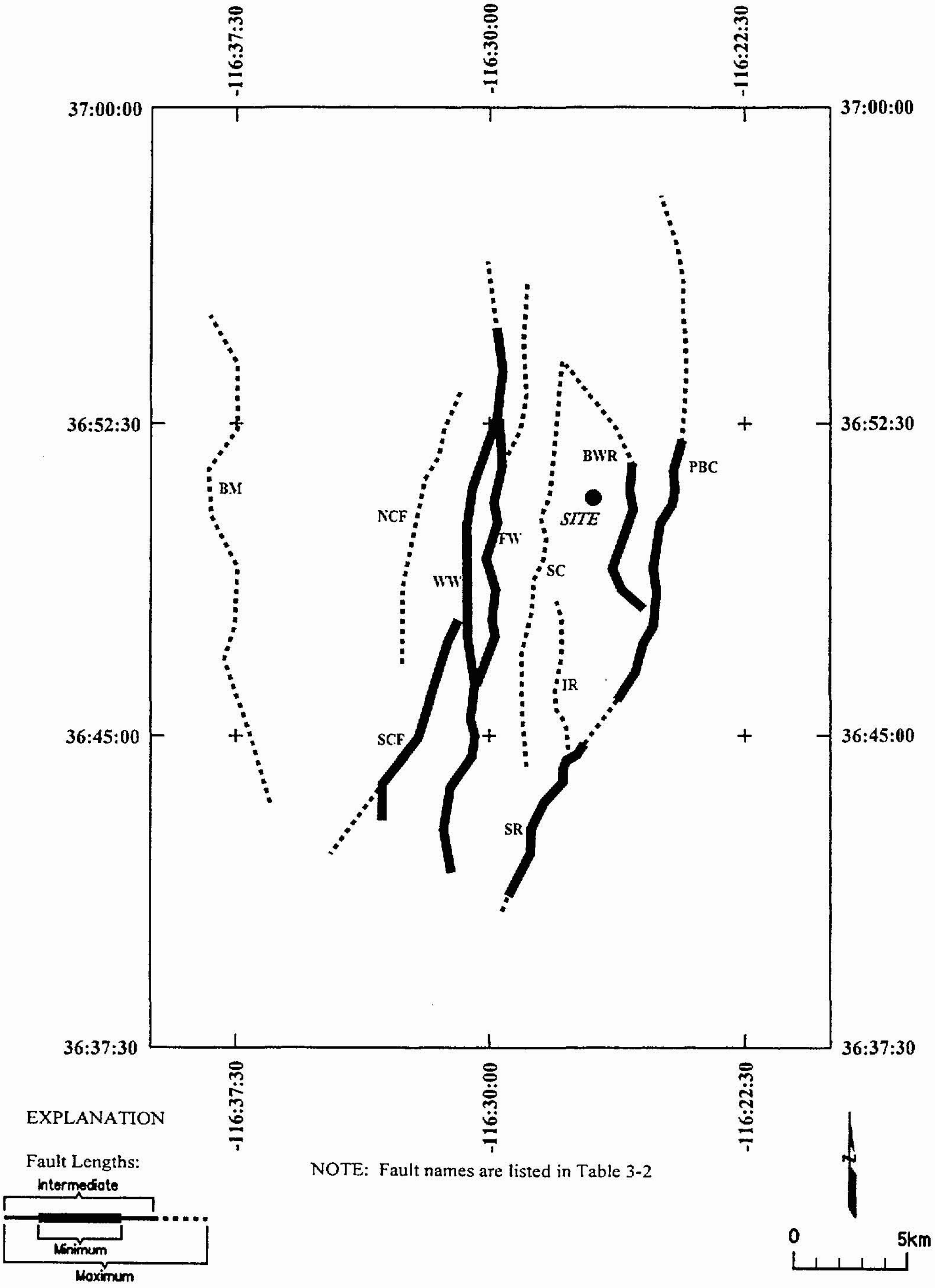


Figure 4-55 Logic tree for local fault sources developed by the SBK team



* sim-link, sim-coales and sim-det are synchronous rupture scenarios that act as additional sources of large events

Figure 4-55 (Cont'd.) Logic tree for local fault sources developed by the SBK team



NOTE: Fault names are listed in Table 3-2

Figure 4-56 Location of local faults characterized by the SBK team

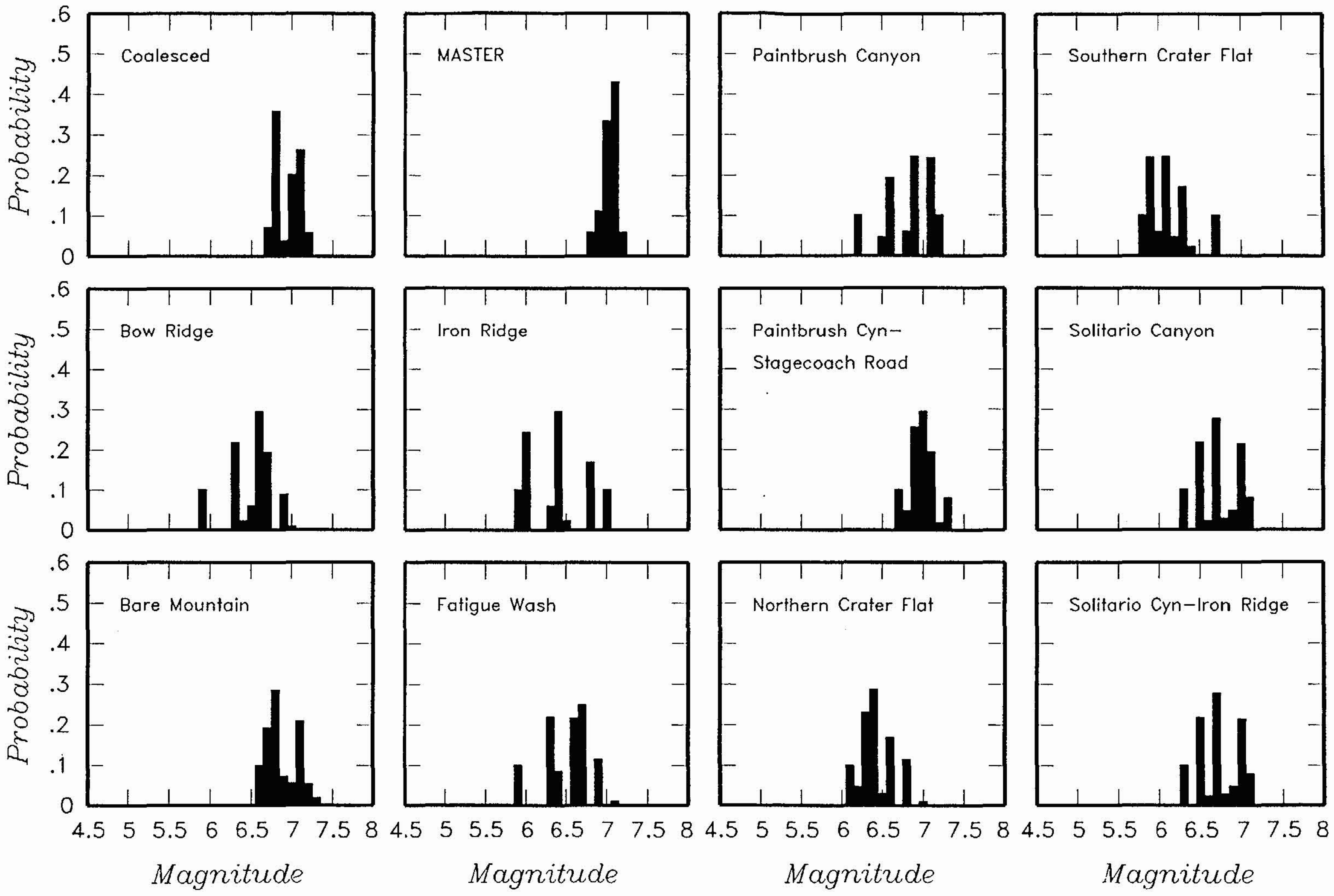


Figure 4-57 Maximum magnitude distributions for SBK team's local fault sources. MASTER–detachment with underlying master fault.

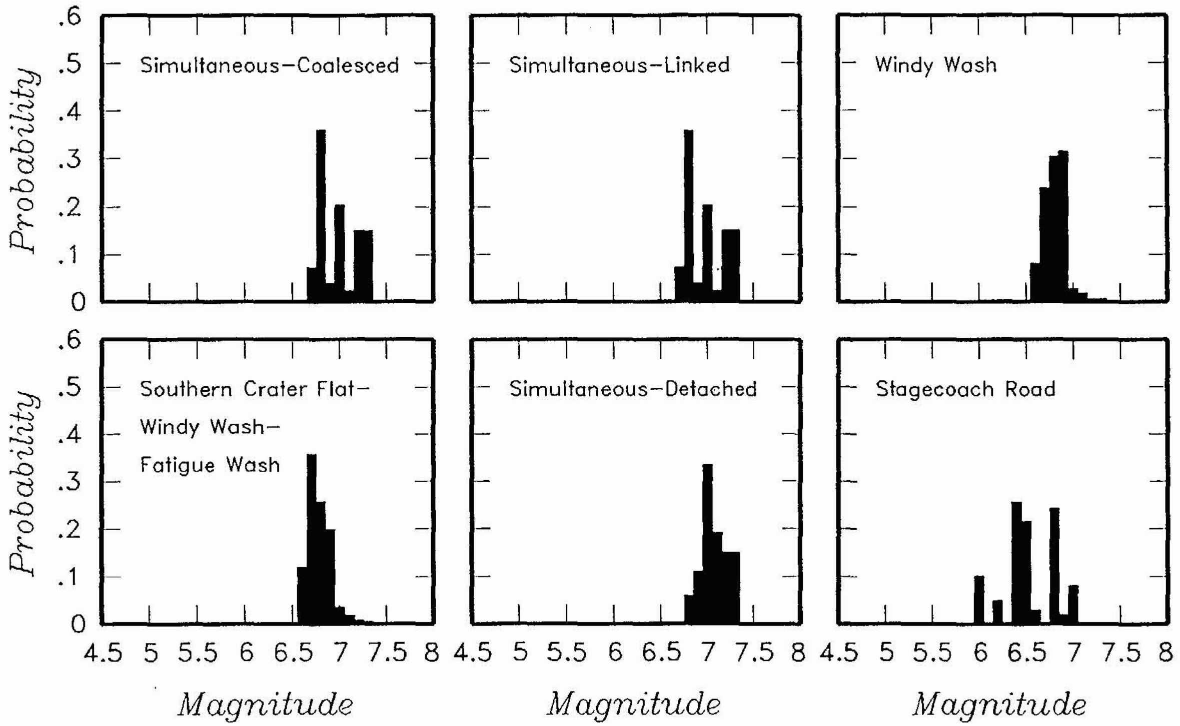
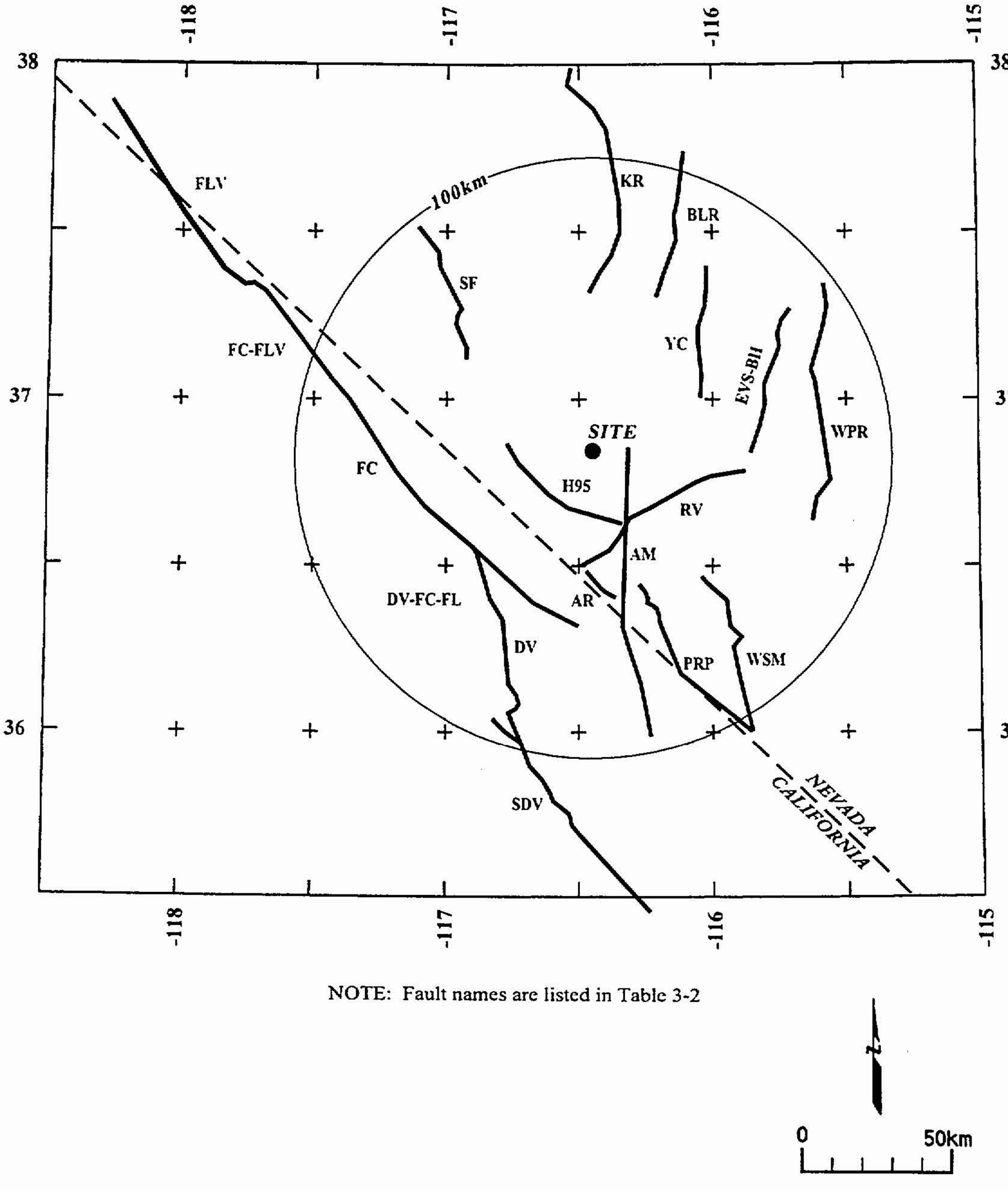


Figure 4-57 (Cont'd.) Maximum magnitude distributions for SBK team's local fault sources. MASTER–detachment with underlying master fault.



NOTE: Fault names are listed in Table 3-2

Figure 4-58 Regional fault sources characterized by the SBK team

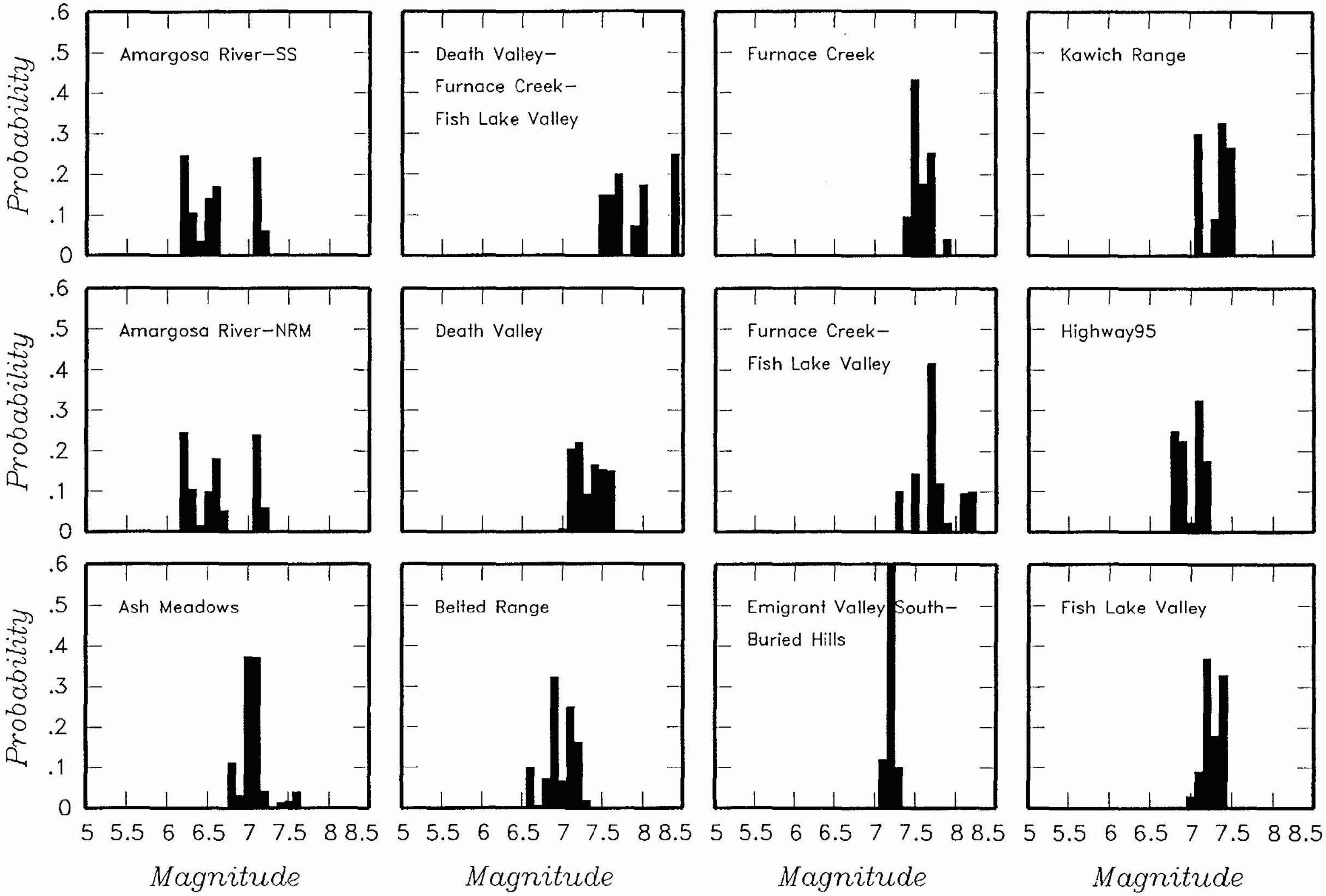


Figure 4-59 Maximum magnitude distributions for SBK team's regional fault sources.
SS–strike slip; NRM–normal slip, OBL–oblique slip.

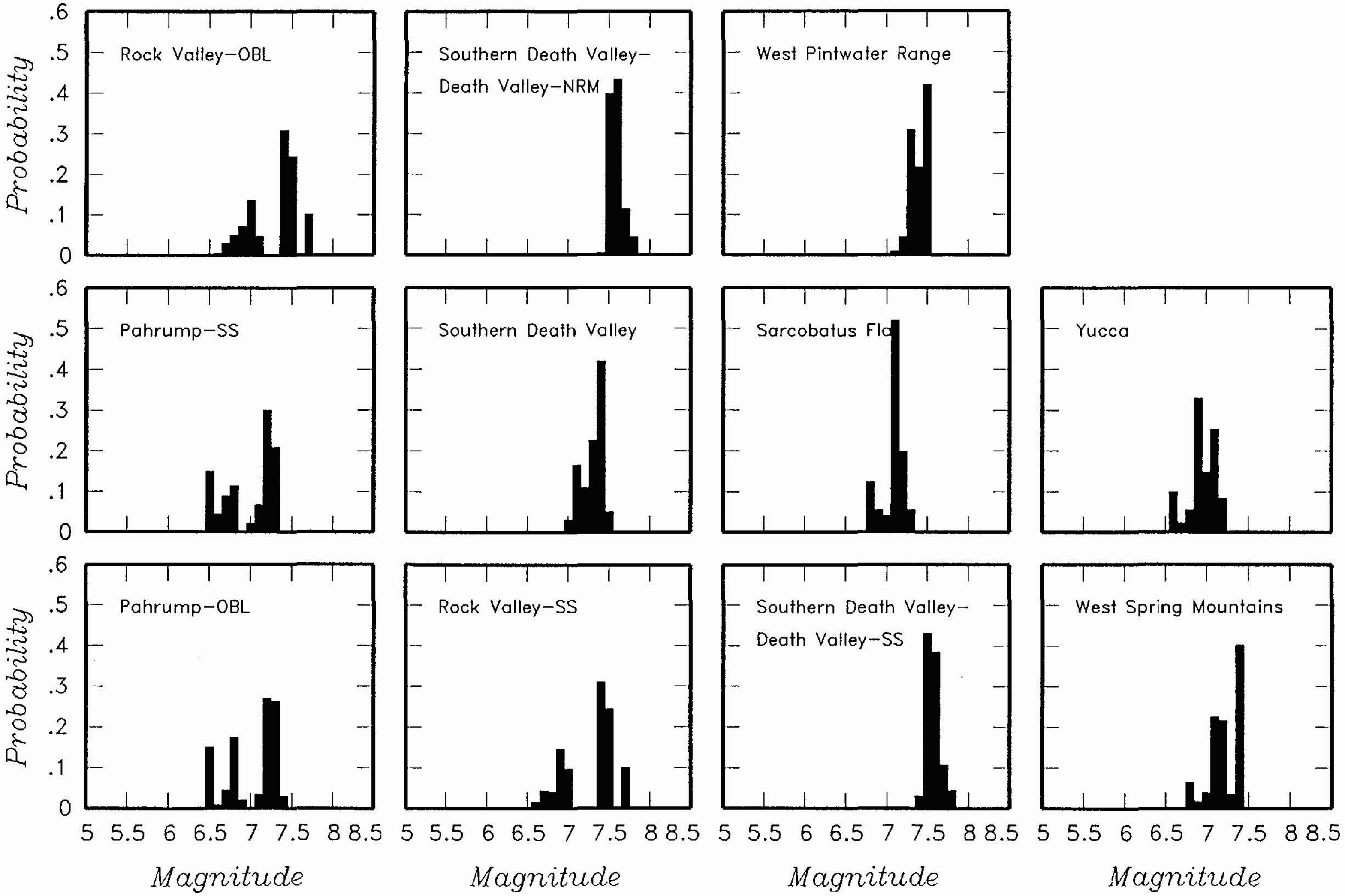


Figure 4-59 (Cont'd.) Maximum magnitude distributions for SBK team's regional fault sources.
SS–strike slip; NRM–normal slip, OBL–oblique slip.

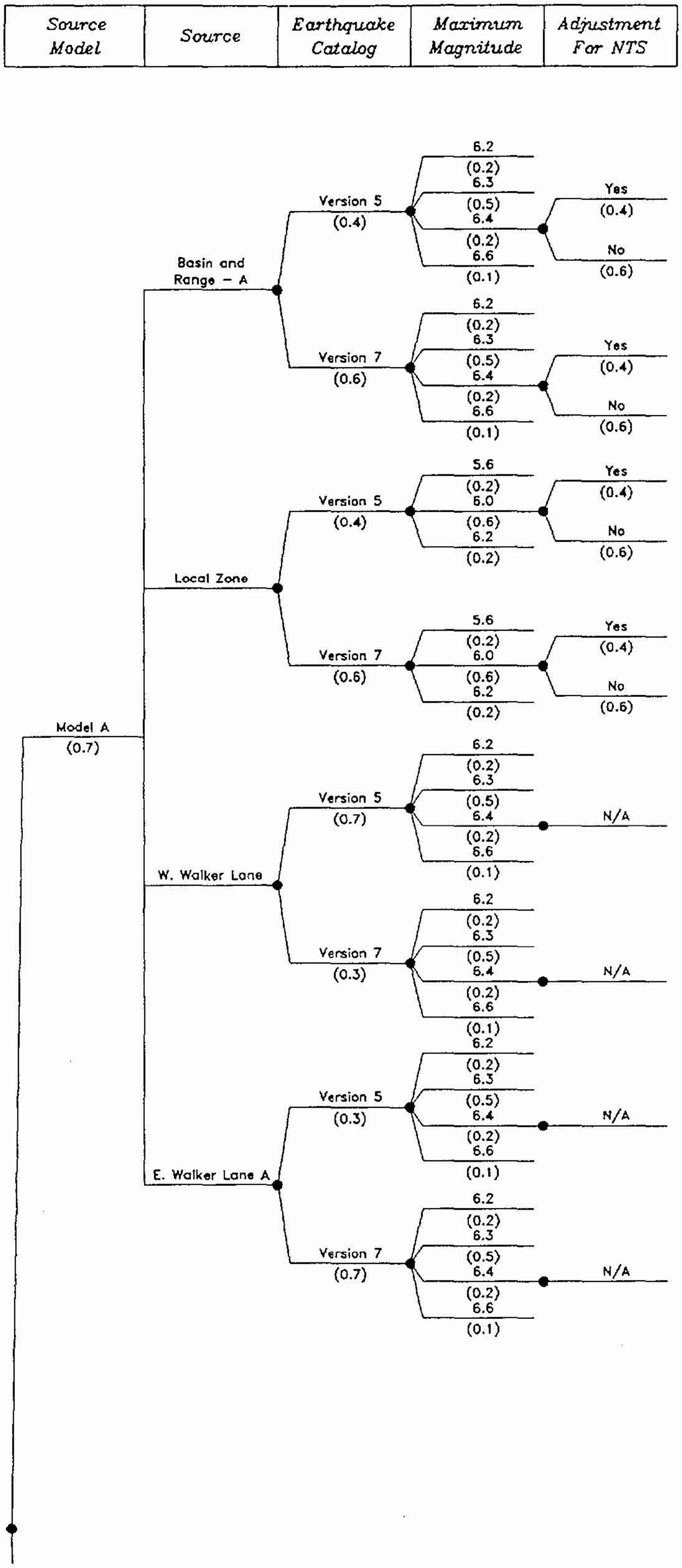


Figure 4-60 Logic tree for regional source zones developed by the SBK team

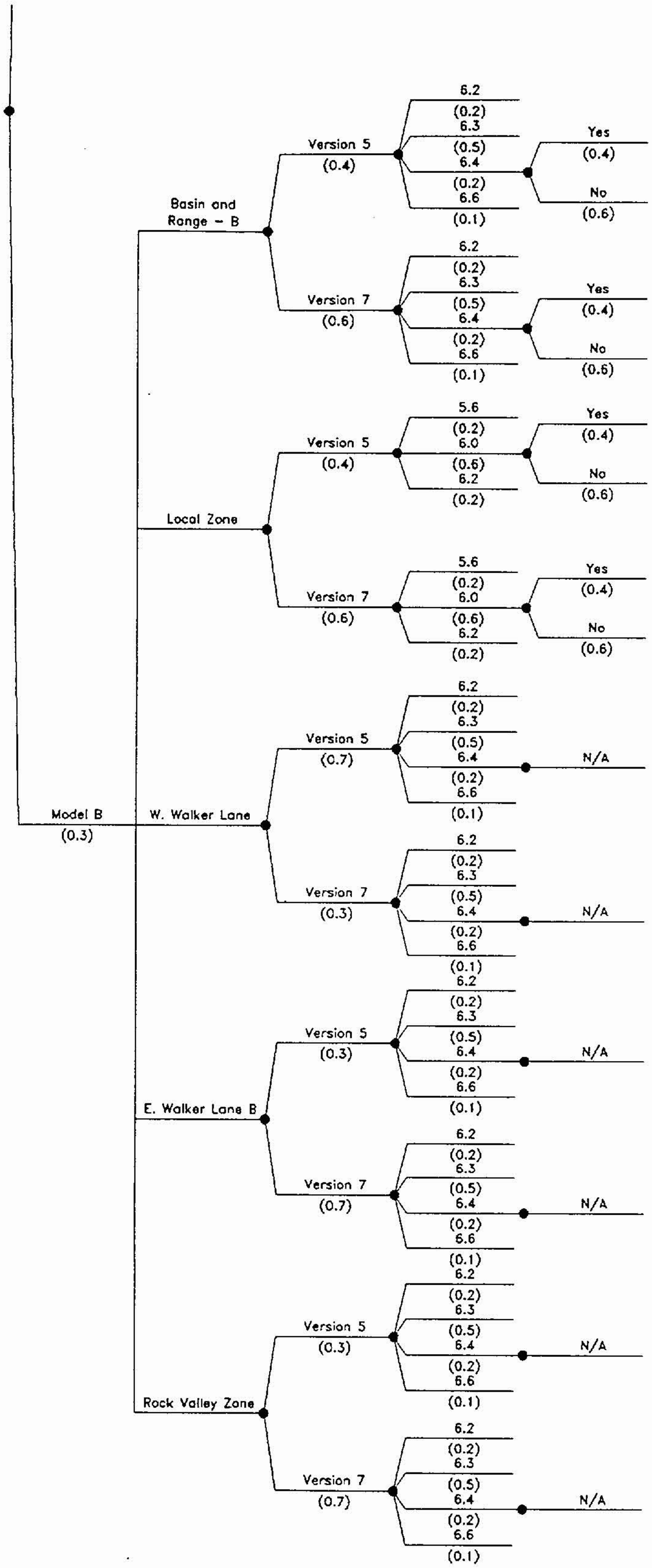


Figure 4-60 (Cont'd.) Logic tree for regional source zones developed by the SBK team

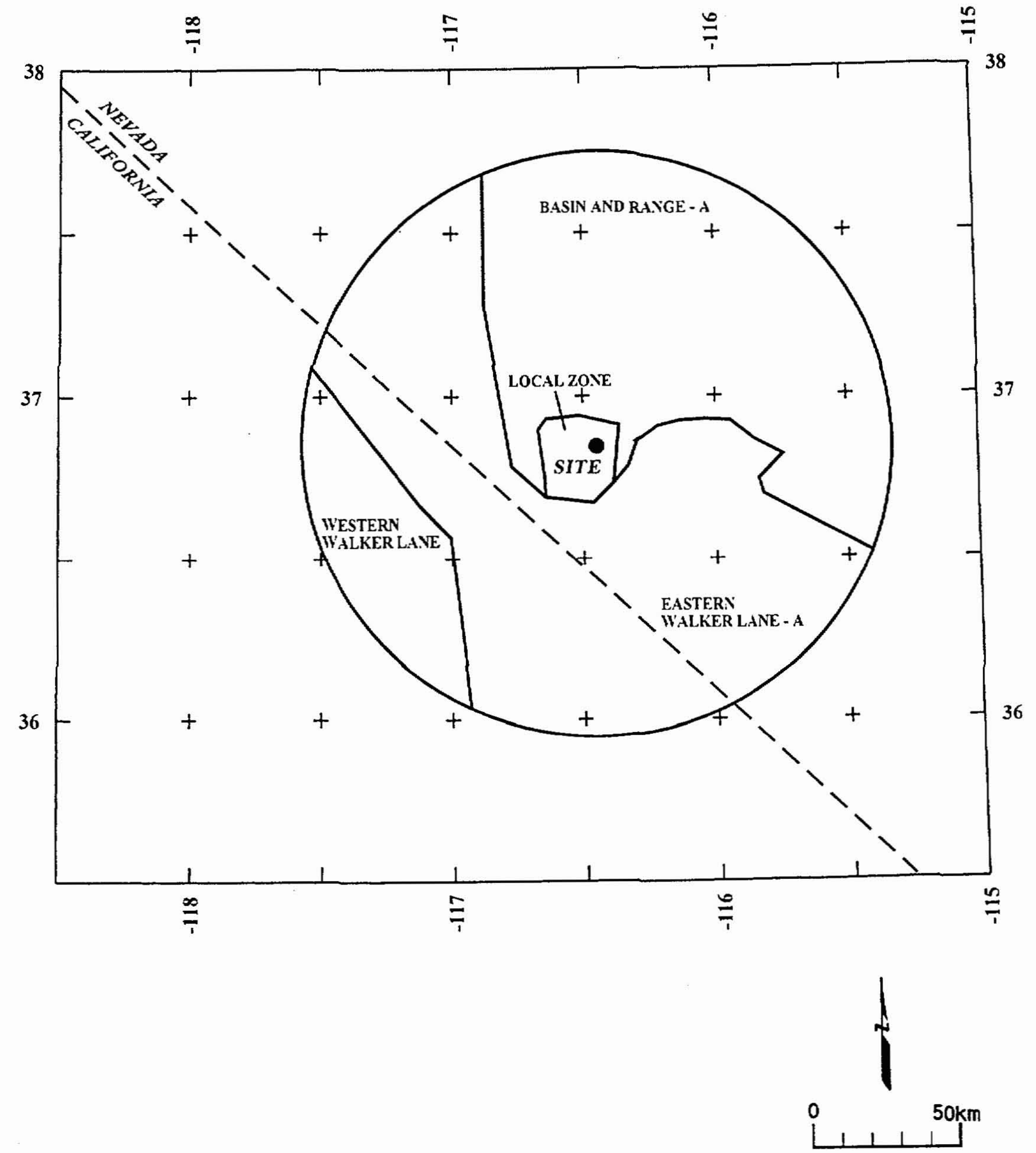


Figure 4-61 Alternative regional source zone models considered by the SBK team

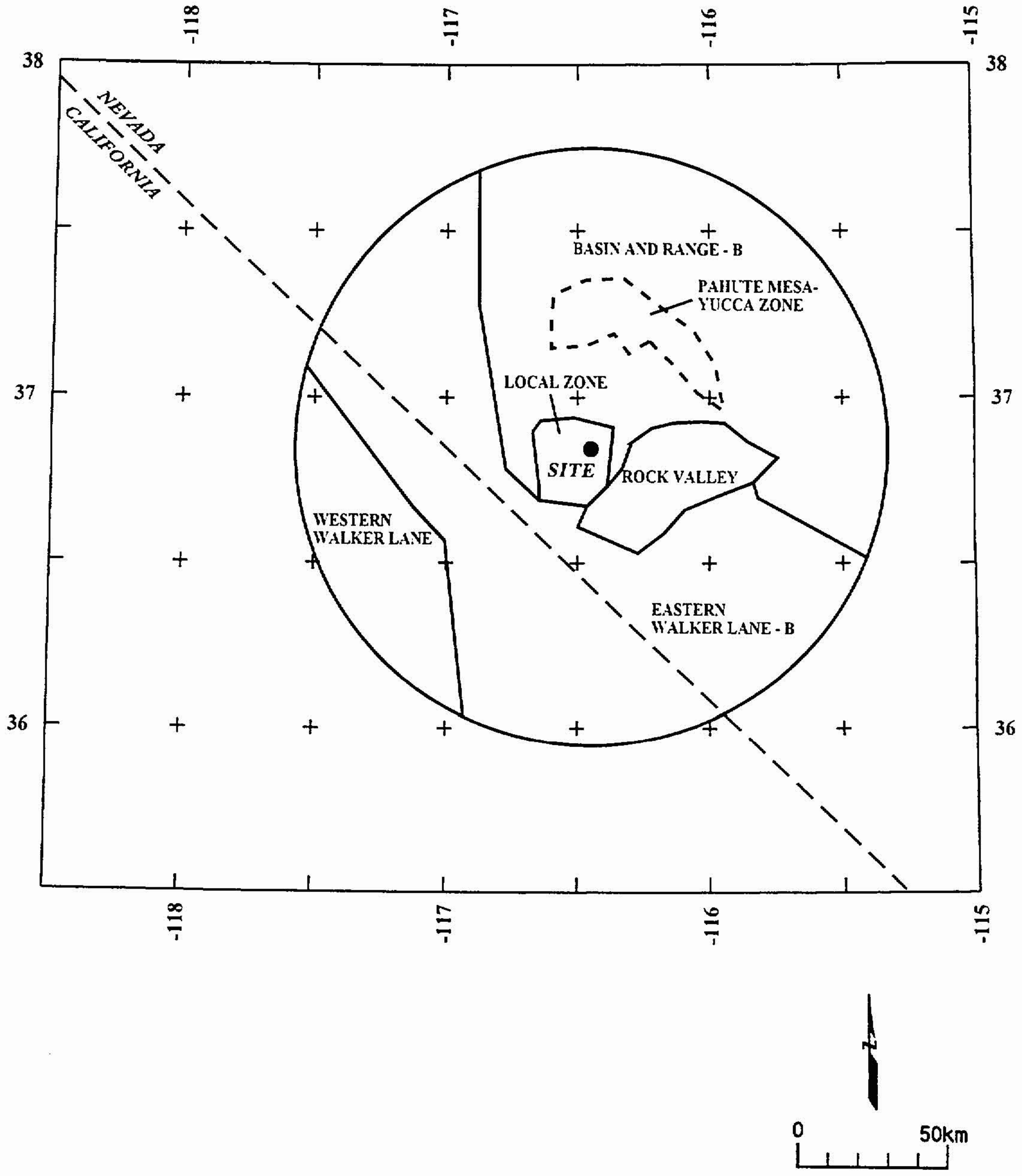


Figure 4-61 (Cont'd.) Alternative regional source zone models considered by the SBK team

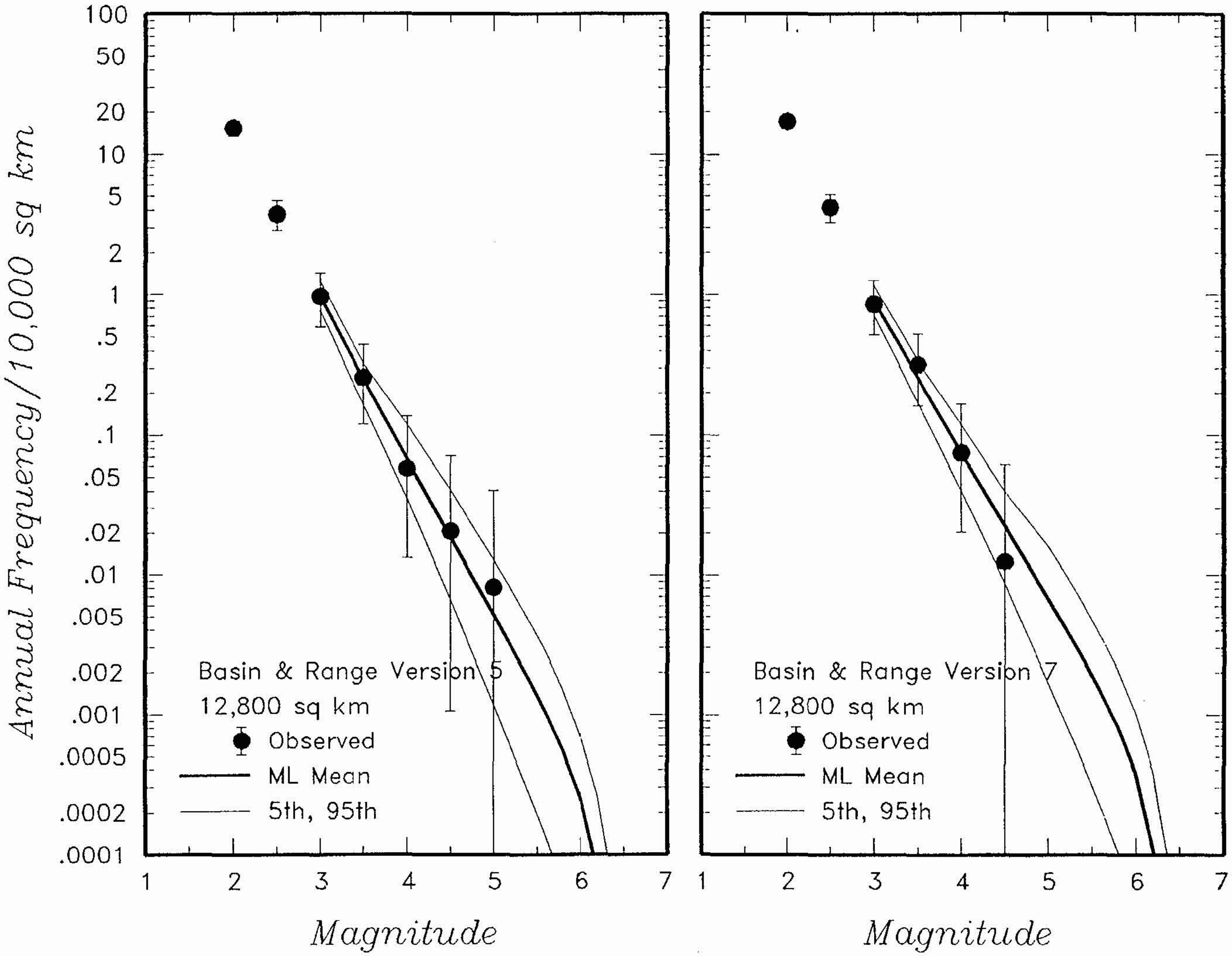


Figure 4-62 Earthquake recurrence relationships for the regional source zones defined by the SBK team. The solid dots with vertical error bars represent the observed data. The thick and thin solid curves are the mean, 5th, and 95th percentiles of the recurrence rates based on the uncertainty in recurrence parameters and maximum magnitude.

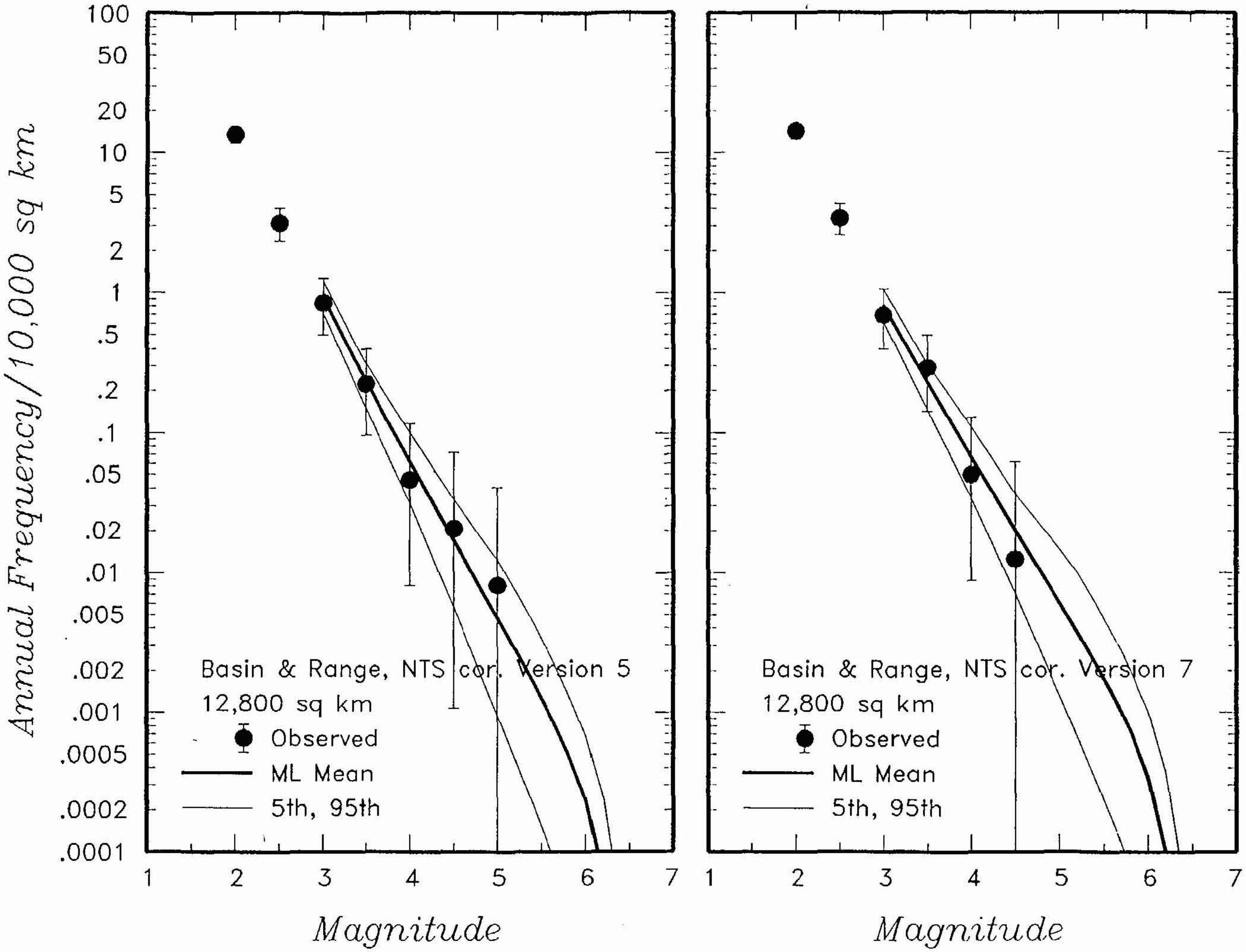


Figure 4-62 (Cont'd.) Earthquake recurrence relationships for the regional source zones defined by the SBK team.

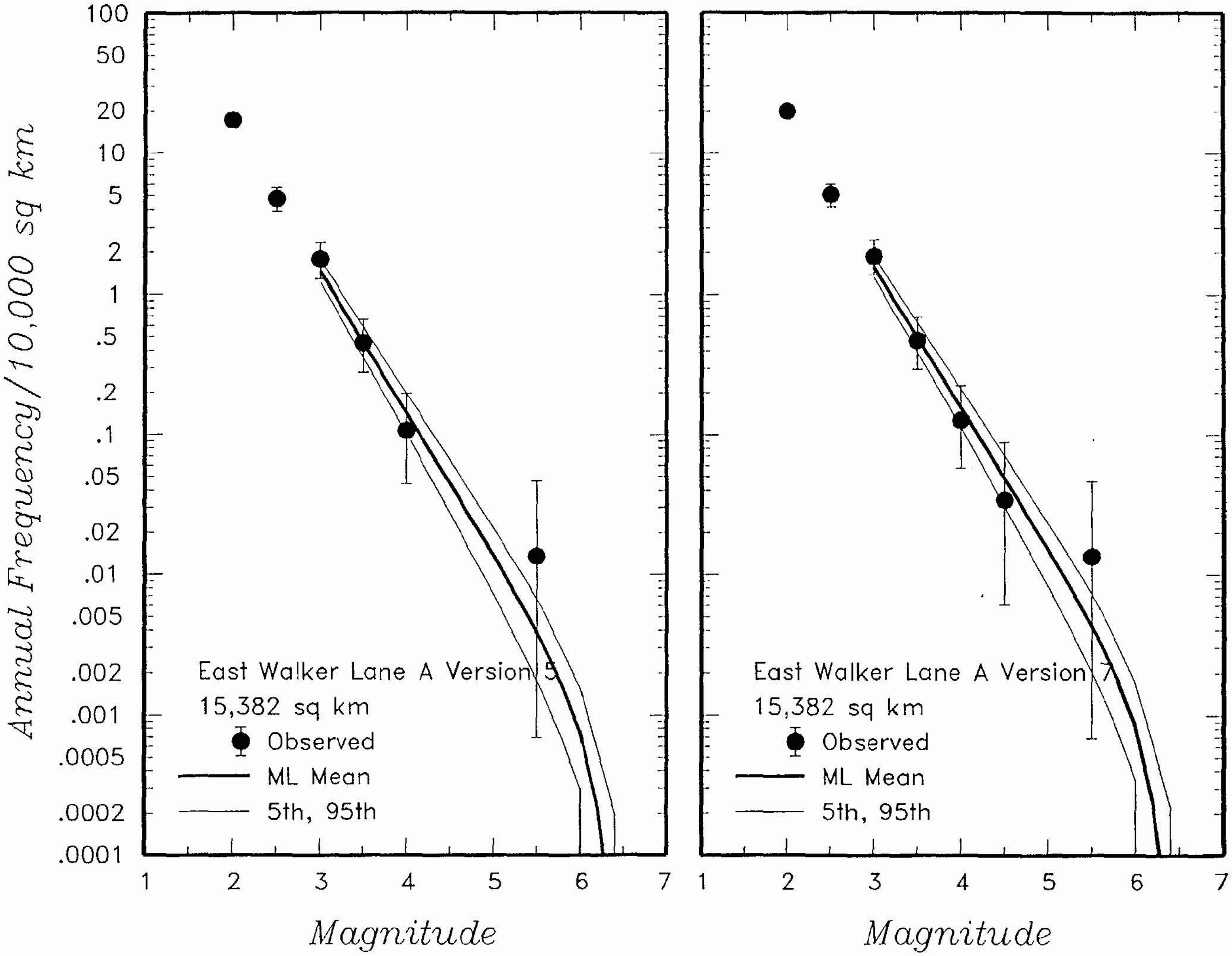


Figure 4-62 (Cont'd.) Earthquake recurrence relationships for the regional source zones defined by the SBK team.

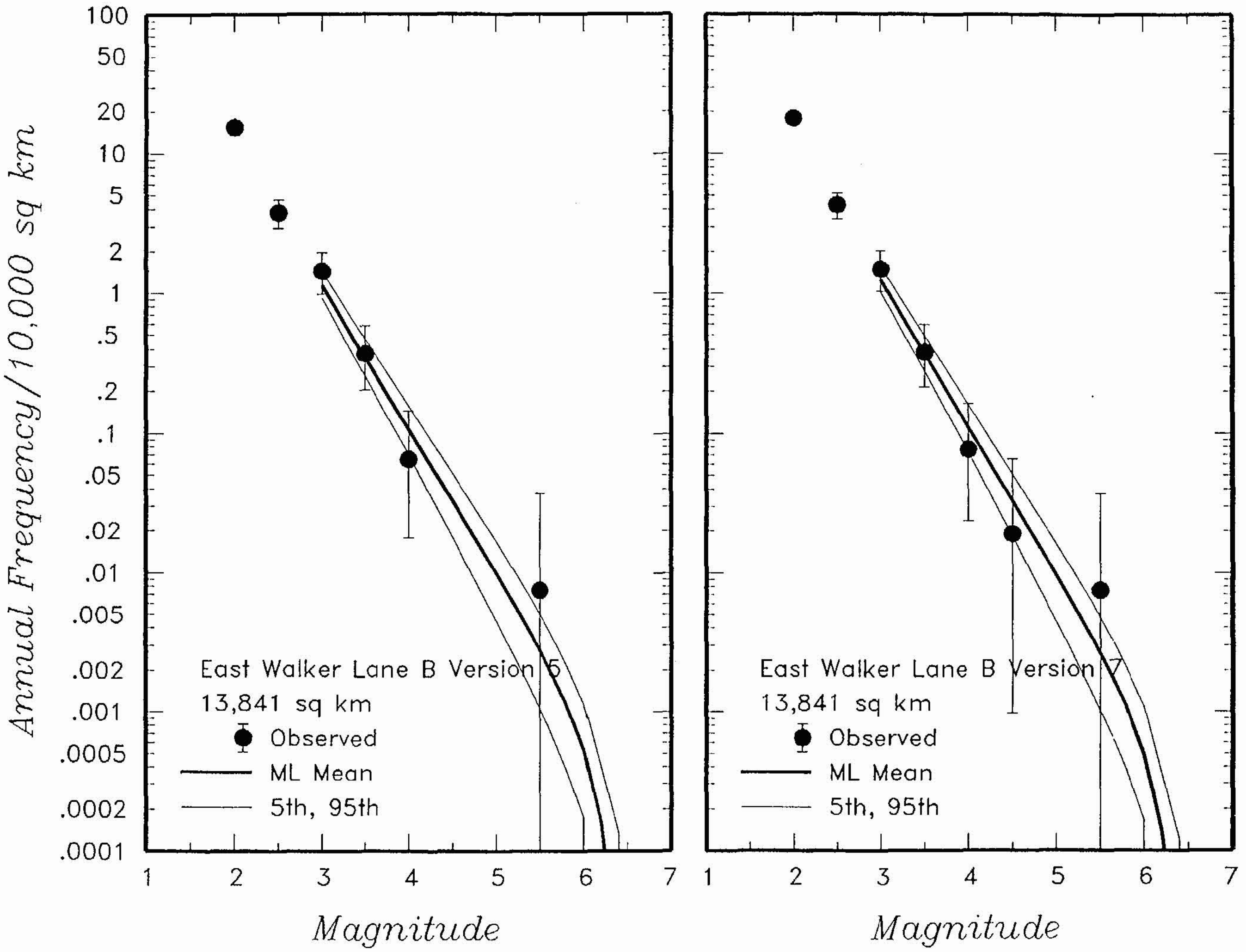


Figure 4-62 (Cont'd.) Earthquake recurrence relationships for the regional source zones defined by the SBK team.

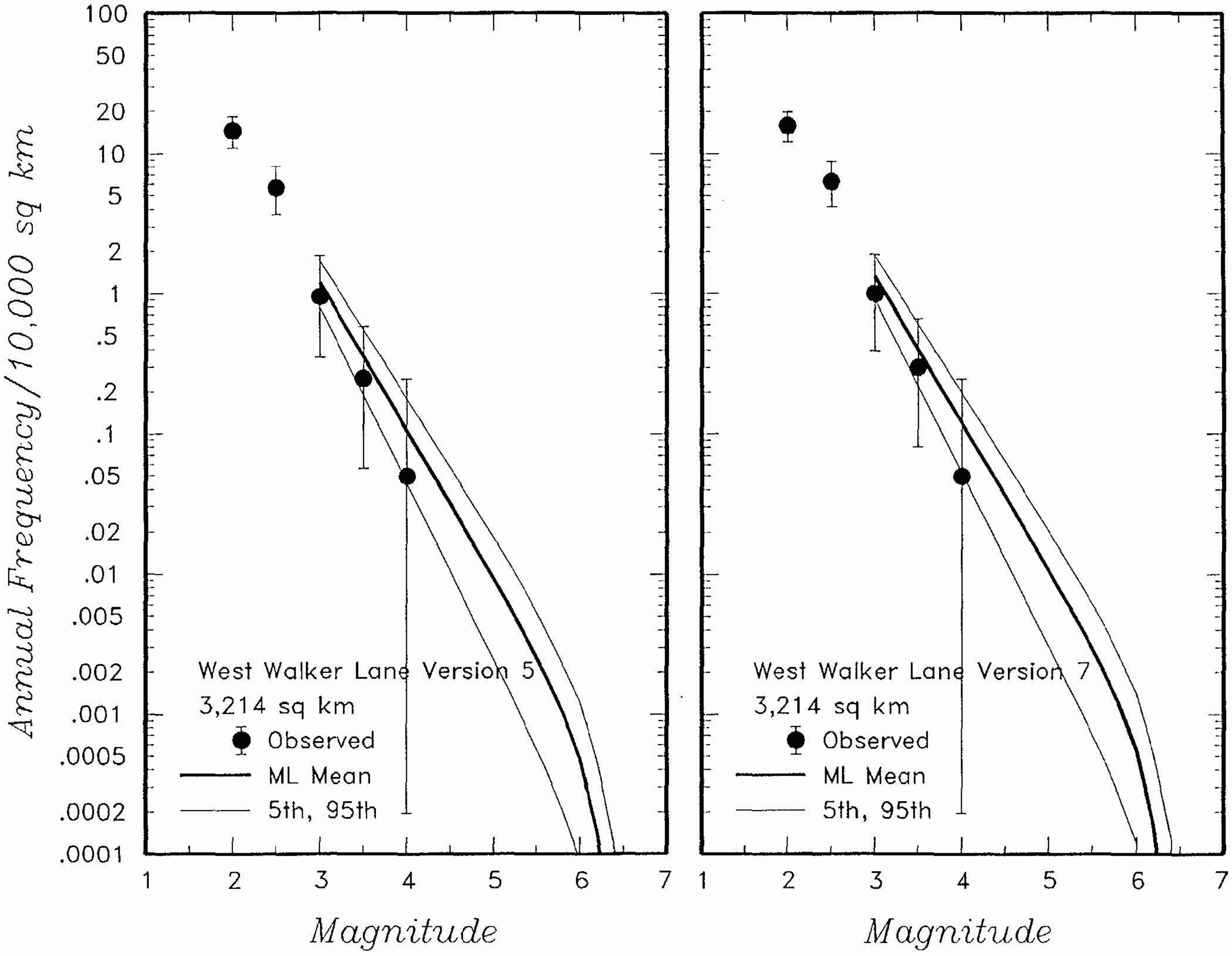


Figure 4-62 (Cont'd.) Earthquake recurrence relationships for the regional source zones defined by the SBK team.

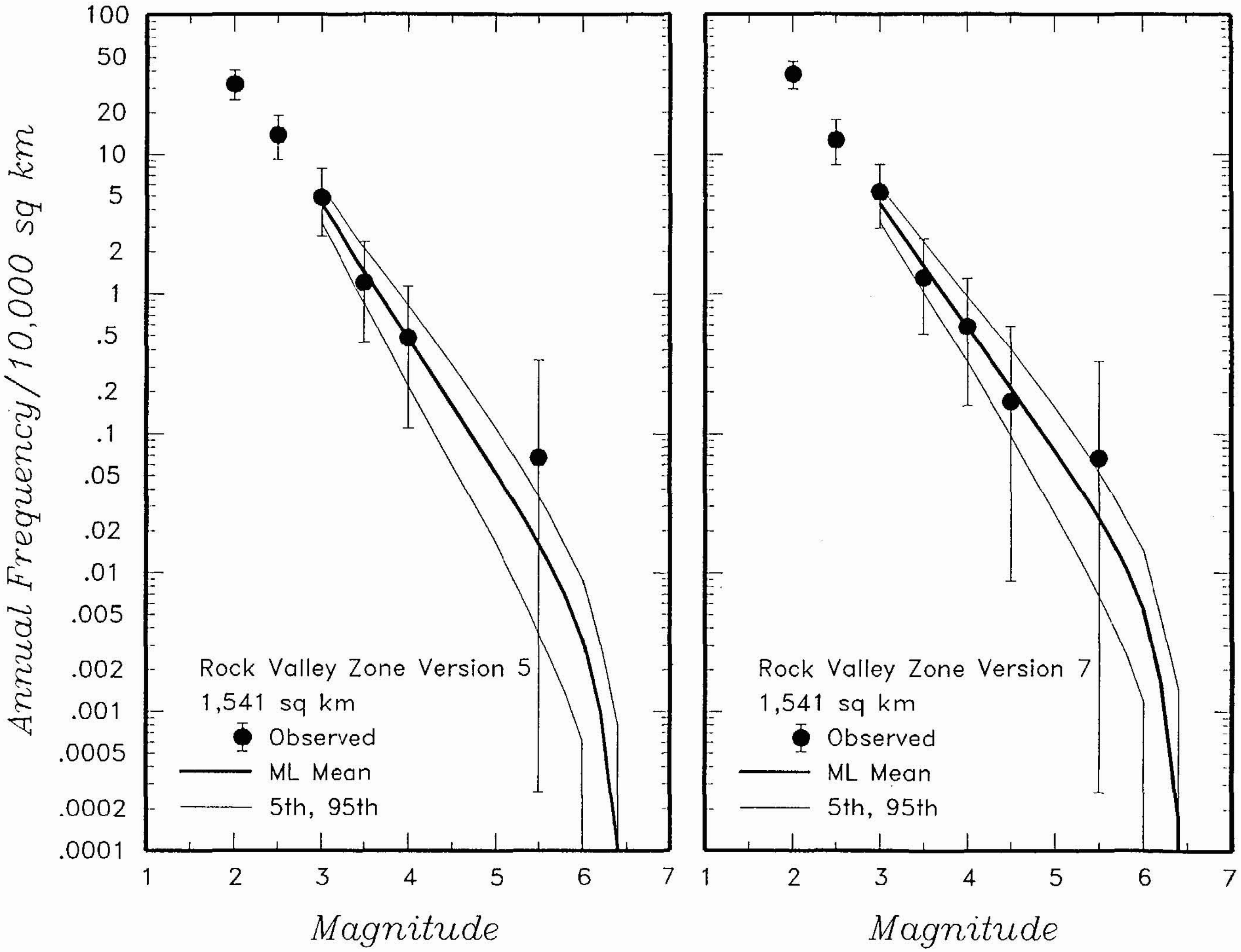


Figure 4-62 (Cont'd.) Earthquake recurrence relationships for the regional source zones defined by the SBK team.

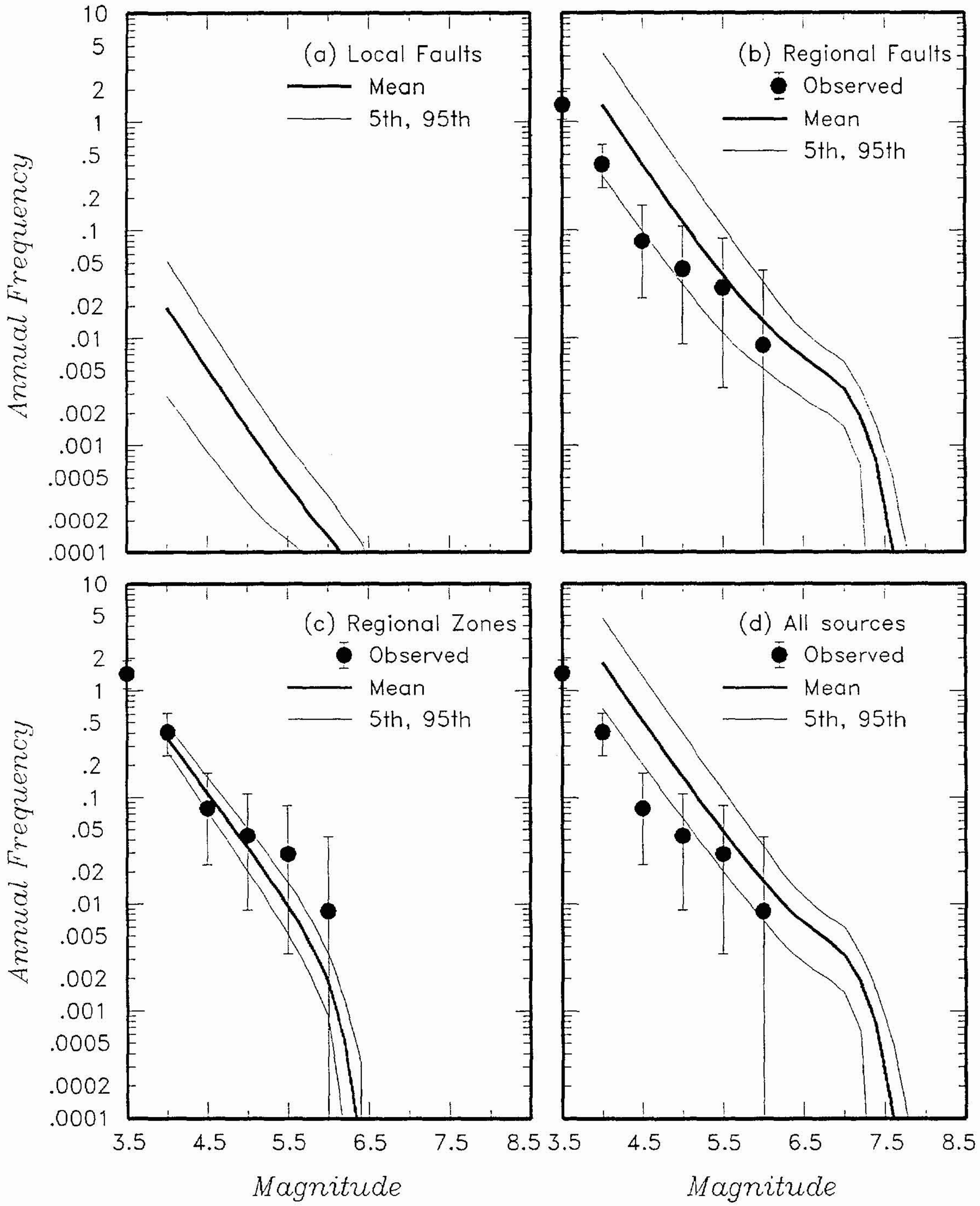


Figure 4-63 Predicted mean, 5th-, and 95th-percentile recurrence rates for (a) local fault sources, (b) regional fault sources, (c) regional source zones, and (d) all sources combined for the SBK team. The solid dots with vertical error bars represent the observed frequency of earthquakes occurring within 100 km of the Yucca Mountain site.

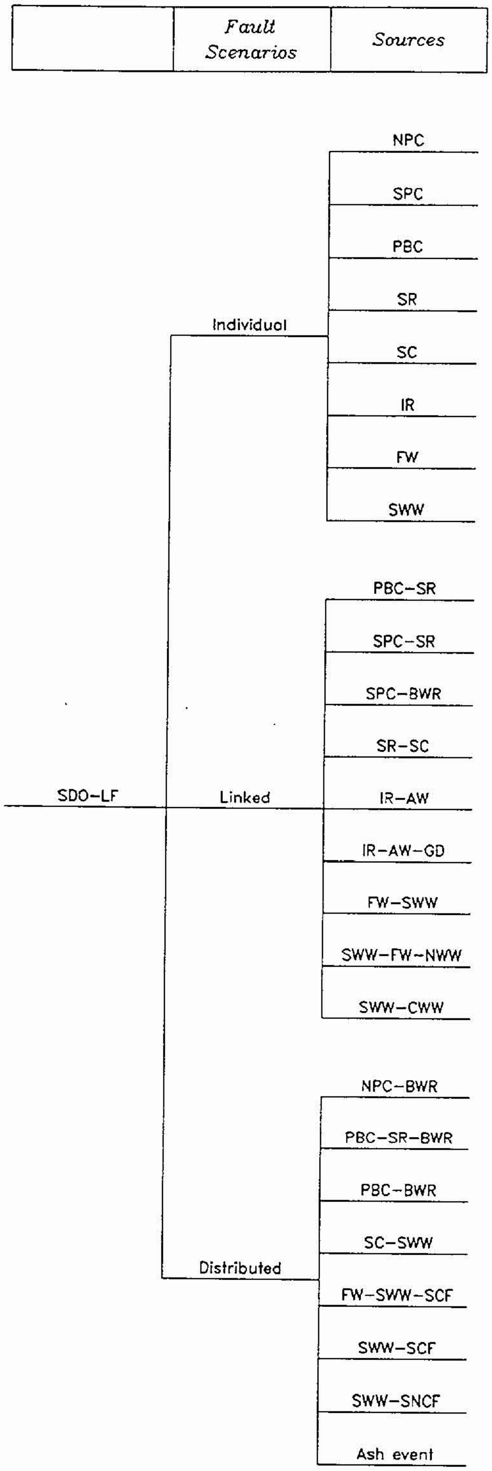


Figure 4-64 Logic tree for local fault sources developed by the SDO team

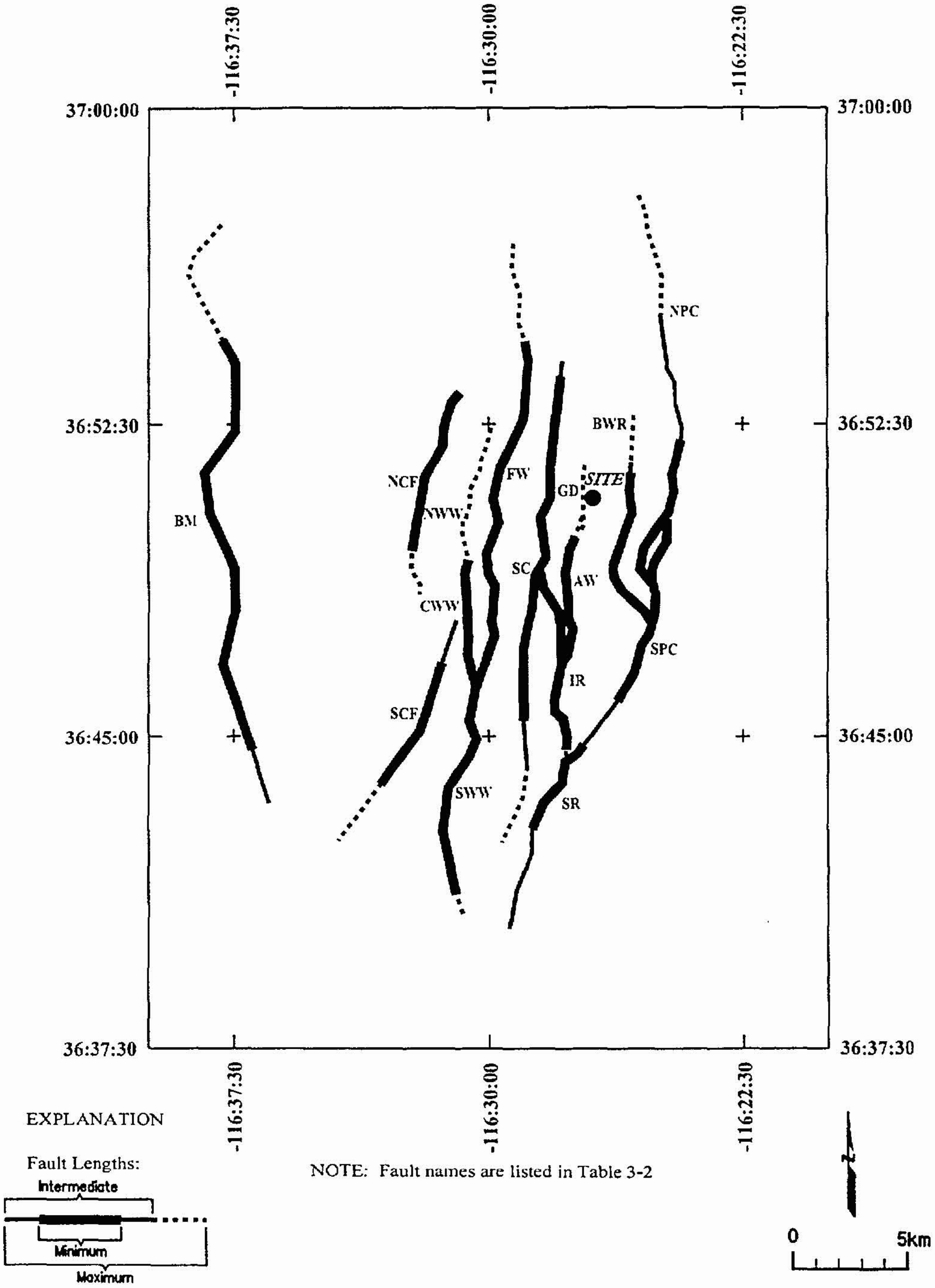
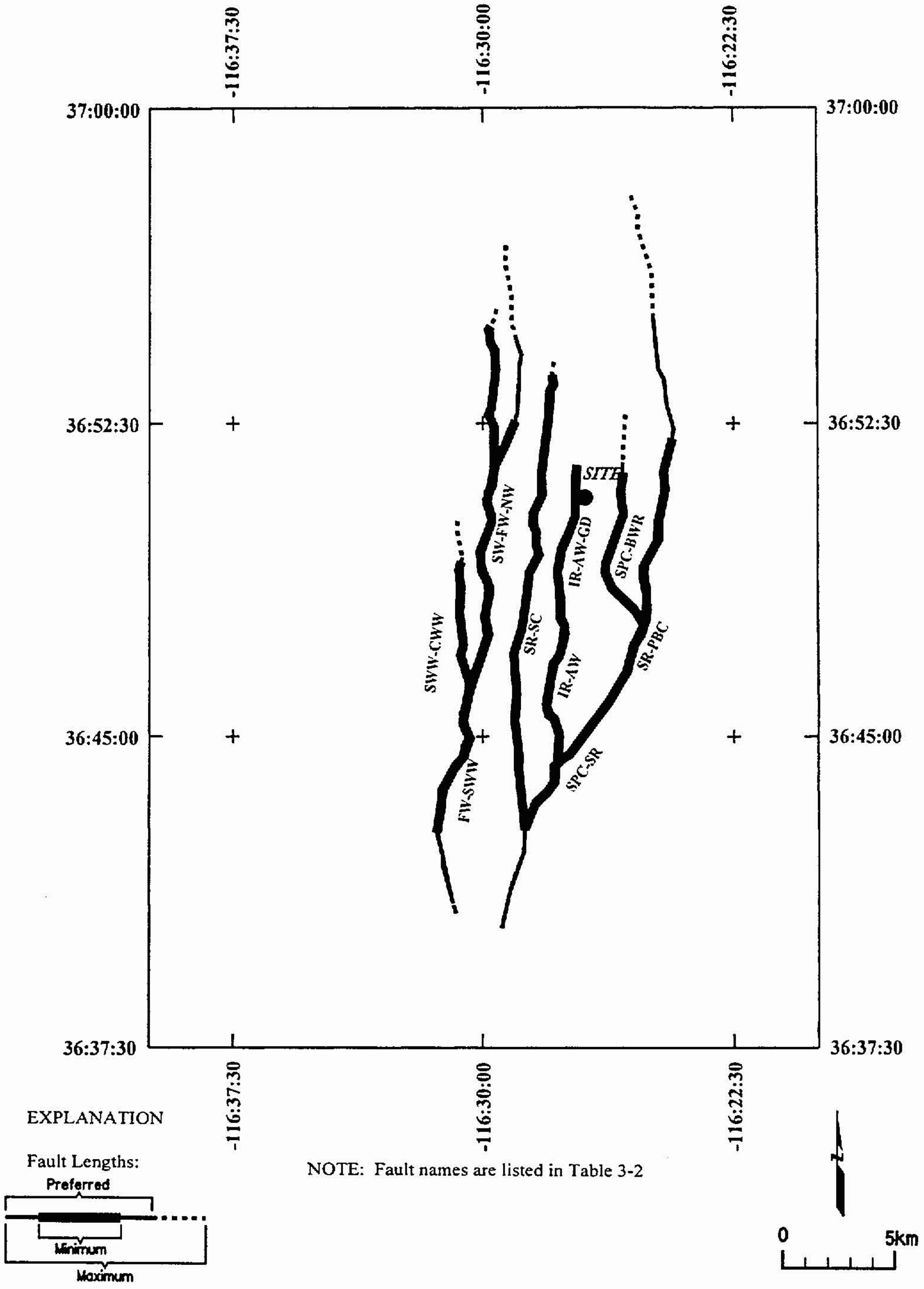


Figure 4-65 Location of local fault sources considered by the SDO team



NOTE: Fault names are listed in Table 3-2

Figure 4-65 (Cont'd.) Location of local fault sources considered by the SDO team

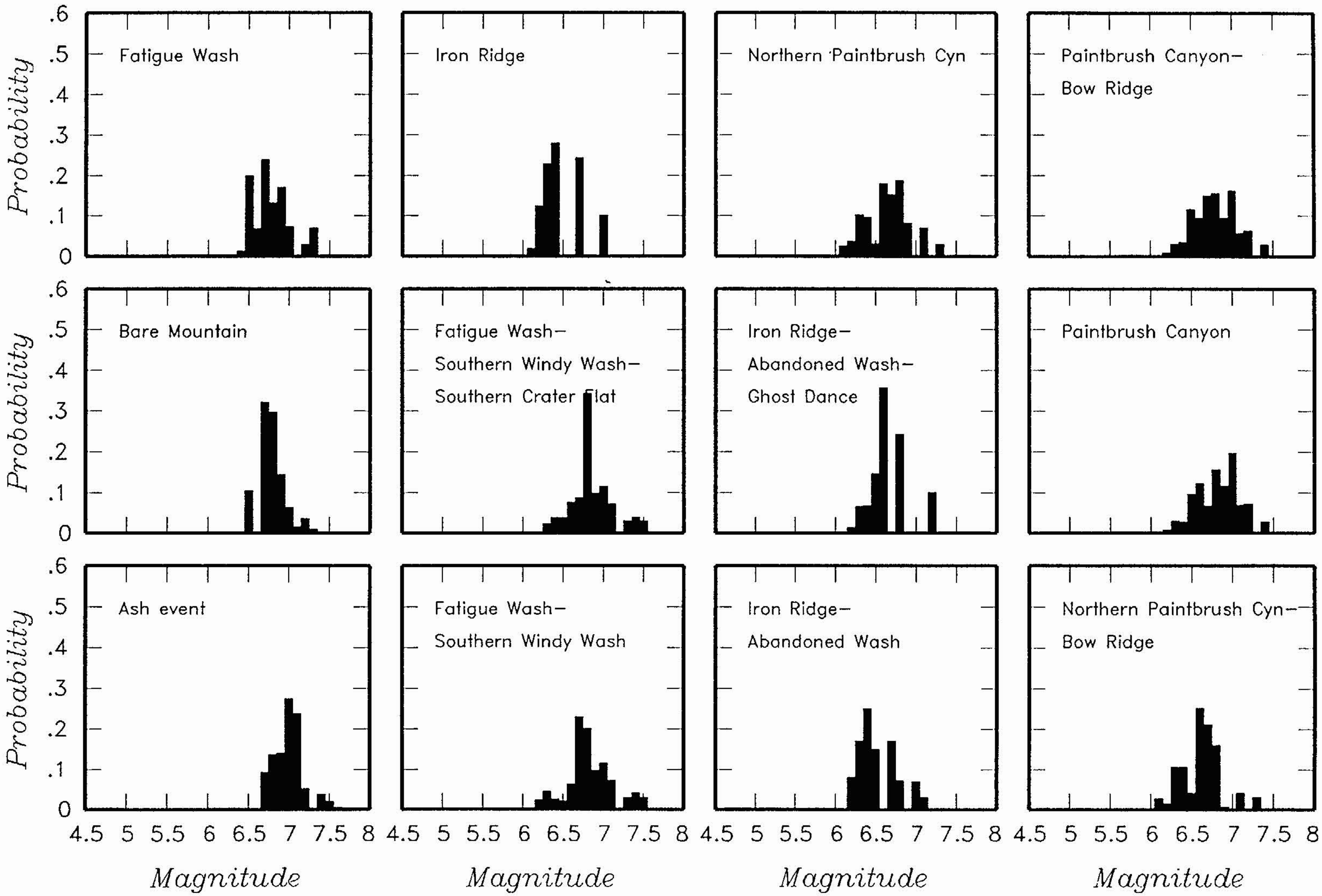


Figure 4-66 Maximum magnitude distributions for SDO team's local fault sources

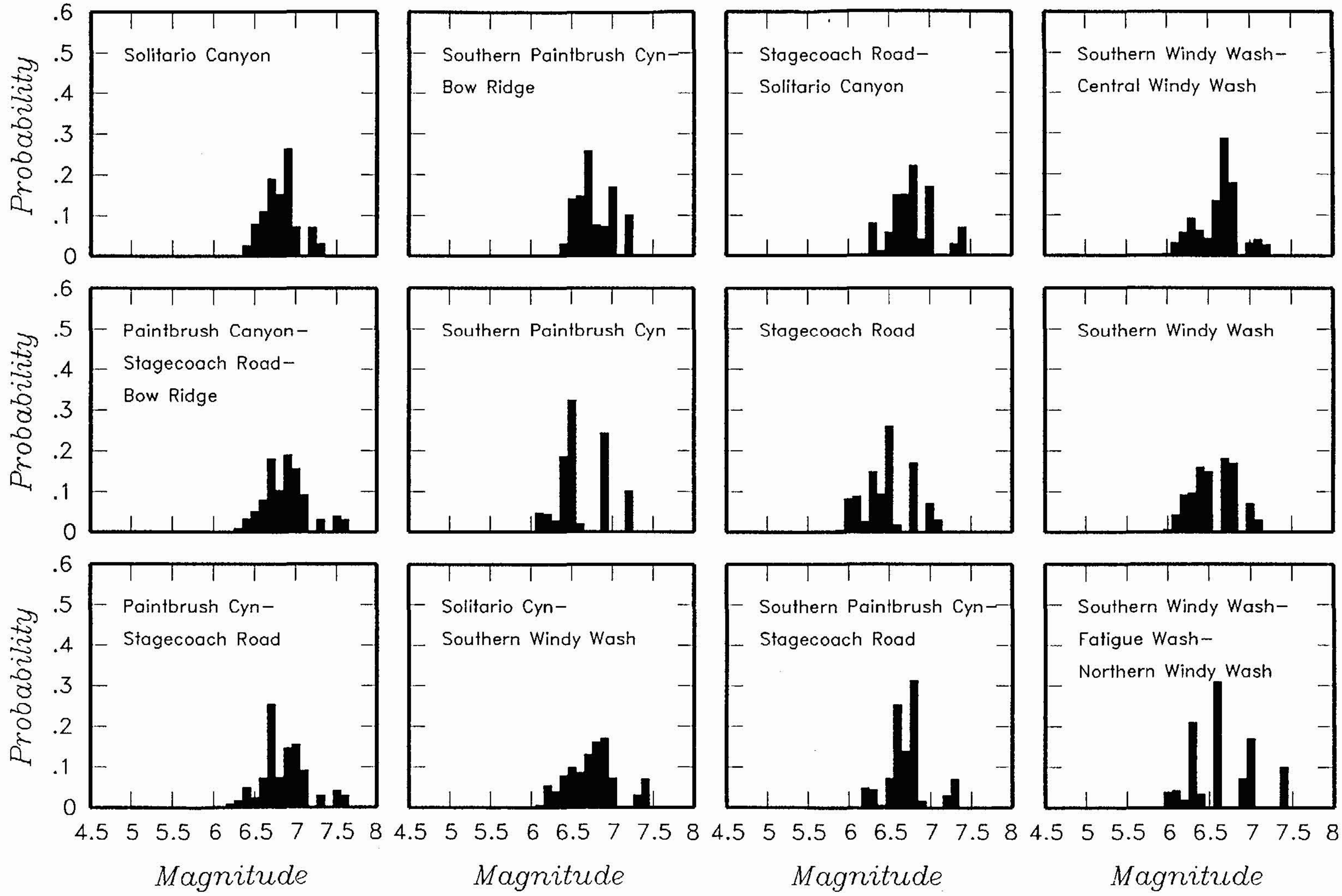


Figure 4-66 (Cont'd.) Maximum magnitude distributions for SDO team's local fault sources

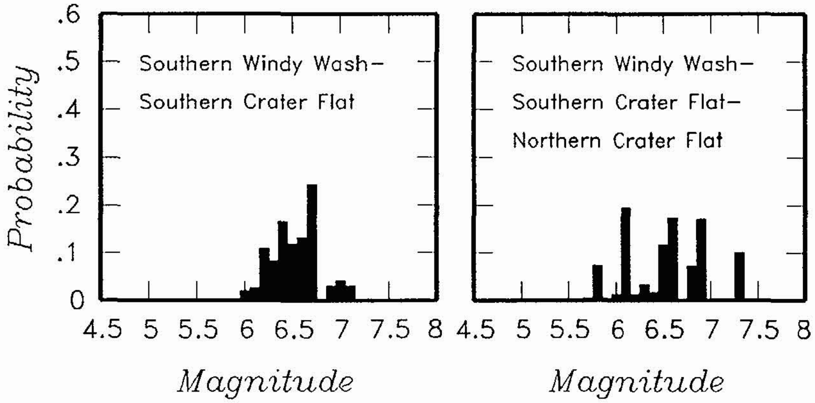
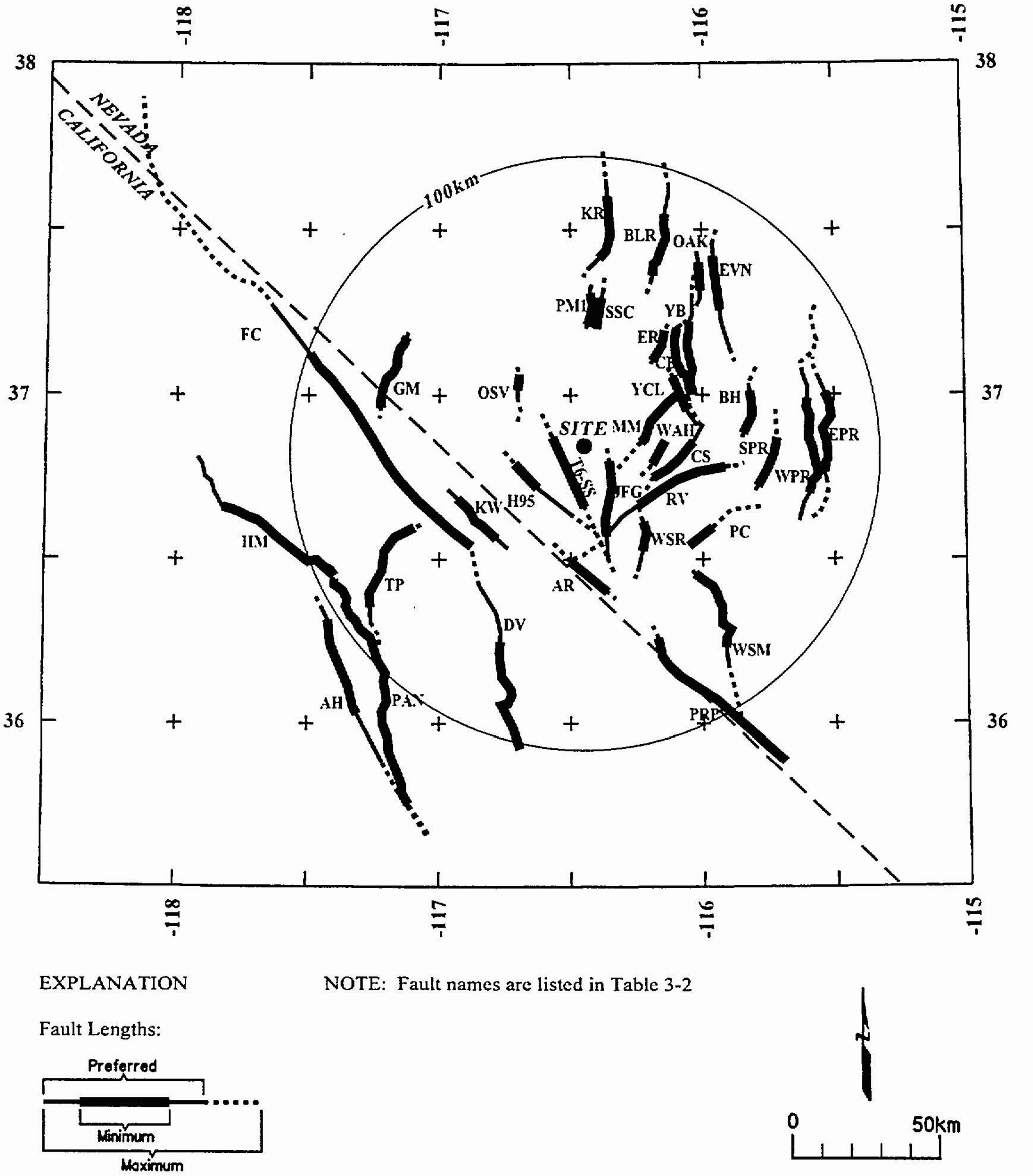


Figure 4-66 (Cont'd.) Maximum magnitude distributions for SDO team's local fault sources



NOTE: Fault names are listed in Table 3-2

Figure 4-67 Regional fault sources considered by the SDO team

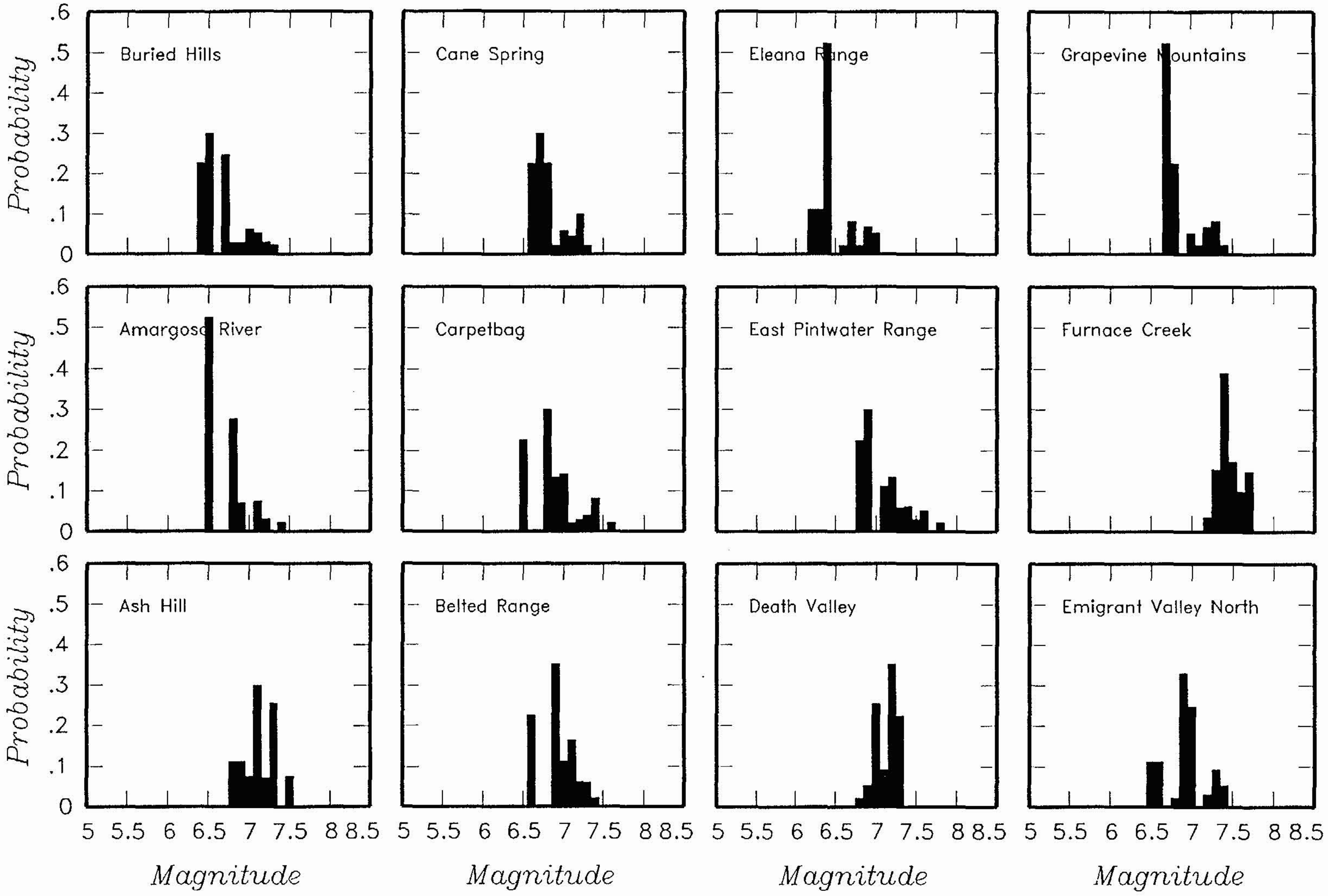


Figure 4-68 Maximum magnitude distributions for SDO team's regional fault sources

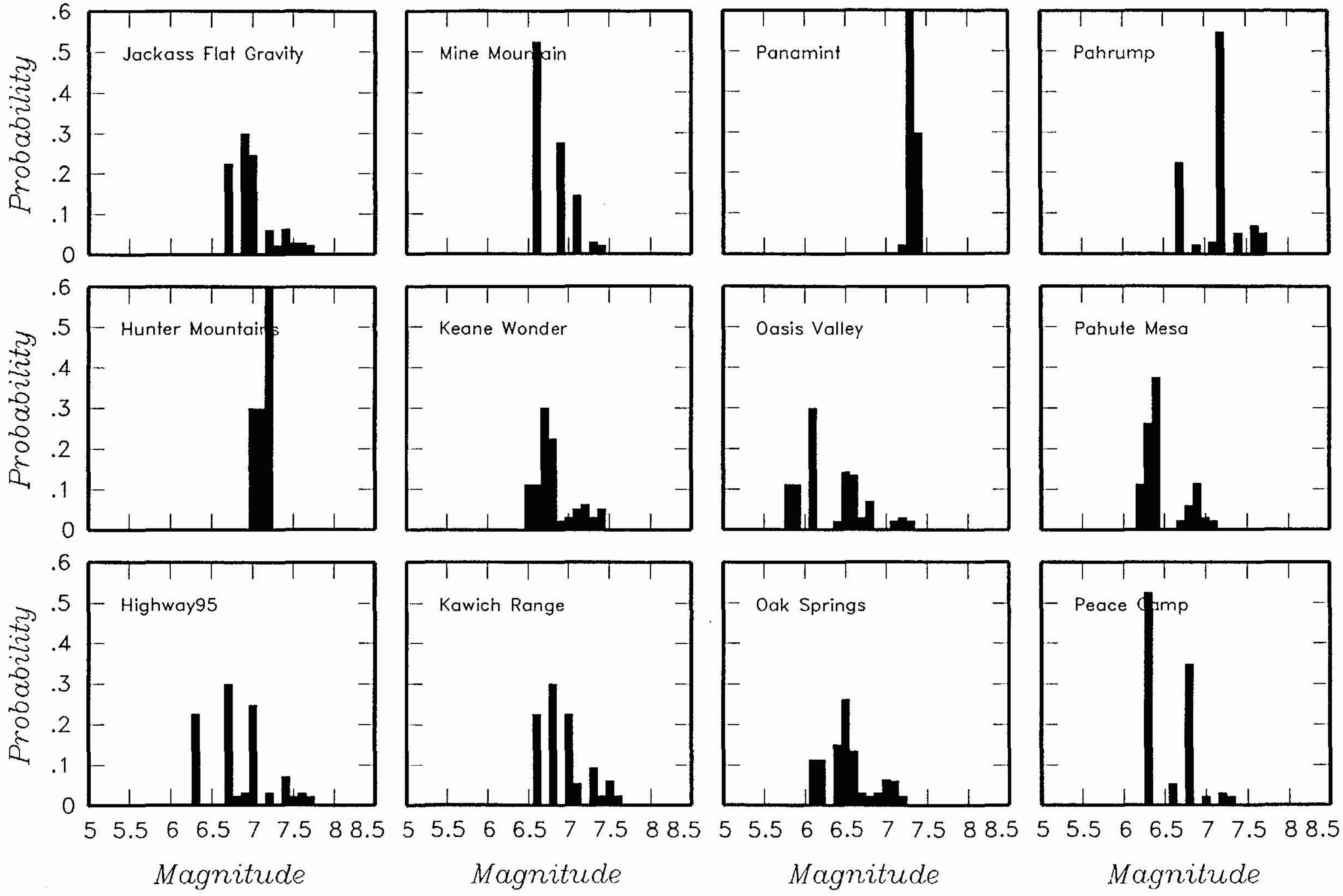


Figure 4-68 (Cont'd.) Maximum magnitude distributions for SDO team's regional fault sources

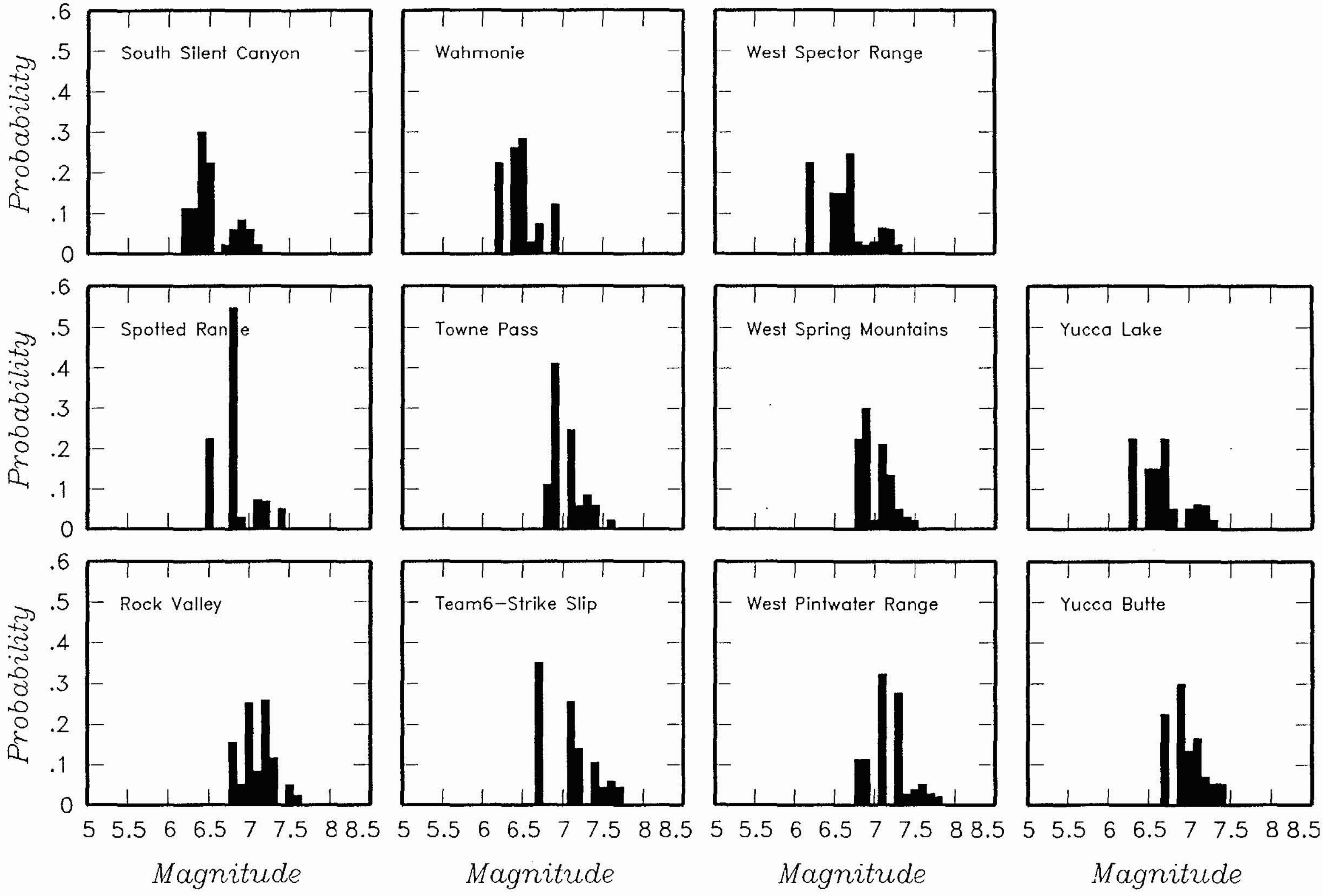


Figure 4-68 (Cont'd.) Maximum magnitude distributions for SDO team's regional fault sources

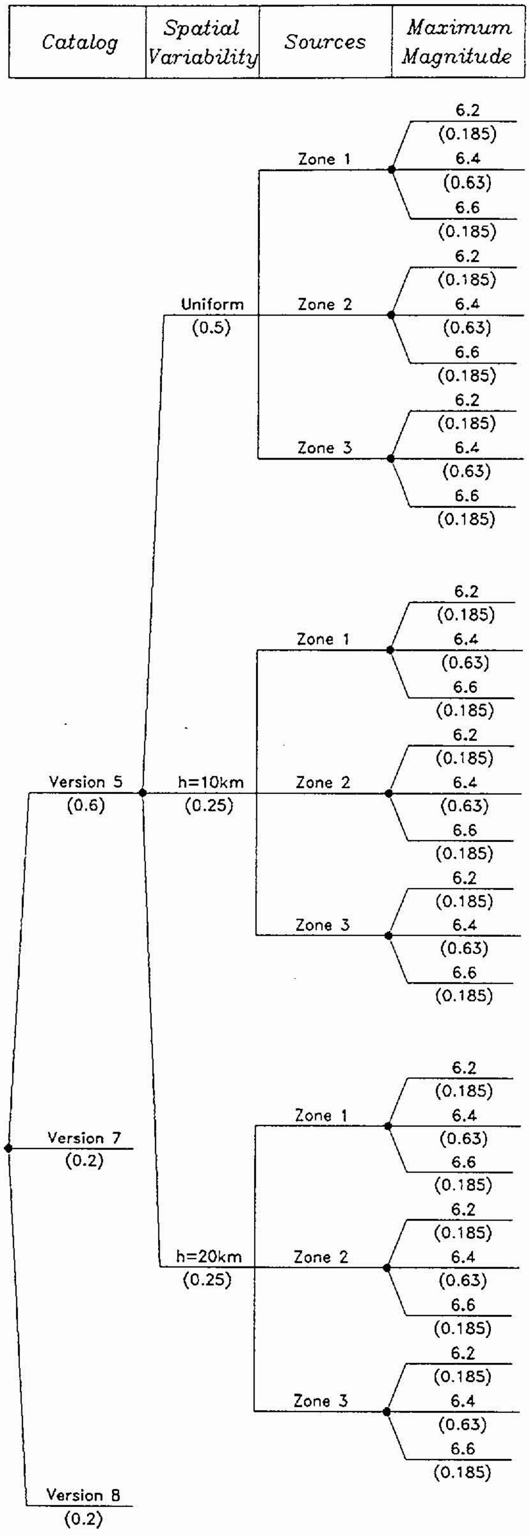


Figure 4-69 Logic tree for regional source zones developed by the SDO team

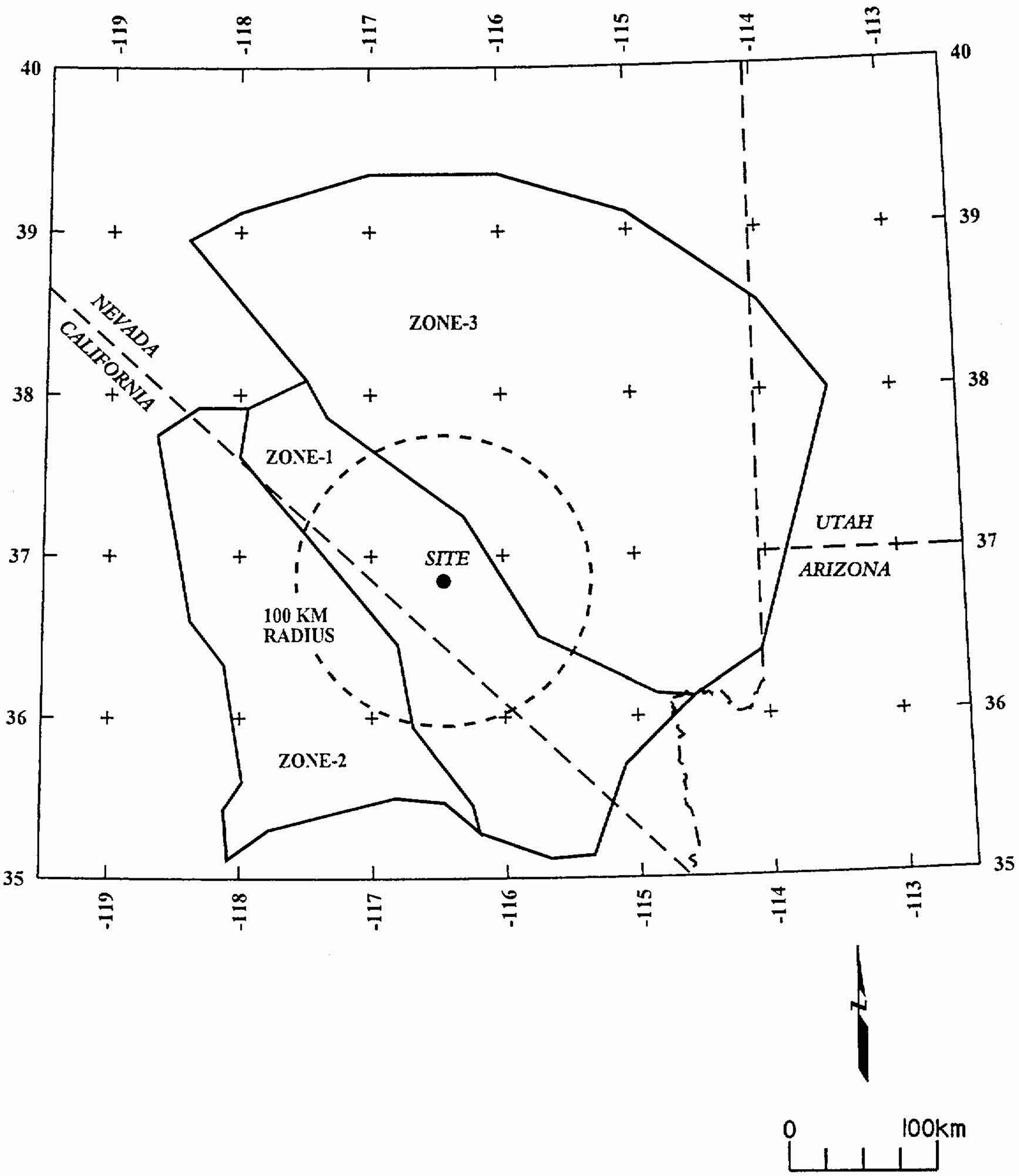


Figure 4-70 Alternative regional source zone models considered by the SDO team

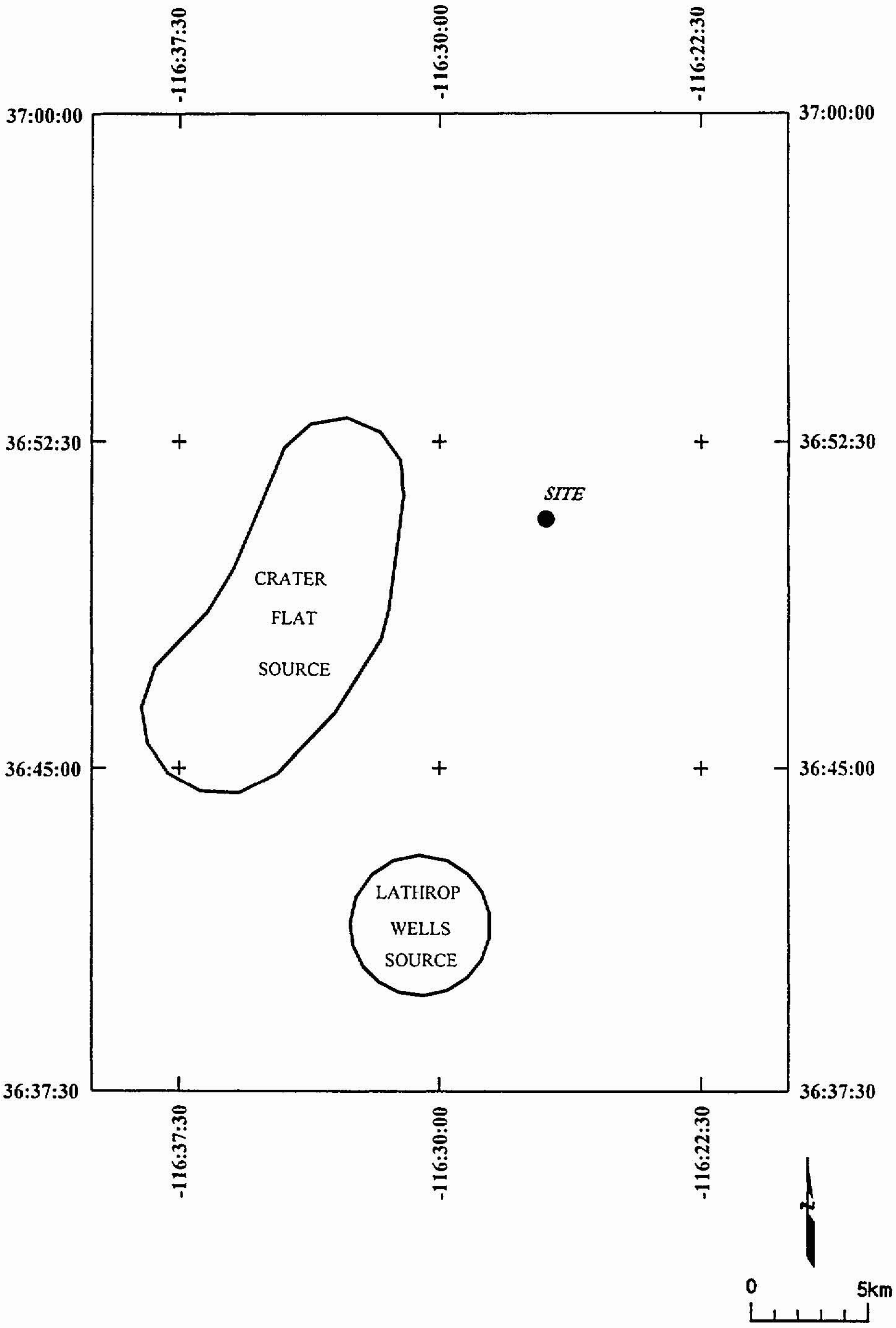


Figure 4-71 Volcanic source zones considered by the SDO team

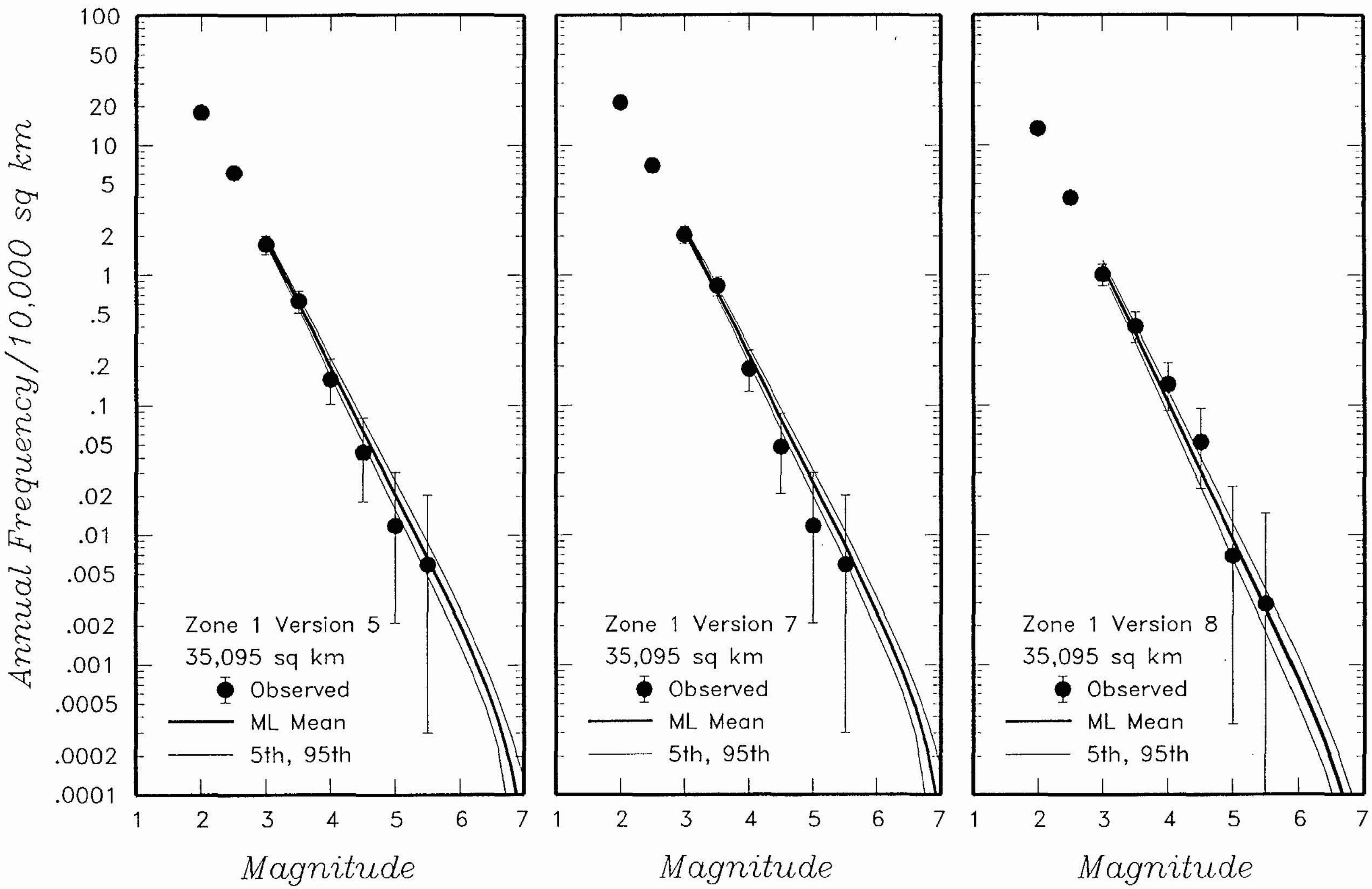


Figure 4-72 Earthquake recurrence relationships for the regional source zones defined by the SDO team. The solid dots with vertical error bars represent the observed data. The thick and thin solid curves are the mean, 5th, and 95th percentiles of the recurrence rates based on the uncertainty in recurrence parameters and maximum magnitude.

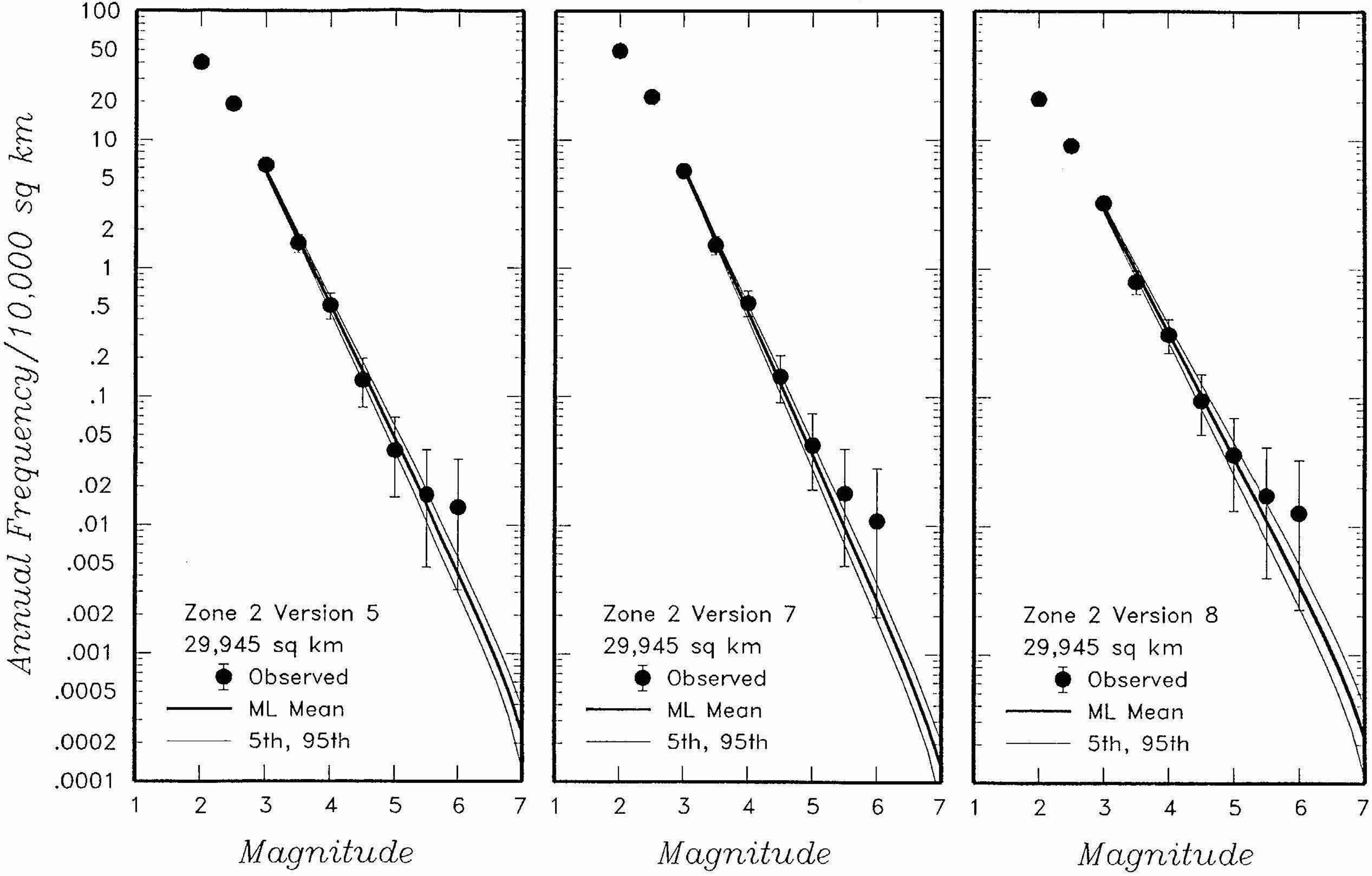


Figure 4-72 (Cont'd.) Earthquake recurrence relationships for the regional source zones defined by the SDO team.

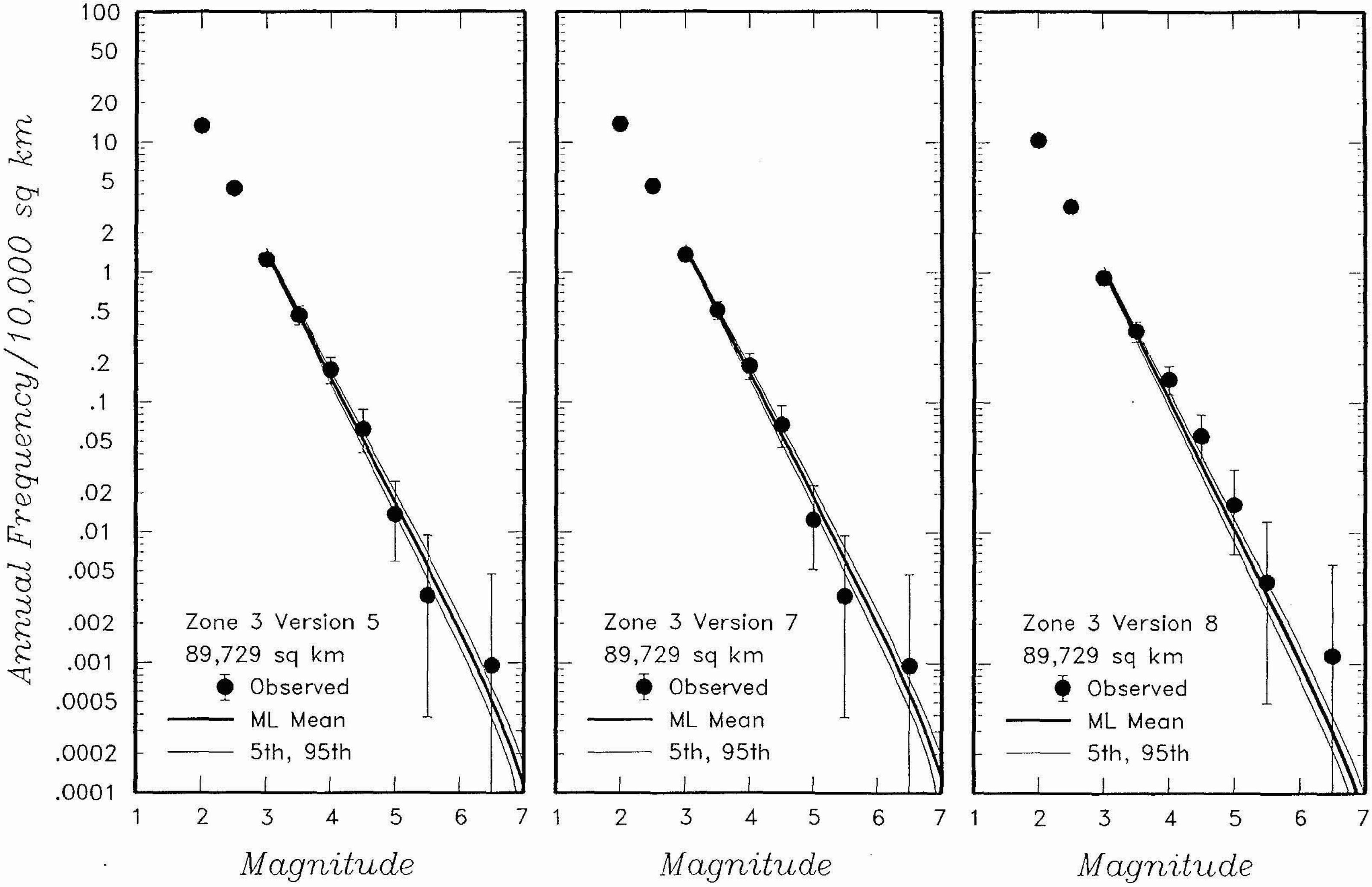


Figure 4-72 (Cont'd.) Earthquake recurrence relationships for the regional source zones defined by the SDO team.

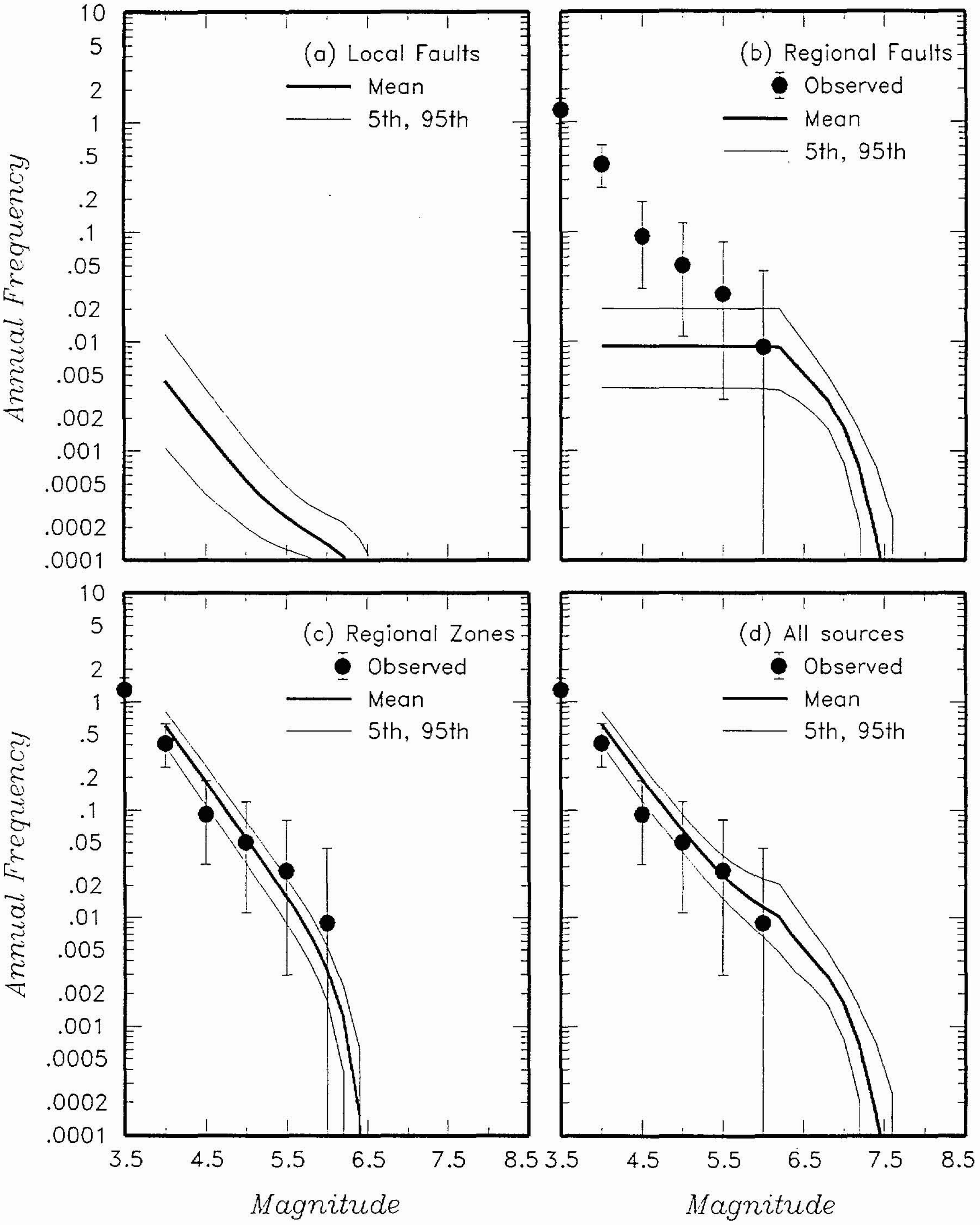


Figure 4-73 Predicted mean, 5th-, and 95th-percentile recurrence rates for (a) local fault sources, (b) regional fault sources, (c) regional source zones, and (d) all sources combined for the SDO team. The solid dots with vertical error bars represent the observed frequency of earthquakes occurring within 100 km of the Yucca Mountain site.

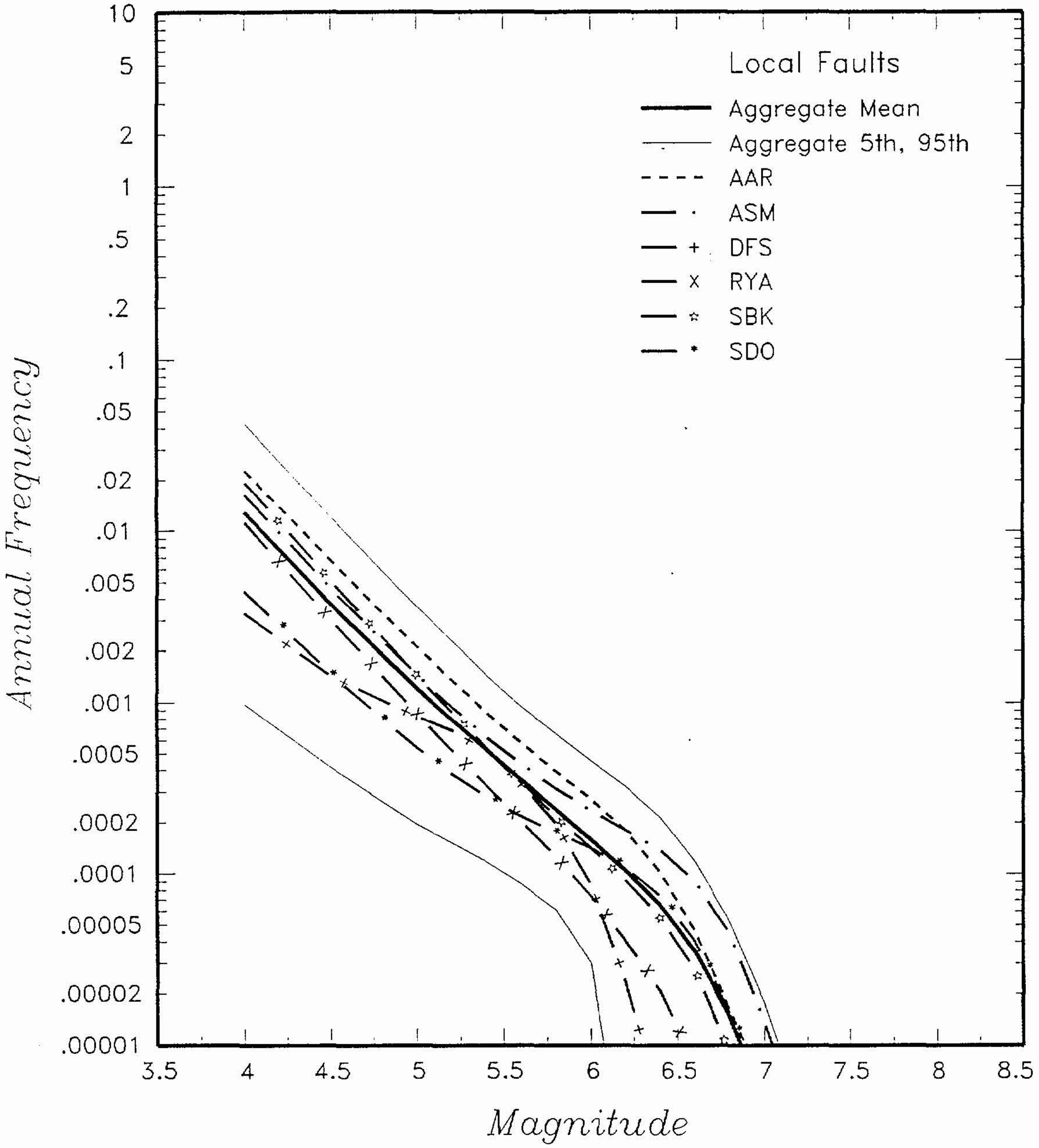


Figure 4-74 Predicted mean, 5th-, and 95th-percentile recurrence rates for local fault sources for all teams combined compared to mean recurrence estimates for individual team.

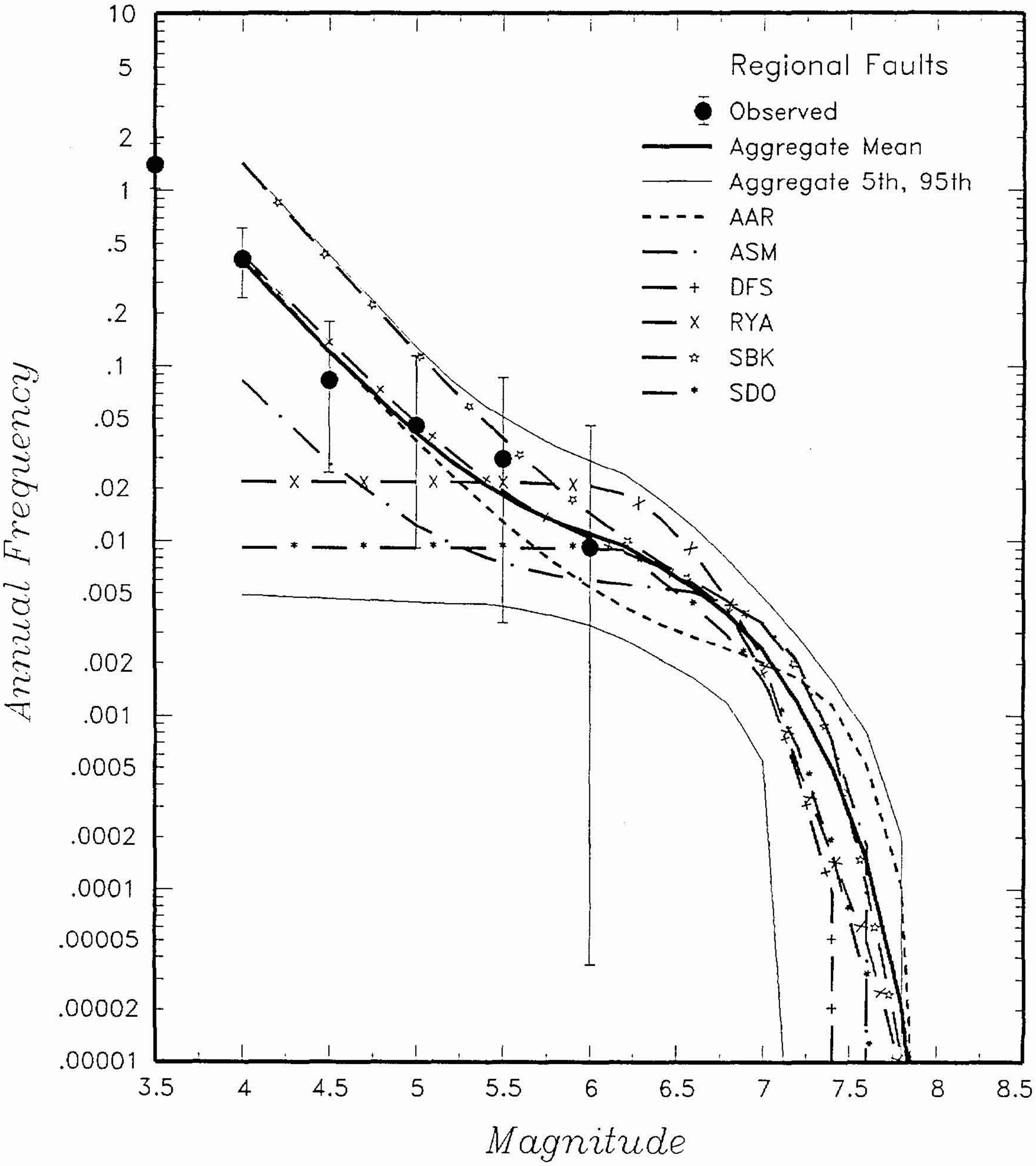


Figure 4-75 Predicted mean, 5th-, and 95th-percentile recurrence rates for regional fault sources for all teams combined compared to mean recurrence estimates for individual teams. The solid dots with vertical error bars represent the observed frequency of earthquakes occurring within 100 km of the Yucca Mountain site.

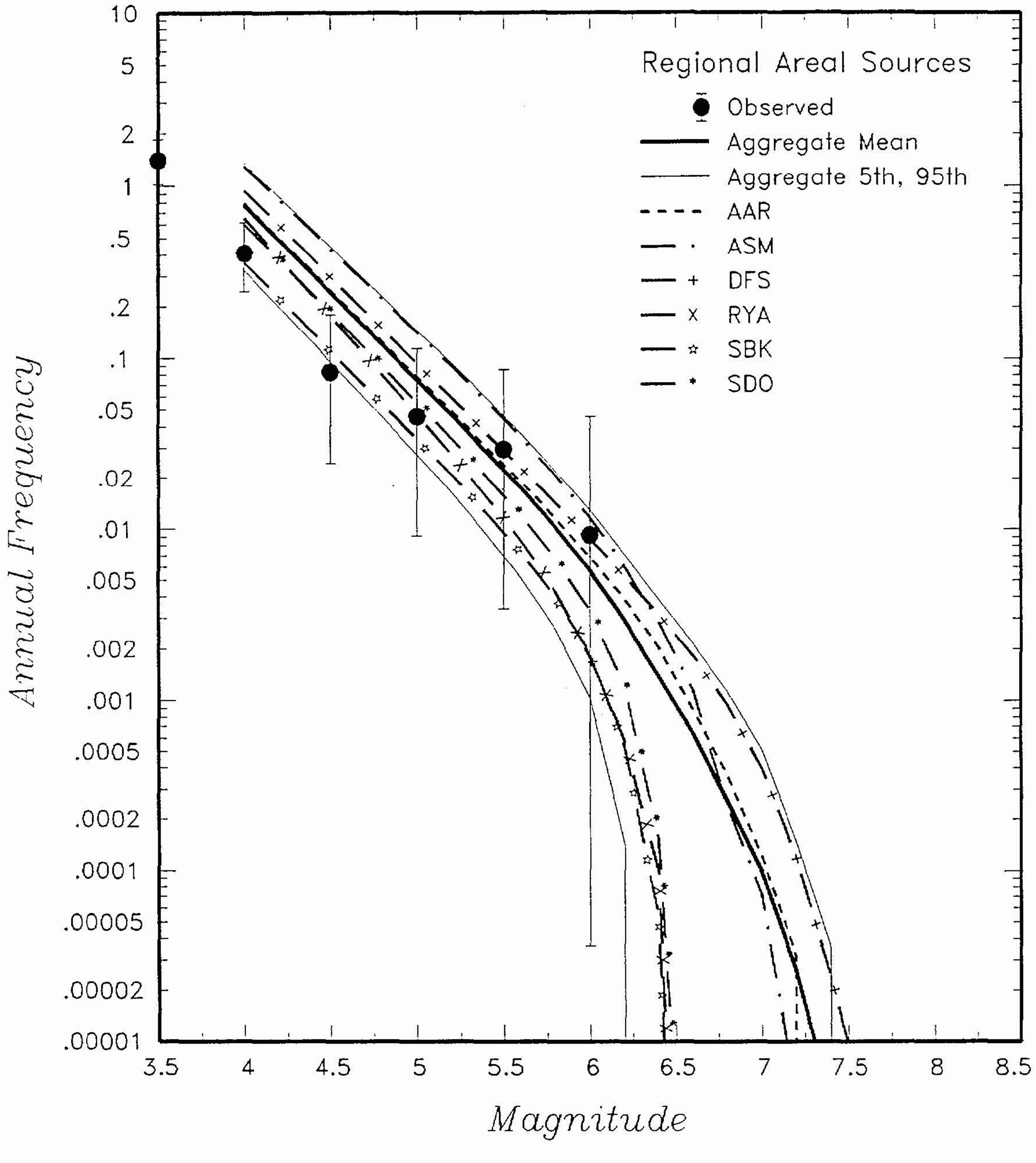


Figure 4-76 Predicted mean, 5th-, and 95th-percentile recurrence rates for regional source zones for all teams combined compared to mean recurrence estimates for individual team. The solid dots with vertical error bars represent the observed frequency of earthquakes occurring within 100 km of the Yucca Mountain site.

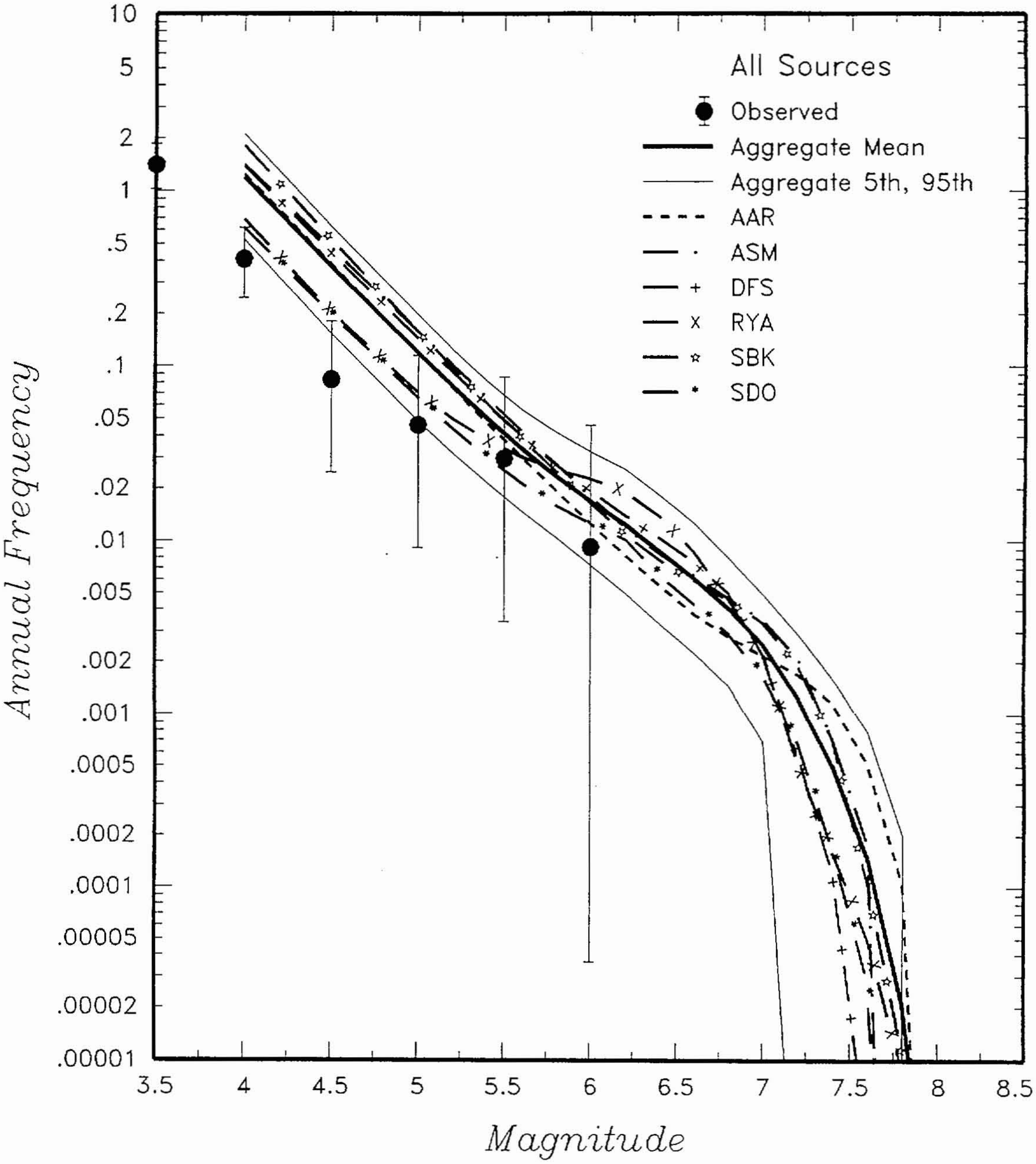


Figure 4-77. Predicted mean, 5th-, and 95th-percentile recurrence rates for all sources combined for all teams combined compared to mean recurrence estimates for individual team. The solid dots with vertical error bars represent the observed frequency of earthquakes occurring within 100 km of the Yucca Mountain site.

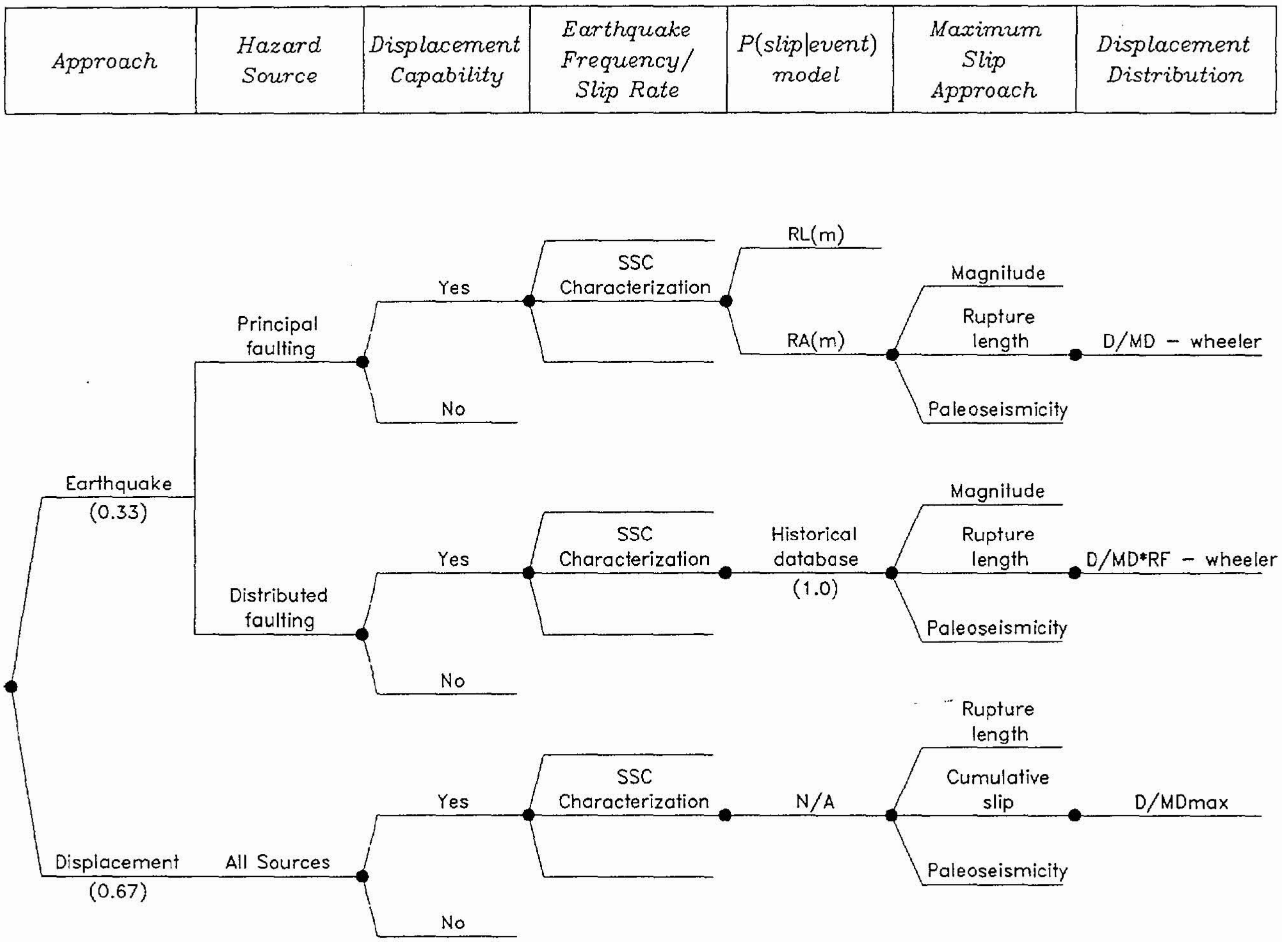


Figure 4-78 Logic tree defining the AAR team's characterization of displacement hazard at sites subject to principal faulting

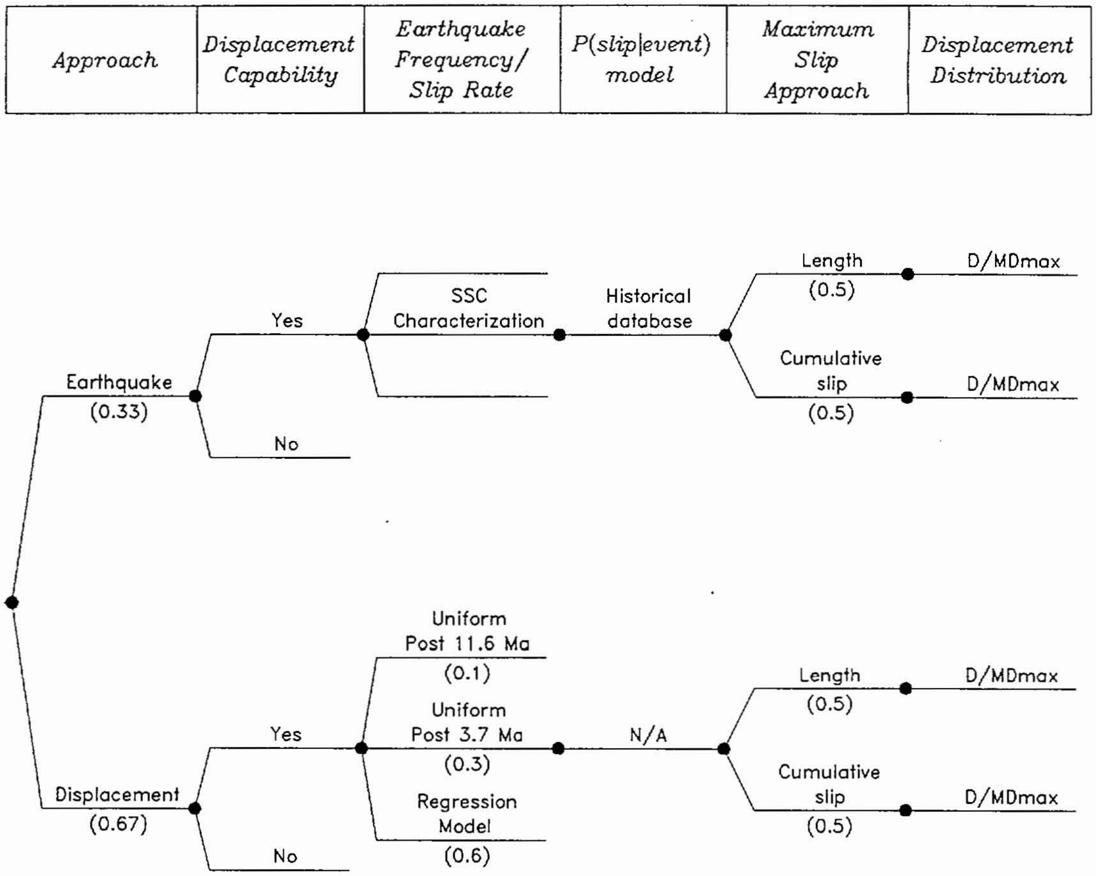


Figure 4-79 Logic tree defining the AAR team's characterization of displacement hazard at sites subject to distributed faulting

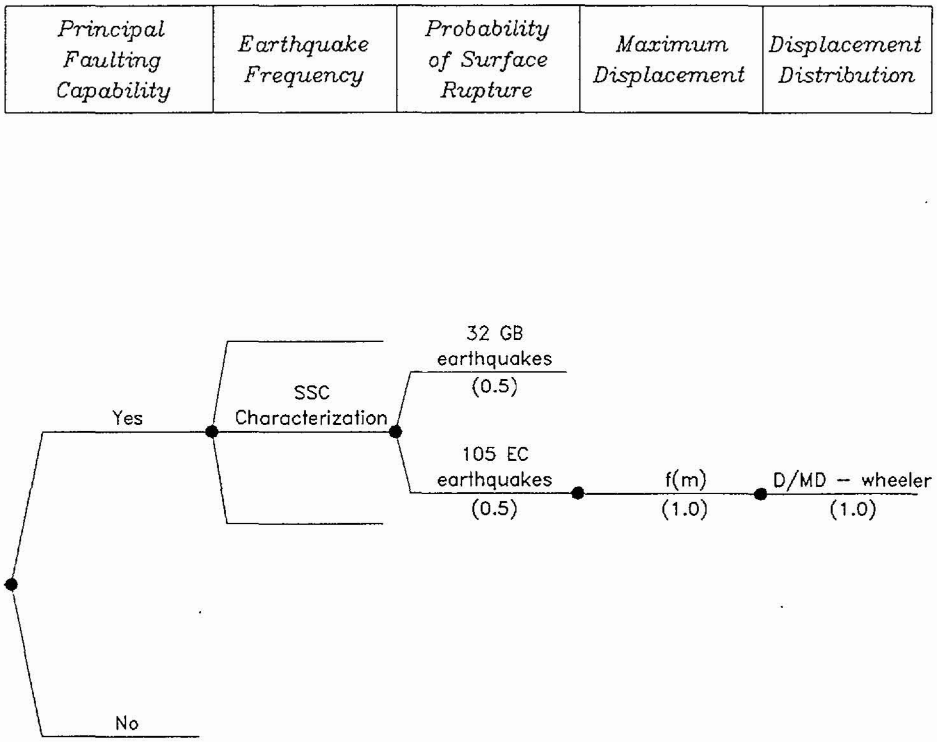


Figure 4-80 Logic tree defining the ASM team's characterization of principal faulting displacement hazard

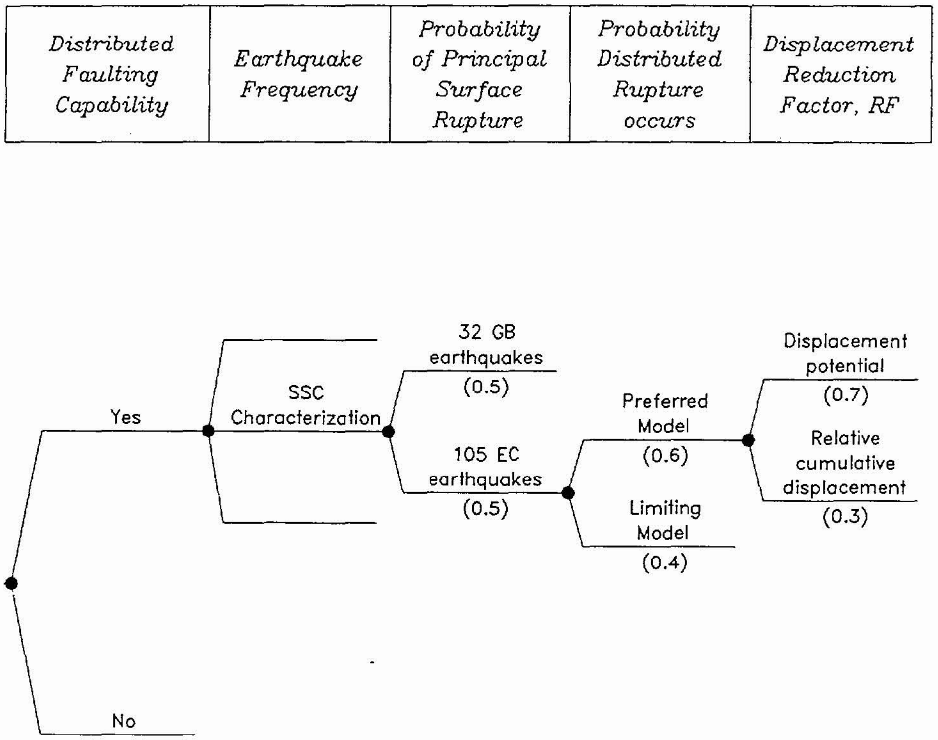


Figure 4-81 Logic tree defining the ASM team's characterization of distributed faulting displacement hazard

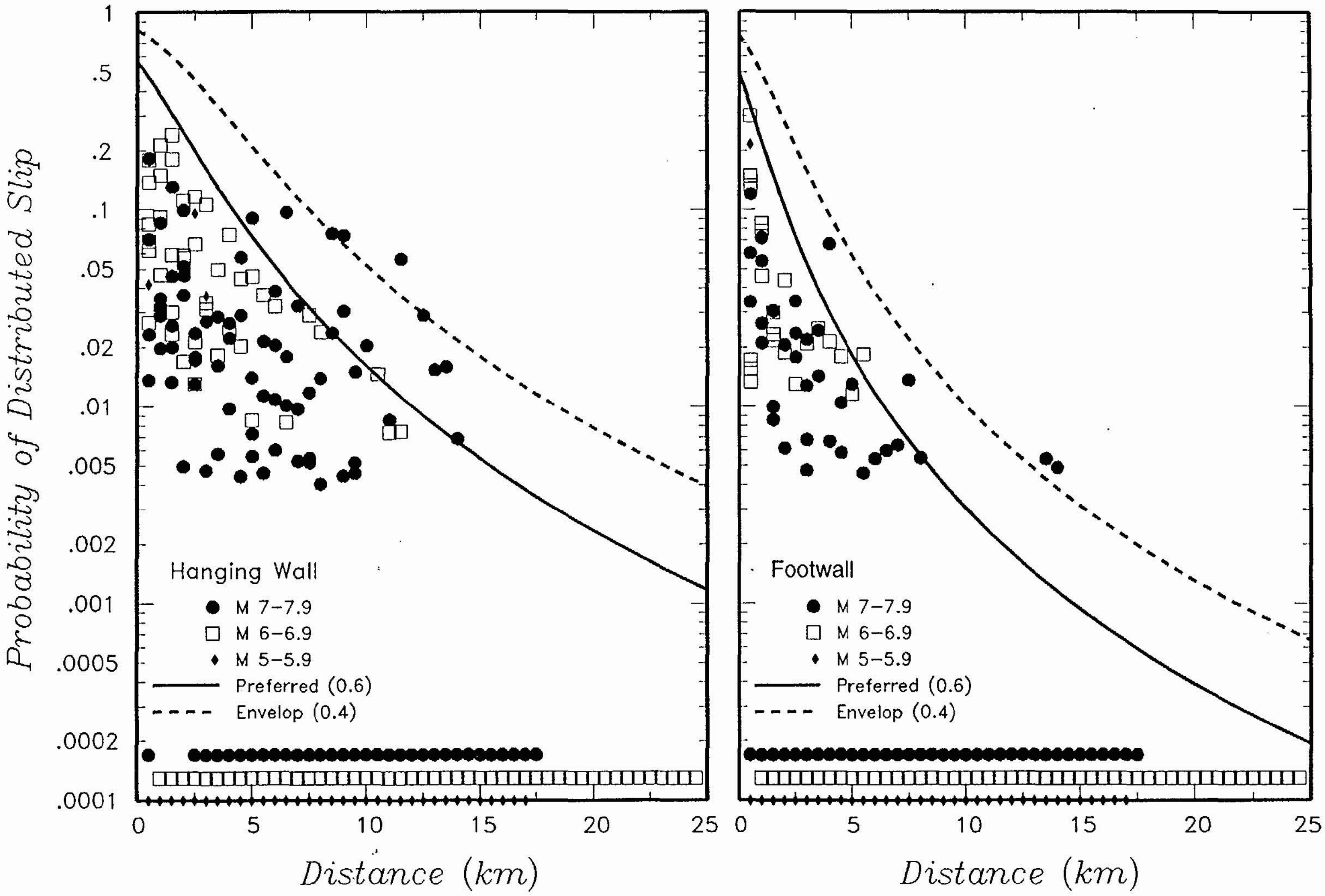


Figure 4-82 Probability of distributed rupture as a function of distance from the principal rupture defined by the ASM team. Data are the same as those presented on Figure H-13b

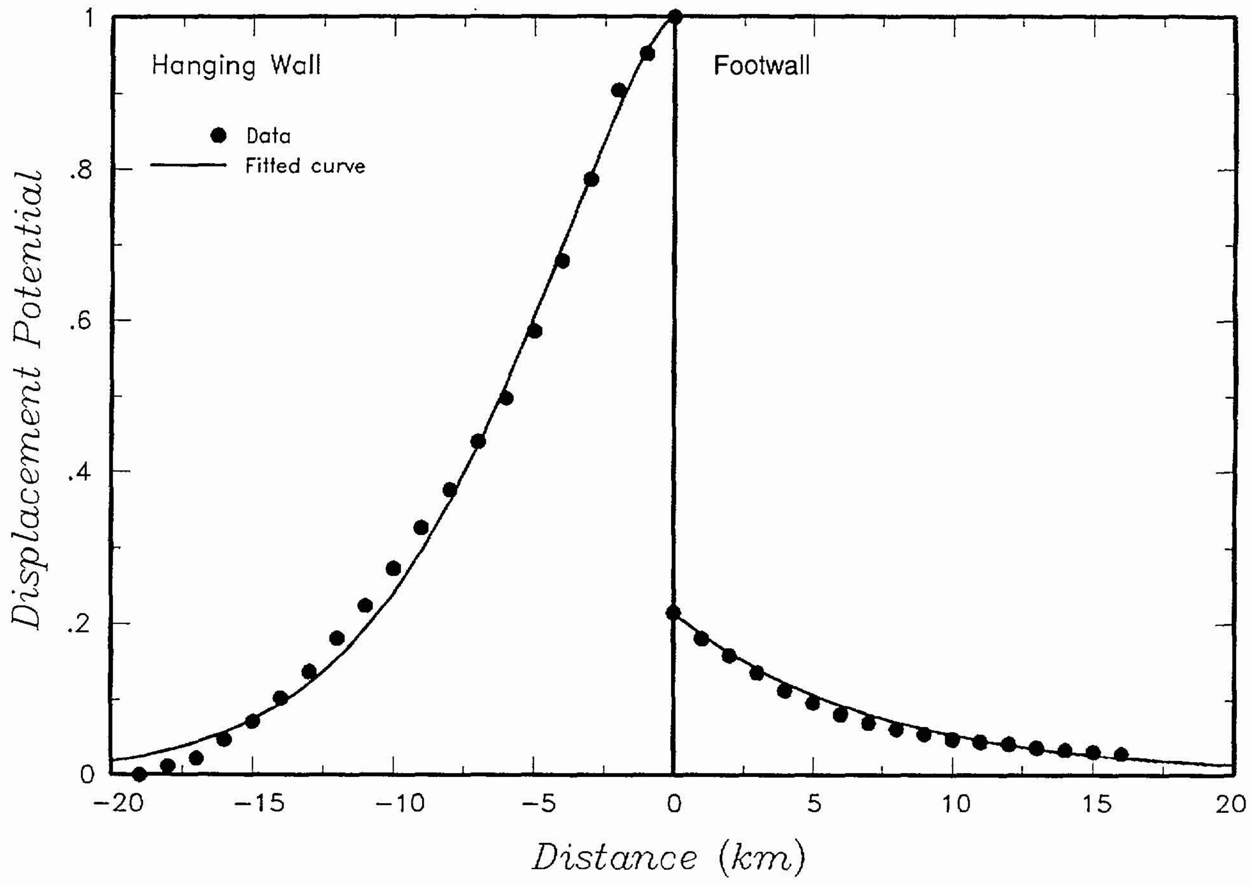


Figure 4-83 Normalized displacement profile for the 1983 Borah Peak, Idaho earthquake used by the ASM team to define the distributed faulting displacement potential

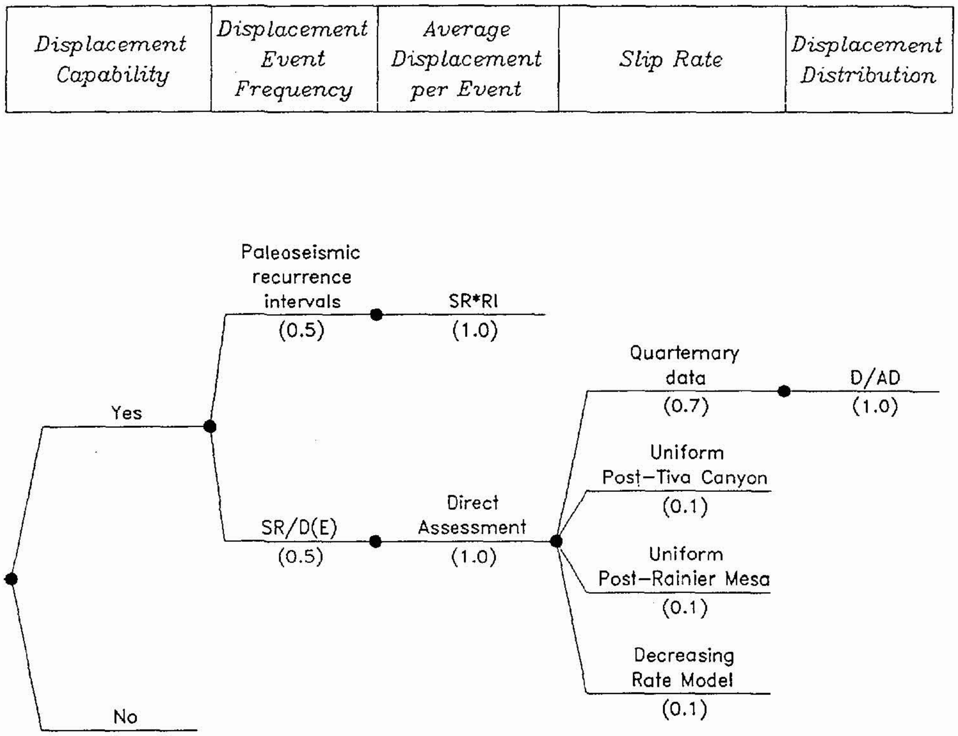


Figure 4-84 Logic tree defining the DFS team's characterization of displacement hazard

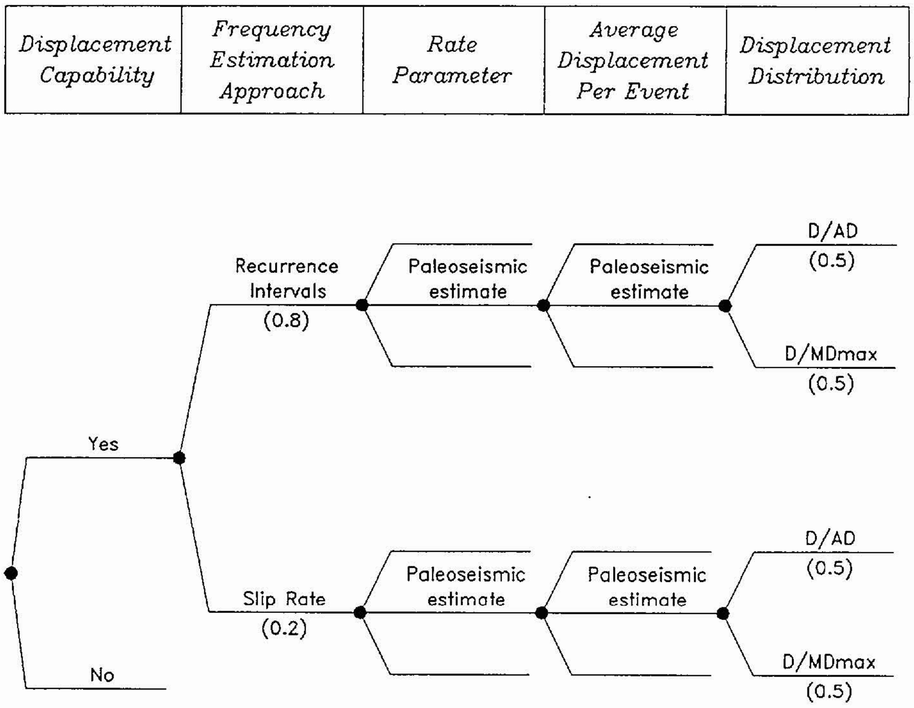


Figure 4-85 Logic tree defining the RYA team's characterization of displacement hazard at sites with Quaternary data for fault displacement

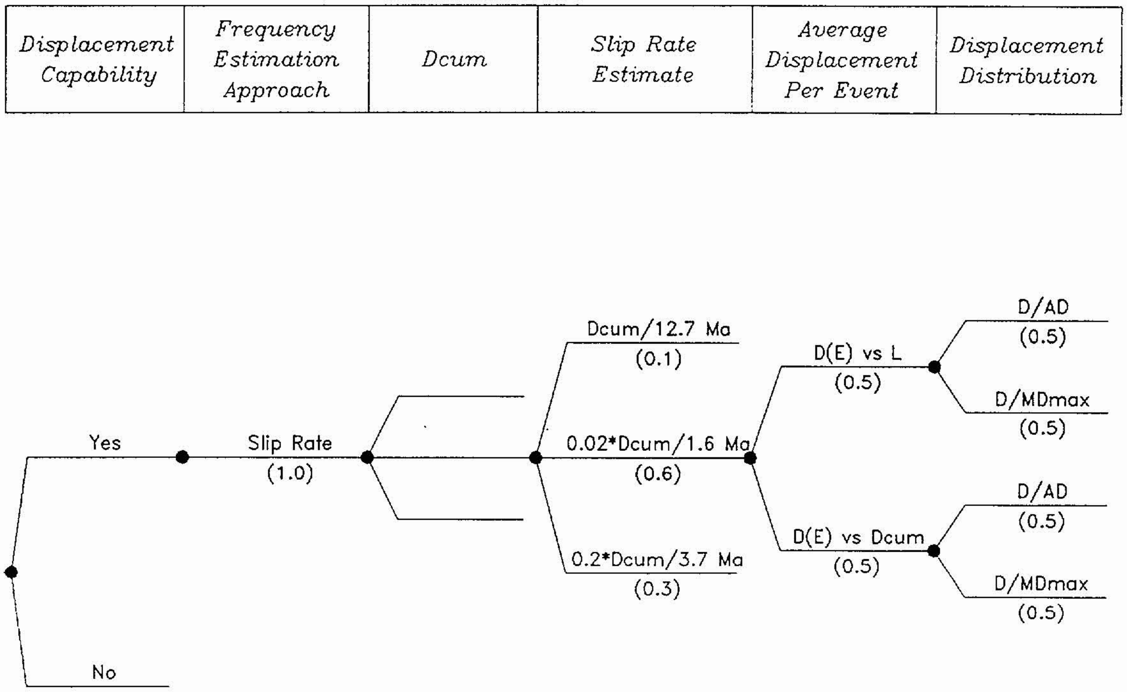


Figure 4-86 Logic tree defining the RYA team's characterization of displacement hazard at sites without Quaternary data for fault displacement

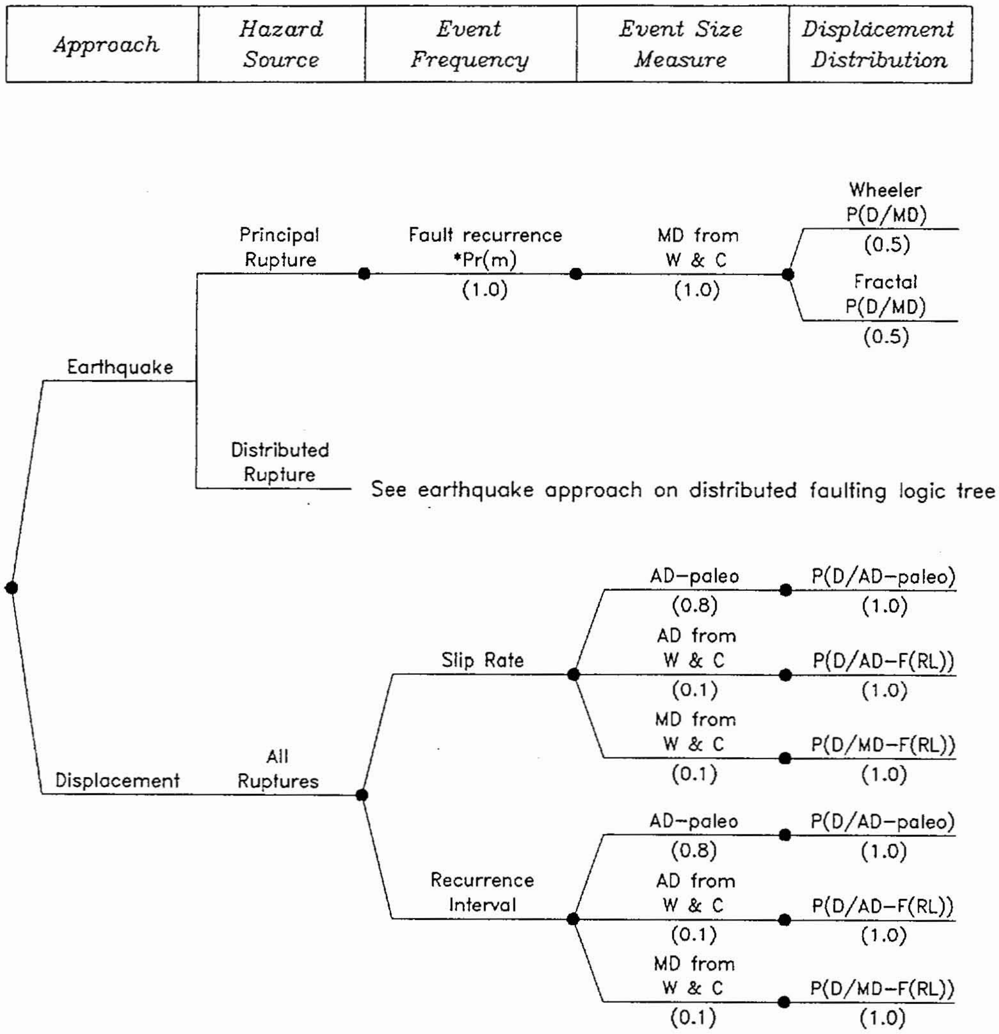


Figure 4-87 Logic tree defining the SBK team's characterization of principal faulting displacement hazard

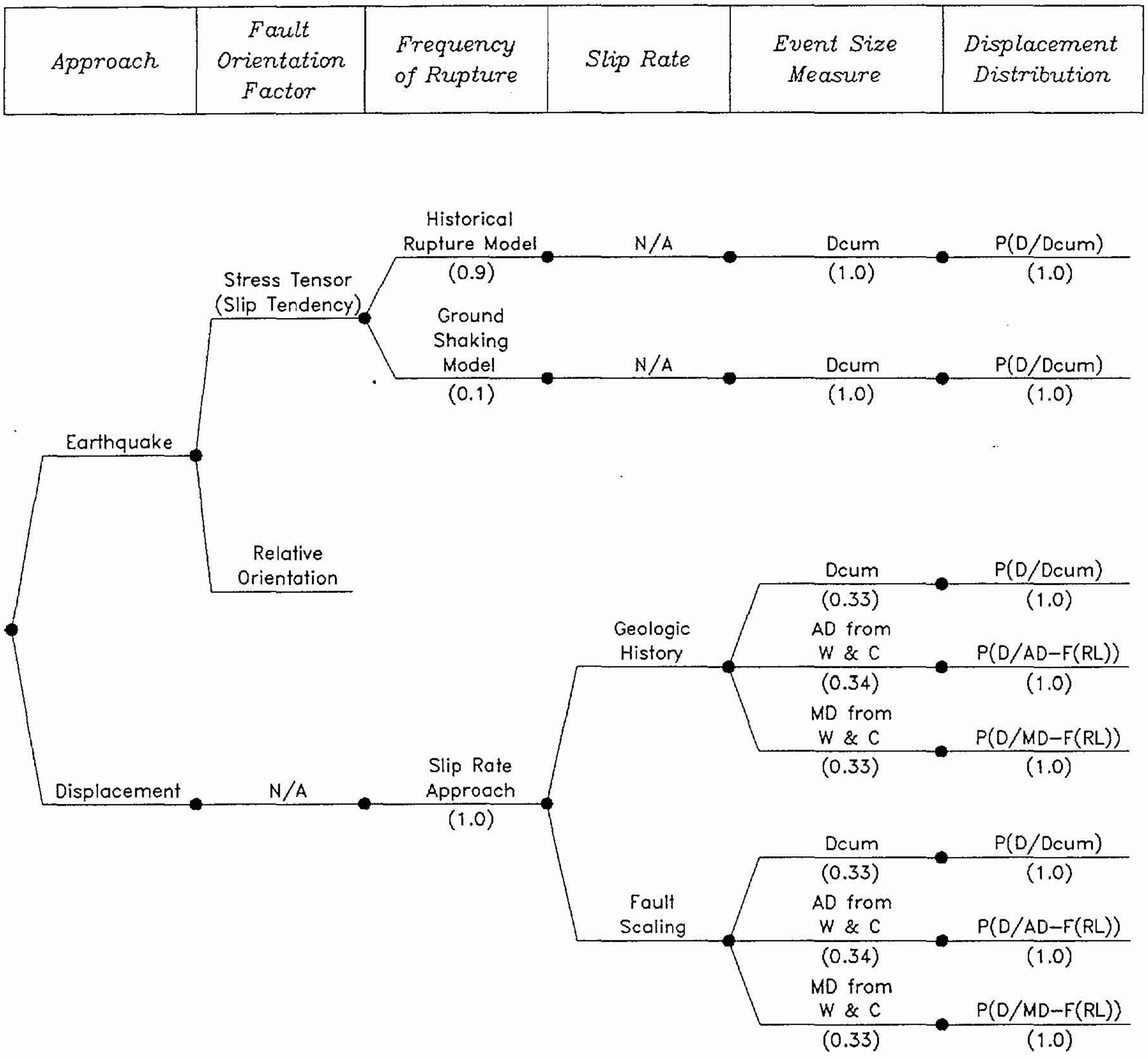


Figure 4-88 Logic tree defining the SBK team's characterization of distributed faulting displacement hazard

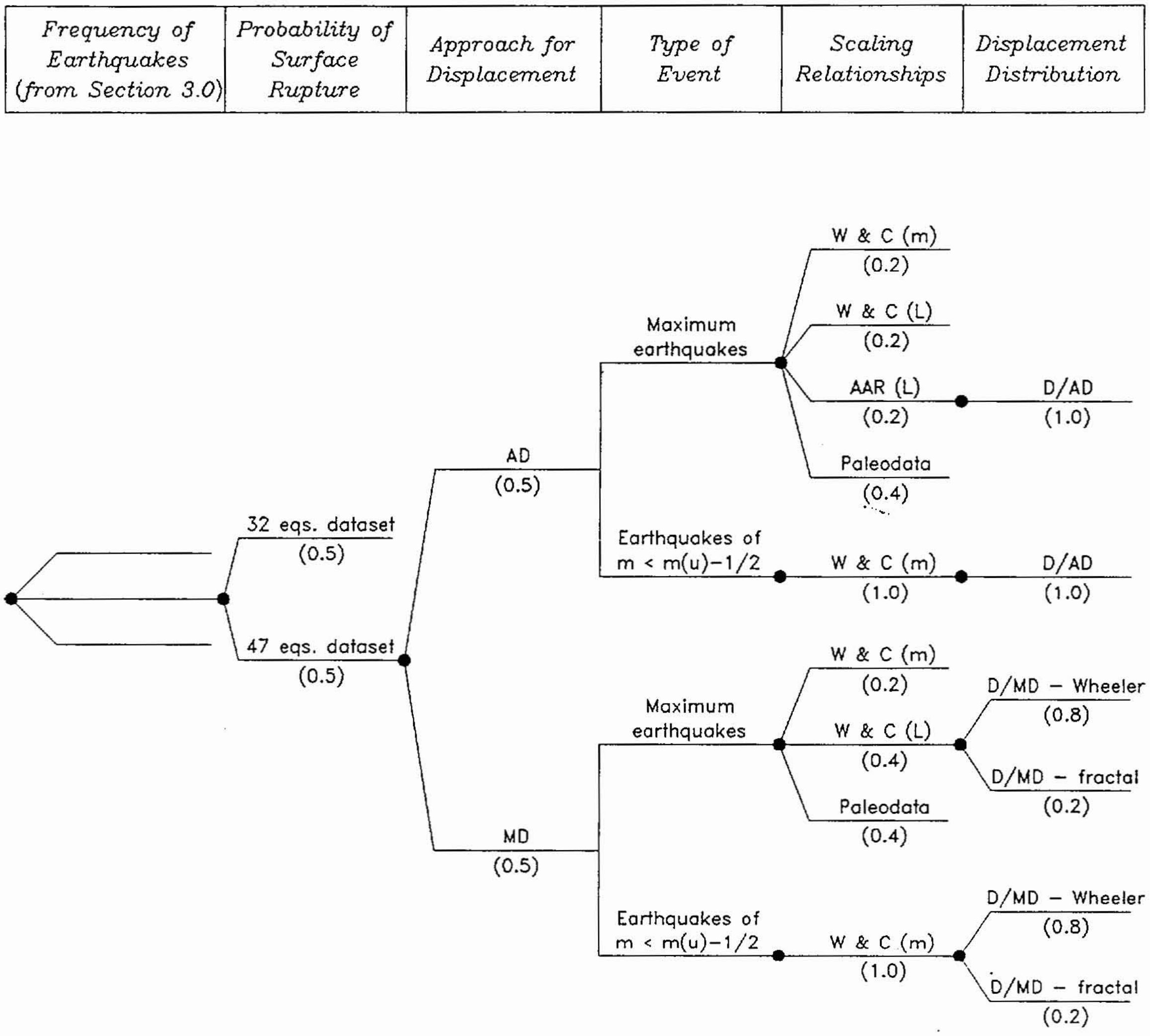


Figure 4-89 Logic tree defining the SDO team's characterization of principal faulting displacement hazard

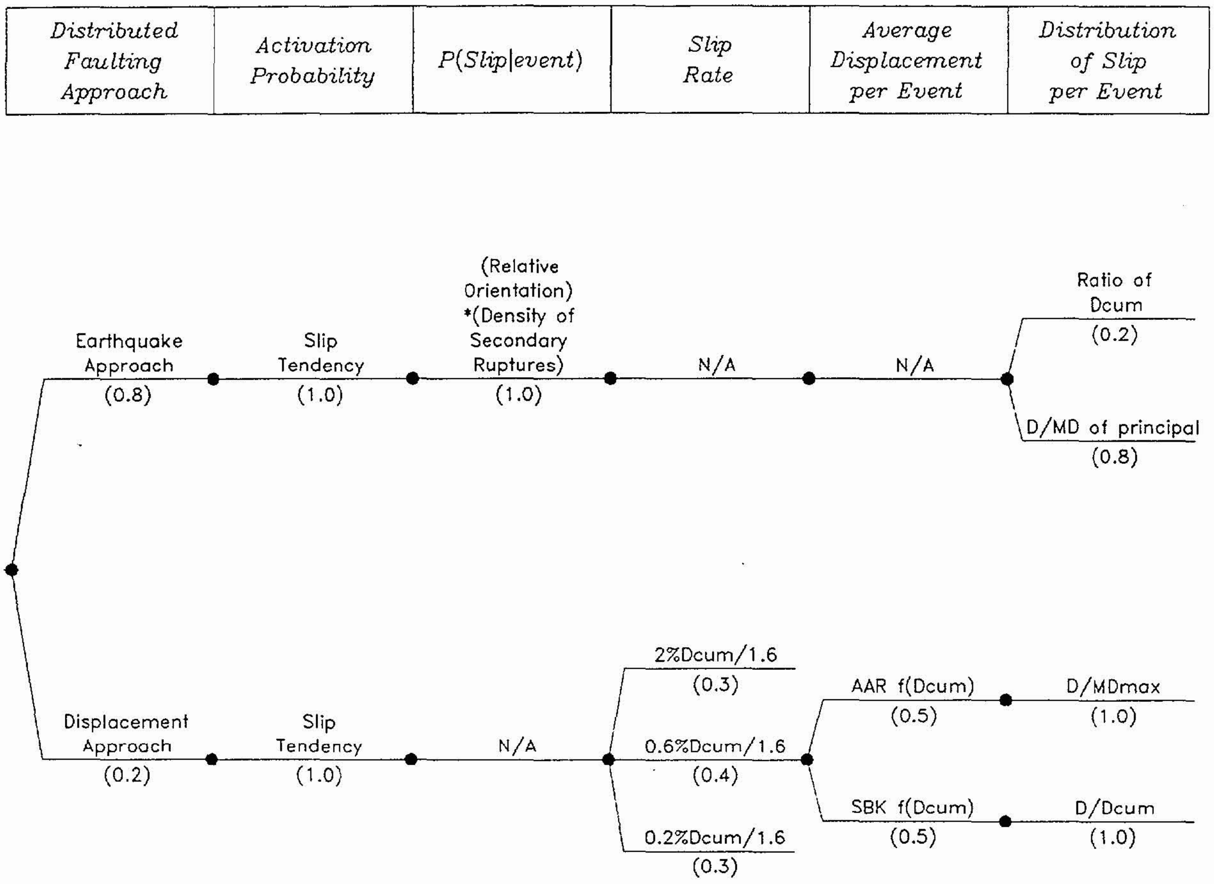


Figure 4-90 Logic tree defining the SDO team's characterization of distributed faulting displacement hazard

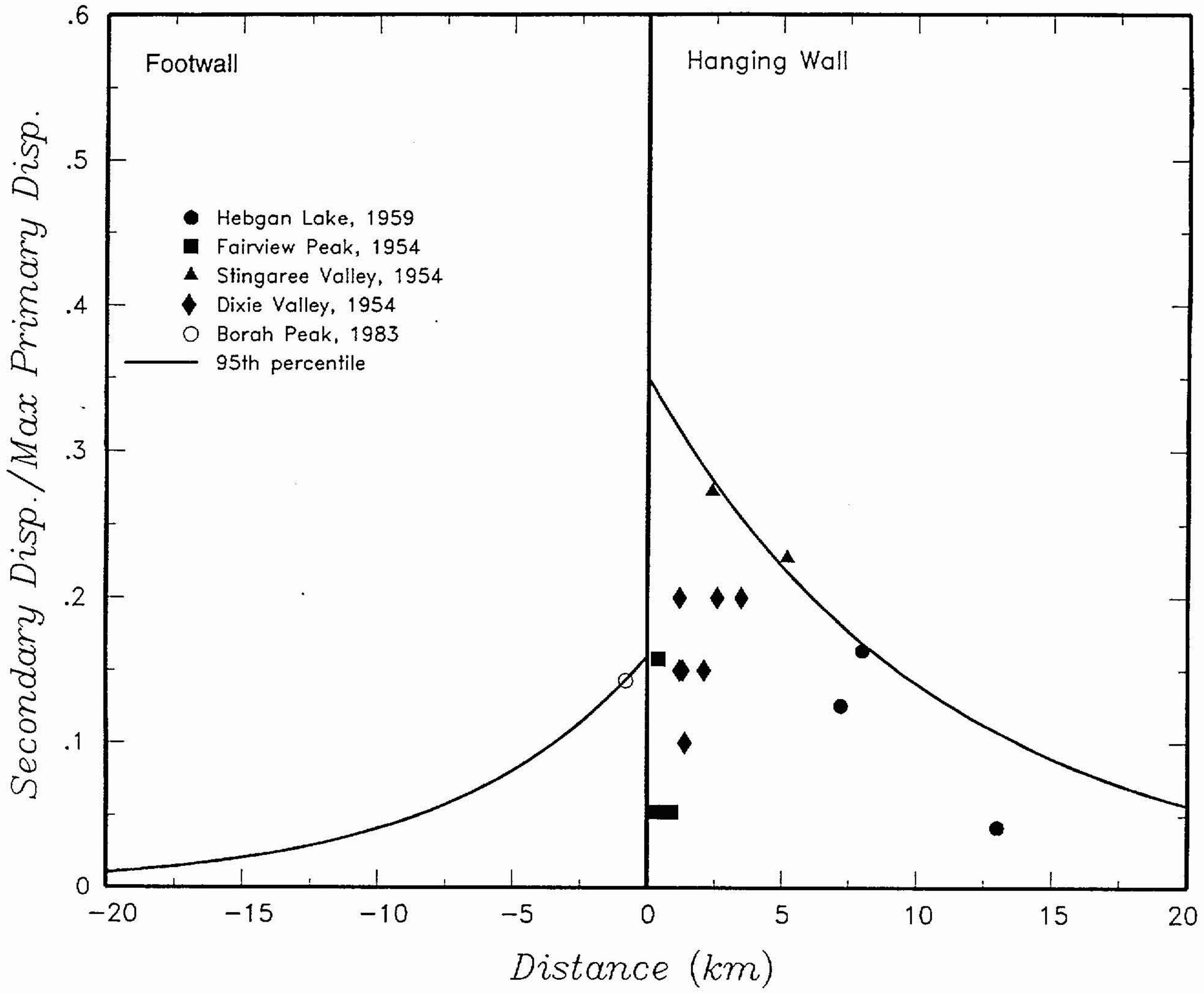


Figure 4-91 Curve defining the 95th percentile of the distribution for displacement on a distributed rupture developed by the SDO team

5.0
GROUND MOTION CHARACTERIZATION FACILITATION APPROACH

The goal of the ground motion characterization was to formulate vibratory ground motion models for input into the PSHA. The description of ground motion in this context consists of ground motion attenuation relations specific to the repository site. The ground motion study has been structured to incorporate the uncertainty in the science of ground motion estimation. A ground motion evaluation necessarily involves interpreting data, existing predictive models, and geologic and geophysical characteristics of Yucca Mountain. These data and the process by which they are synthesized into a predictive model have associated uncertainties. Therefore, fully evaluating uncertainty is an essential element of a comprehensive study. In this chapter, the approach utilized by the GM Facilitation Team to elicit interpretations from the GM experts as well as the experts' methodologies are described.

5.1 EXPERT ELICITATION PROCESS

Development of the expert interpretations was coordinated and facilitated in a series of three technical workshops. Each workshop was designed to accomplish a specific step in the overall process of developing the interpretations in order to ensure that all relevant data and credible interpretations were fully considered by each expert.

The ground motion characterization required coordination with the SSFD Facilitation Team and the PSHA Calculations Team. During the course of the project, the focus of the ground motion activity was tailored to take into account the range of seismic source descriptions identified in that activity. As first envisioned, the relevant sources included normal dip-slip faults and vertical strike-slip faults. Single ruptures of each source were assumed. However, the seismic source characterization activity identified the possibility of multiple ruptures on parallel dipping faults and a possible low-angle detachment surface underlying Yucca Mountain. Consequently, these types of seismic sources were also included in the suite of sources for which ground motion estimates were developed.

Using the various information and data discussed below, the GM experts each developed a series of estimates of ground motion for a defined suite of earthquake magnitudes and distances, fault geometries, and faulting styles. The estimates included the median ground motion and its (aleatory) variability, and the scientific (epistemic) uncertainty on both. These "point estimates" were fitted to yield attenuation equations as a function of all four parameters. The independent variables used in the regression were selected by the expert and the computations were performed by the facilitation team.

Each expert formed his or her interpretations using the information and data presented in three workshops. Additionally, the elicitation process included a formal interview, led by a normative expert, in which each expert presented and defended his or her preliminary point estimates. The facilitator challenged each expert to defend and, as necessary, clarify his or her thought process to ensure that all relevant data and information were evaluated.

As a computational aid, the GM Facilitation Team Leader provided the experts with summaries of proponent model estimates – computed ground motions from numerous empirical attenuation relations and numerical simulations the experts selected for study. All such derivative data are documented in a series of Ground Motion Data Packages, 12 volumes in all. The Data Package volumes are listed in Appendix B.

5.1.1 Compilation and Discussion of Data and Information

To ensure that all experts had equal access to data and information, a key element of the elicitation process was the dissemination of data. Two workshops were organized specifically to facilitate presentation and discussion of the data (Figure 3-1) . Detailed agenda and workshop plans were provided to all participants in advance, copies of all presentation materials were made available during each meeting, and the proceedings were summarized by the GM Facilitation Team. Copies of the workshop summaries are contained in Appendix D.

Workshop #1 - Data Needs held in April 1995 identified the tectonic, geologic, seismologic, and ground motion issues to be evaluated and the primary data sets and derivative products needed to complete the evaluations. This workshop provided the experts a review of the seismologic setting of Yucca Mountain. It allowed the experts to debate the significance of various technical issues and the data and information available to resolve them. As a result, several data needs identified by the experts were subsequently provided in the project.

Workshop #2 - Methods, Models, and Preliminary Interpretations held in January 1997 focused on methods of characterizing ground motion for the PSHA, new data and derivative analyses, and a review of the point estimate format required for the interpretations. Technical presentations centered on competing empirical attenuation models and results of synthetic modeling. Several of these proponent models were developed for other geographic regions. The experts discussed how to interpret ground motions from other regions and also discussed methods of developing adjustment factors that account for the differences between Yucca Mountain and these regions.

Although discussions of the data and other information were most focused among the experts during the workshops, throughout the project there was a continual informal dialog among the experts themselves and between the experts and the GM Facilitation Team Leader. During informal interaction among the experts, an expert was most often acting as a proponent to resolve questions regarding the application of his specific model. During informal interaction between the experts and the GM Facilitation Team, the experts raised issues that required general clarification by the GM Facilitation Team Leader.

In addition to the workshops, two working meetings were held to discuss the proponent models. These two working meetings addressed issues related to the proponent models and conversion factors that had not been resolved at the workshops. The meetings also provided additional feedback to the experts.

5.1.2 Elicitation Interviews

A formal elicitation interview between the GM Facilitation Team and each expert was held following Workshop #2. The interviews were conducted in accordance with guidelines developed by the SSHAC (1997). The elicitation team (Facilitation Team, Dr. Jean Savy, and Dr. Peter Morris) met prior to the first interview to establish a systematic approach to the questioning to ensure that the first expert would be asked the same questions as the last.
Dr. Abrahamson served as a generalist in all interviews. In the first interview (with Silva), Dr. Morris served as the normative expert. In the next four interviews (Walck, Campbell,

Somerville, and Anderson), Jean Savy served as the normative expert. Dr. Morris was not available during the remaining interviews; based on guidance from Dr. Morris and their previous experience with elicitation interviews, Drs. Savy and Abrahamson conducted the remaining interviews. Dr. Becker documented the interviews.

The interviews were private and uninterrupted. Each expert provided written documentation of the proponent models he deemed relevant to the study and the means by which he formed point estimates from the proponent models. In the interview, each expert was asked to explain the procedures he adopted to obtain median estimates, aleatory uncertainties, and the epistemic uncertainties on both. Each defended his selection of 'relevant' proponent models and also explained on what basis other models were rejected.

The elicitation interview was an important source of feedback for the experts. Inconsistencies in the treatment of uncertainty and use of conversion factors were identified and later corrected by the experts. In advance of the interview, several experts had considered only a limited number of proponent models. They tended to expand the number of models considered following challenges in the elicitation to defend their initial selection. Most importantly, in preparation for the interview, all experts had used weighted averages of the proponent models to develop preliminary estimates. All had also used the concept of classes of models; the weights of the individual models were often selected so that a desired relative weight between the model classes was achieved. As a result of the interviews, a formal dual weighting scheme was adopted by each expert in which the weights were separated into weights for classes of models and weights for models within a class.

A major conclusion following the interviews was that the volume of point estimates ultimately requested could not be managed readily by the experts. The key issue was the effort needed for the computation of the weighted combinations of the proponent model estimates and appropriate adjustment factors on which the experts point estimates were based. To facilitate this effort, the GM Facilitation Team calculated the preliminary ground motion estimates for each expert using weights supplied by the expert. Consequently, a single computer program was developed by the GM Facilitation Team Leader for use by all experts to weight proponent models as a step towards forming their point estimates. This computer program (WT_AVE) was used to compute weighted model values (used as preliminary point estimates) for each of the experts. This allowed the experts to simply develop weights for the models freeing them to concentrate on evaluating the resulting point estimates. The weighted values were used solely for preliminary computations: the experts were charged to evaluate the preliminary estimates to form their final point estimates.

5.1.3 Feedback and Revision

Feedback for the experts occurred at several different times in addition to the formal Feedback Workshop. At the working meetings, interaction among the experts was significant as they discussed the alternative approaches and proponent models. As mentioned above, the elicitation interviews resulted in significant feedback in terms of identifying inconsistencies and misconceptions by the experts. The experts were also encouraged to discuss the issues among themselves as needed in between the formal workshops and working meetings.

The Feedback Workshop informed the experts of the implications of their preliminary interpretations on the hazard computation. This workshop included a joint session with the SSFD expert teams to facilitate understanding of the technical issues and models each expert had developed. Preliminary hazard results were also presented and the sensitivity of the hazard to various input parameters was assessed. The workshop primarily consisted of discussions of the technical basis for each expert's point estimates and the attenuation equations developed from the expert's interpretations by the GM Facilitation Team. A few selected cases (magnitude, distance, and frequency combinations) were selected for in-depth discussions among the experts. The reasons for the differences in the point estimates for these cases were explored including discussions of the strengths and weaknesses of the proponent models for each case. As part of this discussion, a formal procedure for developing statistical estimates of the epistemic uncertainties was agreed upon. By the conclusion of the workshop, each participant was fully briefed on the technical basis for all other experts' estimates.

An additional working meeting, which provided additional feedback, was held shortly after the Feedback Workshop. This meeting included an exercise to focus the experts on the values of the point estimates and not on the weights given to the models.

Following the Feedback Workshop and working meeting, the experts revised their estimates. The GM Facilitation Team developed revised attenuation models based on the experts' revised estimates. The experts were then given the opportunity to revise their point estimates and/or the functional form of the regression equations. This process was repeated until the experts were satisfied that the regression models adequately characterized their estimates of the ground motion.

5.1.4 Documentation

Each expert documented the reasoning behind his development of the point estimates. This documentation is given in Appendix D. An outline of key sections was provided to each expert to ensure a standardized format was followed in the reports. The GM Facilitation Team first reviewed the documentation for internal consistency and completeness. The reports were then reviewed by the Project Management Team, and finally by the Review Panel.

5.2 REVIEW OF TECHNICAL ISSUES

Yucca Mountain lies within the Basin and Range Province, a regime primarily characterized by extensional crustal stresses. Known late Quaternary faulting within 20 km of the proposed repository is principally normal dip-slip, occurring both with and without an oblique component. Major strike-slip faults, which contribute to the potential ground shaking hazard at the site, have been identified at distances of 25 km and greater.

Ideally, ground motions recorded from earthquakes in the Yucca Mountain region, or at a minimum the Basin and Range Province, should be used to develop attenuation relations for Yucca Mountain; however, strong motion data from these environments are not sufficient to adequately constrain an empirical model. A key issue in characterizing ground motion attenuation at Yucca Mountain was the applicability of standard western U. S. attenuation models to the Basin and Range Province. Empirical attenuation relations commonly applied in the western U.S. are based primarily on recordings from California strike-slip and reverse earthquakes. For example, in the data base used by Sadigh *et al.* (1993), 15% of the earthquakes and less than 2% of the recordings used to develop their attenuation relations are from normal or normal/oblique faulting events. This data distribution is similar for all other western U.S. attenuation models in common use. Due to the sparse amount of strong motion data recorded from normal faulting earthquakes, separate style-of-faulting factors typically have not been estimated for these types of events. Instead, the normal faulting event data are usually grouped with strike-slip faulting earthquakes because the few recorded normal event strong ground motions had not been found to be statistically different than those predicted for strike-slip events in previous evaluations (Westaway and Smith, 1989).

Further, significant differences may exist in the seismic source, regional crustal, and shallow site properties for Yucca Mountain as compared to the average source, path, and site properties represented in the western U.S. strong motion data set. An issue that the experts addressed was whether, or to what degree, these differences could affect median ground motions or variability in ground motions expected at Yucca Mountain compared to those predicted by those proponent models based primarily on California data.

5.3 GROUND MOTION WORKSHOPS AND MEETINGS

Three workshops and two working meetings on ground motion characterization were held and they are summarized below. The complete workshop summaries are contained in Appendix D.

5.3.1 Workshop #1 - Data Needs

The goal of Workshop #1 was to identify critical data needs requiring additional analyses and, secondarily, to provide site-specific information about ground motion attenuation at Yucca Mountain. The goals of the PSHA and the relevance of the ground motion characterization within the overall PSHA project were presented as background to the experts.

Because incorporation of scientific uncertainty was a key element of the study, the means by which uncertainty is characterized were discussed. Total uncertainty was decomposed as epistemic and aleatory, each of which is partitioned into parametric and modeling variability.

Various technical issues and available seismologic data were presented. Known and suspected Quaternary faults and their characteristics were described. Data on source parameters, crustal structure, attenuation parameter Q, and site effects were summarized and ranges of stress drops and Q values reported in various studies were noted. The effect of site conditions on spectra using empirical and theoretical data was illustrated. Using theoretical data, the potential influence of the uncertainty in the site properties as compared to the potential influence of the variability of source properties was examined in terms of the resulting variability of the ground motion. Key seismological data include records of the June 29, 1992 Little Skull Mountain main shock and aftershock sequence and the 1993 Rock Valley sequence. The experts were briefed on source focal mechanisms, event locations, and seismograms from this sequence. Estimated values of kappa and site amplification were provided corresponding to several stations in the Yucca Mountain region. Site response effects were examined using UNE data, which indicate strong azimuthal dependence. The data were evaluated for two-dimensional crustal structure to explain the amplification.

Two ongoing Yucca Mountain Project site characterization activities had direct relevance to the ground motion characterization activity. The first was to evaluate empirical vibratory ground motion models for extensional tectonic regimes. Spudich *et al.* (1996) had assembled a worldwide data set from normal and strike-slip faulting in these regions. Their goal was to first evaluate several empirical attenuation relations and, if they did not adequately describe the data, to develop correction factors for the relations or alternatively produce a new relation based on the extensional data (Spudich *et al.*, 1996). The second activity was the ground motion modeling of scenario earthquakes at Yucca Mountain (J. F. Schneider *et al.*, WCFS, written communication, 1996). The activity was aimed at developing ground motion time histories and response spectra for realistic earthquake faulting scenarios. As part of this project, the modeling procedures were calibrated against the Little Skull Mountain records.

Ground motion estimation methods were reviewed including empirical attenuation relations, numerical simulations, and hybrid empirical-numerical schemes. The input required by each model was summarized as well as source parameters that were not well defined at the time at Yucca Mountain.

5.3.1.1 Issues from the Data Needs Workshop.

Throughout Workshop #1, the GM Facilitation Team Leader and experts discussed the technical issues to be resolved and data required for a thorough assessment of ground motions. Six principal issues were identified for further study and were prioritized as to importance by the experts (Table 5-1). Most arose from a lack of detailed information or from a need to further evaluate an available data set.

Issue #1 Site Response. The reference site condition considered at the Data Needs Workshop was for a site located on the top of "typical" tuff at Yuuca Mountain. To develop ground motions for this site condition, the experts require detailed information on the shear-wave velocity and non-linear properties of the shallow tuff at Yucca Mountain (primarily the top 50 m). A preliminary velocity profile for the shallow tuff had been estimated as part of the Scenario Earthquake Modeling Project (J. F. Schneider *et al.*, WCFS, written communication, 1996), but this velocity profile was not well constrained. The available laboratory testing studies to determine the non-linear properties were also not adequate to meet the experts needs. Therefore, the experts requested that additional site data be collected.

Issue #2 Stress Drops for Normal Faulting Earthquakes. The ground motion evaluation presented by Spudich *et al.* (1996) found lower ground motions for earthquakes in extensional regimes than for earthquakes in transpressional regimes. Since the Spudich *et al.* (1996) analysis was based on residuals from attenuation relations, it was not clear that this difference was due to the earthquake source rather than site or path effects. The experts requested that stress drops be computed for the Spudich *et al.* (1996) data set to compare with stress drops for California earthquakes to determine the causes of the ground motion differences.

Issue #3 Shallow Slip. The numerical simulation methods used in the scenario earthquake report do not include significant seismogenic slip in the top few km, although shallow slip has occurred in past earthquakes and can occur on the local faults at Yucca Mountain. The validity of not including seismogenic shallow slip in the numerical simulations was questioned.

Issue #4 Numerical Simulations. Numerical simulations of ground motions at Yucca Mountain were available for the earthquakes considered in the Scenario Earthquake Modeling Project; however, the experts are required to estimate the ground motions for a much larger range of magnitudes and distances than was considered in that study. Therefore, the experts requested that numerical simulations be generated for the full set of events (point estimates) that the experts had considered. Three preferred methodologies were identified by the experts from the six included in the Scenario Earthquake Modeling Project. The selected procedures were those by Zeng and Anderson, Silva, and Somerville. These procedures were selected based on their perceived superior modeling ability as evidenced by comparisons included in the Scenario Earthquake Modeling Project (J. F. Schneider *et al.*, WCFS, written communication, 1996). The experts requested that ground motions based on these three numerical simulation methods be generated.

Issue #5 Regional Q Models. Discrepancies in the literature regarding regional attenuation (Q) were identified; a consistent Q model was required for use by the experts.

Issue #6 2-D and 3-D Effects. Data recorded at Yucca Mountain from UNEs show significant lateral variations indicating strong 2-D and 3-D effects in the wave propagation. The importance of these effects on earthquake ground motions was questioned.

5.3.1.2 Resolution of Data Needs Issues. The site response characteristics specific to Yucca Mountain (Issue 1), the source parameters (stress drops) for earthquakes in the extensional regimes (Issue 2), reported 2-D and 3-D effects on ground motion amplification from UNEs (Issue 6) were resolved by additional evaluations of new or existing data. Yucca Mountain-specific ground motions predicted by numerical ground motion simulations (Issue 4) were requested, which was a furtherance of the Scenario Earthquake Modeling Project (J. F. Schneider *et al.*, WCFS, written communication, 1996).

Issue #1 Site Response. Limited studies to evaluate the shear-wave velocity and non-linear properties of the shallow tuff were conducted. Since these additional studies did not fully define the site properties to the extent required for site-specific application, it was decided to define the reference site condition by removing the top 300 m from the shear-wave velocity profile used in the Scenario Earthquake Modeling Project. This site condition was called the "reference rock outcrop" in this report.

To define the appropriate kappa for the reference rock outcrop site condition, laboratory studies of the low strain damping of the tuff in the top 300 m were conducted (K. H. Stokoe *et al.*, University of Texas, Austin, written communication, 1998). The low strain damping was found to be very low with an equivalent kappa of 0.0014 sec in the top 300 m. The average kappa for sites at the surface at Yucca Mountain had been previously estimated to be 0.02 sec based on studies of Su *et al.* (1996). Subtracting the kappa in the top 300 m from the surface kappa of Su *et al.* (1996) results in a kappa of 0.0186 sec for the reference rock outcrop.

The reference rock outcrop provided a well defined reference site condition for the experts to estimate their ground motions and allowed the ground motion study to proceed without complete site characterization which was not available. With the change of the reference site condition from the surface of the tuff to the reference rock outcrop, the nonlinear properties of the tuff are not needed for the development of ground motions in this study. In addition, using the reference rock outcrop motion provides a better reference for estimating the motions at the repository depth. Accounting for updates to the ground motion estimates as additional site information becomes available is discussed below in Section 5.7.

Issue #2 Stress drops for Normal Faulting Earthquakes. Median stress drops were computed using the normal-faulting earthquakes in the Spudich *et al.* (1996) worldwide data set and were found to be consistently lower than those for California events, which comprise the majority of the strong ground motion data base used to develop empirical attenuation relations. Ground motion scale factors accounting for the change in stress drop were developed.

Issue #3 Shallow Slip. Additional analyses were conducted using foam rubber modeling to evaluate the effect of ignoring shallow slip. Weak surficial layers were shown to significantly reduce the ground motion from near-surface slip due to increased rise-time. This supports ground motion modeling experience, which consistently shows reduced high-frequency ground motions radiated from shallow slip. In addition, it was also shown that significant differences in near-fault ground motions for normal and reverse faults are observed in foam rubber models.

The proponents of the numerical models also stated that their models required small amounts of shallow seismogenic slip otherwise they would greatly overpredict observed near fault ground motions. Therefore, the assumption of little or no seismogenic shallow slip is part of the numerical modeling procedure. None of the experts felt that this issue was important for their evaluations of the ground motions from the numerical simulations.

Issue #4 Numerical Simulations. Ground motions for the required point estimates were generated the three requested numerical simulation procedures (Silva, Somerville, and Anderson and Zeng). These procedures focused on the larger magnitude simulations because the models are calibrated for larger magnitude earthquakes and the subevent size for Silva and for Somerville's methods is approximately a M_w 5. Only the Anderson and Zeng procedure was used to generate ground motions for the M_w 5 events since it is applicable to smaller magnitudes (a result of using a range of subevent sizes). The numerical simulations used the revised site condition discussed in Issue #1 above.

Issue #5 Q Model. The basis for the apparent discrepancies in regional attenuation (combined effect of Q and geometrical spreading) (Issue 5) was investigated and resolved. Self-consistent Q and geometrical spreading coefficients were developed.

Issue #6 2-D and 3-D Effects. Observed lateral variations in the ground motions from UNEs recorded at NTS were evaluated. The shallow depths of UNEs result in large surface waves which are strongly affected by lateral variations in the velocity and structure of the shallow crust. However, confined shallow seismic sources such as blasts are unlike large earthquakes which extend to seismogenic depths. The conclusion of the evaluation was that variability in ground motion amplitudes from energy released at typical earthquake depths due to shallow lateral velocity variations in the crust would be much less than that observed in the blast data.

5.3.2 Workshop #2 - Methods, Models, and Preliminary Interpretations

The second workshop was held after a 1-year project hiatus. The primary goals of this workshop were to refamiliarize the experts with the issues, present available models for characterizing ground motions (proponent models), and discuss ways in which elements inherent to the proponent models may differ from conditions at Yucca Mountain. Secondarily, the technical issues raised in Workshop #1 were addressed. The experts also participated in a preliminary ground motion modeling exercise for a postulated earthquake. The exercise was intended to focus the workshop discussions on modeling techniques and highlight issues that were to be resolved in the workshop. Lastly, the range of the magnitude and distance modeling to be covered by the experts' interpretations was specified.

An important change from Workshop #1 was the reference site condition. In Workshop #1, the reference site condition was a site on the surface of the tuff. The reference site condition was redefined as a reference rock outcrop at the ground surface with properties equivalent to the existing conditions at repository level. The reference rock outcrop velocity profile is based on the Yucca Mountain velocity profile from the Scenario Earthquake Modeling Project (J. F. Schneider *et al.*, WCFS, written communication, 1996) with the top 300 m removed. This velocity profile is listed in Table 5-2. This change in the reference site condition was made to facilitate estimation of the ground motion at the depth of the repository using procedures currently being developed for the NRC. Using reference rock outcrop ground motions is the best approach for computing the ground motions at any of the SSC locations (at depth or on the surface).

5.3.2.1 Proponent Models. The balance of Workshop #2 focused on proponent models. The point-source random vibration theory (RVT) model, the hybrid empirical model, models derived from nuclear blast data, the finite source numerical simulation models arising from the Scenario Earthquake Modeling Project, and available empirical models were all presented. During the workshop, the experts added to the list of proponent models they wished to consider in their deliberations. For example, McGarr's (1984) model relating peak ground motions with stress state and focal depth was included. All models ultimately evaluated by the experts are listed in Table 5-3.

The Spudich *et al.* (1996) data base of strong ground motion records in extensional tectonic regimes was presented and these ground motions were compared with existing empirical attenuation relations. The data set contains both strike-slip and normal faulting events from extensional regimes around the world. The study focused on calculating correction factors for empirical relations to better fit the extensional data and on developing a new predictive relation derived from the extensional data. The factors included a bias correction and a standard deviation correction, and many showed a frequency dependence. The new attenuation relations were presented, and as they are based solely on extensional regime data, could be applied at Yucca Mountain without changes to the source.

Although the Yucca Mountain region has not experienced a major earthquake in historic times, the western boundary of the Basin and Range Province has, and clues to ground motion attenuation may be found in studies of the numerous precariously balanced rocks found regionwide. The distance of balanced rocks from historic ruptures, combined with the ground accelerations required to topple these rocks, provide physical evidence of the attenuation of ground motion from an historic earthquake. This information was collated to provide a constraint on ground motion attenuation in the region.

The GM experts presented trial estimates of median ground motion and uncertainties for two postulated M_w 6.5 earthquakes occurring at 10 km distance: one event as a result of strike-slip faulting and the other, normal faulting. The purpose of the exercises was to familiarize the experts with the process and the point estimate format. Several experts only used their own proponent models as their estimates rather than evaluating the suite of alternative credible models. (Consequently, the distinct roles of proponent expert and evaluator expert were again emphasized.) As a result, expert-to-expert variability in estimates was large; the estimates of the median peak ground acceleration varied by about a factor of two for the strike-slip case, up to three for the hanging wall of the normal faulting case, and over three for the footwall.

The experts were presented with the range of earthquake magnitudes, source distances, faulting styles, and fault geometries to be interpreted. They were to develop ground motions as a series of point estimates for 51 specified magnitudes and source - site geometries (Tables 5-4 and 5-5). Both strike-slip faulting on a vertical surface and normal slip on a moderately dipping fault were to be considered. Horizontal and vertical motions were to be estimated for peak ground acceleration (PGA), peak ground velocity (PGV), and spectral acceleration at frequencies of 0.3, 0.5, 1, 2, 5, 10, and 20 Hz. The experts were to provide the median motion, aleatory variability, and the epistemic uncertainties on both the median and the aleatory variability.

5.3.3 Working Meeting #1

Subsequent to Workshop #2, an interim working meeting was held for the experts at which they were provided with the first of several volumes of documentation of proponent models and the estimates derived from the proponent models. These "Ground Motion Data Packages" (Appendix B) were provided throughout the project as a tool to facilitate the experts' comparisons of their point estimates against the many proponent models and against the estimates of the other experts. Discussions at the working meeting were focused by the GM Facilitation Team Leader on the differences between estimates arising from the various classes of proponent models and also the differences between estimates arising from the various proponent models in each class. For convenience of comparison, classes of models were defined as empirical, finite source numerical, point source (RVT), and blast. These estimation methodologies had been presented previously in the workshops.

5.3.4 Elicitation Interview

In the formal elicitation interviews, each GM expert explained the procedures he/she adopted to obtain estimates of the median (μ), aleatory uncertainty (σ), and the epistemic uncertainties on both (σ_μ, σ_σ). As each expert explained the reasoning for the weights given to each model, it became apparent that all of the experts had included the concept of assigning weights to general classes of models and then assigning separate weights to the models within each class. The underlying logic was a dual weighting scheme with the weight for a model given by the product of the class weight and the model weight, although not all experts formally applied the approach. Once this dual weighting scheme was identified during the interviews, the experts all adopted a formal class/model weighting approach. With this common structure to the model weights, it became much easier to compare the weights used by the experts.

In general, each expert developed weighting schemes for the proponent models, applied the weights, and evaluated the resulting ground motions. In most cases, the weights were not the same for all magnitudes, distances, and frequencies as the experts considered the strengths and weaknesses of each of the classes of models and of the individual models within each class. Two experts included unique aspects in their approaches. Marianne Walck developed a method to identify outlier points among the proponent values and eliminated these from further consideration. John Anderson implemented two weighting schemes, which he then combined to develop his estimates. In the first scheme, he accommodated all relevant proponent models and developed a uniform distribution between the maxima and minima of all of the empirical models. In the second scheme he selected preferred empirical and numerical simulation proponent models.

In all interviews, inconsistencies in the treatment of the aleatory uncertainty (σ) and epistemic uncertainty on the median estimates (σ_m) and on the aleatory uncertainty (σ_σ) were identified. Therefore, the treatment of uncertainty was reviewed and each expert worked out how it should be applied in the context of his estimates.

In order to modify the empirical models to reflect Yucca Mountain repository-depth conditions, several proponent scaling and conversion factors had been provided earlier in the project. While the technical aspects of the development of the conversion factors were well understood, some inconsistencies in the details of their application were identified. Misconceptions were clarified by reviewing the sections in the Ground Motion Data Package that summarized the factors.

Substantial revisions in the experts' point estimates resulted from the interviews, largely the product of clarifying misconceptions, identifying inconsistencies, and formalizing the dual class/model weighting approach. Further, when challenged to defend their use or elimination of each model, in some instances experts identified previously unconscious bias in their approach. The tendency was to expand the number of models considered by each expert.

As a result of the elicitation interviews, many of the differences in the ground motion estimates were identified as not resulting from differences in scientific opinion, but rather from misconceptions or other inconsistencies. Removal of these unintended differences was one of the main goals of the expert elicitation process.

5.3.5 Workshop #3 - Feedback

To give the GM experts a better understanding of the technical issues of the overall PSHA, a joint session was held with the SSFD experts. In the joint session, preliminary models developed by the experts in the two groups were summarized. Although the SSFD expert teams developed models with numerous fault geometries, the GM experts developed ground motion estimates for a few specified fault geometries. These geometries were taken as representations of 'average' geometries, and the fault geometry variation within a range was incorporated as aleatory uncertainty in the ground motion estimates. Seismic source characteristics that introduce additional uncertainty in the estimates include deviations from the specified geometry, multiple ruptures on parallel faults, and a subhorizontal detachment fault. The latter two cases deviate so far from the average models that special consideration was needed. These special cases were discussed subsequently during the workshop.

Preliminary hazard computations were presented, based on the preliminary models developed by the source characterization teams and the fits based on the preliminary ground motion point estimates. Large magnitude earthquakes on distant faults dominated the hazard at long period and the contribution from faults and areal sources more local to the site dominated at all other periods. Significant hazard arose from multiple ruptures. However, many of the multiple ruptures coalesce at shallow depths. Separate ground motions were not estimated for these cases using numerical simulations because the numerical proponent models consider shallow slip to be nearly aseismic, which is the consensus of expert opinion. However, there were some cases for rupture coalescing at depths of 5 km or more. These cases were evaluated using numerical simulations to develop scaling factors for multiple-rupture scenarios. In general, the preliminary results showed that the largest contribution to uncertainty in the hazard is uncertainty in the ground motion models, emphasizing the importance of proper treatment of uncertainty in the ground motion estimates.

Because the focus of Workshop #3 was feedback and discussion among the experts, all outlined their approach to developing their point estimates. Each of the experts employed a weighting scheme to compute their preliminary point estimates from the proponent models.

Due to the large number of points to be estimated, using a weighted average of the proponent models was the only practical approach to developing the preliminary estimates; however, it was reiterated that the role of the experts is to develop point estimates of the ground motion and not weights for models. The weights are a means of getting preliminary results, but the need for the experts to focus on the resulting ground motions was emphasized.

Using the weights for the median ground motion and aleatory uncertainty was straightforward and well understood by all the experts, but the methodology for computing the epistemic uncertainties (in both μ and σ) was not well understood. In particular, an issue that was raised was how the epistemic uncertainties from the individual proponent models should be combined with the epistemic uncertainties computed from the weighted proponent models. At the workshop, a procedure was agreed upon. This procedure is described in the documentation of the WT_AVE computer program (see Data Package Vol. 1b).

To facilitate comparisons between the individual experts' point estimates, a series of plots of these estimates and the proponent model estimates on which they were based was shown. For a given earthquake magnitude and distance, and at a given response frequency, the proponent model estimates had a bimodal distribution. Empirical estimates were generally tightly grouped separately from the numerical simulation estimates, which were less closely clustered. Because the experts weighted both empirical attenuation relations and numerical simulation proponent estimates, in general their point estimates lay between the two distributions. The experts discussed differences in the numerical proponent models at length to determine if differences in modeling methodology would require further adjustments in the point estimates. This discussion led to further checking of the numerical simulations subsequent to the workshop. These checks identified several errors in the inputs to the finite-fault numerical simulation proponent model calculations. Corrected proponent ground motions for these models were computed and these corrections were explained to the experts and discussed by them at Working Meeting #2, which was held shortly after the Feedback Workshop. After the corrections were made, the bimodal nature of the empirical estimates and the simulations was reduced. In most cases, the distributions overlapped significantly (see Data Package Vols. 2, 7, and 8).

Closure was reached on the study of precarious rocks. At four locations near large historic earthquakes, the motion required to topple the rocks was computed and compared to motions for a M_W 6.5 earthquake estimated by the experts. In general, the expert estimates significantly exceeded the toppling motions suggesting that the estimates were in turn larger than the motions that had actually occurred. However, because the study evaluated only rocks that had not toppled, and not those that had, and because the effects of motion duration, frequency content, and location in a possible shadow zone could not be quantified in the case of the precarious rocks, most of the experts believed that this information could not yet be incorporated in their estimates.

Two seismic sources had been defined by the SSFD expert teams that were significantly different than the strike-slip and normal faulting cases the GM experts had evaluated. The two rupture scenarios were (1) multiple ruptures on parallel faults, perhaps coalescing at depth, and (2) rupture on a low-angle detachment zone with multiple parallel faults near the surface. The multiple rupture scenario was shown to have a large contribution to the preliminary hazard computation for both shallow (3 km) and deeply (8 km) coalescing faults whereas the contribution from a low-angle rupture had little effect. The first scenario was investigated in numerical modeling studies. For the multiple rupture scenario, both the parallel faults and deep coalescing model results suggested that the rate of attenuation was approximately the same whether several faults ruptured or whether only the central fault ruptured. Issues that pertain to estimating these motions were identified as including moment partitioning among the rupture planes, the relative timing of the ruptures, and the distances of each plane to the site. Regarding rupture on a low-angle detachment fault, issues that affected ground motions included the stress drops of the events and the geometry. Because these issues cannot be determined *a priori*, the experts were to address any changes to their point estimates for these scenarios by incorporating additional uncertainty.

At the close of the workshop, experts briefly described potential changes to their weighting schemes applied to the proponent models based on the workshop presentations. None of the experts anticipated major modifications to their procedures, but rather refinements based on closer reevaluations of various proponent models.

5.3.6 Working Meeting #2

A second working meeting was held following the Feedback Workshop. Its first goal was to correct errors identified in checks of the finite source simulations. Inconsistencies in kappa and the crustal model had been uncovered that affected two of the models, and directivity effects were corrected in a third model. Discussions centered on the effect of these modifications on the numerical simulations. The second goal was a training exercise developed to focus the experts on their point estimates as opposed to model weights. They were shown a plot of proponent estimates (median, aleatory uncertainty, and epistemic uncertainties) and each visually formed a preferred composite estimate. This training was effective in drawing their attention to the 'estimates' themselves and not the numerical weights given to the models.

5.4 PROPONENT MODELS

The GM Facilitation Team provided an initial list of candidate proponent models for the experts to consider. The experts added additional models that they wanted to evaluate. The proponent models were separated into classes: empirical attenuation relations, hybrid empirical, point source numerical simulation, finite-fault numerical simulations, and blast models. A complete list of the models is shown in Table 5-3.

The empirical attenuation models are results of regression analyses of empirical strong motion recordings. The models are primarily based on recordings from California earthquakes, but the hybrid model, developed by Campbell, incorporates the conversion factors discussed below directly into the model. The details of the development of this model are given in the Data Package Vol. 1.

The numerical simulations are computer-generated ground motions based on seismological models of the source, path, and site effects. There are two groups of numerical simulations: point source models and finite source models. The point source models are the simplest models with the smallest number of parameters. The point source model (with an omega-squared source) is well understood. The major source of uncertainty is in the selection of the median stress-drop, its aleatory variability, and the epistemic uncertainty in both the median and aleatory variability. To allow each expert freedom to set the stress-drops to the values that he/she preferred, the results of this proponent model were presented with median stress-drops, aleatory variability of stress-drops, and epistemic uncertainties in both as parameters to be set by each expert.

The finite-source numerical simulation models significantly differ in the model parameters required and in the procedures used to estimate ground motion. These differences can lead to significant variations in the predicted ground motions. Therefore, three different finite fault simulation procedures were used: Zeng and Anderson, Silva, and Somerville. The first two proponents additionally provided results for various alternative modeling cases. Zeng and Anderson presented three alternative models (A, B, and C) for the ground motions from their model. Case A, their base model, used the specified source geometries. Case B used shorter fault rupture lengths for the M_W 7.5 and 8.0 events to reflect the geometric constraints on the fault length determined from faults in the region. Case C used the same fault dimensions as case B, but with nonlinear properties of the shallow tuff (top 12 km) applied to the reference rock outcrop.

Silva presented two models. His base model (Case A) included the spatial variability of ground motion along the length of the fault. The variability was very large for long ruptures because the ground motion estimates off the ends of the fault were lower than elsewhere along the fault length. (This variability was not included in the other two proponent finite fault models.) In an alternative model (Case B) for the large-magnitude events, he computed the median and parametric aleatory variability for a single site located 1/3 of the rupture length from the end of the rupture (consistent with the approach used by the other two finite fault simulation methods). Case B resulted in higher median ground motion estimates and lower variability than Case A.

The blast models are based on empirical recordings from UNEs at NTS. The three blast models include alternative approaches to account for the differences in the source of earthquakes and sources of explosions.

5.4.1 Conversion Models

The ground motions developed in this study are intended to characterize surface shaking at a hypothetical site (reference rock outcrop) with properties the same as those encountered at a depth of 300 m at Yucca Mountain ("YM300"). The faulting styles considered are normal and strike-slip. These conditions are different than those represented by events comprising the data sets used to develop the WUS empirical relations.

A fundamental question that the experts were to address is whether ground motions at Yucca Mountain differ significantly from the motions represented by the data set that forms the basis for empirical models and, if they differ, by how much. Differences could be caused by source effects (extensional versus compressional regimes and normal versus strike-skip faulting), path effects (differences in the regional crustal structure), or site effects (differences in the shallow site properties). The region-and site-specific aspects of the ground motion can be directly incorporated as input for the numerical simulations, but for the empirically based models, proponent conversion factors were developed to account for these differences.

Suites of conversion factors were computed to address the experts' needs. They were developed specifically in this project using the results of (1) numeric finite-fault simulations, (2) stochastic point source simulations, and (3) empirical attenuation relations. Complete summaries of the conversion factors are presented in Data Package Vol. 1. The conversion factors included corrections for

- Source - western U.S. sources to Yucca Mountain extensional sources (values ranging between about 0.35 to 0.9),
- Crust - western U.S. crust to Yucca Mountain crust (ranging between about 0.9 and 1.2),
- Site - reference rock outcrop to Yucca Mountain surface (ranging between about 1.1 and 2.2).

The proponent conversion models for source and crust/site effects considered by the experts are listed in Tables 5-6a and b, respectively. For each proponent model estimate, the experts selected whichever source and crust/site conversions they wished to be applied. If a model did not require a correction term, "no correction" was selected. For example, the numerical simulations were computed for Yucca Mountain reference rock outcrop conditions so no crust/site correction was needed and none was applied.

An additional issue was that many of the empirical models did not cover the full range of ground motion parameters required in this study. In particular, not all of the empirical models included 20 Hz spectral acceleration, peak velocity, horizontal component-to-component variability, or vertical component ground motions. Therefore scaling rules to estimate these ground motion parameters were also required. These models are listed in Table 5-7a, b, c, and d. Again, the experts selected the appropriate scaling factors for each model. For example, the Boore *et al.* (1994) empirical model does not include 20 Hz estimates. To use this model at 20 Hz, rules for computing it must be specified (e.g., log-log interpolation). If no correction is selected for a model that does not include the desired parameter, then that model is not used in a weighted average (e.g., zero weight).

In Workshops #1 and #2, the experts had requested that the numerical simulations developed in the Scenario Earthquake Project (J. F. Schneider *et al.*, WCFS, written communication, 1996) be reevaluated to encompass the suite of magnitudes and distances needed to characterize attenuation and also to reflect reference rock outcrop (YM300) conditions. They identified three finite fault simulation methods for this additional study (Table 5-4) and the requested computations were made. Results are summarized in Data Package Vols. 1, 1B, and 2. Further, they requested that the stochastic point source/RVT model also be used to develop motions and, consequently, an attenuation model. Synthetics from this model are presented in Data Package Vols. 1 and 2.

5.5 WEIGHTING PROCEDURE

Due to the large volume of estimates required, the experts used numerical weighting of proponent model estimates to develop their initial estimates. The weighting procedure applied two levels of weights. The models were first separated into classes and weights were assigned to each class based on the expert's judgment as to the applicability of each class. Then for each range of magnitude, distance, and fault type, weights were assigned to the models within each class based on the expert's judgment as to the strengths and weaknesses of each model in terms of its applicability to Yucca Mountain. In general, each expert varied the class and model weights on a case-by-case basis to reflect his or her assessment of the applicability of each model. For example, an expert may have downweighted or eliminated an empirical model outside the magnitude range represented by the data on which the empirical model was based. The weighting procedure produced initial estimates of the median ground motion, aleatory uncertainty, and the epistemic uncertainties on the median and aleatory uncertainty. The proponent models and conversion factors that each expert included in his analysis are summarized in Tables 5-8 and 5-9a through 5-9f.

Plots of the estimates of the ground motion resulting from the weighting procedure were provided to the experts. They reviewed the plots and revised their estimates on a case-by-case basis by either adjusting the weights, setting bounds, or by setting the values of the point estimates themselves. This process was repeated until the experts were satisfied with their estimates. Some experts revised their point estimates only once whereas others made up to five revisions.

5.6 EXPERTS POINT ESTIMATES

The experts estimated median ground motion, aleatory uncertainty, and associated epistemic uncertainties for a matrix of event magnitudes, distances, and faulting styles and at a suite of spectral frequencies. The experts' documentation of their evaluations is included as Appendix F. The information on which these estimates were based includes the many proponent models and combinations of conversion factors. The matrix of point estimates consisted of 51 combinations of parameters, which was judged to adequately define attenuation for the seismic sources considered in the PSHA. The matrix (Tables 5-4, 5-5, and Data Package Vol. 1) covers a range of M_w 5.0 to 8.0, distances from 1 to 160 km, strike-slip and normal faulting, and both hanging wall and footwall for the latter style. These magnitude-distance pairs were selected to provide adequate constraints on the attenuation without burdening the experts. The frequencies were selected to cover the range of interest for all facilities. The range was defined as 0.3 to 20 Hz. As with the magnitude-distance pairs, a minimum number of frequencies needed to adequately describe the spectral shape was used. The frequencies were selected to vary by approximately a factor of two between each frequency. The selected frequencies are: 0.3, 0.5, 1, 2, 5, 10, and 20 Hz plus PGA and PGV.

All proponent data are summarized in Data Package Vols. 1, 1B, and 2. The experts' initial and revised point estimates are contained in a series of Data Package volumes. The proponent data are plotted together with the Revision 1 expert estimates in Data Package Vol. 3 (horizontal) and Vol. 4 (vertical). The experts' Revision 1 estimates are compared in Vol. 5. The proponent data are plotted together with the Revision 2 expert estimates in Data Package Vol. 7 (horizontal) and Vol. 8 (vertical). The experts' Revision 2 estimates are compared in Vol. 9. The final estimates (Revision 3) are compared in Vol. 12.

All point estimates for the 51 cases are plotted in Data Package Vol. 9. Median response spectral values (μ), aleatory variability (σ), epistemic uncertainty on the median (σ_μ), and epistemic uncertainty on the aleatory variability (σ_σ) are plotted for three cases on Figures 5-1 through 5-12. Shown are estimates for a smaller event (M_w 5.8) at moderate distance (20 km) and for a moderate event (M_w 6.5) at close distance (5 km), corresponding to hanging wall sites in normal faulting (Figures 5-1 through 5-8). Estimates for a larger (M_w 7.5), relatively distant (50 km), strike-slip event are also included (Figures 5-9 through 5-12).

The two special faulting scenarios (on parallel multiple faults and on a deep, shallow-dipping detachment surface) were not envisioned when the matrix of cases was developed. In lieu of expanding the case definitions following the Feedback Workshop, the experts evaluated the adjustments to their point estimates needed to model the two scenarios. The adjustments consisted of modifications to the median estimates (μ) and the aleatory uncertainty (σ). Their documentation and the adjustments are also included in Appendix F.

5.7 SITE-SPECIFIC MODIFICATIONS TO THE REFERENCE SITE CONDITION

As discussed in Section 5.3.2, the ground motions were computed for a free-field reference rock outcrop condition with a shear-wave velocity of 1900 m/sec. The shallow velocity at the ground surface above the repository is expected to be less than this reference velocity. For any application, the ground motion estimates for the reference rock outcrop will need to be modified by a transfer function to account for the shallow material. This modification will be needed for both rock and soil sites. Any non-linear response of the tuff or soils will be included in the site response analysis.

5.7.1 Accounting for Updates to Kappa

In addition to accounting for the shallow material in site response analysis, the ground motion evaluations provided by the experts may need to be modified for site-specific application if information from continuing studies of kappa at Yucca Mountain result in modification of the value used. The reference rock outcrop site condition included a median kappa of 0.0186 sec for the material below a shear-wave velocity of 1900 m/sec. This was the best estimate of median kappa for the reference rock outcrop at the time of this study.

The kappa for the reference rock outcrop is an estimate of the median value over the Controlled Area. However, for deriving site-specific ground motions, it may be appropriate to vary kappa over the Controlled Area. The use of the specified kappa of 0.0186 sec does not imply that there is no variability of kappa over the Controlled Area, rather it is the median value. The effect of variability in kappa on the variability of the ground motion has already been accounted for since the experts used estimates of the ground motion variability based on empirical data evaluated from either standard deviations for empirical attenuation relations or modeling uncertainty for numerical simulations. The empirical estimates of ground motion variability account for kappa variability within broad site categories (e.g. rock or deep soil). The variability of the log (kappa) for the strong motion sites within a site category used in either the empirical attenuation relations or validations of the numerical simulations is considered to be similar to the variability of log (kappa) at Yucca Mountain. Thus the effect of kappa variability is already included in the expert's estimates of ground motion standard deviations.

If ongoing studies find that the median kappa for material below 1900 m/sec depth is different from 0.0186 sec, the median attenuation models provided by the experts can be adjusted using scale factors for kappa. Only the median ground motion would be modified.

TABLE 5-1
KEY ISSUES IDENTIFIED AT THE DATA NEEDS WORKSHOP

Issue 1	What are the site response characteristics specific to Yucca Mountain?
Issue 2	What is the range of values of source parameters for earthquakes in this region of the Basin and Range?
Issue 3	What is the explanation for the apparent aseismic slip in the uppermost few kilometers of crust for earthquakes with rupture that reaches the surface?
Issue 4	What is the Yucca Mountain specific ground motion attenuation predicted by various numerical simulation procedures?
Issue 5	What is the basis for apparent discrepancies in the literature regarding regional attenuation (combined effect of Q and geometrical spreading?
Issue 6	What is the explanation for the reported large amplification of motions at Yucca Mountain compared to other NTS sites?

TABLE 5-2
YUCCA MOUNTAIN VELOCITY AND Q PROFILES

LAYER	DEPTH TO TOP (m)	V_S (km/sec)	V_P (km/sec)	DENSITY (g/cm^3)	Q_S	Q_P
1	0	0.6	1.8	1.7	25	80
2	40	1.2	2.5	2.0	40	120
3	80	1.5	2.9	2.3	40	120
4	220	1.9	3.2	2.4	70	150
5	1000	2.1	3.6	2.4	100	200

Source: J. F. Schneider *et al.* (WCFS, written communication, 1996)

TABLE 5-3
MODEL CLASSES AND PROPONENT MODELS

MODEL CLASS	PROPONENT MODELS IN CLASS	USED FOR FINAL ESTIMATES?
Empirical	Abrahamson and Silva (1997)	Yes
	Boore *et al.* (1997) (Vs model)	Yes
	Boore *et al.* (1994) (Class A)	No
	Boore *et al.* (1994) (Class B)	No
	Campbell (1997) (Soft Rock)	Yes
	Campbell (1997) (Hard Rock)	No
	Campbell (1993, 1994)* (Hard Rock)	No
	Campbell (1990, 1994) (Soft Rock)	No
	Campbell (1990) (Soil, Soft Rock)	No
	Idriss (1993) (Rock, Stiff Soil)	No
	Idriss (written comm. 1997) (Rock, Stiff Soil)	Yes
	Joyner and Boore (1988) (Rock)	Yes
	Sadigh *et al.* (1997) (Rock)	Yes
	Sabetta and Pugliese (1996) (Rock)	Yes
	Spudich *et al.* (1996) (Rock)	Yes
	McGarr (1984) (Rock)	Yes
Hybrid Empirical	Campbell (This Study)	Yes
Finite Fault Simulation	Silva (This Study)	Yes
	Somerville (This Study)	Yes
	Zeng and Anderson (This Study)	Yes
Point Source RVT	Silva (This Study)	Yes
Blast	Bennett Model 1 (1995 Scenario Study)	No
	Bennett Model 2 (1995 Scenario Study)	Yes
	Bennett Model 3 (1995 Scenario Study)	No

*Campbell 1994 is Campbell and Borzognia (1994)

TABLE 5-4
POINT ESTIMATE MATRIX

DISTANCE[1]	DEEP FOCUS[2]		SHALLOW FOCUS[2]					
(KM)	**M 5.0**	**5.8**	**5.0**	**5.8**	**6.5**	**7.0**	**7.5**	**8.0**
1	SS[3]		SS, HW[3]	SS	SS, HW, FW[3]	SS	SS	
5	SS, HW	HW, FW		HW, FW	SS, HW, FW			
10		SS	SS, HW	SS, HW, FW	SS, HW, FW	SS, HW, FW	SS, HW	
20		HW			SS, HW, FW			
50			SS, HW	SS, HW	SS, HW	SS, HW	SS, HW	SS
100					SS			
160			SS		SS			SS

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[1] Horizontal distance from surface expression of fault (up-dip extension).

[2] Shallow focus is centered at 5 km depth; bottom of deep focus rupture is at 14 km depth. See Data Package Vol. 1 for full definitions.

[3] HW refers to hanging wall location in normal faulting, FW to footwall location in normal faulting, and SS to strike-slip faulting.

TABLE 5-5
51 CASE DEFINITIONS FOR POINT ESTIMATES

CASE NO.	MAGNITUDE (M_W)	DEPTH[1]	X-DISTANCE[2] (km)	FAULTING STYLE[3]	R_{RUPT}[4] (km)	R_{JB}[4] (km)	R_{SEIS}[4] (km)
1	5.0	Shallow	1	SS	3.2	1.0	3.2
2	5.0	Shallow	1	HW	3.4	0.9	3.4
3	5.0	Deep	5	SS	11.3	5.0	11.3
4	5.0	Deep	5	HW	10.7	1.1	10.7
5	5.8	Deep	10	SS	12.2	10.0	12.2
6	5.8	Deep	20	HW	17.3	11.9	17.3
7	6.5	Shallow	1	SS	1.0	1.0	3.2
8	6.5	Shallow	1	HW	0.9	0.0	3.1
9	6.5	Shallow	-1	FW	1.0	1.0	4.1
10	6.5	Shallow	5	HW	4.3	0.0	4.4
11	6.5	Shallow	-5	FW	5.0	5.0	7.4
12	6.5	Shallow	50	SS	50.0	50.0	50.1
13	6.5	Shallow	50	HW	44.1	45.3	45.3
14	7.0	Shallow	10	SS	10.0	10.0	10.4
15	7.5	Shallow	50	SS	50.0	50.0	50.1
16	7.5	Shallow	50	HW	44.2	41.9	44.2
17	5.0	Deep	1	SS	10.2	1.0	10.2
18	5.8	Deep	5	HW	7.9	0.0	7.9
19	5.8	Deep	-5	FW	12.4	9.6	12.4
20	5.0	Shallow	10	SS	10.5	10.0	10.5
21	5.0	Shallow	10	HW	8.7	6.1	8.7
22	5.0	Shallow	50	SS	50.1	50.0	50.1
23	5.0	Shallow	50	HW	46.6	46.1	46.6
24	5.0	Shallow	160	SS	160.0	160.0	160.0
25	5.8	Shallow	1	SS	1.8	1.0	3.2
26	5.8	Shallow	5	HW	4.3	0.4	4.4
27	5.8	Shallow	-5	FW	6.4	6.1	7.4
28	5.8	Shallow	10	SS	10.1	10.0	10.4
29	5.8	Shallow	10	HW	8.7	5.4	8.7
30	5.8	Shallow	-10	FW	11.3	11.1	12.1
31	5.8	Shallow	50	SS	50.0	50.0	50.1
32	5.8	Shallow	50	HW	46.1	45.4	46.1
33	6.5	Shallow	5	SS	5.0	5.0	5.8
34	6.5	Shallow	10	SS	10.0	10.0	10.4
35	6.5	Shallow	10	HW	8.7	4.1	8.7
36	6.5	Shallow	-10	FW	10.0	10.0	12.1

TABLE 5-5 (Continued)

CASE NO.	MAGNITUDE (M_W)	DEPTH[1]	X-DISTANCE[2] (km)	FAULTING STYLE[3]	R_{RUPT}[4] (km)	R_{JB}[4] (km)	R_{SEIS}[4] (km)
37	6.5	Shallow	20	SS	20.0	20.0	20.2
38	6.5	Shallow	20	HW	17.3	14.1	17.3
39	6.5	Shallow	-20	FW	20.0	20.0	21.9
40	6.5	Shallow	100	SS	100.0	100.0	100.0
41	6.5	Shallow	160	SS	160.0	160.0	160.0
42	7.0	Shallow	1	SS	1.0	1.0	3.2
43	7.0	Shallow	10	HW	8.7	1.9	8.7
44	7.0	Shallow	-10	FW	10.0	10.0	12.1
45	7.0	Shallow	50	SS	50.0	50.0	50.1
46	7.0	Shallow	50	HW	44.2	41.9	44.2
47	7.5	Shallow	1	SS	1.0	1.0	3.2
48	7.5	Shallow	10	SS	10.0	10.0	10.4
49	7.5	Shallow	10	HW	8.7	1.9	8.7
50	8.0	Shallow	50	SS	50.0	50.0	50.1
51	8.0	Shallow	160	SS	160.0	160.0	160.0

[1] Shallow depth indicates rupture is centered at a depth of 5 km; deep depth indicates the bottom edge of rupture occurs at 14 km depth.

[2] X-distance is the horizontal distance from the surface "trace" of the fault.

[3] HW refers to hanging wall location in normal faulting, FW to footwall location in normal faulting, and SS to strike-slip faulting.

[4] R_{Rupt} is rupture distance, the closest distance from the site to the fault rupture surface; R_{JB} is the Joyner-Boore distance, the closest distance to the surface projection of the rupture surface; R_{Seis} is seismogenic distance, the closest distance to the assumed seismogenic part of the rupture surface, here used as the part of the rupture surface that lies at least 3 km below the ground surface.

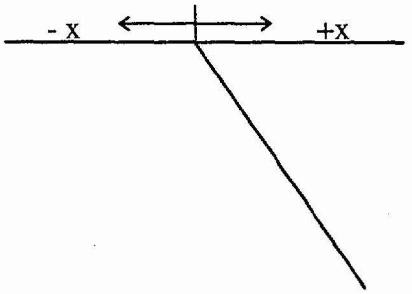

TABLE 5-6a
PROPONENT SOURCE CONVERSION FACTORS

Model #	Model
1	No correction for source
2	Spudich *et al.* (1996) extensional regime scale factors (d<20 km)[1]
3	Spudich *et al.* (1996) extensional regime scale factors (all distances)[1]
4	Campbell point source RVT (this study)[2]
5	Silva point source RVT (this study)[2]
6	Abrahamson and Silva (this study) normal faulting factors (horizontal comp)[3]
7	Abrahamson and Silva (this study) normal faulting factors (vertical comp)[3]
8	1/2 Abrahamson and Silva (this study) normal faulting factors (horizontal comp)[3]
9	1/2 Abrahamson and Silva (this study) normal faulting factors (vertical comp)[3]

[1] Based on the mean residuals of empirical attenuation relations

[2] Based on differences in $\Delta\sigma$ between California and Yucca Mountain (YM)

[3] Based on mean residuals for the Abrahamson and Silva (1997) empirical attenuation relation

TABLE 5-6b
PROPONENT CRUST/SITE CONVERSION FACTORS

Model #	Model
1	No correction for crust/site
2	Campbell point source RVT (this study): CA -> YM Repository outcrop[1]
3	Silva point source RVT (this study): CA -> YM Repository outcrop[1]
4	Silva point source RVT (this study): YM Surface-> YM Repository outcrop[2]
5	Silva finite fault (this study): YM Surface -> YM Repository outcrop[2]

[1] Based on differences in Q, kappa, and velocity profile from California to YM repository outcrop

[2] Based on differences in velocity profile and kappa from YM surface to YM repository outcrop

Note: Conversion factors are completely documented in Data Package Vol. 1.

TABLE 5-7a
PROPONENT VERTICAL/HORIZONTAL RATIO MODELS

Model #	Model
1	No correction
2	Campbell (1997) empirical attenuation
3	Silva (YM point source, this study)
4	Abrahamson & Silva (1997) empirical attenuation
5	Spudich *et al.* (1997) empirical attenuation
6	Sabetta & Pugliese (1996) empirical attenuation
7	Zeng and Anderson finite fault simulation (this study)
8	Somerville finite fault simulation (this study)

TABLE 5-7b
PROPONENT PEAK VELOCITY/SA(F) RATIO MODELS

Model #	Model
1	No correction
2	pgv/pga Campbell (1997) empirical attenuation
3	pgv/pga Silva (YM point source this study)
4	pgv/pga Joyner and Boore (1988) empirical attenuation
5	pgv/pga Sabetta & Pugliese (1996) empirical attenuation
6	pgv/pga Zeng and Anderson finite fault simulation (this study)
7	pgv/pga Somerville finite fault simulation (this study)
8	pgv/ pga Silva finite fault simulation (this study)
9	pgv/Sa(f=1 Hz) Campbell (1997) empirical attenuation
10	pgv/Sa(f=1 Hz) Silva (YM point source this study)
11	pgv/Sa(f=1 Hz) Joyner and Boore (1988) empirical attenuation
12	pgv/Sa(f=1 Hz) Sabetta & Pugliese (1996) empirical attenuation
13	pgv/Sa(f=1 Hz) Zeng and Anderson finite fault (this study)
14	pgv/Sa(f=1 Hz) Somerville finite fault simulation (this study)
15	pgv/Sa(f=1 Hz) Silva finite fault simulation (this study)

Note: Models are completely documented in Data Package Vol. 1.

TABLE 5-7c
PROPONENT HORIZONTAL COMPONENT-TO-COMPONENT VARIABILITY MODELS

Model #	Model
1	No correction
2	Boore *et al.* (1997) empirical attenuation
3	Spudich *et al.* (1996) empirical attenuation

TABLE 5-7d
PROPONENT 20 HZ SPECTRAL ACCELERATION INTERPOLATION MODELS

Model #	Model
1	No correction
2	Average coefficients for pga and 10 Hz
3	log-log interpolation between 33 Hz (pga) and 10 Hz
4	Boore scaling (this study)

Note: Models are completely documented in Data Package Vol. 1.

TABLE 5-8
PROPONENT MODELS USED BY EACH EXPERT

MODEL CLASS	PROPONENT MODELS IN CLASS	ANDERSON	BOORE	CAMPBELL	MCGARR	SILVA	SOMERVILLE	WALCK
Empirical	Abrahamson and Silva (1997)	Yes	Yes	Yes[1]	Yes	Yes	Yes	Yes
	Boore *et al.* (1997) (Vs model)	Yes	Yes	Yes[1]	Yes	Yes	No	Yes
	Campbell (1997) (Soft Rock)	Yes	Yes	Yes[1]	Yes	Yes	Yes	Yes
	Idriss (University of California, Davis, written communication, 1997) (Rock, Stiff Soil)	Yes	Yes	Yes[1]	Yes	No	Yes	Yes
	Joyner and Boore (1988) (Rock)	No	Yes	Yes[1]	Yes	Yes	Yes	Yes
	McGarr (1984) (Rock)	No	Yes	No	Yes	No	No	Yes
	Sadigh *et al.* (1997) (Rock)	Yes	Yes	Yes[1]	Yes	Yes	Yes	Yes
	Sabetta and Pugliese (1996) (Rock)	Yes	No	No	No	No	No	Yes
	Spudich *et al.* (1996) (Rock)	Yes	Yes	Yes[1]	Yes	No	Yes	Yes
Hybrid Empirical	Campbell (This Study)	No	No	Yes	No	No	No	No
Finite Fault Simulation	Silva Case A (This Study)	Yes	Yes	Yes	Yes	Yes	Yes	Yes
	Silva Case B (This Study)	No	No	No	No	No	No	No
	Somerville (This Study)	Yes	Yes	Yes	Yes	Yes	Yes	Yes
	Zeng and Anderson Case A (This Study)	Yes	Yes	Yes	Yes	Yes	Yes	Yes
	Zeng and Anderson Case B (This Study)	Yes	No	No	No	No	No	No
	Zeng and Anderson Case C (This Study)	Yes	No	No	No	No	No	No
Point Source RVT	Silva (This Study)	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Blast	Bennett Model 2 (1995 Scenario Study)	No	No	No	No	No	Yes	Yes

[1] These empirical models are incorporated in the Hybrid Empirical model.

TABLE 5-9a
SOURCE CONVERSION FACTORS USED BY EACH EXPERT

Conversion Factor	Anderson	Boore	Campbell	McGarr	Silva	Somerville	Walck
Spudich (d < 20 km)	No	No	No	No	No	No	No
Spudich (all distances)	No	No	No	No	No	No	No
Campbell (point source RVT)	No	No	Yes	No	No	No	Yes
Silva (point source RVT)	No	Yes	No	Yes	No	No	Yes
Abrahamson & Silva (horizontal)	No	No	No	No	No	Yes	No
Abrahamson & Silva (vertical)	No	No	No	No	No	No	No
1/2 Abrahamson & Silva (horizontal)	No	No	No	No	Yes	No	No
1/2 Abrahamson & Silva (vertical)	No	No	No	No	Yes	No	No

TABLE 5-9b
CRUST/SITE CONVERSION FACTORS USED BY EACH EXPERT

Conversion Factor	Anderson	Boore	Campbell	McGarr	Silva	Somerville	Walck
Campbell (point source) CA -> YM outcrop	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Silva (point source) CA -> YM outcrop	Yes	No	No	No	No	No	No
Silva (point source) YM surface -> YM outcrop	Yes	No	No	No	No	No	No
Silva (finite fault) YM surface -> YM outcrop	Yes	No	No	No	No	No	No