Description of Prediction Procedures and General Background

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Summary of Results from Initial Phase of Work
As submitted for inclusion in Phase 1 report.

97040101133 – Part 4

Empirical Ground Motion Predictions for Yucca Mountain Repository Using Experience from NTS Underground Nuclear Explosions

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Presented at Yucca Mountain Ground Motion Workshop #2

Salt Lake City, Utah

January 9-10, 1997

Explosion-Based Empirical Modeling Results

Background and Method Development

As noted above, the explosion-based empirical modeling approach described in this section is fundamentally different from the physical modeling methods used by the other investigators to predict ground motion for the scenario earthquakes at the Yucca Mountain site. In developing an empirical basis for predicting strong ground motion from earthquakes at a site like Yucca Mountain, the ideal would be to have recorded ground motion in the site vicinity covering a range of earthquake magnitudes which might be expected and covering distances at which such events might affect the site. However, as is the case with most engineering projects, such information is generally not available for the Yucca Mountain site. What we do have for Yucca Mountain are the records of strong ground motion made in the same general region as the site for a fairly large earthquake (viz. the 1992 Little Skull Mountain event) and for a large number of seismic events (viz. underground nuclear explosion tests) covering a range of strong motion levels and distances similar to those which are of interest for earthquake-resistant design at the Yucca Mountain site. These data provide information on region-specific attenuation, site response, and the uncertainties associated with these elements of the ground motion prediction problem. One objective of this project has been to identify procedures which permit us to utilize this region-specific knowledge of strong-ground motion to make reasonable inferences about seismic motions from large scenario earthquakes which might be postulated for the Yucca Mountain site. Our investigations under this element of the program have focused on utilization of the nuclear explosion experience base and the strong motion records from the Little Skull Mountain earthquake.

From the late 1950's until just recently, hundreds of underground nuclear explosions have been conducted at NTS. The yields of these explosions have ranged from less than 1 kiloton (kt) to 1200 kt, and the ground motions produced by these events were recorded at ranges from less than 1 km out to more than 100 km (cf. ERC, 1974; Bennett and Murphy, 1993). More than 1300 strong motion observations from this large explosion database were analyzed by ERC (1974) and used to develop prediction relations for the region surrounding NTS. These ERC prediction relations took the form of a power law model

$$A = A_0 W^B R^C$$

where A is either a peak time-domain ground motion measure or the spectral response at some frequency, W is explosion yield in kilotons, and R is range. The coefficient term, A_0, and the exponential terms, B and C, were derived from standard regression and covariance analyses of the explosion data. Similar power law models and regression analyses have subsequently been used by other authors to further analyze NTS explosion observations and to predict ground motions for the Yucca Mountain site (cf. Vortman, 1986; Phillips, 1991; Bennett and Murphy, 1993) from potential future NTS nuclear explosion tests. For the spectral response, which is the main focus of the studies presented in this section, A is a function of frequency and the coefficient and exponential terms are frequency dependent and determined by the regression analysis for each frequency. The response spectra predicted by these empirical relations have been found to be quite reliable for analyzing ground motion and building response from explosions at sites throughout the region.

The procedures used to extend this model to predict earthquake ground motions have been developed over the relatively short term of this project. Three distinct schemes based on the NTS explosion knowledge base have been identified and implemented to predict earthquake ground motions for the vicinity of the Yucca Mountain site. These three models are characterized as follows:

- Equivalent explosion with NTS attenuation relationship
- Geomatrix/ATC spectral shape with NTS attenuation relationship

Empirical Procedures for Estimating Earthquake Ground Motions Derived from NTS Explosion and Little Skull Mountain Earthquake Experience

The empirical ground motion prediction procedures based on NTS explosion experience are quite different from the fault rupture modeling methods described in other parts of this report. Because of the long history of underground nuclear explosion testing at NTS, there exists a large knowledge base (ERC, 1974; Vortman, 1986; Phillips, 1991) for seismic events covering a range of strong ground motion levels and distances similar to those which are of interest for earthquake-resistant design at the Yucca Mountain site. This knowledge base should be particularly valuable to ground motion assessment at Yucca Mountain because it incorporates information on attenuation and site conditions which are comparable to those in the vicinity of Yucca Mountain.

Our objective in this element of the project has been to relate the experience with ground motion from NTS explosions in a meaningful way to help predict ground motions from earthquake scenarios for the Yucca Mountain site. To accomplish this goal we have developed and investigated three distinct empirical-based procedures for predicting ground motion spectral response. All three procedures are based on the ground motion prediction relationships derived for NTS explosions (cf. ERC, 1974) which incorporate a power law model of the form

$$A(f) \;=\; A_0(f)\, W^{B(f)}\, R^{C(f)}$$

where A(f) is the spectral response, W is explosion yield (kilotons), and R is range (km). Coefficients, $A_0(f)$, and exponential terms, B(f) and C(f), in this model were originally derived using standard regression analyses of the empirical explosion data. The large data sample used in these analyses included more than 1300 strong motion measurements for sites at ranges from less than 1 km to more than 100 km. The empirical observations of strong ground motion (in this case the maximum spectral response, although similar analyses have also been performed on peak motion measurements from the time domain) for the large NTS explosion database were used to fix the coefficients and exponential terms at each frequency, and the resulting relationships were applied to successfully predict ground motions from subsequent explosions for use in assessing structural design response and building safety throughout the surrounding region.

In extending this model to predict earthquake ground motion, we have considered in these initial investigations three very simple schemes. The first scheme uses the explosion prediction relationships to estimate the ground motion spectra for an explosion with yield equivalent to the magnitude of the postulated earthquake and evaluated at the appropriate distance range. To arrive at the appropriate yield for the equivalent explosion, empirical relationships between magnitude scales based on worldwide earthquake experience and between magnitude and yield based on NTS results were used (cf. below for additional detail). The second prediction procedure is based on the empirical Geomatrix response spectrum (Sadigh et al., 1995) evaluated for the appropriate earthquake magnitude at some reference distance (viz. 10 km) scaled to closer or farther ranges using the NTS explosion experience. In this procedure greater attenuation in the NTS experience compared to the database contributing to the Geomatrix model produces modest (generally less than a factor of two) departures between the response spectra at ranges away from 10 km. The third approach utilizes a response spectral shape derived from the observations of the 1992 Little Skull Mountain earthquake scaled to different ranges using the NTS explosion relationship and scaled to different magnitudes using the same magnitude dependence as that in the Geomatrix spectrum model. This last approach has the advantage of including knowledge based on a large earthquake in the vicinity of the Yucca Mountain site but can be relied on only to the extent that the Little Skull Mountain earthquake is thought to be representative of future earthquake scenarios there. In all cases, these ground motion predictions correspond to the average site conditions for the analyzed data sets and not specifically to those at the Yucca Mountain site. Site response variations can be strong, and this fact is reflected in the uncertainty bounds on the predictions.

model causes the modified Geomatrix/ATC spectrum to lie above the standard spectrum at ranges less than 10 km and fall below the standard spectrum at farther ranges.

The third empirical model which we developed uses a reference response spectrum derived from the 1992 Little Skull Mountain earthquake which has been modified using the attenuation information from NTS explosion experience and scaled for magnitude based on the Geomatrix/ATC model, described above. In developing this model we used the 5-% damped PSRV spectra computed at eight strong motion sites for the 5.68 M_W Little Skull Mountain earthquake to determine a power law spectral model based on those observed data alone. We next derived a spectrum at a reference distance of 36 km, the average distance of the eight stations. This reference spectral shape was then scaled to nearer and farther distances corresponding to postulated scenario earthquakes using the NTS explosion-based attenuation exponents. After determining the spectrum for the appropriate distance, we scaled the ground motion up to the appropriate magnitude using the same magnitude dependence which is built into the Geomatrix/ATC empirical model. As will be shown in the following section, this model does a very good job in predicting the observed response spectra for the Little Skull Mountain earthquake, as would be expected since the ground motion attenuation observed from the Little Skull Mountain earthquake is not greatly different from that based on NTS explosion experience and no magnitude scaling is required.

Comparison of Predictions to 1992 Little Skull Mountain Earthquake Observations

The 1992 Little Skull Mountain earthquake is clearly important in seismic design consideration for the Yucca Mountain site because it represents a fairly large earthquake in a similar tectonic and propagation environment like that for several of the postulated scenario earthquakes. The main shock with magnitude 5.68 M_W was recorded at several surrounding strong motion stations at ranges between 12.9 km and 99.1 km from the fault. These strong motion records provide an excellent data sample to analyze characteristics of the ground motion from earthquakes in the vicinity of Yucca Mountain and to test modeling and prediction capability for such motions. As part of this project, we performed analyses of the attenuation characteristics of the PSRV spectra observed at the eight strong motion sites which recorded the Little Skull Mountain earthquake and attempted to test the explosion-based empirical prediction techniques described in the preceding section using the observed response spectra.

To analyze the attenuation of the strong motion observations from the main shock, we applied a power law model similar to that described above. Because we were concerned with attenuation from a single event, there was no dependence on magnitude and the model reduced to

$$L(f) = L_0(f)\ R^{n(f)}$$

for the PSRV spectra. Comparison of the N-S and E-W components of the PSRV spectra revealed insignificant (less than a factor of two) differences between the two observations at most stations and frequencies. We, therefore, performed the regression analyses on the combined data set with both horizontal components included as separate observations at each frequency. The attenuation exponent, n(f), was determined for each frequency as the slope of the least-squares linear fit to the response spectra measurements in log-log space. The attenuation exponents determined from the analysis of the Little Skull Mountain earthquake observations are compared to the attenuation exponents from the NTS explosion experience in Figure 3. The attenuation exponents from the NTS experience are seen to lie within the 95-% confidence limits bounding the mean values determined for the Little Skull Mountain earthquake at all periods in the left-hand figure. However, on the right the attenuation exponents for the Little Skull Mountain earthquake are seen to lie slightly above the rather narrow confidence bounds about the average NTS experience in a period band from about 0.2 to 2.0 seconds. Thus, over this band the Little Skull Mountain earthquake appears to show somewhat greater attenuation than that based on average NTS explosion experience; but the differences are well within the statistical uncertainty in both

- Little Skull Mountain earthquake spectral shape with NTS attenuation relationship and Geomatrix/ATC magnitude scaling

For the first of these models, we have attempted to use empirical relationships between magnitude and yield to identify an explosion source which is approximately equivalent to the postulated earthquake scenario. The scenario earthquakes are specified in terms of moment magnitude, M_W, while the most reliable relationship between magnitude and yield for underground nuclear explosions uses the body-wave magnitude, m_b. Lacking reliable empirical relationships between moment magnitude and yield for explosions, we resorted to an indirect approach. It is well known from seismic discrimination studies (e.g. Bolt, 1976; OTA, 1988) that nuclear explosions and earthquakes are generally different with respect to their relative excitation of long-period versus short-period seismic waves and this produces differences in surface-wave magnitude, M_S, with respect to m_b between the two source types. Similar differences are also implied for M_W versus m_b for the two source types. If we assume that seismic events with the same M_W have approximately equal M_S, then, based on experience with worldwide earthquakes (cf. Richter, 1957) and with NTS explosions (cf. Marshall et al., 1971; Murphy, 1977; Bache, 1982; OTA, 1988), for the same M_W we can infer

$$m_b \text{ (Explosion)} \approx m_b \text{ (Earthquake)} + 0.60$$

at magnitude levels of interest here. Finally, using empirical relations based on NTS experience between m_b and yield for explosions and the results of Houston and Kanamori (1986) for the empirical relationship between m_b and M_W for worldwide earthquakes, we have after some simplification

$$\log W \text{ (Equivalent Explosion)} \approx 0.654\, M_W \text{ (Earthquake)} - 0.780$$

where W is the yield in kilotons for the explosion equivalent to the earthquake with moment magnitude of M_W. To arrive at the ground motion predictions for this model, we used this approximate relationship to estimate yields for the equivalent explosions corresponding to the M_W's for the scenario earthquakes and simply applied the NTS explosion prediction relationship to obtain the 5-% damped PSRV response spectra. Figure 1 shows a comparison of 5-% damped PSRV spectra based on this equivalent explosion model for a fixed reference distance (viz. 10 km) and corresponding to a set of moment magnitudes, M_W, in the general range of interest. It should be noted for this and subsequent predictions derived from the NTS explosion experience that the period band for the spectra are somwhat more limited, mainly due to response of the recording systems

The second explosion-based empirical model involves a modification of the Geomatrix/ATC response spectra empirical model, as defined by Geomatrix (1992) and Sadigh et al. (1995), to include the region-specific attenuation information from the explosion experience appropriate to the vicinity of NTS and the Yucca Mountain site. The original Geomatrix model was based on analyses of the large empirical database of earthquake strong motion records principally from the California region. In our modified model we use the Geomatrix model to develop 5-% damped PSRV response spectra for the horizontal rock motions at a reference distance of 10 km for each of the postulated scenario earthquakes. Thus, the Geomatrix model establishes the level and the shape of the response spectrum at this reference distance. We then use the attenuation relationship from the power law model, derived from the experience with NTS explosions, to scale the spectrum at the reference distance to nearer or farther ranges. It is clear from this procedure that the calculated response spectra will generally match the standard Geomatrix model at distances near the reference distance and that departures away from that distance should be indicative of attenuation differences between the NTS region and the average for the Geomatrix data sample. Figure 2 shows that the somewhat stronger attenuation in the NTS for comparisons between the explosion-based empirical model predictions and observations for the Little Skull Mountain earthquake spectra at other strong motion sites. These test cases for the Little Skull Mountain earthquake appear to provide some confirmation that the explosion-based empirical modeling schemes defined here, or some variant of those schemes, can provide a useful supplement to the alternative ground motion prediction methods based on physical models.

Ground Motion Predictions for Earthquake Scenarios at the Yucca Mountain Site

The earthquake hazard to the Yucca Mountain site can be defined in terms of a number of scenario earthquakes associated with faults in the general vicinity of the site. For this project six faults were considered: Bow Ridge, Paintbrush Canyon, Solitario Canyon, Bare Mountain, Rock Valley, and Furnace Creek. For the first four faults the scenario earthquakes have normal-slip mechanisms, based on the dominant sense of displacement observed for the fault, and are assumed to be represented by a moment magnitude of 6.4 M_W. For the Rock Valley and Furnace Creek faults the scenario earthquakes have strike-slip mechanisms, again based on the dominant sense of displacement, and are assumed to be represented by moment magnitudes of 6.71 M_W and 7.04 M_W respectively. For each of these scenario earthquakes, we used the explosion-based empirical models to predict 5-% damped PSRV spectra.

In specifying the distance to use in the ground motion calculations, we assumed hypocenters located at two different focal depths (viz. 6 km and 9 km) on the faults to provide some range of depth within the crust for the earthquake sources. Because our models essentially represent simple point sources with no effect of radiation pattern, the only effect of the focal depth differences is to alter the hypocentral distances used in the calculations. It should be noted in this regard that small differences in the assumed hypocentral distance produce relatively insignificant perturbations for the response spectra considering the other uncertainties associated with the predictions. For the normal fault scenarios, the faults were assumed to have a common dip of 57.5° with dip direction measured from field observations. The distances were then measured from the site to the hypocenter at the appropriate focal depth on each of the dipping faults. With these assumptions the hypocentral distances used for the base case normal fault scenario predictions ranged from 6.0 km to 13.3 km. For the strike-slip scenarios, the faults were assumed to be vertical; and the distances were again determined from the site to the appropriate hypocenter at each assumed focal depth on the fault. Because these faults are at fairly large horizontal distances from the Yucca Mountain site, the differences between the two assumed focal depths for the scenario earthquakes have little effect on the hypocentral distances. As a result, hypocentral distances for the Rock Valley fault scenario earthquakes are 26 km and 27 km, and hypocentral distances for the Furnace Creek fault scenario earthquakes are 51 km and 52 km.

For each of the scenario earthquakes, we calculated the PSRV spectral responses for the three empirical models described above. Thus, we generated a total of 36 response spectra for the 12 earthquake scenarios (i.e. two focal depths for each of the six faults). Figure 6 shows a representative prediction for the base case normal fault scenario with a magnitude of 6.4 Mw and a range of 9.1 km. This prediction corresponds to the Paintbrush Canyon fault scenario earthquake with a focal depth of 9 km. In Figure 6 we show comparisons of the predictions for each of the explosion-based empirical models with the prediction determined for the same scenario earthquake using the standard Geomatrix/ATC empirical model. The plot on the left shows fairly close agreement between the prediction for the equivalent explosion model and the standard Geomatrix/ATC model. At short periods, 0.05 to 0.1 seconds, and again at long periods, 0.9 to 3 seconds, the equivalent explosion model prediction lies slightly (about a factor of 1.5) above the standard Geomatrix/ATC model prediction; while at intermediate periods, 0.1 to 0.9 seconds, the two predictions overlap. The middle plot compares the standard Geomatrix/ATC empirical model prediction with the prediction using the Geomatrix/ATC model spectrum modified based on NTS explosion attenuation experience. The distance range is not much different from the reference distance used for the latter model, and as a result the two predictions are quite close. The modified Geomatrix/ATC model prediction lies slightly above the standard model because of somewhat estimates. The insignificance of the attenuation differences was further demonstrated by comparing the observed Little Skull Mountain response spectra at the eight strong motion sites with spectral predictions (1) based on the power law model derived directly from the Little Skull Mountain earthquake data and (2) based on the Little Skull Mountain earthquake spectral shape from a fixed reference distance scaled to other distance ranges using the NTS explosion attenuation exponents. There was little discernible difference found in the fits to the observations using these two approaches; the predictions for both approaches were generally within a factor of two of the observations at all stations and periods, and residuals for the two approaches were seen to have similar trends.

Figure 4 shows the 5-% damped PSRV spectrum derived from the power law model applied to the Little Skull Mountain earthquake observations. The figure compares the spectrum from the model at the average distance of the strong motion sites (viz. 35.7 km) with response spectra predicted for three other models: (1) the standard Geomatrix/ATC empirical model, (2) the modified Geomatrix/ATC model including NTS attenuation, and (3) the equivalent explosion model. At short periods (up to nearly 1 second) the three models show reasonable agreement among themselves and with the spectrum derived from the Little Skull Mountain earthquake observations. The standard Geomatrix/ATC empirical model actually appears to provide a somewhat better fit to the observed Little Skull Mountain earthquake spectrum over the period band from about 0.05 to 0.3 seconds. This is a little surprising considering that within this period range the attenuation derived from the Little Skull Mountain earthquake observations agreed quite well with NTS explosion experience, and this region-specific attenuation would be expected then to provide a better fit. Nevertheless, we find the agreement (within a factor of two) between the models within the short period band, up to almost 1-second period, is quite remarkable, particularly considering the simplicity of the assumptions used to develop some of the models, like the equivalent explosion model. It is only at long periods that we see divergence, with the three predictions all overestimating the observed response. One explanation for the differences seen here might be relatively poor excitation of longer-period surface waves or higher modes by the Little Skull Mountain earthquake because of a somewhat deeper than normal focal depth. We would certainly expect this to be the case for the equivalent explosion model because of the shallow explosion sources that contribute to the spectral shape there, but predictions based on the Geomatrix/ATC spectral shape are also significantly enhanced relative to the observations at periods from about 1 to 3 seconds. As described above, we have used the spectral estimate at the reference distance shown here for the Little Skull Mountain earthquake observations as the basis for our third ground motion prediction scheme. Thus, the PSRV spectrum labeled "LSM Observed" in Figure 4 serves as the reference spectral shape which we adjust for distance using NTS attenuation and scale with magnitude where necessary to provide our predictions.

We used the three explosion-based empirical models to compute 5-% damped PSRV spectral predictions for each of the eight strong motion sites from the Little Skull Mountain earthquake. For these calculations we used the magnitude of 5.68 M_W and the ranges to the stations measured from the surface projection of the fault - i.e. ranges between 12.9 km and 99.1 km. Figure 5 shows the spectra determined for the three modeling schemes at 12.9 km, the distance to the nearest station. The figure presents comparisons between the model predictions and the horizontal-component PSRV response spectra observed for the Little Skull Mountain earthquake at the Lathrop Wells site. The predictions all match the observations fairly well at periods up to about 1 second. At periods less than 0.1 seconds the predictions are tightly grouped and agree with the observations within a factor of about 1.4. Between periods of 0.1 and 1 second, there is somewhat more variability in the observations, but the predictions are generally within about a factor of 2. The best fit appears to be that provided by the Little Skull Mountain earthquake spectral shape scaled using the NTS attenuation, which provides a good fit to the two horizontal-component observations over nearly the entire period band shown, including longer periods. The other prediction schemes again tend to overestimate the observations at longer periods; the largest divergence from the observations is seen in the equivalent explosion prediction which overestimates by about a factor of 4 at periods near 2 seconds. Similar results were found respectively. For these two scenarios there is more variation in the spectral prediction between our explosion-based models, and the difference between the spectra for those models and the median of the physical models is greater. The biggest differences seem to be those in the middle plot (i.e. Rock Valley scenario). There the equivalent explosion and scaled Little Skull Mountain earthquake spectrum fall below the physical model median by about a factor of 2 to 3 over a fairly broad period band, while the modified Geomatrix/ATC predictions are up to a factor of 4 lower than the physical model median. The predictions are more in agreement for the Furnace Creek scenario earthquake (shown in the right-hand figure), where maximum differences between the physical model median spectrum and the equivalent explosion and scaled Little Skull Mountain predictions are again low but only by about a factor of 2 at short periods, less than 1 second. We would suggest that the larger differences between the explosion-based and physical model predictions for the two strike-slip scenario earthquakes may be largely attributable to attenuation differences, which appear enhanced at the larger distances for these events. As noted above, the NTS explosion experience appears to indicate stronger attenuation in this region than for California. The prediction comparisons here seem to indicate that the stronger attenuation in the NTS region is not being adequately accounted for in the physical models.

Summary and Conclusions Regarding the Explosion-Based Empirical Modeling Procedures

Our objective in this element of the project has been to identify how the extensive experience with strong ground motion from NTS underground nuclear explosions might be used to assist in assessing earthquake ground motion predictions for use in design at the Yucca Mountain site. As part of these investigations, we analyzed strong ground motion observations from the 1992 Little Skull Mountain earthquake and compared those to the NTS explosion experience. Three explosion-based empirical models which take advantage of the NTS explosion experience as well as ground motion characteristics observed from the Little Skull Mountain earthquake were developed. We have applied these explosion-based empirical models to predict ground motions for the Little Skull Mountain earthquake and compared the results to observations as a test of the modeling procedures. The same models were then used to predict ground motions for several postulated scenario earthquakes which are being considered in assessing seismic design for the Yucca Mountain site.

In general, we find that the explosion-based empirical models do a fairly good job of predicting earthquake strong ground motion response spectra when compared to the Little Skull Mountain earthquake observations and to the alternative empirical and physical model predictions. With regard to specific model performance, we found that spectral predictions developed for our simple equivalent explosion model agreed surprisingly well with other prediction methods. Predictions based on the Little Skull Mountain earthquake spectral shape were generally found to be anomalously low at long periods compared to the other empirical prediction methods and to the physical model predictions; this might be associated with anomalous source depth. However, at periods below about 1 second, all three explosion-based models agree fairly well among themselves, with other empirical earthquake models, and with observations from the Little Skull Mountain earthquake, particularly at the nearer recording sites. Analyses of the 1992 Little Skull Mountain earthquake strong motion records indicate that the observed attenuation is not significantly different from that based on NTS explosion experience, so we would conclude that the explosion experience should play a role in assessing strong motion attenuation from postulated earthquakes in the region. This might be important considering that stronger attenuation in the NTS region does not appear to be properly accounted for in the physical models, particularly for more distant scenarios.

greater attenuation in the modified model, as discussed above. The plot on the right illustrates the steps in the process of scaling the Little Skull Mountain earthquake spectrum to the appropriate range and magnitude. Comparing the final predictions we note that the prediction based on the scaled Little Skull Mountain earthquake spectrum lies above the standard Geomatrix/ATC model prediction (by about a factor of 1.5 to 2) over the short period band, 0.05 to 0.3 seconds; while above 0.6 seconds the scaled Little Skull Mountain spectrum falls below the standard model predictions.

Figure 7 presents a similar set of predictions for the Furnace Creek fault scenario earthquake with a magnitude of 7.04 M_W and range of 52 km (9 km focal depth). The equivalent explosion spectrum generally agrees quite well with the standard Geomatrix/ATC spectral prediction over nearly the entire period band; maximum differences are less than a factor of about 1.5. For the modified Geomatrix/ATC model, we see in the middle plot that the predicted spectrum falls consistently below the standard model prediction by about a factor of 2. The differences are again apparently due to the stronger attenuation based on the NTS explosion experience; such differences tend to appear enhanced at the relatively large range for this scenario. Finally, the plot on the right in Figure 7 compares the scaled Little Skull Mountain earthquake spectrum with the standard Geomatrix/ATC model spectrum. The two predictions match very closely at short periods, 0.05 to 0.5 seconds. However, the spectral shapes are quite different; so that the scaled Little Skull Mountain prediction falls below the standard model spectrum by up to a factor of 3 at longer periods, above about 0.5 seconds.

As described elsewhere in this report, a number of physical fault rupture models were also used to provide strong ground motion predictions for the scenario earthquakes associated with the faults in the vicinity of the Yucca Mountain site. In Figure 8 we show a few examples of comparisons between those physical model results and the predictions developed for the explosion-based empirical models. The physical model spectra shown in each of these comparisons correspond to the median values determined from the spectral estimates derived from multiple realizations of four different physical models for each scenario. The four physical models contributing to the estimates shown here were (1) the barrier source model implemented by the University of Southern California, (2) the composite fractal source method used by the University of Nevada - Reno, (3) the stochastic method with subevents used by Pacific Engineering and Analysis, and (4) the broadband Green's function method used by Woodward-Clyde Consultants. As noted, the spectrum shown in each plot for these physical models is a median value and variations in the estimates, attributable to methodological differences and uncertainty in source parameter specification and attenuation, may be quite large, as evidenced by scatter between realizations.

The plot on the left in Figure 8 compares the explosion-based empirical model predictions determined for an earthquake with magnitude of 6.4 M_W at a range of 6.0 km with the prediction from the physical model. This prediction corresponds to the Paintbrush Canyon fault scenario earthquake for which we assumed a focal depth of 6 km. It should be noted that the plots in this figure correspond to 5-% damped acceleration response spectra in g's. Somewhat surprisingly the match between the spectra determined using our simple explosion-based empirical models and the median for the physical model spectrum is remarkably good. This is particularly notable considering that the estimates are for a close range site where the physical models would be expected to do a better job of accounting for near-source effects like radiation pattern which are disregarded in the explosion-based empirical models. At most periods the differences seen in the plot on the left amount to less than a factor of 2. Both the equivalent explosion and the scaled Little Skull Mountain earthquake spectra agree quite closely with the physical model prediction at short periods, 0.05 up to 0.2 seconds. Differences at longer periods are somewhat greater, particularly for the scaled Little Skull Mountain spectral prediction. However, even there it would appear that the uncertainty bounds about the median for the physical models probably envelope the explosion-based model predictions.

The middle and right-hand plots in Figure 8 correspond to the two strike-slip scenario earthquakes associated with the Rock Valley (6.71 M_W) and Furnace Creek (7.04 M_W) faults

Figure Captions

Figure 1 Comparison of 5-% damped PSRV spectra predictions at a range of 10 km for the NTS equivalent explosion model for different moment magnitudes in the range of interest.

Figure 2 Comparison of standard Geomatrix/ATC 5-% damped PSRV spectral predictions with predictions produced using the Geomatrix/ATC spectral shape at 10 km scaled with distance using NTS explosion attenuation experience. Note the two predictions coincide at the nominal reference distance of 10 km.

Figure 3 Comparison of distance attenuation exponents and their 95-% confidence limits for NTS explosion experience and Little Skull Mountain (LSM) earthquake observations. NTS experience falls within the larger confidence limits about the LSM average (left), while LSM attenuation falls within or just above the smaller confidence limits surrounding average NTS experience (right).

Figure 4 Comparison of 5-% damped PSRV spectral predictions for three models with the spectrum at R = 35.7 km derived from the power law model applied to the Little Skull Mountain earthquake observations.

Figure 5 Comparison of 5-% damped PSRV spectral predictions for the three explosion-based empirical models with the spectra observed at the Lathrop Wells site (R = 12.9 km) for the Little Skull Mountain earthquake.

Figure 6 Comparison of 5-% damped PSRV spectral predictions for the base case normal scenario earthquake (Mw = 6.4) for the Yucca Mountain site at a range of 9.1 km for the equivalent explosion model (left), modified Geomatrix/ATC model (center), and Little Skull Mountain earthquake spectral shape scaled with NTS attenuation and Geomatrix/ATC magnitude dependence (right). For reference the model results are compared to similar spectral predictions based on the standard Geomatrix/ATC empirical model.

Figure 7 Comparison of 5-% damped PSRV spectral predictions for the Furnace Creek fault strike-slip scenario earthquake (Mw = 7.04) for the Yucca Mountain site at a range of 52 km for the equivalent explosion model (left), modified Geomatrix/ATC model (center), and Little Skull Mountain earthquake spectral shape scaled with NTS attenuation and Geomatrix/ATC magnitude dependence (right). For reference the model results are compared to similar spectral predictions based on the standard Geomatrix/ATC empirical model.

Figure 8 Comparison of 5-% damped acceleration response spectral predictions for the three explosion-based empirical models with the median of the spectral predictions determined from four physical models for the Solitario Canyon fault scenario earthquake (left), the Rock Valley fault scenario earthquake (center), and the Furnace Creek fault scenario earthquake (right).

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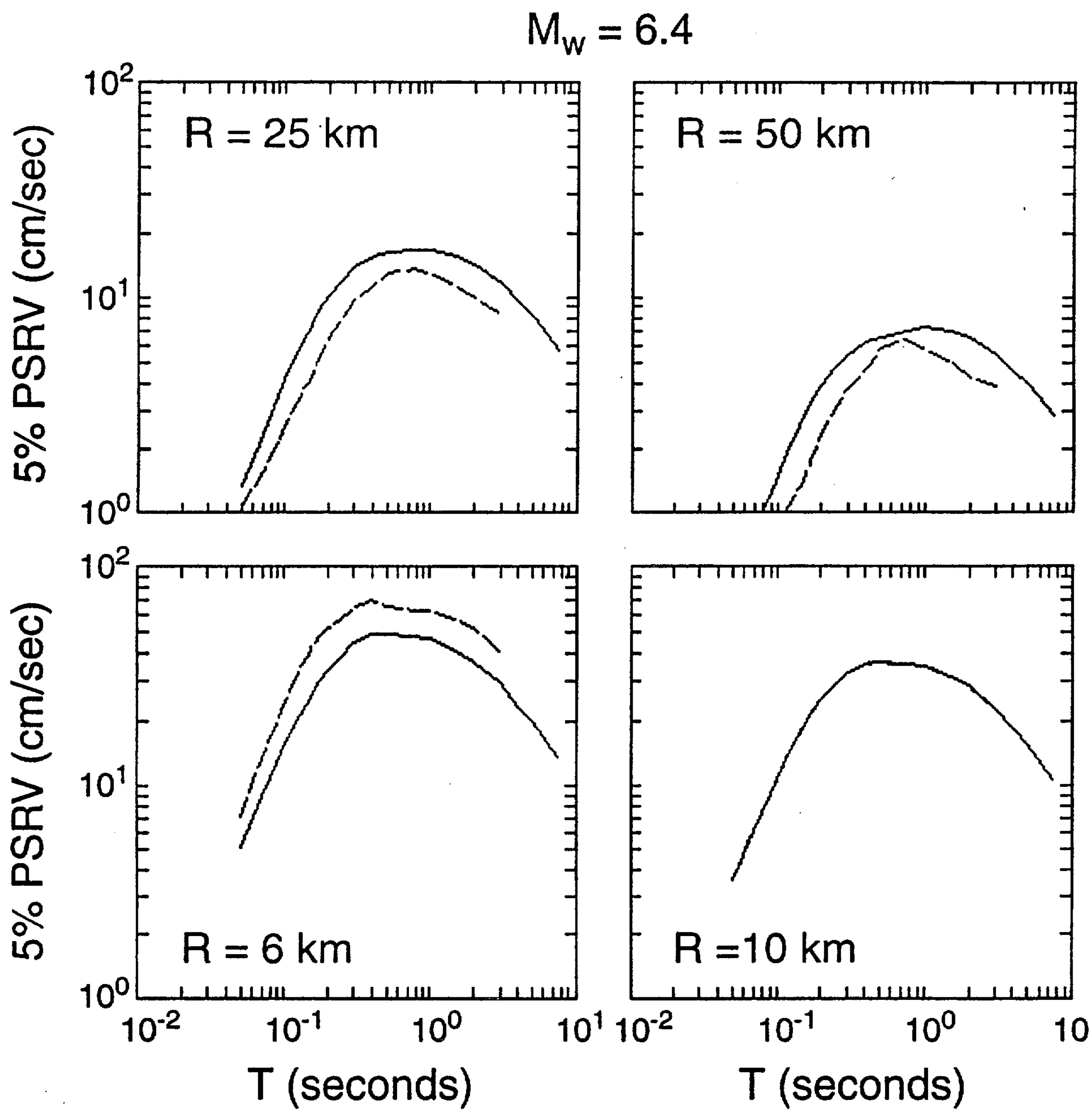
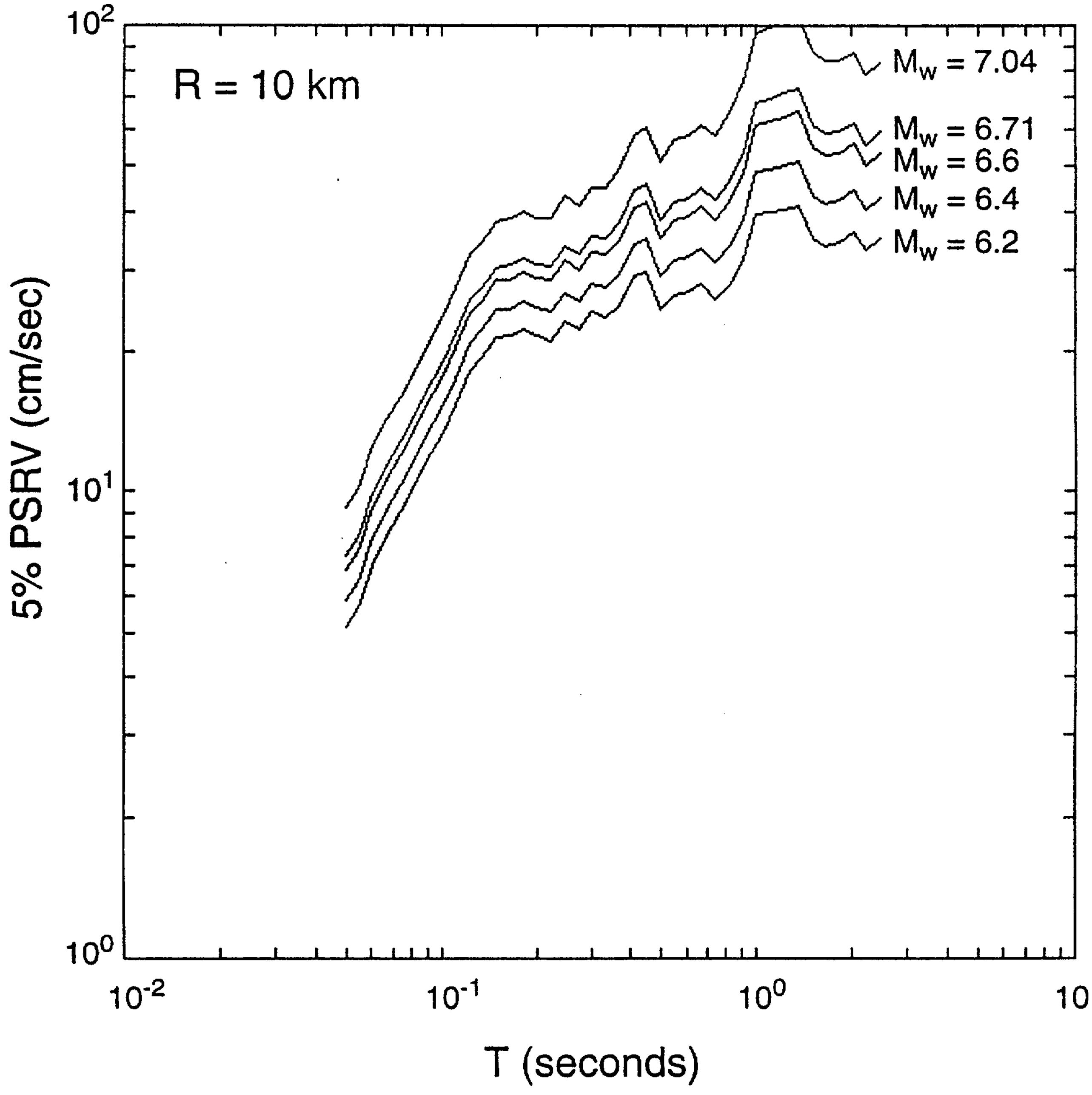
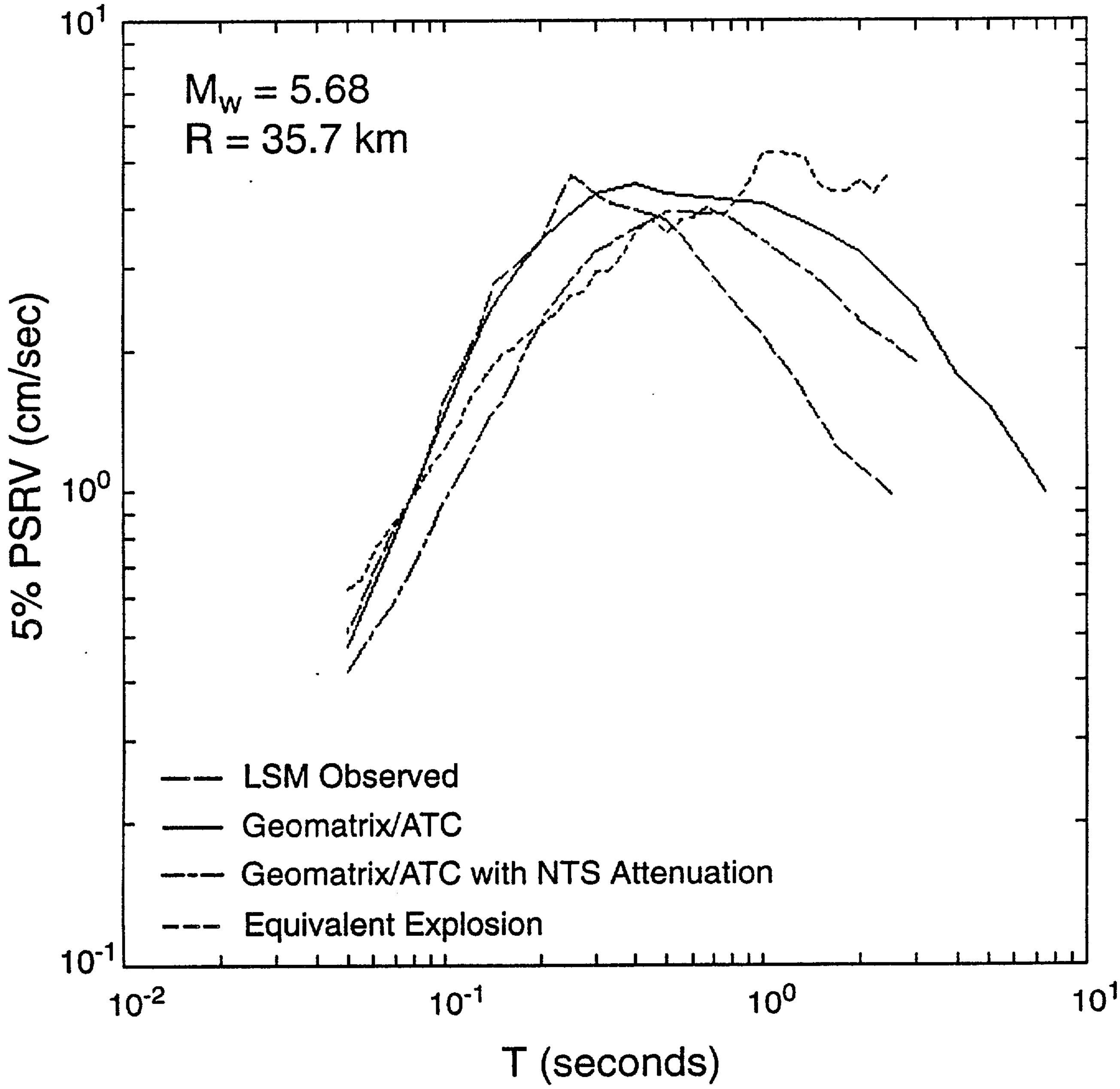


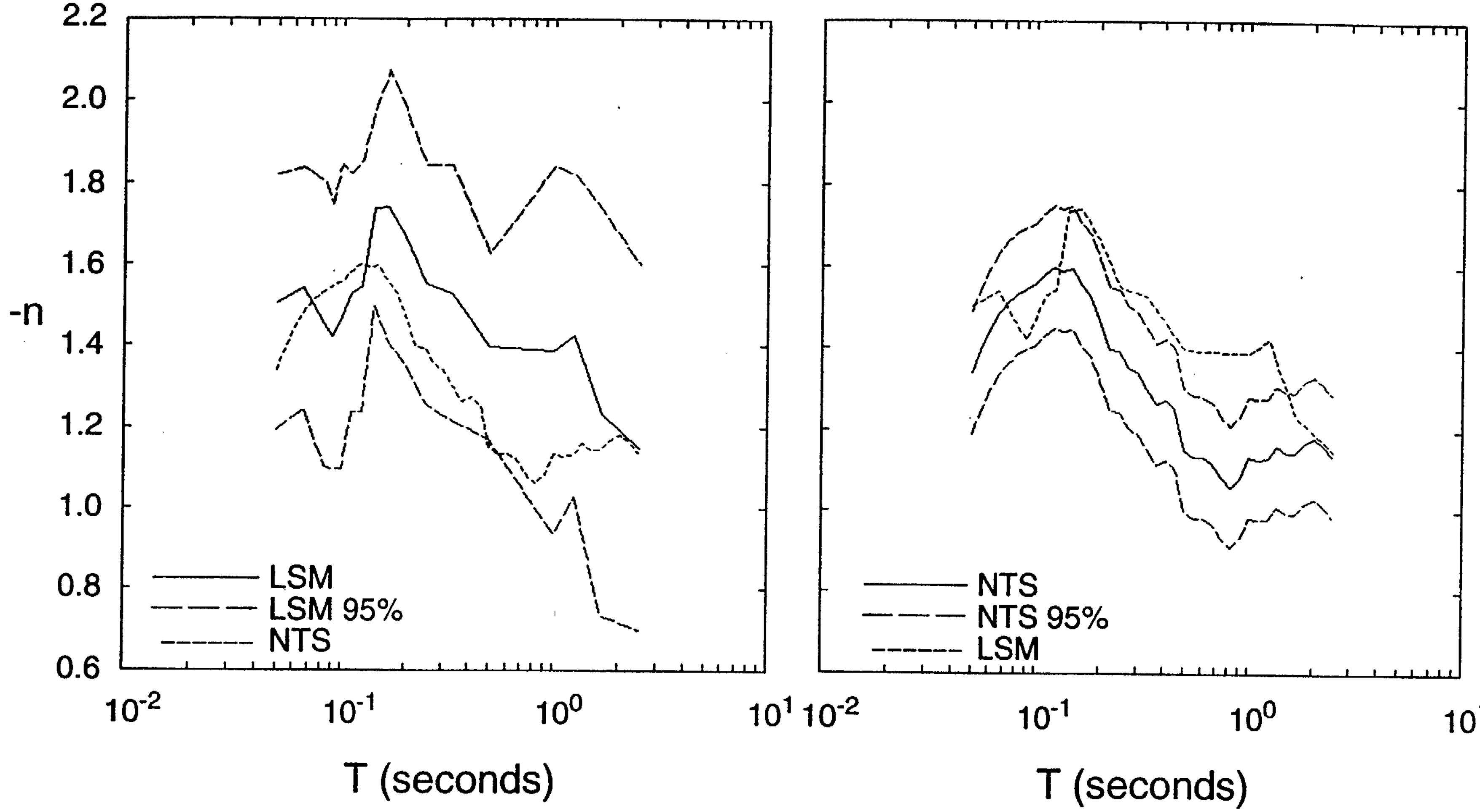
M_W = 6.4
R = 25 km
R = 50 km
R = 6 km
R =10 km
5% PSRV (cm/sec)
5% PSRV (cm/sec)
T (seconds)
T (seconds)
10^0
10^1
10^2
10^-2
10^-1
10^0
10^1



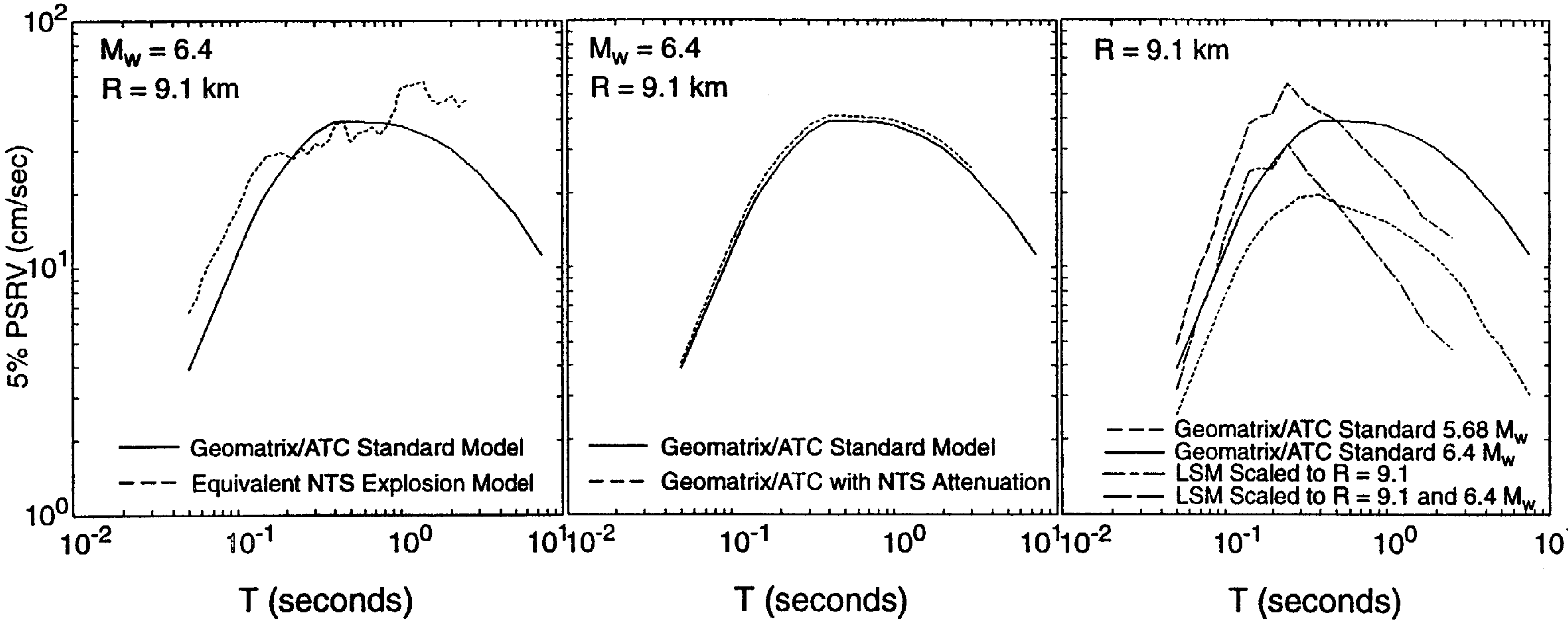
R = 10 km
M_w = 7.04
M_w = 6.71
M_w = 6.6
M_w = 6.4
M_w = 6.2
5% PSRV (cm/sec)
10^2
10^1
10^0
10^{-2}
10^{-1}
10^0
10^1
T (seconds)



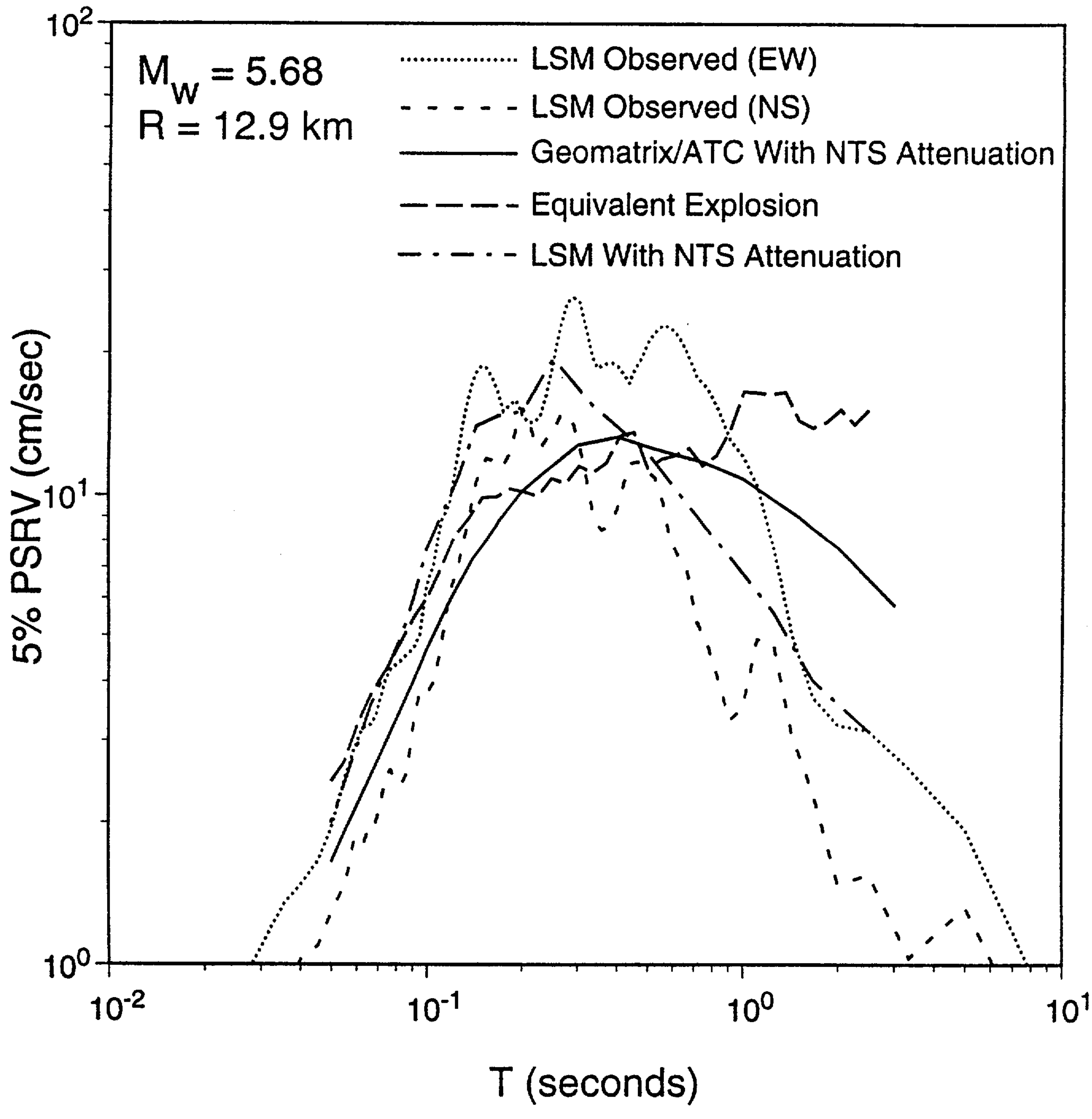
$M_w = 5.68$
R = 35.7 km
5% PSRV (cm/sec)
T (seconds)
LSM Observed
Geomatrix/ATC
Geomatrix/ATC with NTS Attenuation
Equivalent Explosion
10^{1}
10^{0}
10^{-1}
10^{-2}



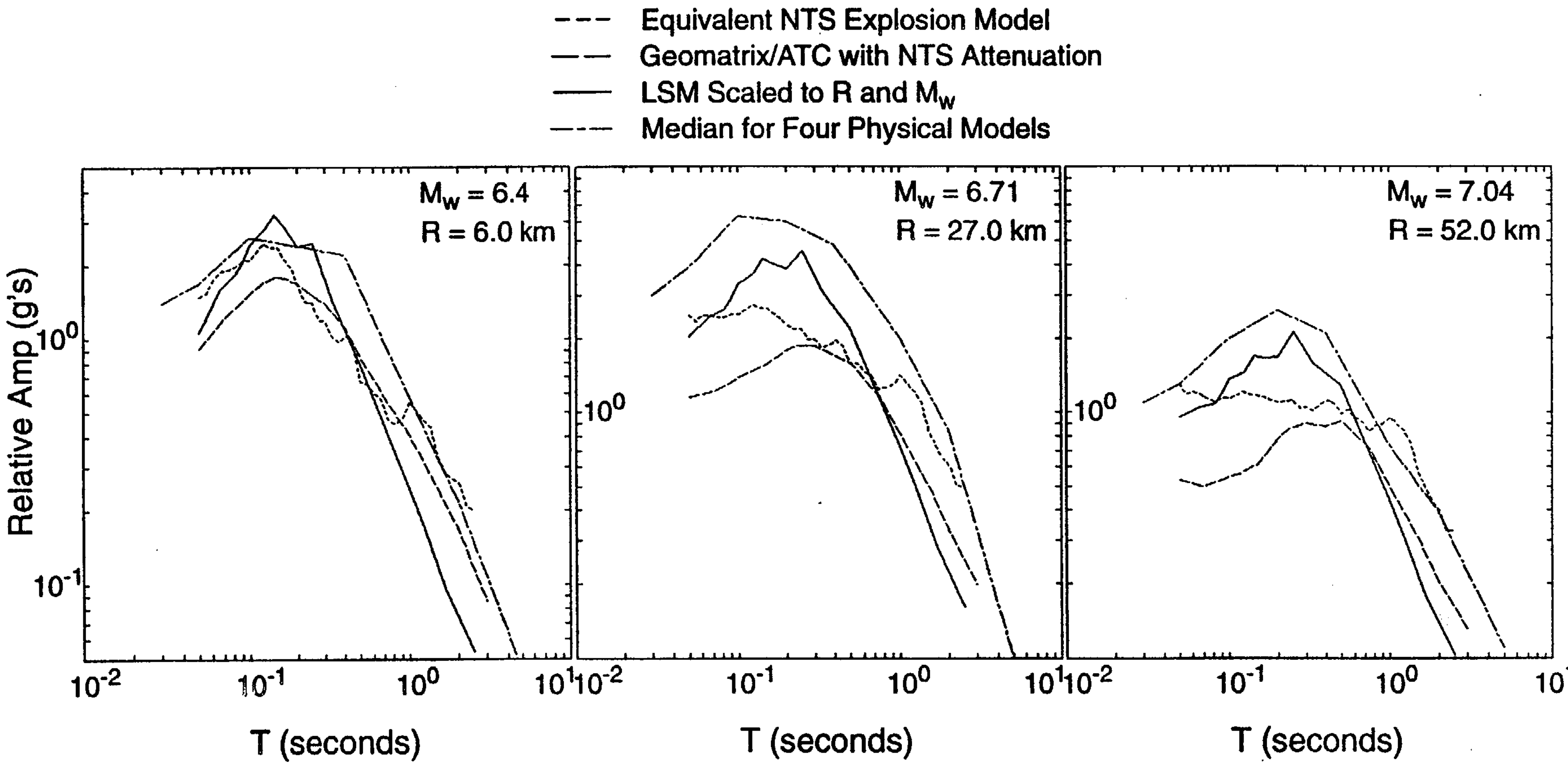
2.2
2.0
1.8
1.6
-n
1.4
1.2
1.0
0.8
0.6
LSM
LSM 95%
NTS
10^{-2}
10^{-1}
10^{0}
10^{1}
T (seconds)
NTS
NTS 95%
LSM
10^{-2}
10^{-1}
10^{0}
10^{1}
T (seconds)



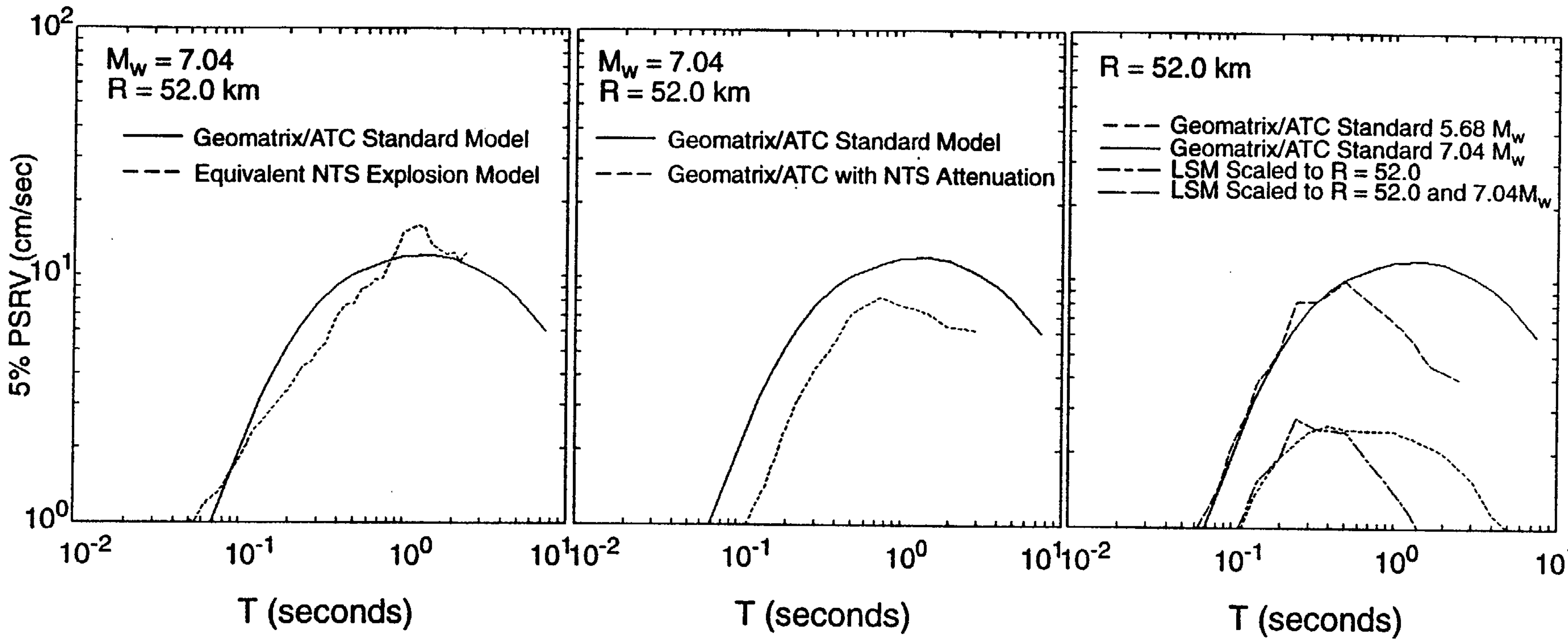
$M_w = 6.4$
R = 9.1 km
Geomatrix/ATC Standard Model
Equivalent NTS Explosion Model
$M_w = 6.4$
R = 9.1 km
Geomatrix/ATC Standard Model
Geomatrix/ATC with NTS Attenuation
R = 9.1 km
Geomatrix/ATC Standard 5.68 M_w
Geomatrix/ATC Standard 6.4 M_w
LSM Scaled to R = 9.1
LSM Scaled to R = 9.1 and 6.4 M_w
5% PSRV (cm/sec)
T (seconds)



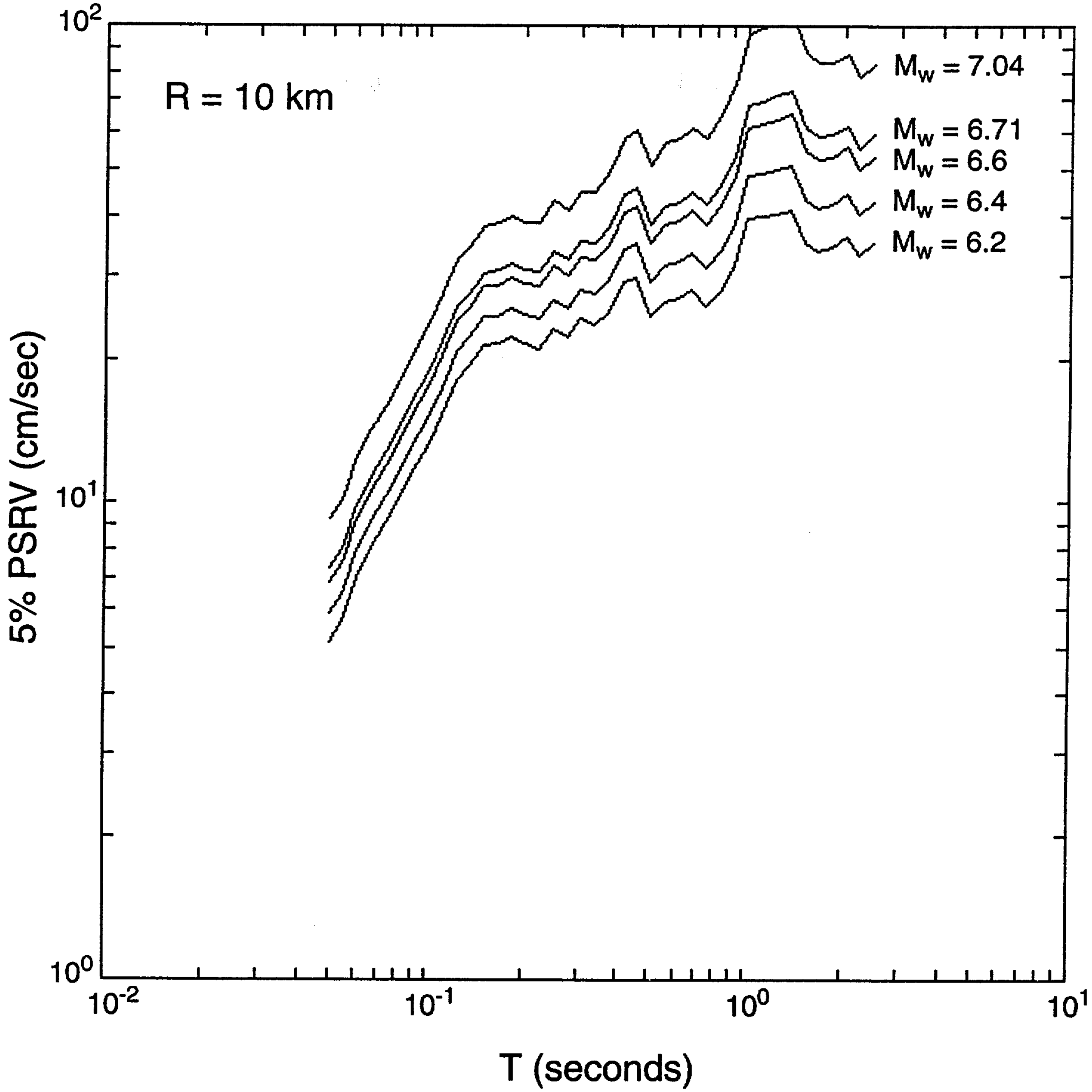
M_w = 5.68
R = 12.9 km
LSM Observed (EW)
LSM Observed (NS)
Geomatrix/ATC With NTS Attenuation
Equivalent Explosion
LSM With NTS Attenuation
5% PSRV (cm/sec)
10²
10¹
10⁰
10⁻²
10⁻¹
10⁰
10¹
T (seconds)



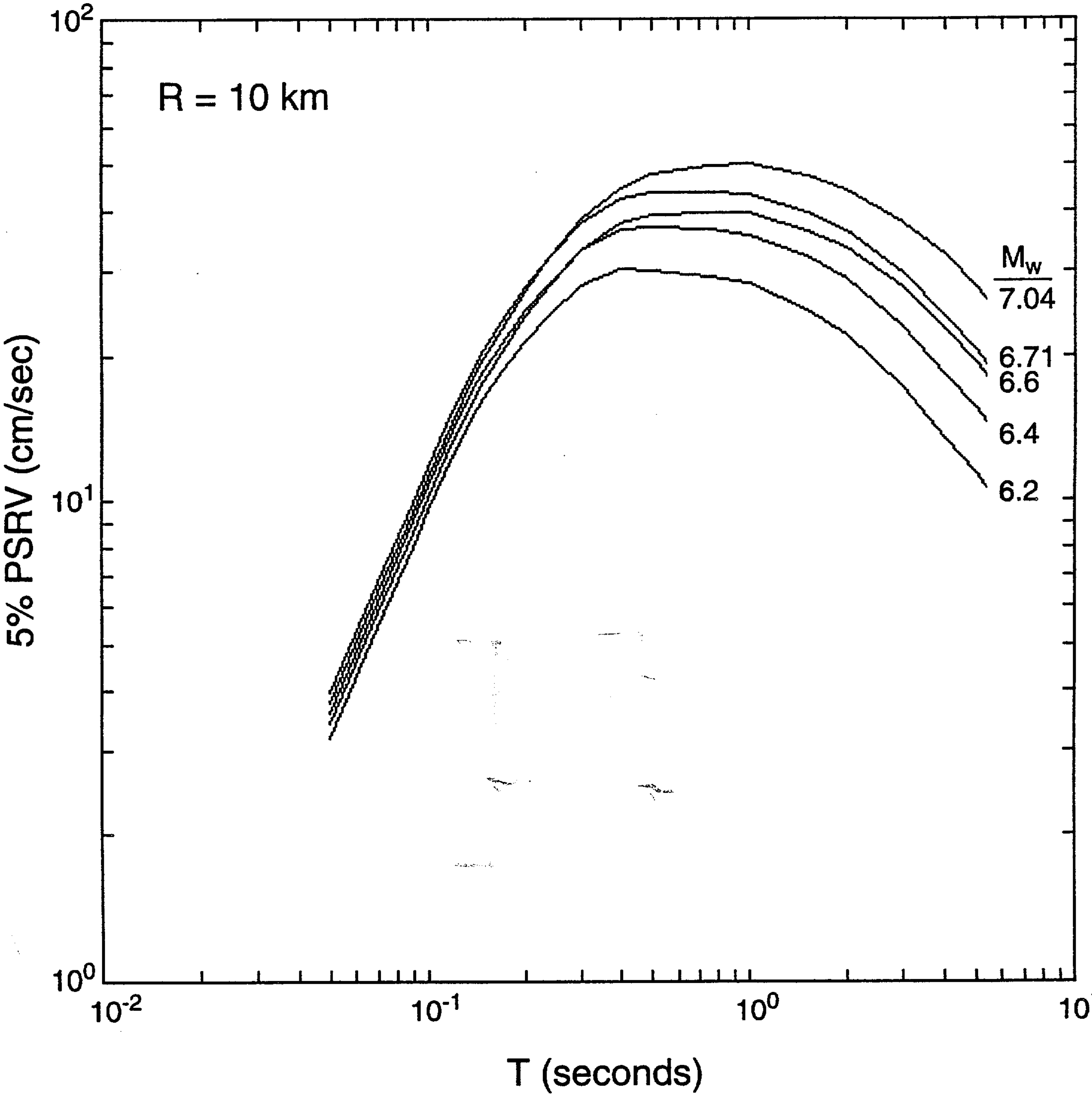
Equivalent NTS Explosion Model
Geomatrix/ATC with NTS Attenuation
LSM Scaled to R and M_w
Median for Four Physical Models
$M_w = 6.4$
R = 6.0 km
$M_w = 6.71$
R = 27.0 km
$M_w = 7.04$
R = 52.0 km
Relative Amp (g's)
10^0
10^{-1}
10^{-2}
10^{1}
T (seconds)
T (seconds)
T (seconds)



10^2
10^1
10^0
5% PSRV (cm/sec)
$M_w = 7.04$
R = 52.0 km
Geomatrix/ATC Standard Model
Equivalent NTS Explosion Model
$M_w = 7.04$
R = 52.0 km
Geomatrix/ATC Standard Model
Geomatrix/ATC with NTS Attenuation
R = 52.0 km
Geomatrix/ATC Standard 5.68 M_w
Geomatrix/ATC Standard 7.04 M_w
LSM Scaled to R = 52.0
LSM Scaled to R = 52.0 and 7.04M_w
10^{-2}
10^{-1}
10^0
10^1
T (seconds)
T (seconds)
T (seconds)



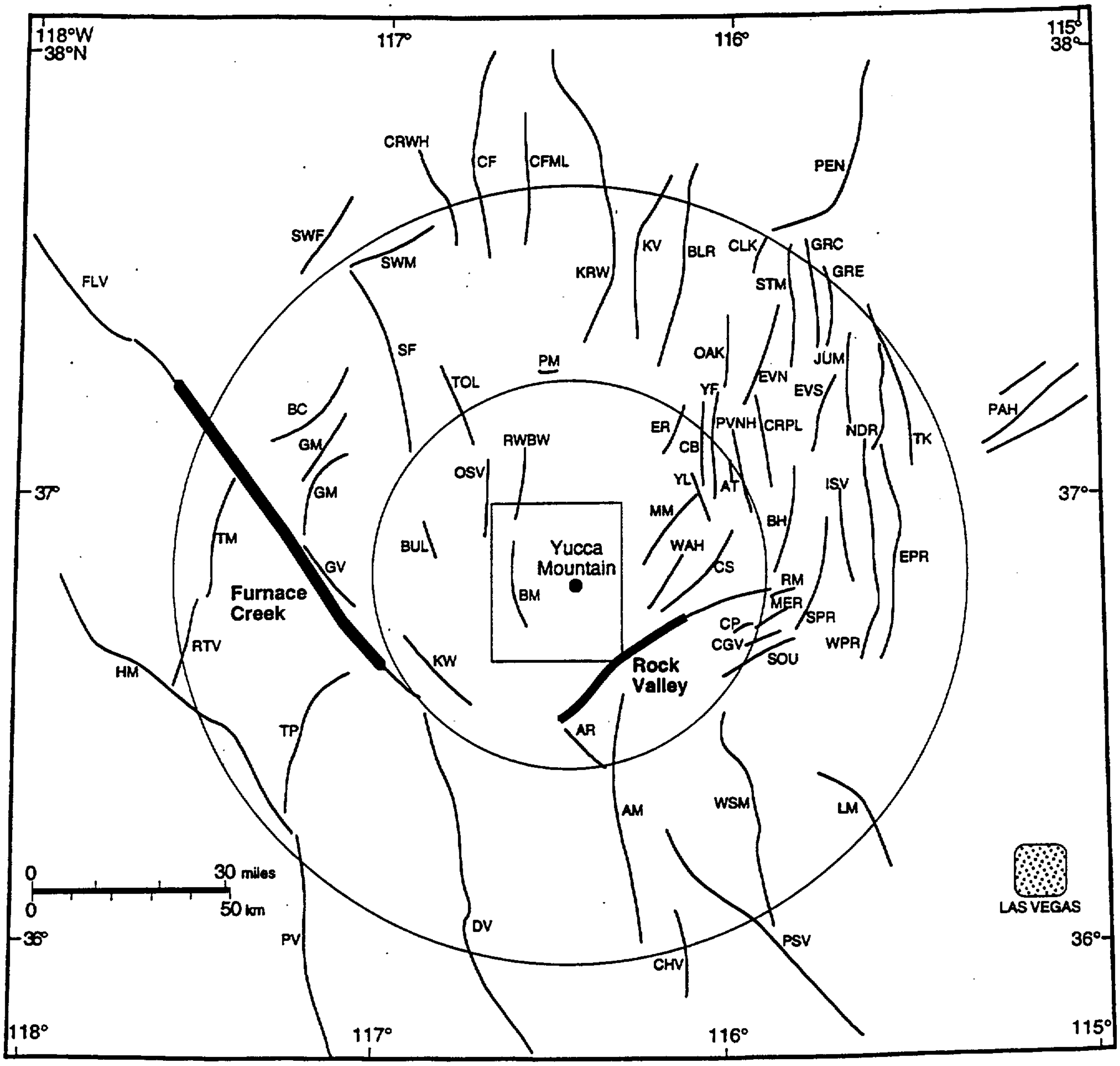
Comparison of 5% PSRV spectra predictions for NTS equivalent explosion model for different moment magnitudes in range of interest.

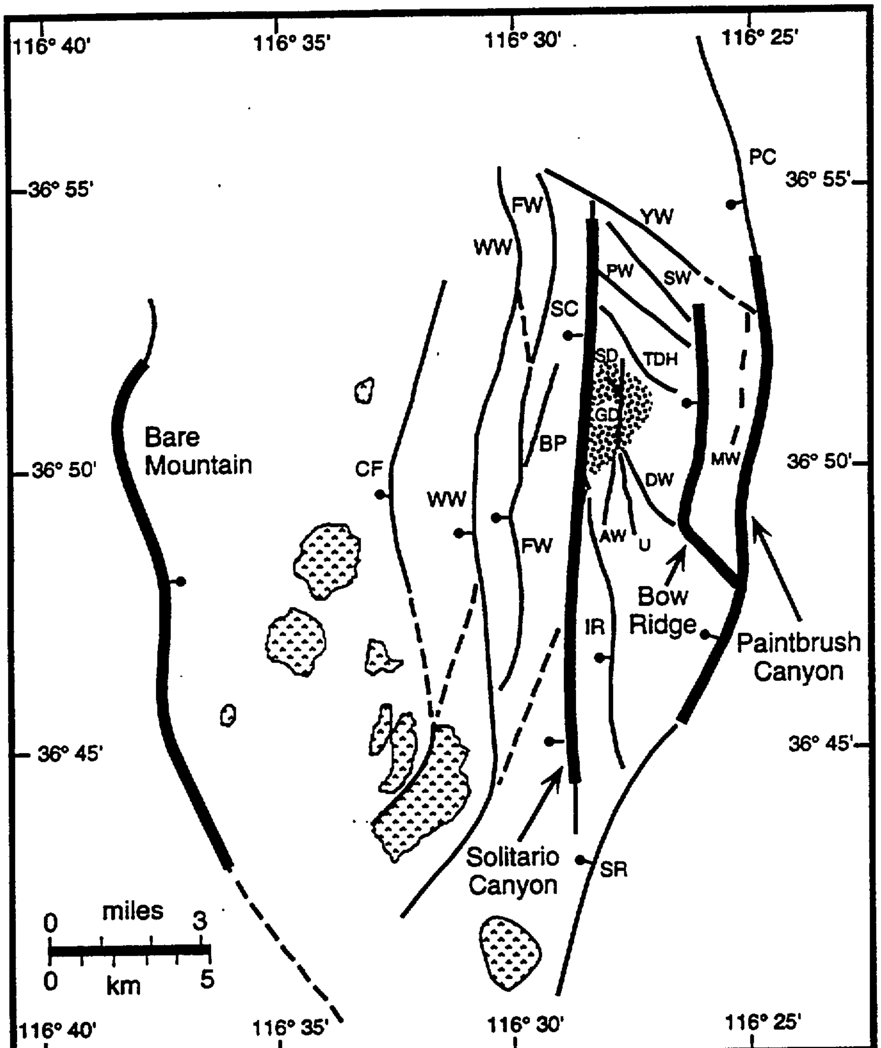


Comparison of 5% PSRV spectra predictions for Geomatrix/ATC standard model for different moment magnitudes in range of interest.

Scenario Earthquake Study Results

Norm Abrahamson
Jan 10, 1997


118°W
38°N
117°
116°
115°
38°
37°
36°
FLV
CRWH
CF
CFML
PEN
SWF
SWM
KRW
KV
BLR
CLK
GRC
GRE
STM
SF
TOL
PM
OAK
JUM
EVN
EVS
YF
PAH
BC
GM
ER
PVNH
CRPL
NDR
TK
RWBW
CB
OSV
YL
AT
ISV
GM
MM
BH
TM
BUL
WAH
Yucca
Mountain
EPR
GV
CS
Furnace
Creek
BM
RM
MER
SPR
RTV
CP
CGV
WPR
KW
Rock
Valley
SOU
HM
TP
AR
AM
WSM
LM
0
30 miles
0
50 km
LAS VEGAS
PV
DV
PSV
CHV
118°
117°
116°
115°



EXPLANATION

Potential Repository Area

Quaternary volcanic centers

FAULT SYMBOLS

Abbreviation	Fault Name	Abbreviation	Fault Name
AW	Abandoned Wash	PC	Paintbrush Canyon
BM	Bare Mountain	PW	Pagany Wash
BP	Boomerang Point	SC	Solitario Canyon
BR	Bow Ridge	SD	Sundance
CF	Crater Flat	SR	Stagecoach Road
DW	Dune Wash	SW	Sever Wash
FW	Fatigue Wash	TDH	Teacup-Drill Hole Wash
GD	Ghost Dance	U	unnamed
IR	Iron Ridge	WW	Windy Wash
MW	Midway Valley (buried fault)	YW	Yucca Wash

Table 3.3 Summary of physical modeling methods

Model	Modeling Method		
	Source	Path	Site
USC	• finite specific barrier model; Brune sub-event • BLWN RVT • fmax	• 1/R geometrical spreading and Q(f)	• S-wave amplification factors (Boore, 1986) (high freq atten in source)
USGS	• finite model with stochastic Brune source function; phase randomized over several realizations • Kostrov slip-velocity function	• 1/R geometric spreading and Q (f)	• 1-D crustal amplification factor and kappa
S-cubed	• empirical ground motion models based upon NTS data, modified to account for differences between earthquake and explosion sources	• explosion-based attenuation functions	• explosion-based site response

Table 3.3 (continued) Summary of physical modeling methods.

Model	Modeling Method		
	Source	Path	Site
PEA	• finite with BLWN RVT • finite slip distrib. from f-k model • constant rupture velocity, randomized rise time, average radiation	• 1/R geometrical spreading, or 1-D or 2-D Ou & Herrmann	• kappa/ equiv. linear for non-linear site-specific response
WCC	• finite with slip dist. from f-k model • variable rake angle, rise time, radiation • low f: continuous slip function w/ theoretical radiation pattern • high f: discretized grid w/ empirical source functions, corrected to the source	• low f: Green functions from f-k integration, complete response and Q for layered medium • high f: simplified Green functions from G-R theory, dominant rays and Q for layered medium • 2- and 3-D modeled with G-R for high f and finite diff. for low f.	• incorporated in empirical Green's functions, corrected for kappa. • normally elastic; equiv-lin. analysis possible

Table 3.3 (continued) Summary of physical modeling methods.

Model	Modeling Method		
	Source	Path	Site
UNR	• composite finite model; superposition of circular sub-events with fractal distribution	• 1-D Green functions • scattering	• 2 approaches: elastic model of site-specific soil profile; or amplification factors and Kappa

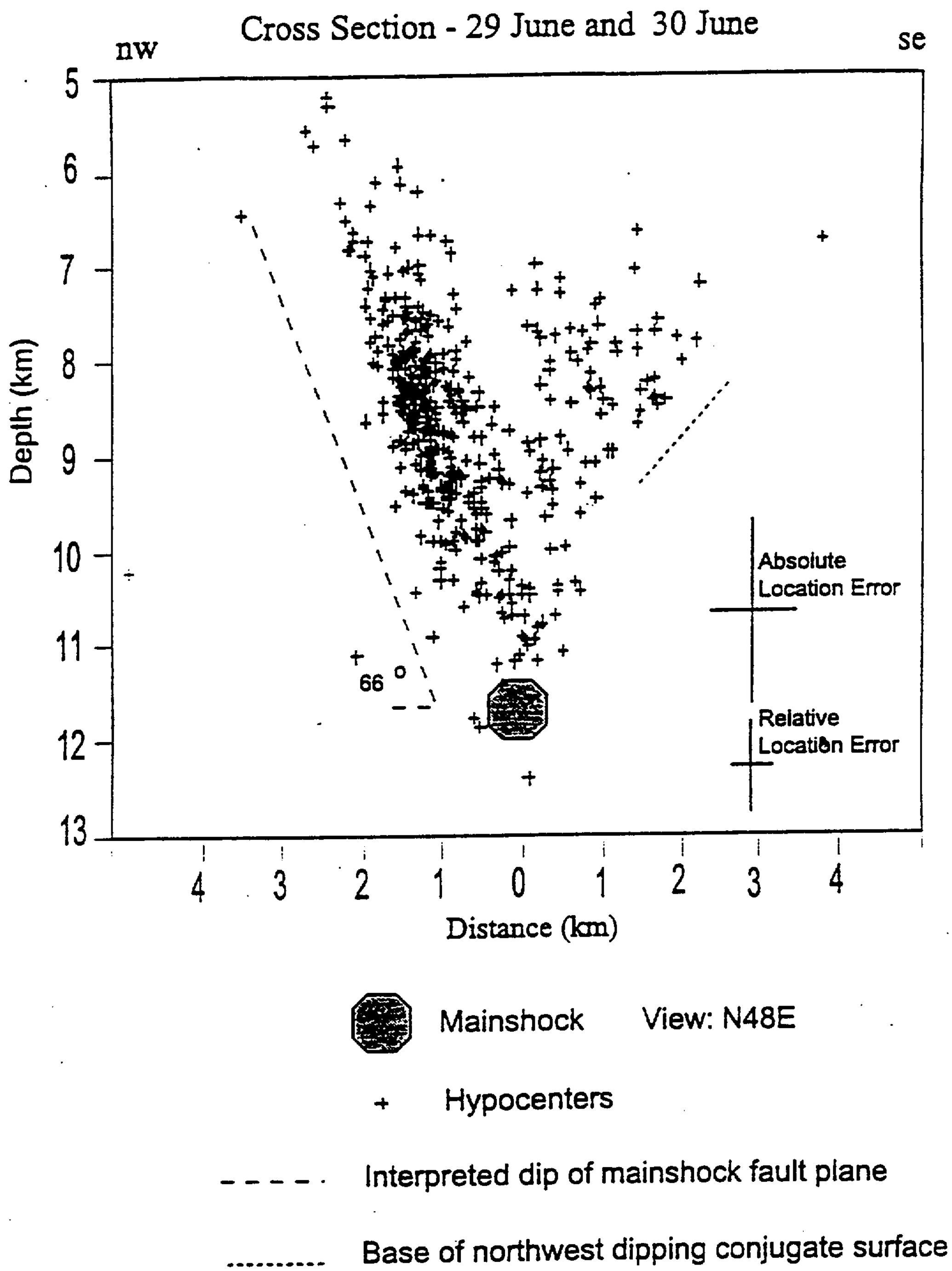


Figure 6.2. Estimated fault areas superimposed upon a vertical cross section of Little Skull Mountain aftershock locations.

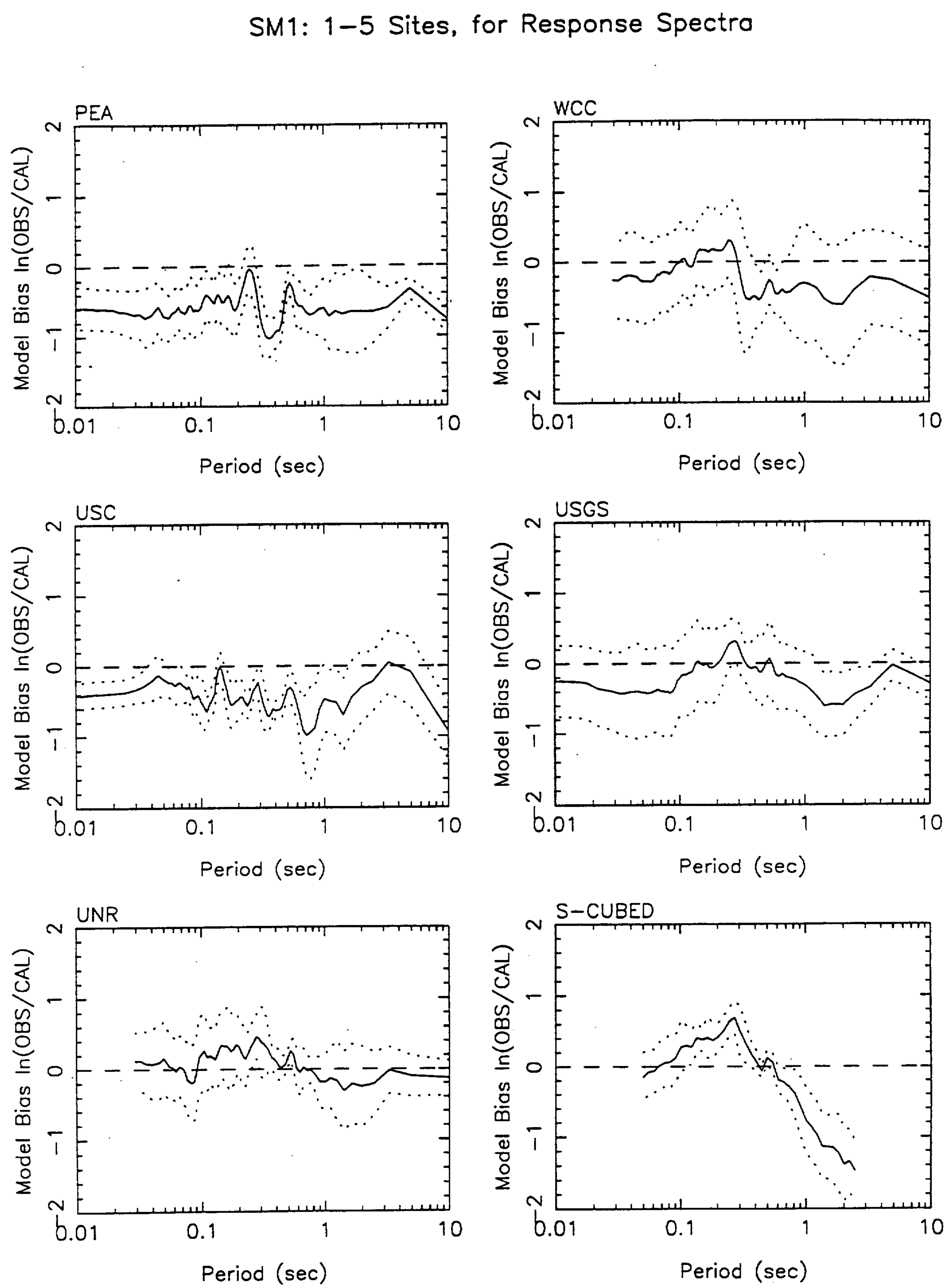


Figure 6.16. Model bias of observed relative to calculated response spectra for SM1. Negative model bias corresponds to overprediction of calculated response. Dotted lines represent ±1σ bounds.

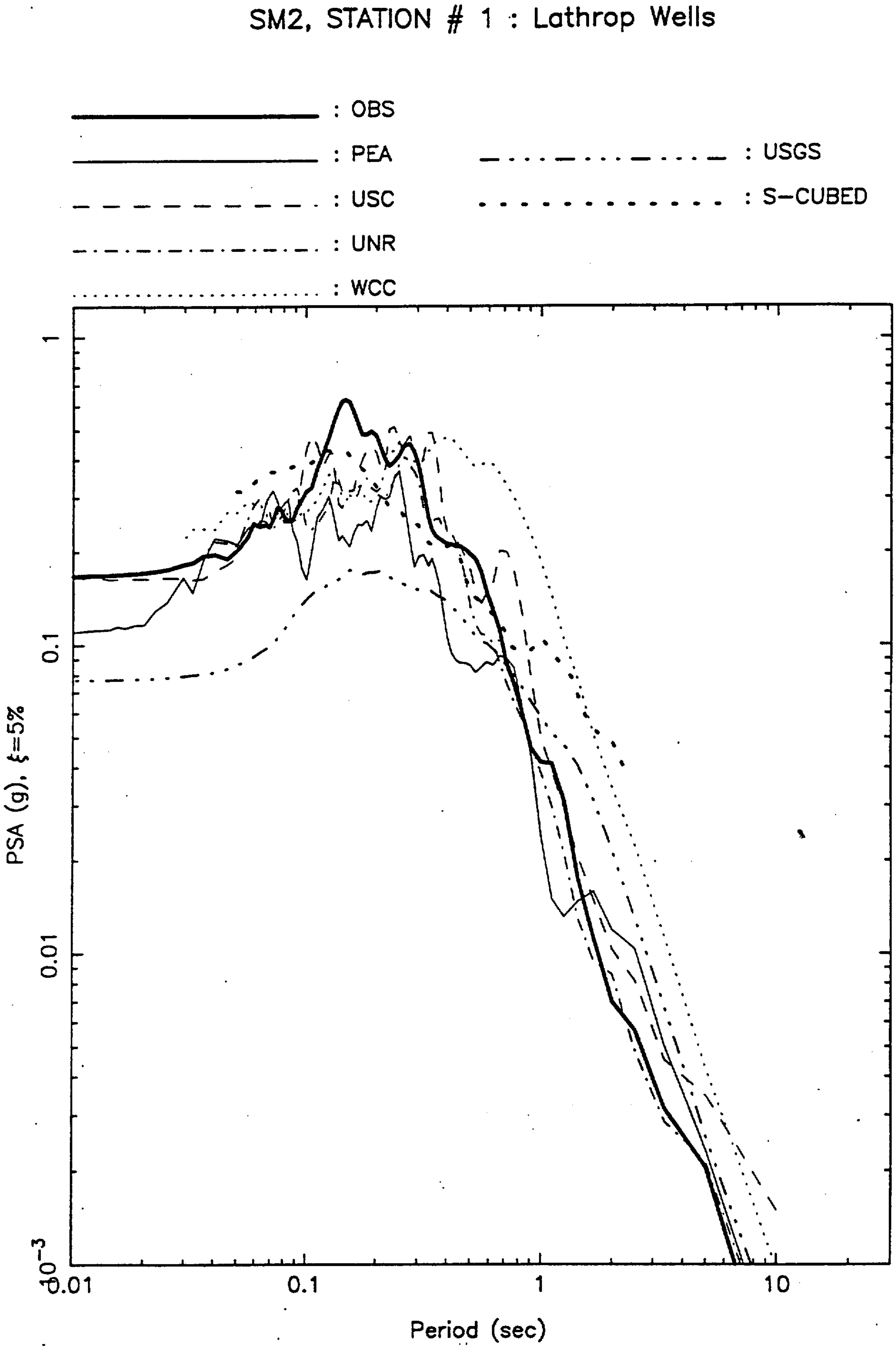


Figure 6.19 Calculated versus observed 5% damped acceleration response spectra for Station 1 (Lathrop Wells) for the Little Skull Mountain Exercise SM2 (preferred case).

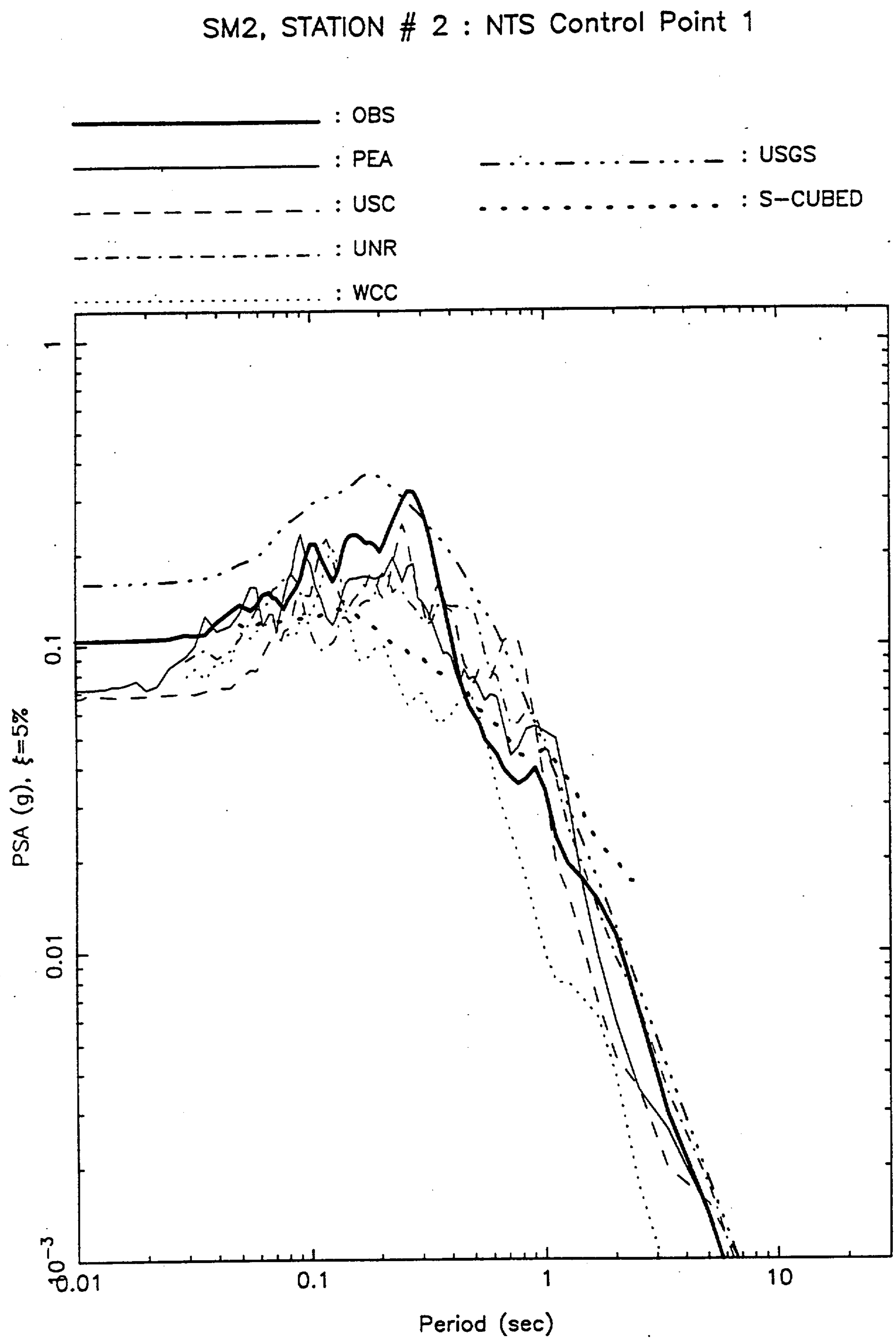


Figure 6.20 Calculated versus observed 5% damped acceleration response spectra for Station 2 (NTS Control Point 1) for the Little Skull Mountain Exercise SM2.

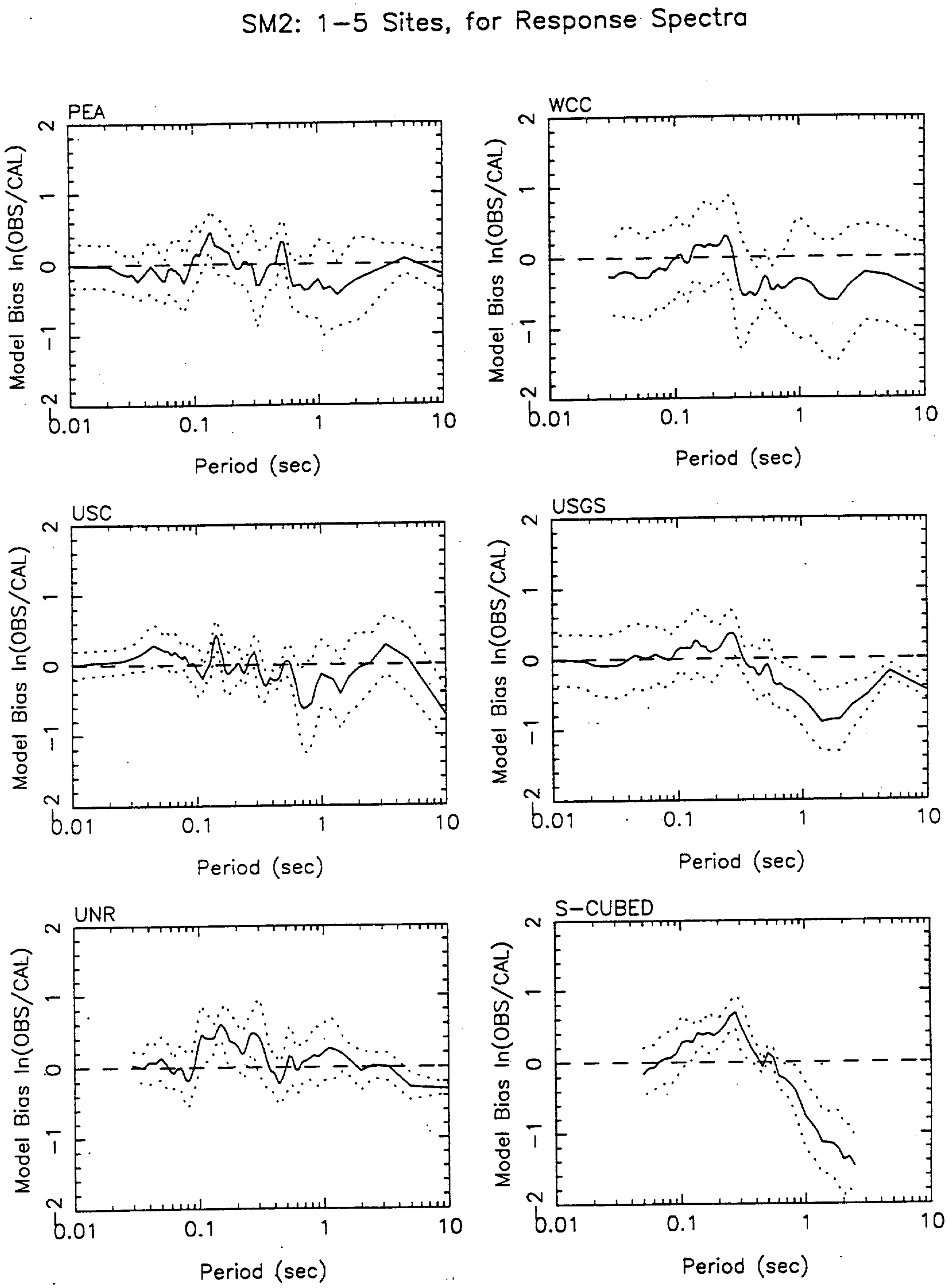


Figure 6.25 Model bias of observed relative to calculated response spectra for the Little Skull Mountain Exercise SM2.

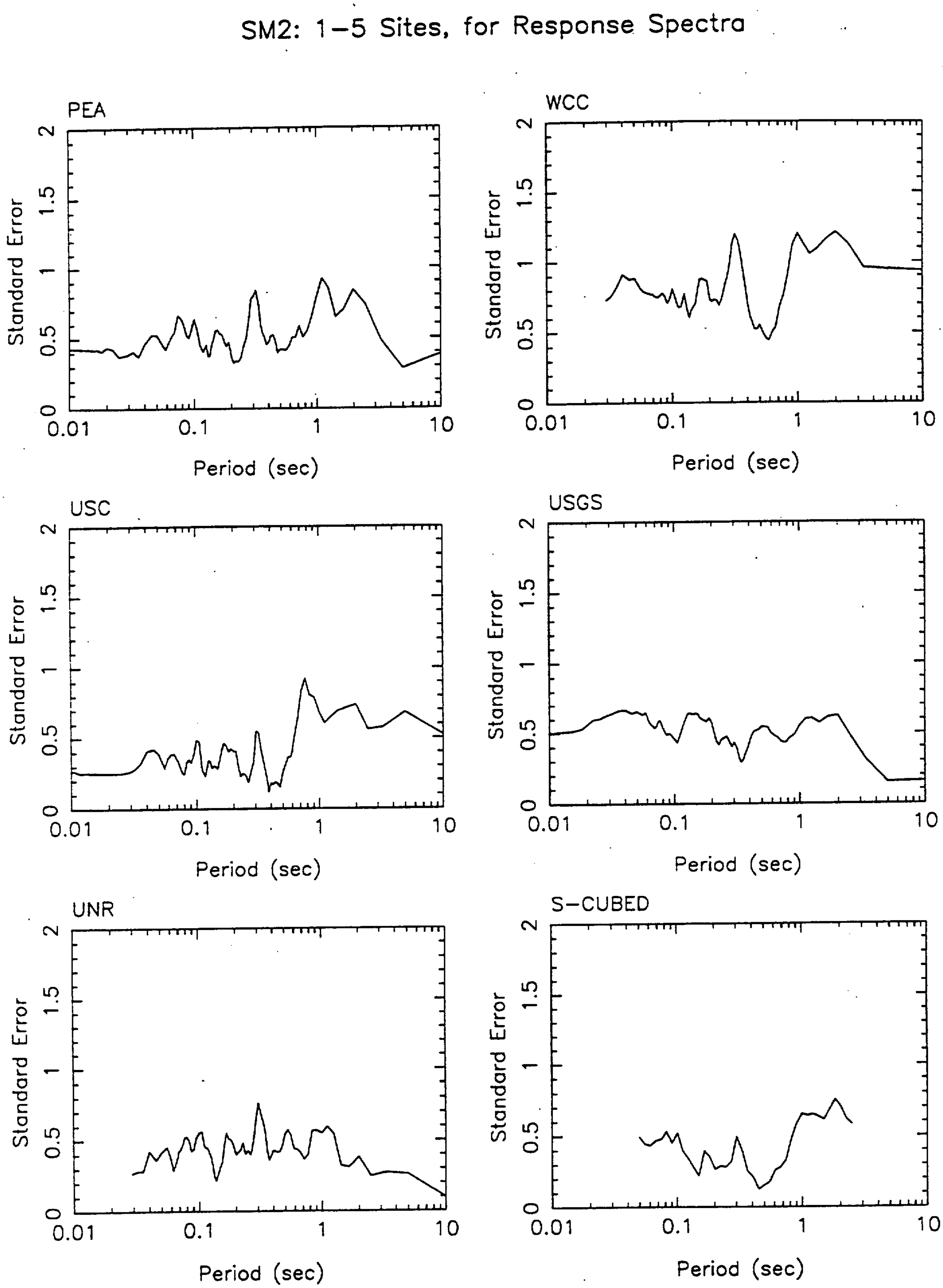


Figure 6.24 Standard error of observed versus calculated acceleration response spectra for the Little Skull Mountain Exercise SM2.

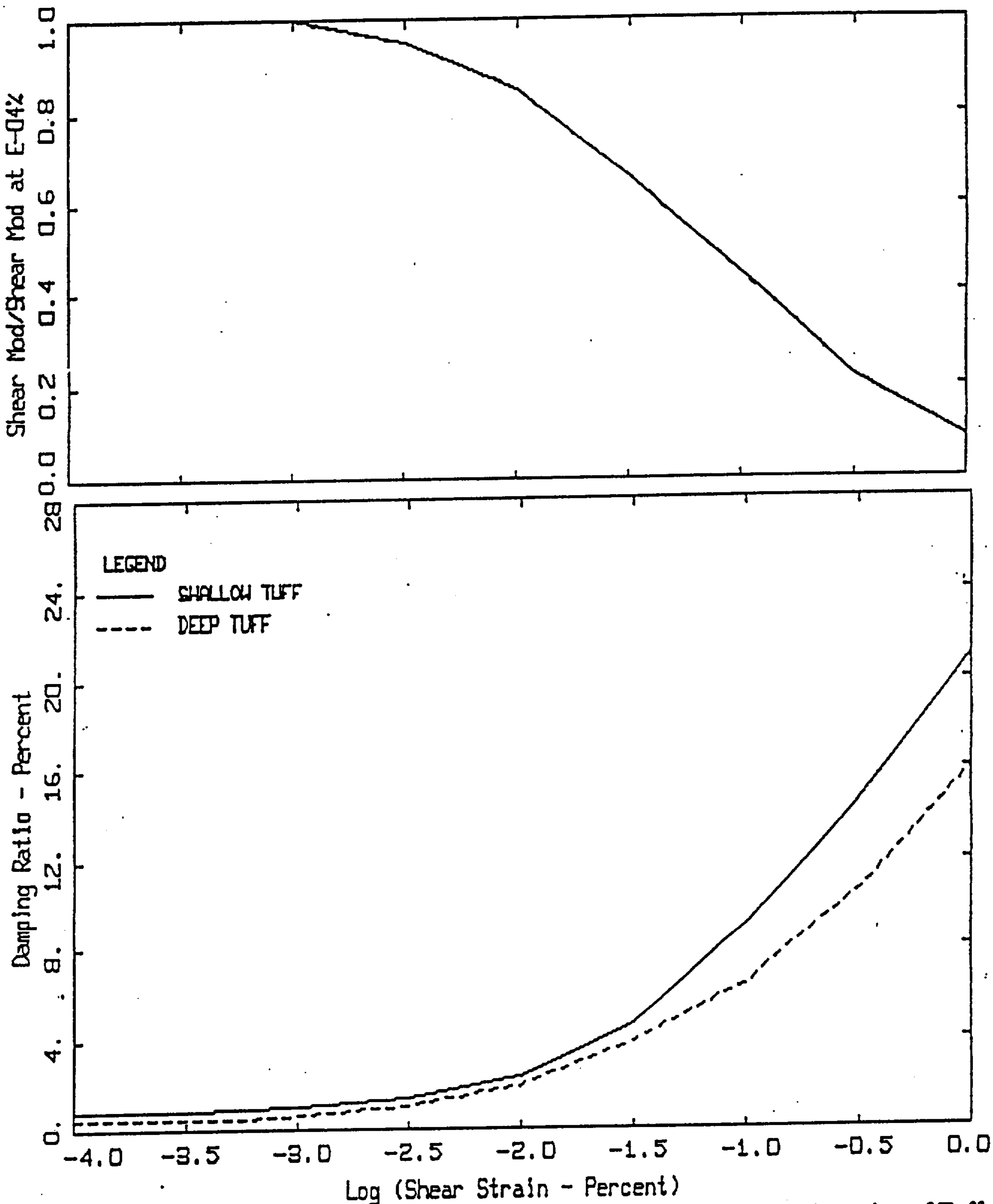
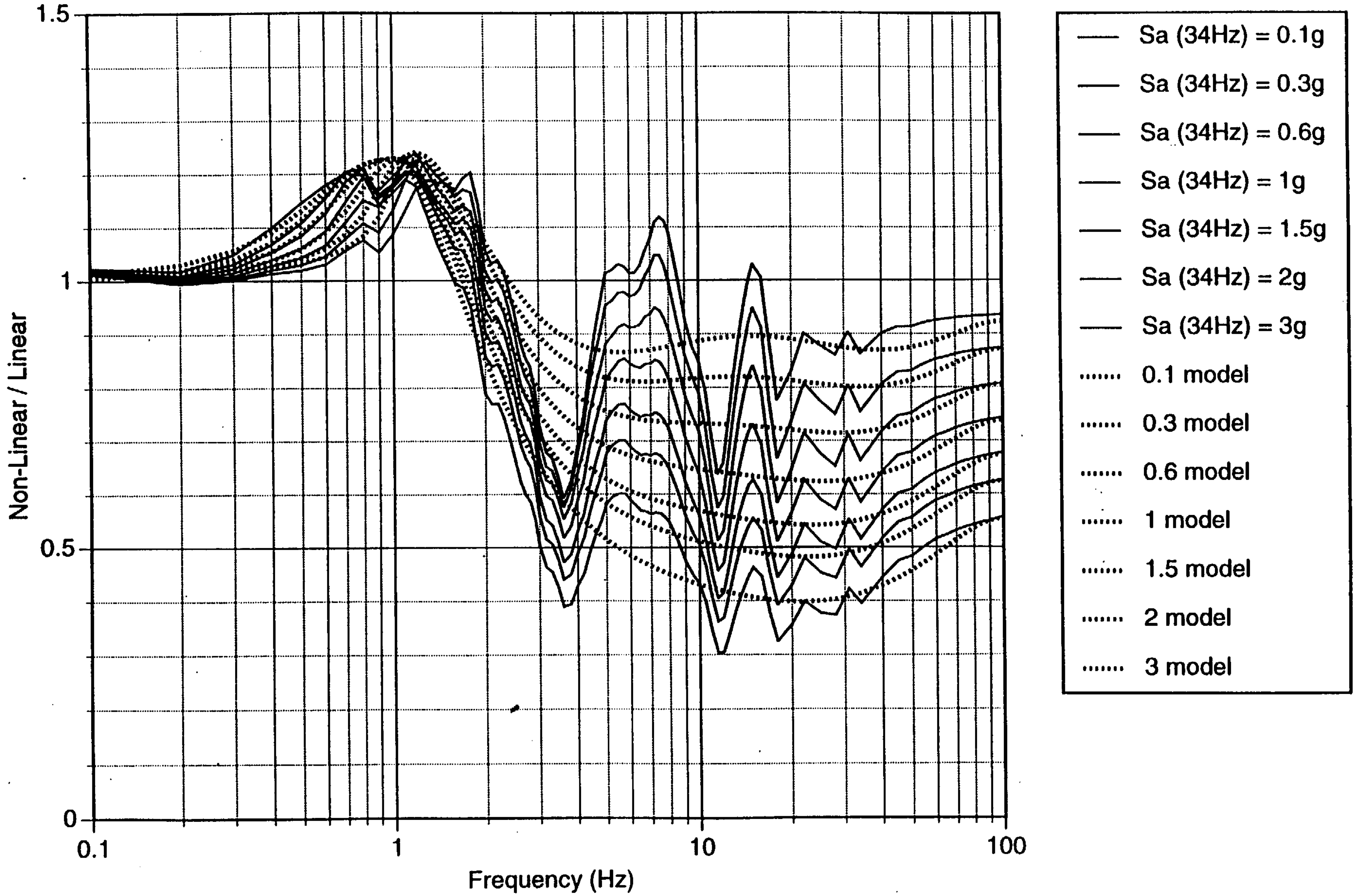
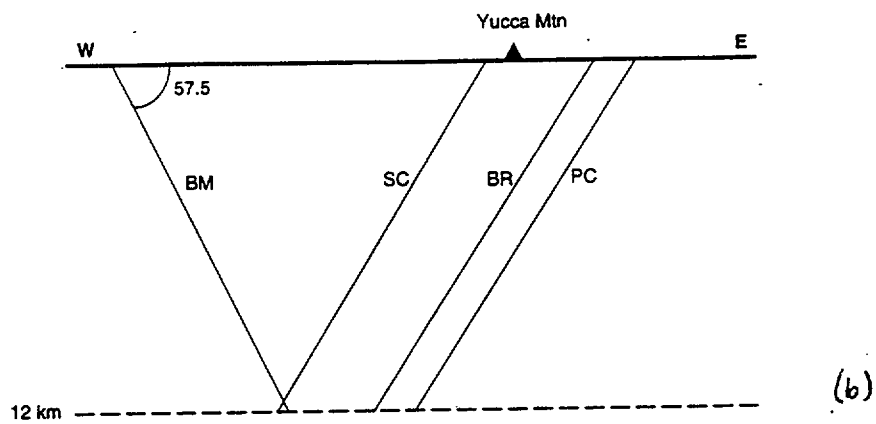


Figure 7.2. Modulus reduction and damping curves based on laboratory dynamic testing of Tuff samples taken at the Los Alamos National Laboratory (Wong et al., 1993). The shallow Tuff was sampled in the top 44m, is moderately welded, has a shear-wave velocity of about 600m/sec and is unsaturated. The deep Tuff was sampled at 157m, is nonwelded, has a shear-wave velocity of 700m/sec, and was 63% saturated.



1.5
1
0.5
0
0.1
1
10
100
Frequency (Hz)
Non-Linear / Linear
Sa (34Hz) = 0.1g
Sa (34Hz) = 0.3g
Sa (34Hz) = 0.6g
Sa (34Hz) = 1g
Sa (34Hz) = 1.5g
Sa (34Hz) = 2g
Sa (34Hz) = 3g
0.1 model
0.3 model
0.6 model
1 model
1.5 model
2 model
3 model

Normal Faults
X - Section through YM



Normal Faults
Reciprocal Fault-Station Section

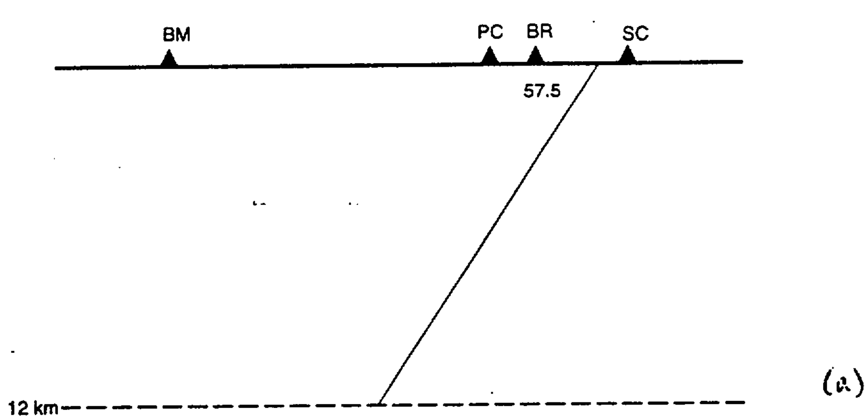
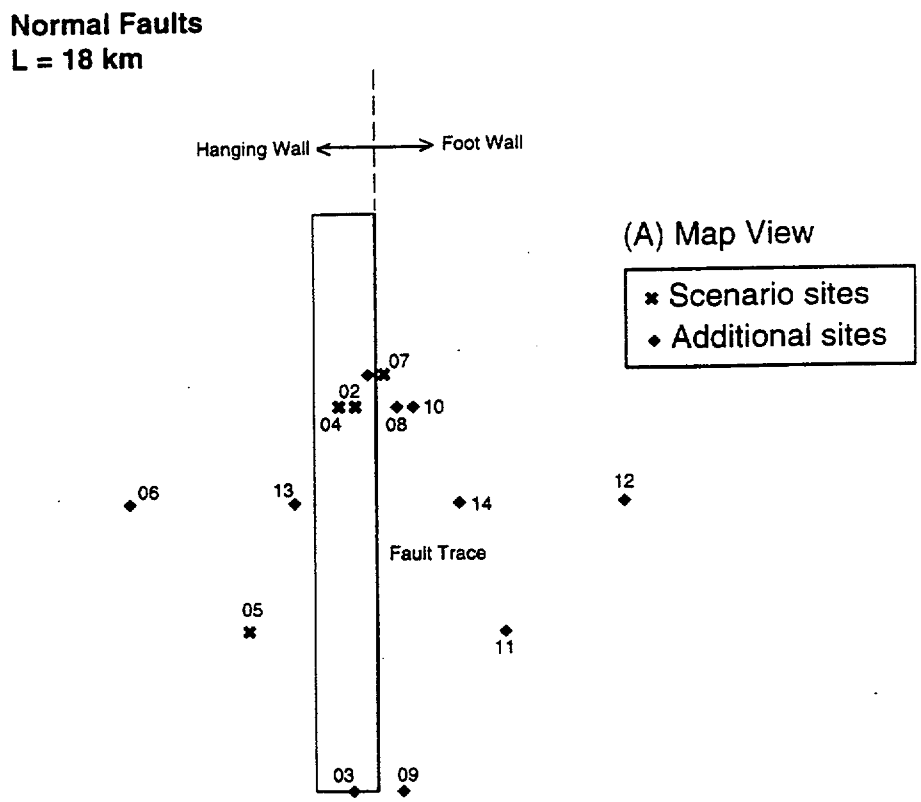
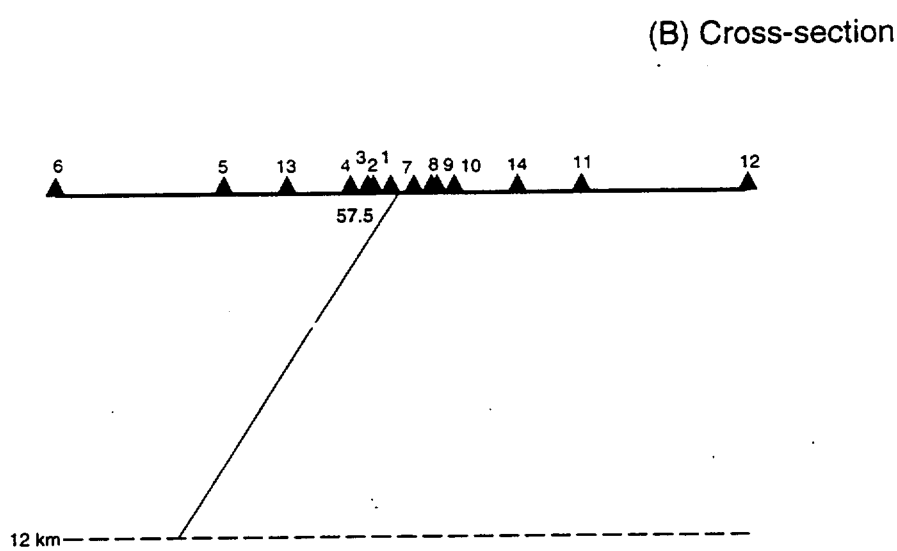


Figure 8.1



Normal Faults
L = 18 km
Hanging Wall
Foot Wall
(A) Map View
Scenario sites
Additional sites
07
02
10
04
08
06
13
14
12
Fault Trace
05
11
03
09



(B) Cross-section
6
5
13
4
3
2
1
7
8
9
10
14
11
12
57.5
12 km

Figure 8.2

Table 8.6 Source parameters for additional normal faulting exercise.

	Finite Source				
Run Set	M	Dip (deg)	L (km)	W (km)	$\Delta\sigma$ (bars)
N01	6.4	57.5	18	14	30
N02		Not Used			
N03	6.4	45.0	18	14	30
N04	6.4	70.0	18	14	30
N05	6.2	57.5	18	14	15
N06	6.6	57.5	18	14	60
N07	6.4	57.5	29	14	15
N08	6.4	57.5	11	14	60

M 6.4 Normal Fault (NO1)
Spectral Acceleration vs Distance (20.0 Hz)

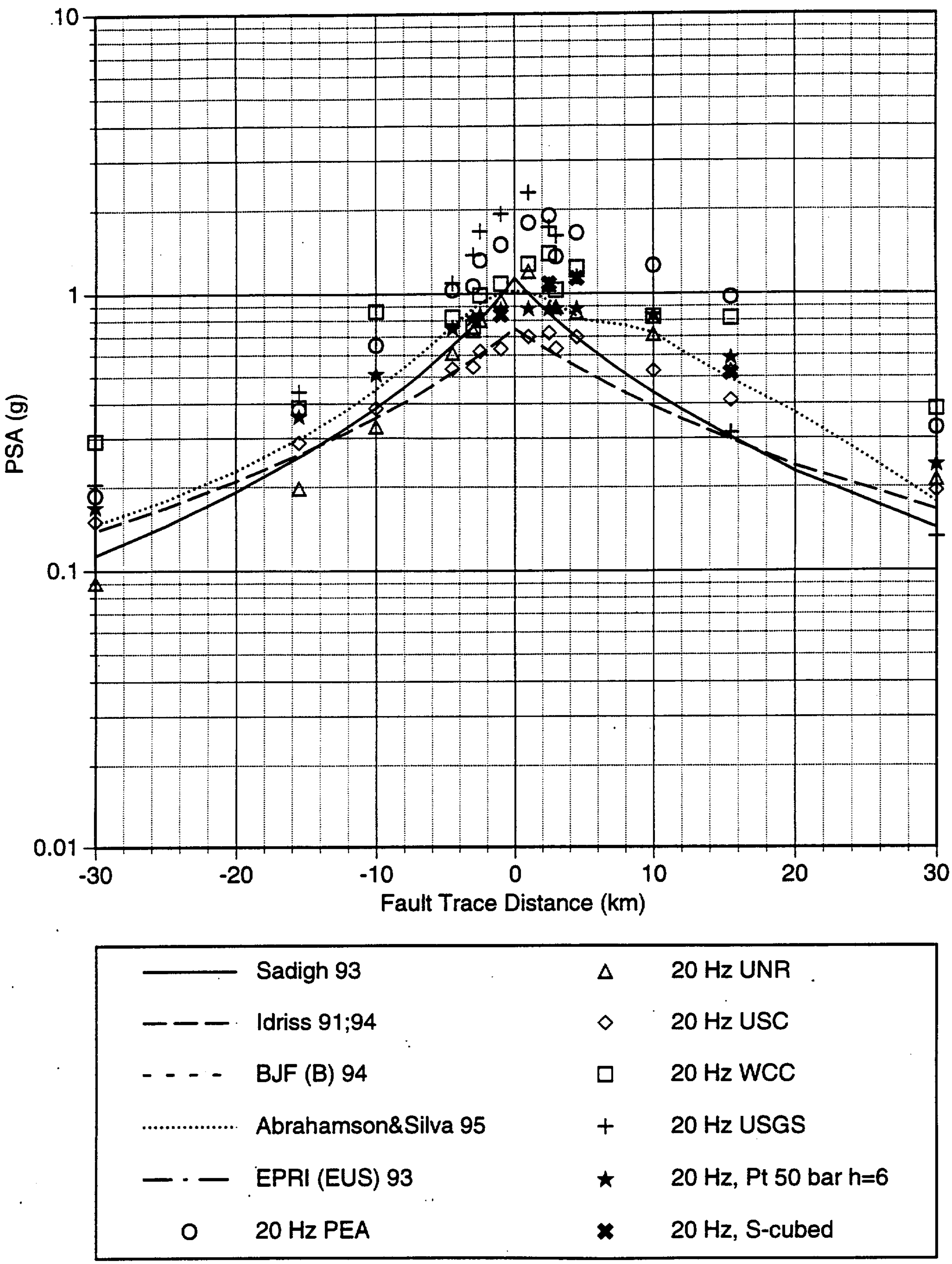
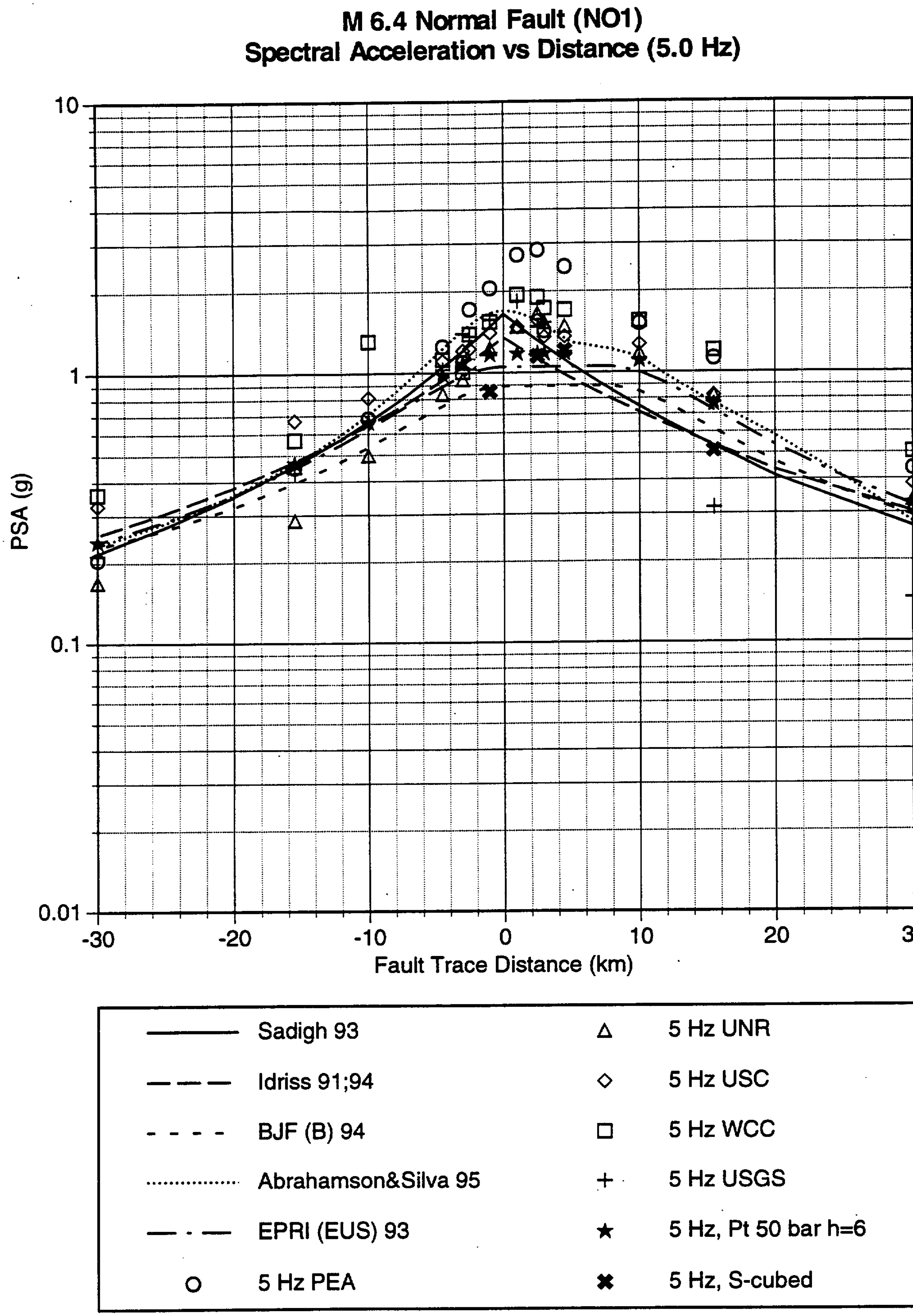


Figure 2.4(b)



M 6.4 Normal Fault (NO1)
Spectral Acceleration vs Distance (5.0 Hz)
10
1
0.1
0.01
PSA (g)
-30
-20
-10
0
10
20
30
Fault Trace Distance (km)
Sadigh 93
Idriss 91;94
BJF (B) 94
Abrahamson&Silva 95
EPRI (EUS) 93
5 Hz PEA
5 Hz UNR
5 Hz USC
5 Hz WCC
5 Hz USGS
5 Hz, Pt 50 bar h=6
5 Hz, S-cubed

Figure 8.4 (d)

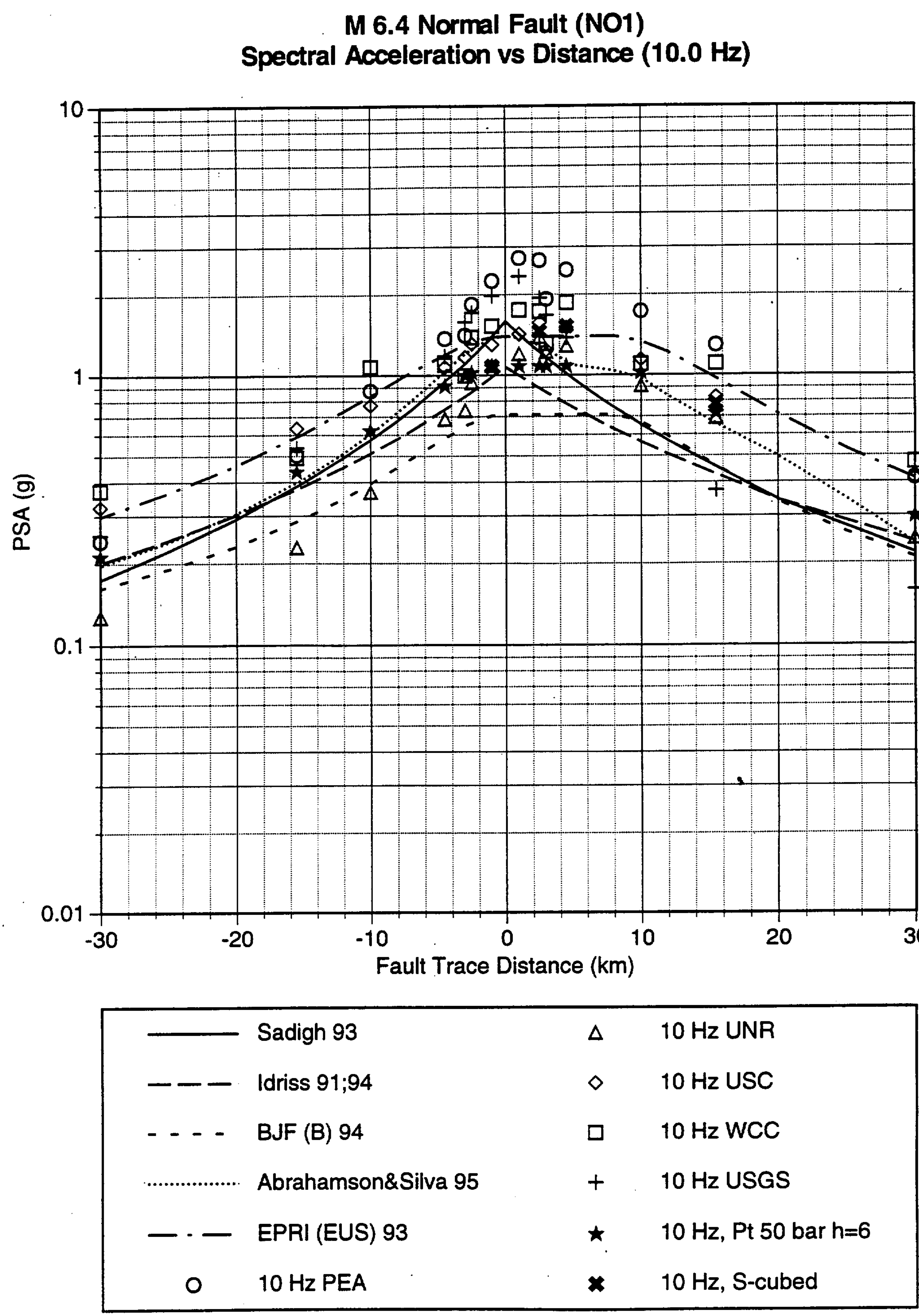

M 6.4 Normal Fault (NO1)
Spectral Acceleration vs Distance (10.0 Hz)
10
1
0.1
0.01
PSA (g)
-30
-20
-10
0
10
20
30
Fault Trace Distance (km)
Sadigh 93
Idriss 91;94
BJF (B) 94
Abrahamson&Silva 95
EPRI (EUS) 93
10 Hz PEA
10 Hz UNR
10 Hz USC
10 Hz WCC
10 Hz USGS
10 Hz, Pt 50 bar h=6
10 Hz, S-cubed

Figure 8.4 (c)

M 6.4 Normal Fault (NO1)
Spectral Acceleration vs Distance (1.0 Hz)

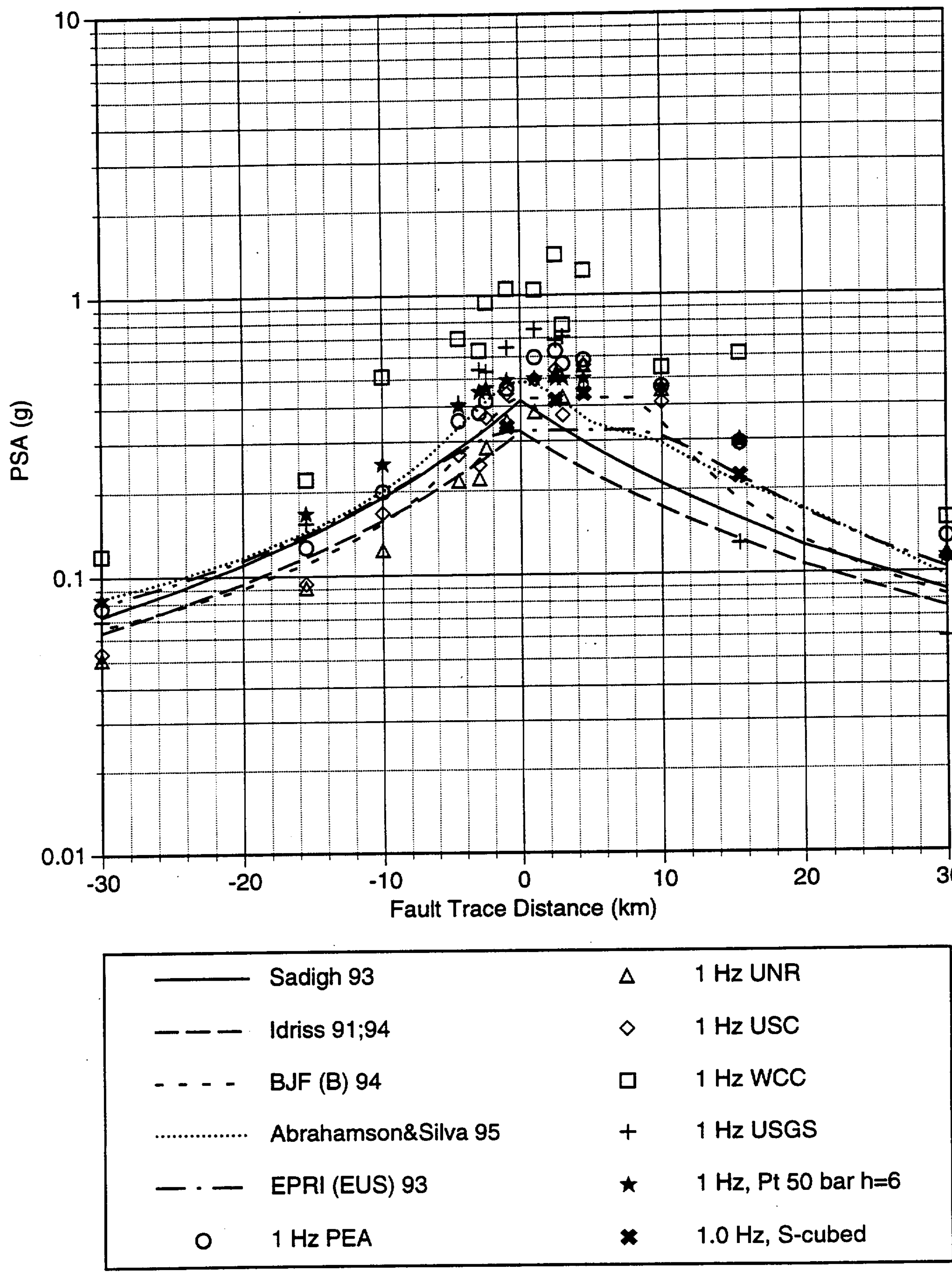


Figure 8.4 (c)

Yucca Mountain: NO1

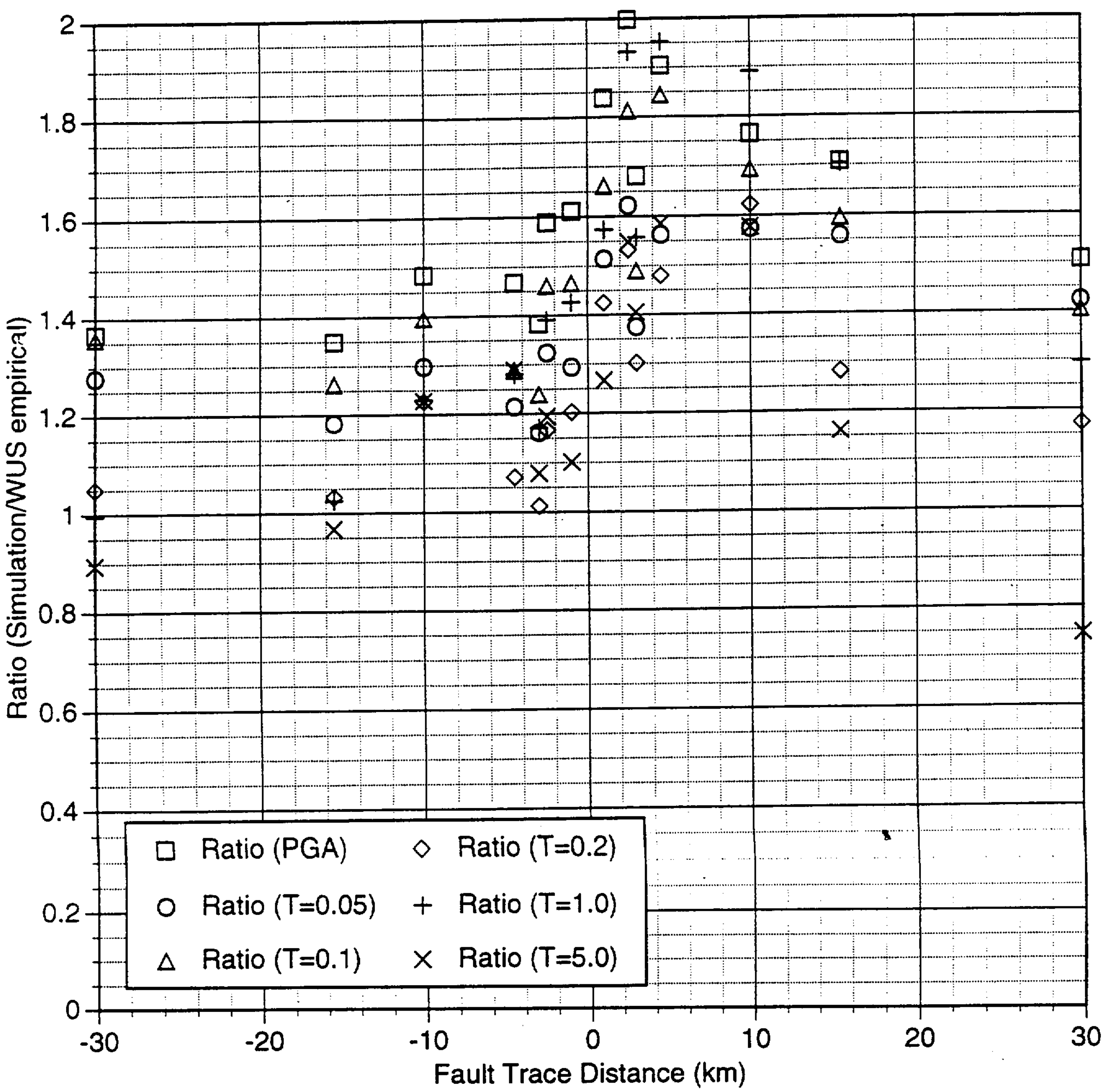


Figure 8.5

n01, STATION # 2

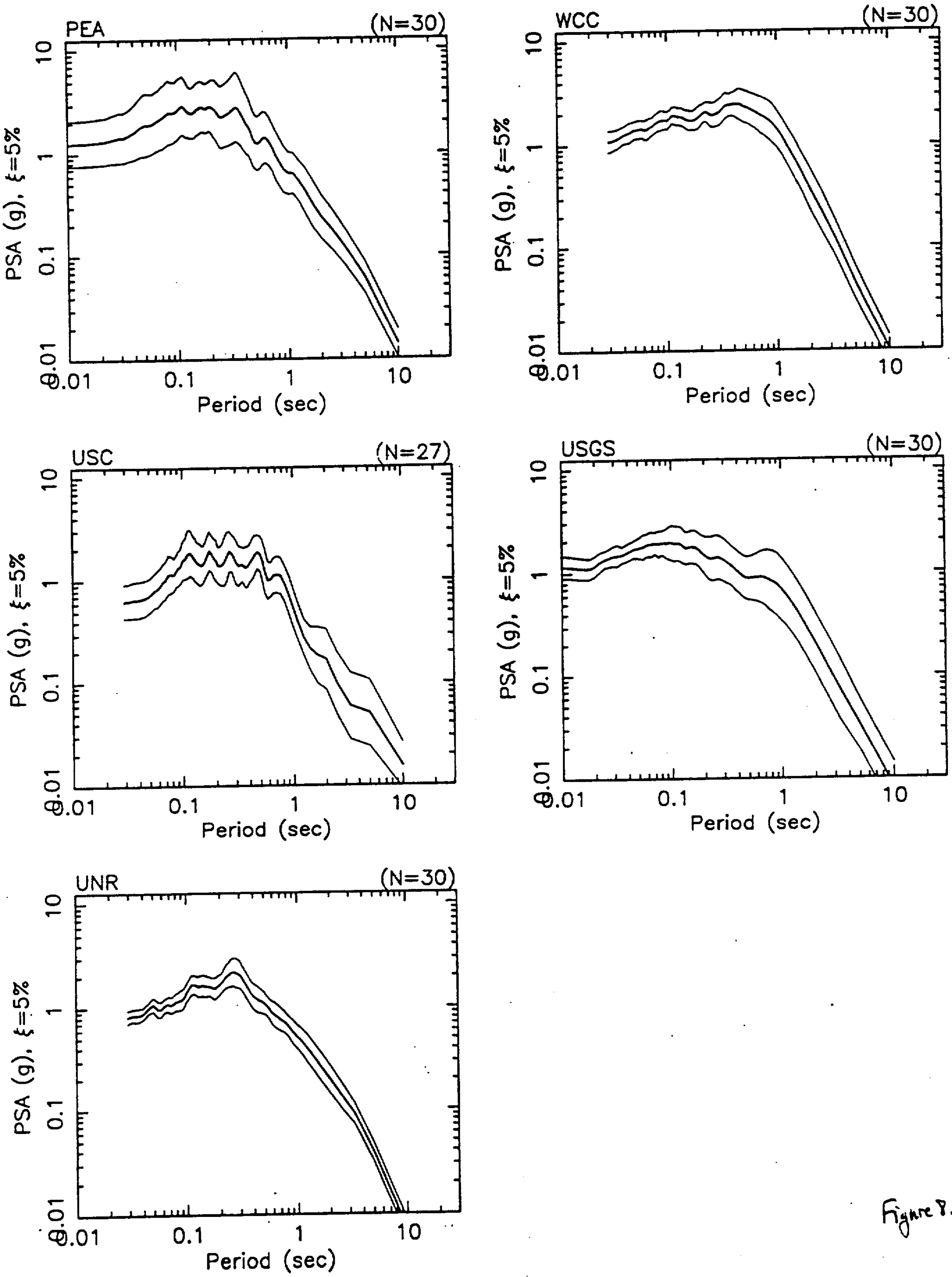


Figure 8.6

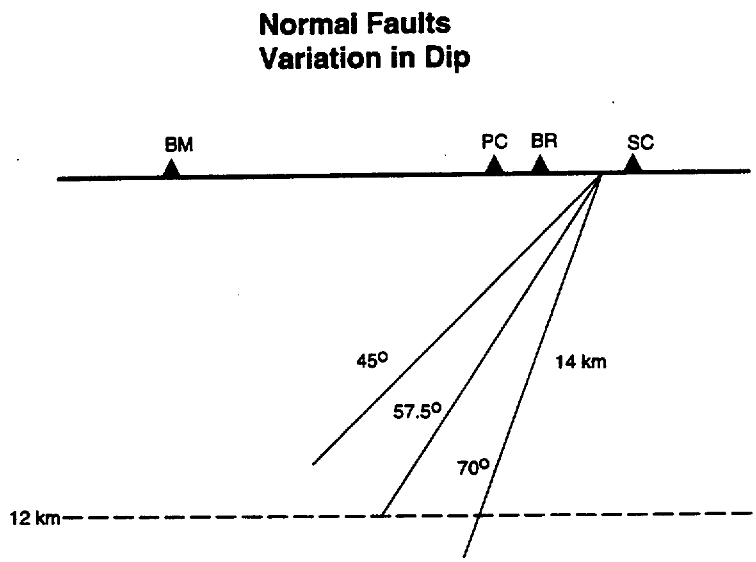
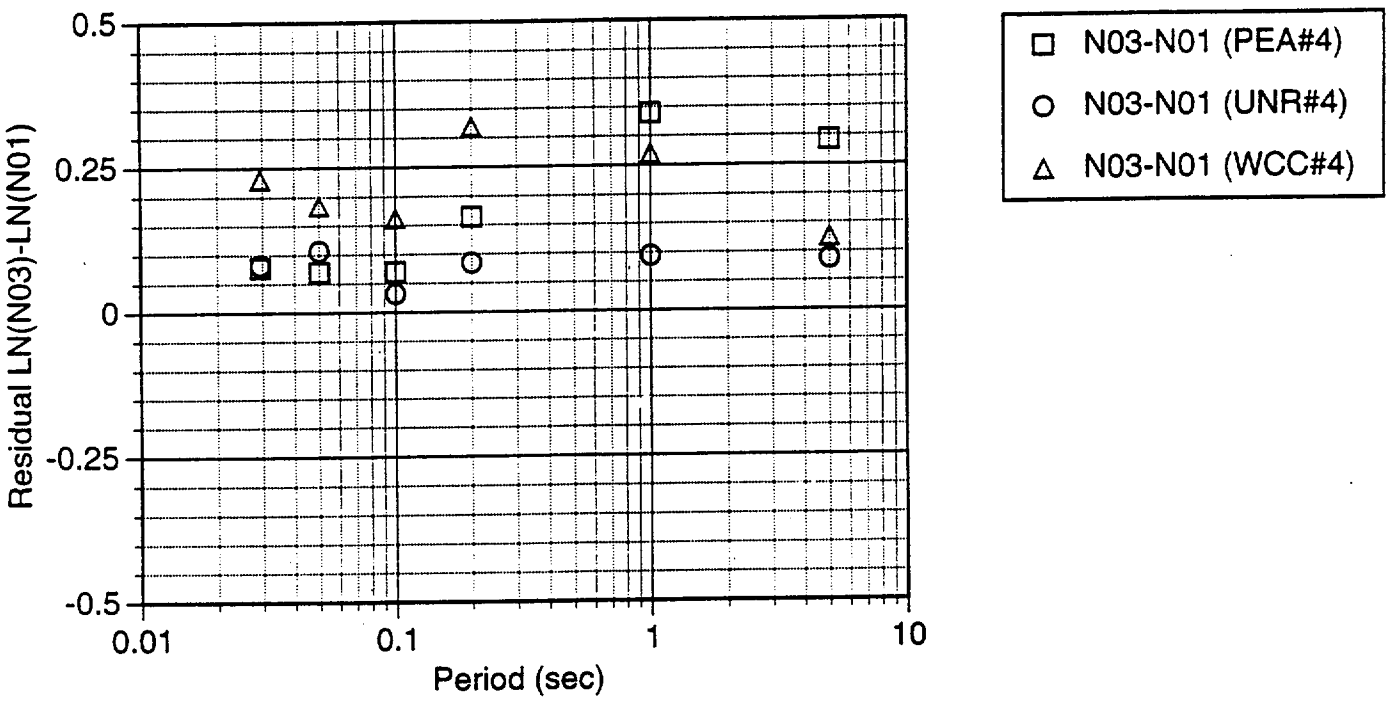
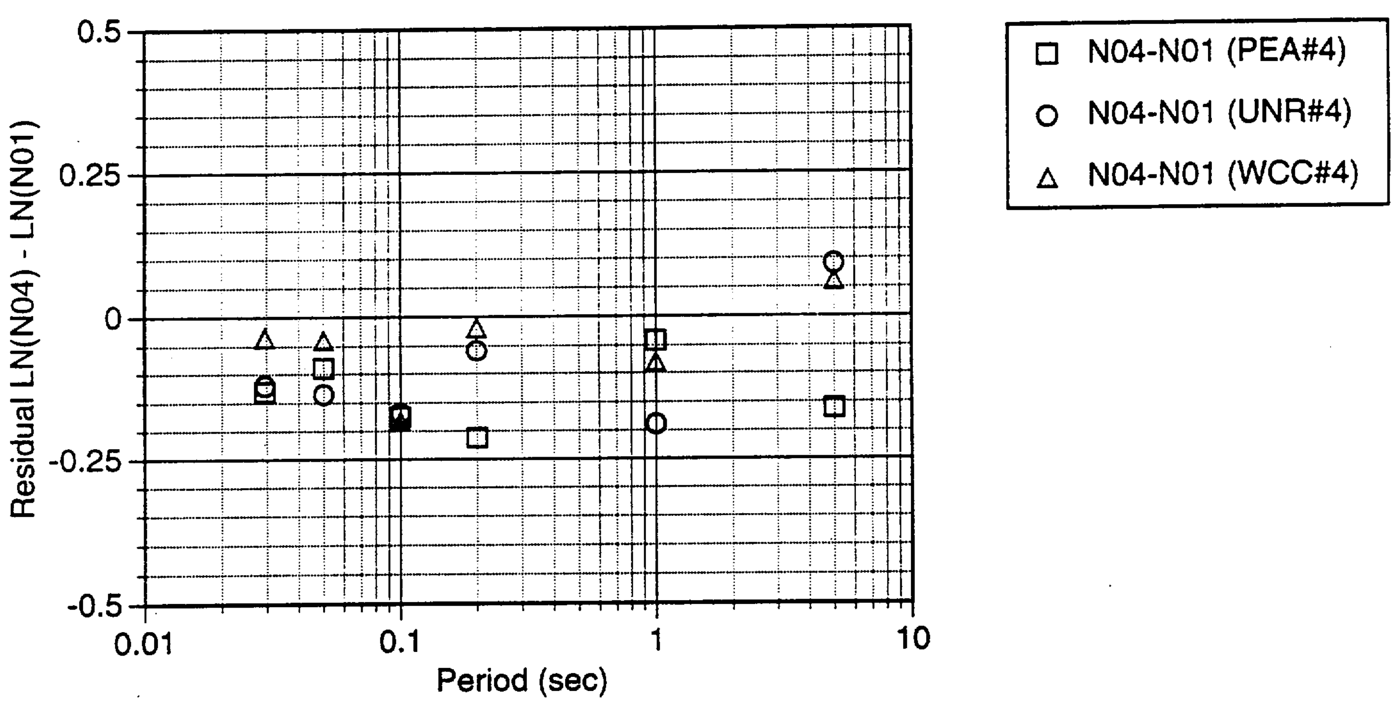


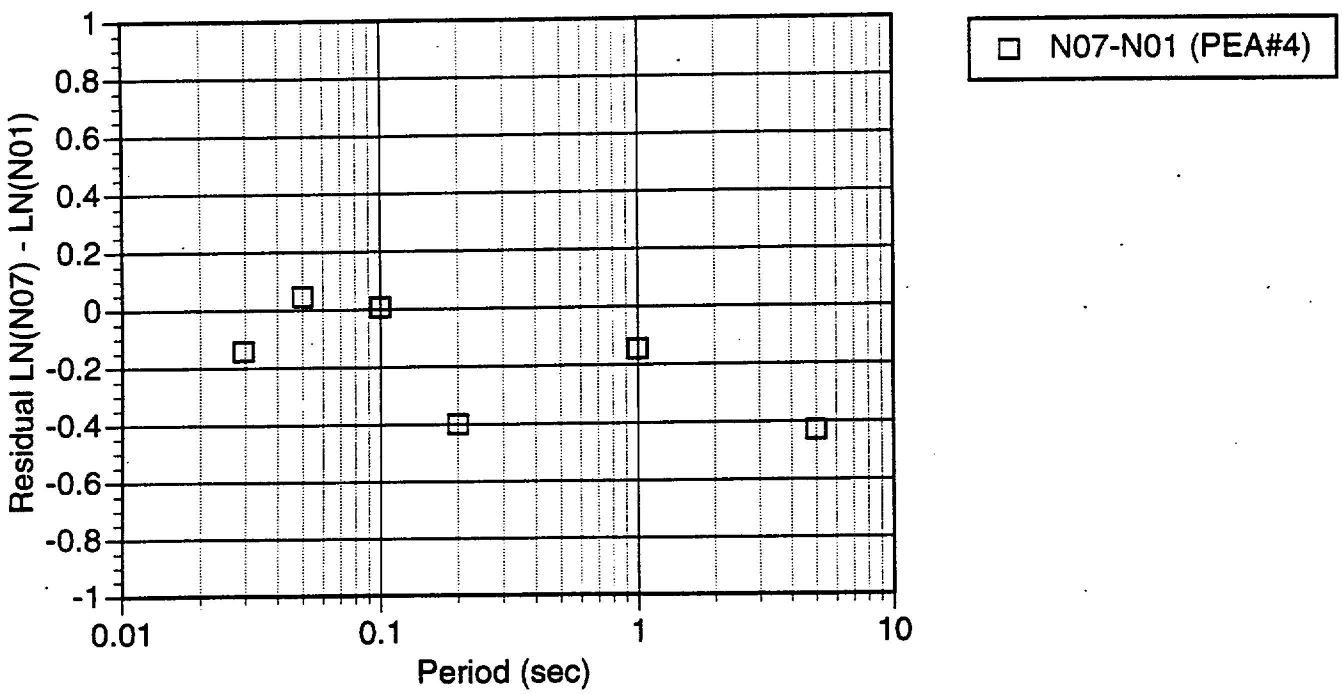
Figure 8.20

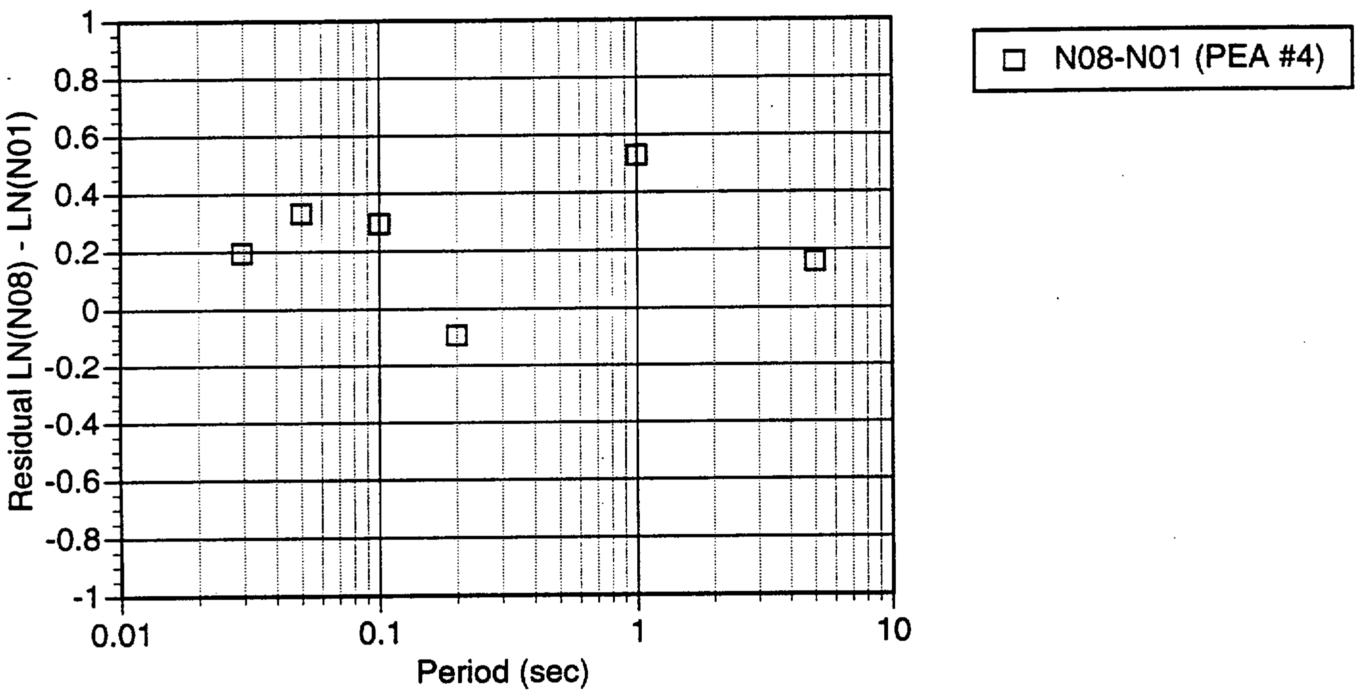
Residuals: Station #4



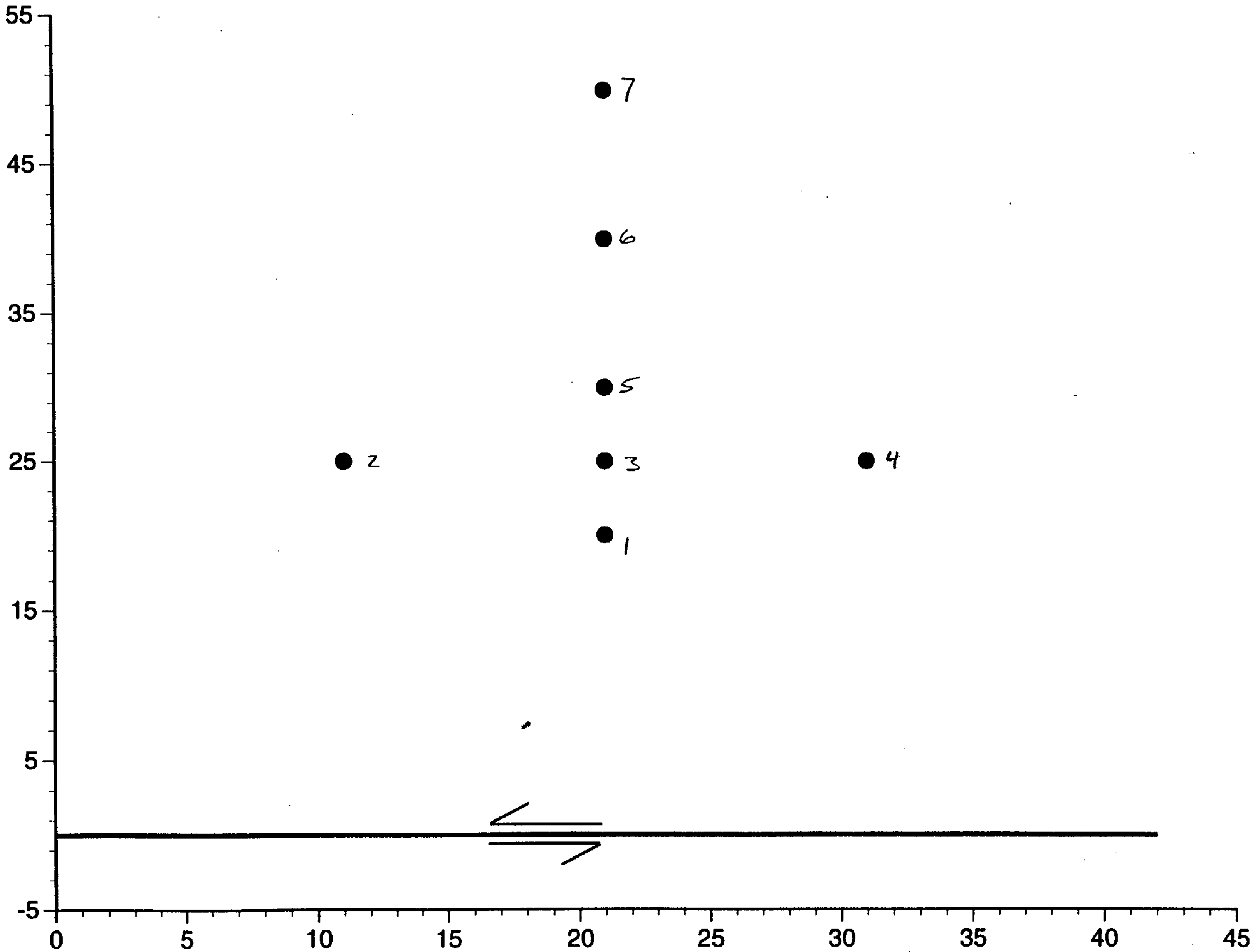


Residuals: Station #4



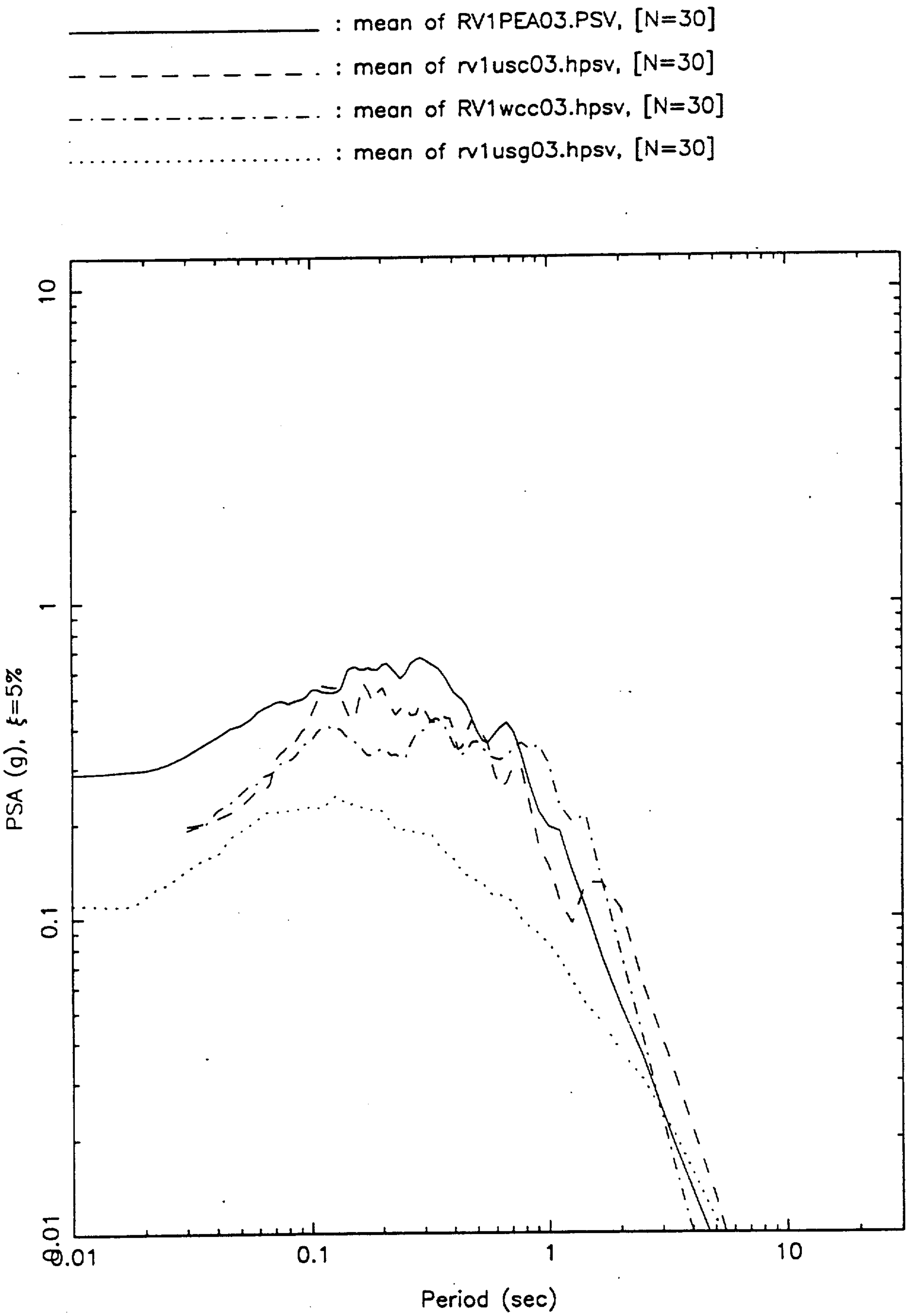


Rock Valley Fault

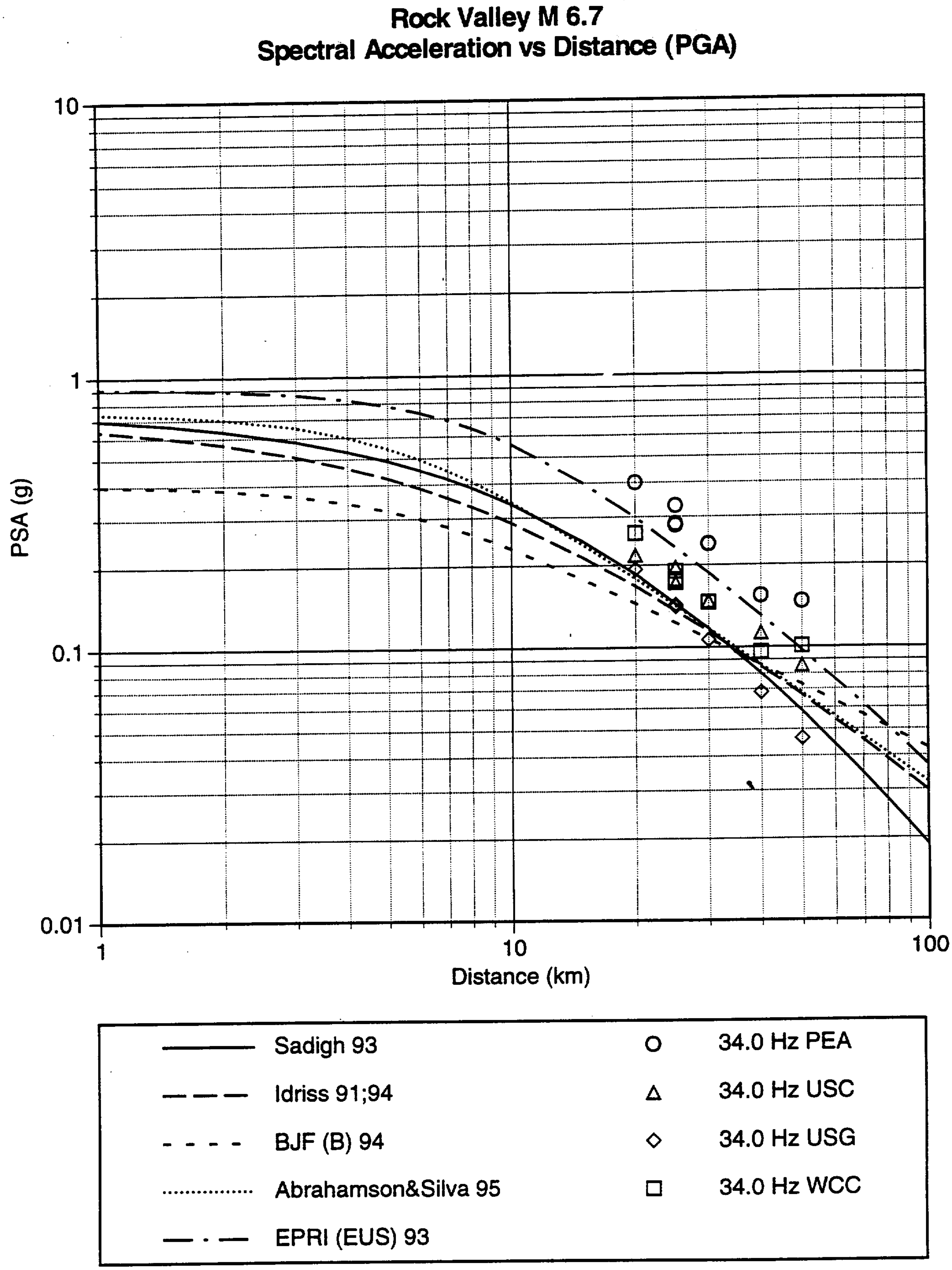


9-1

rv1, STATION # 3



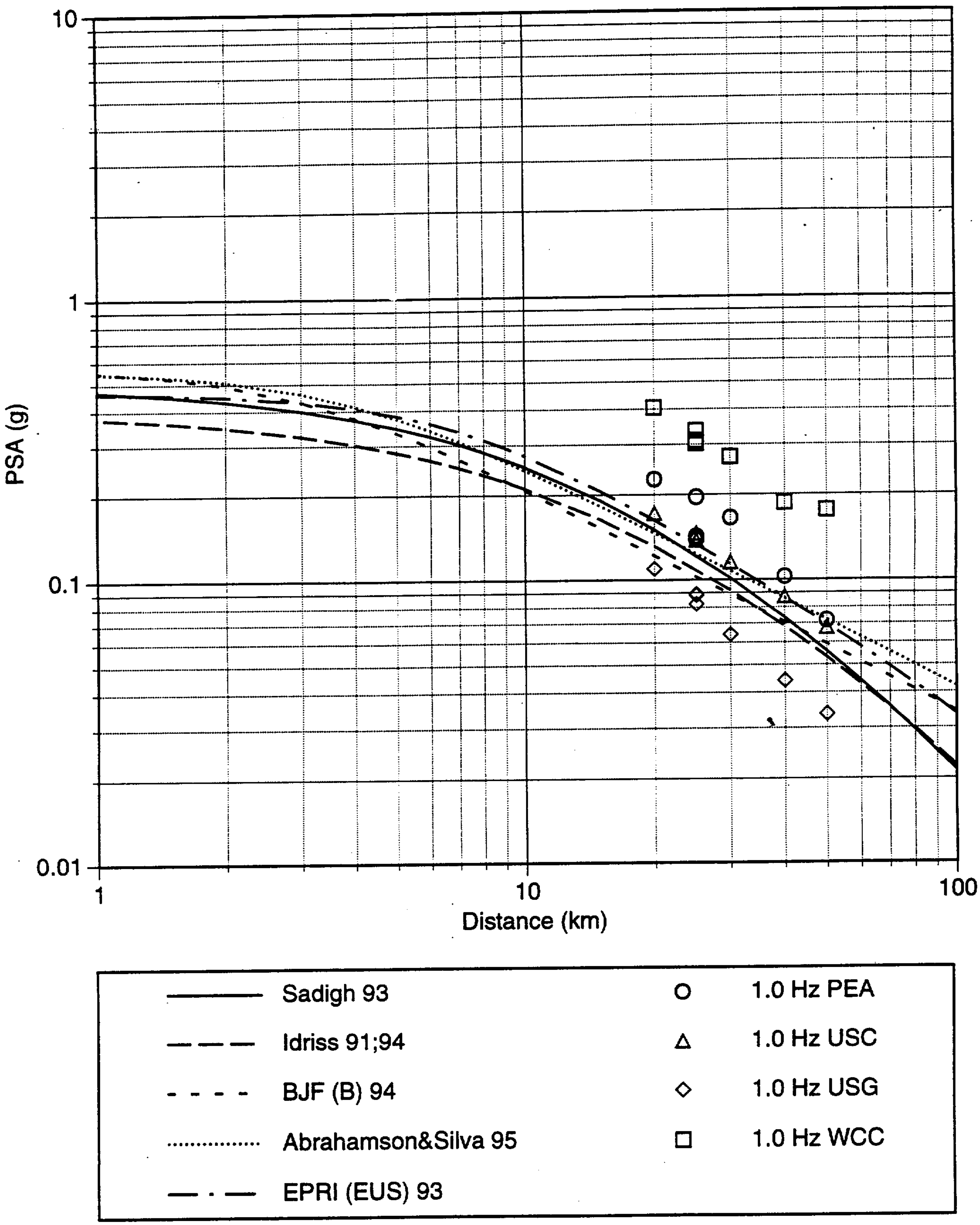
9-3a



Rock Valley M 6.7
Spectral Acceleration vs Distance (PGA)
PSA (g)
10
1
0.1
0.01
1
10
100
Distance (km)
Sadigh 93
Idriss 91;94
BJF (B) 94
Abrahamson&Silva 95
EPRI (EUS) 93
34.0 Hz PEA
34.0 Hz USC
34.0 Hz USG
34.0 Hz WCC

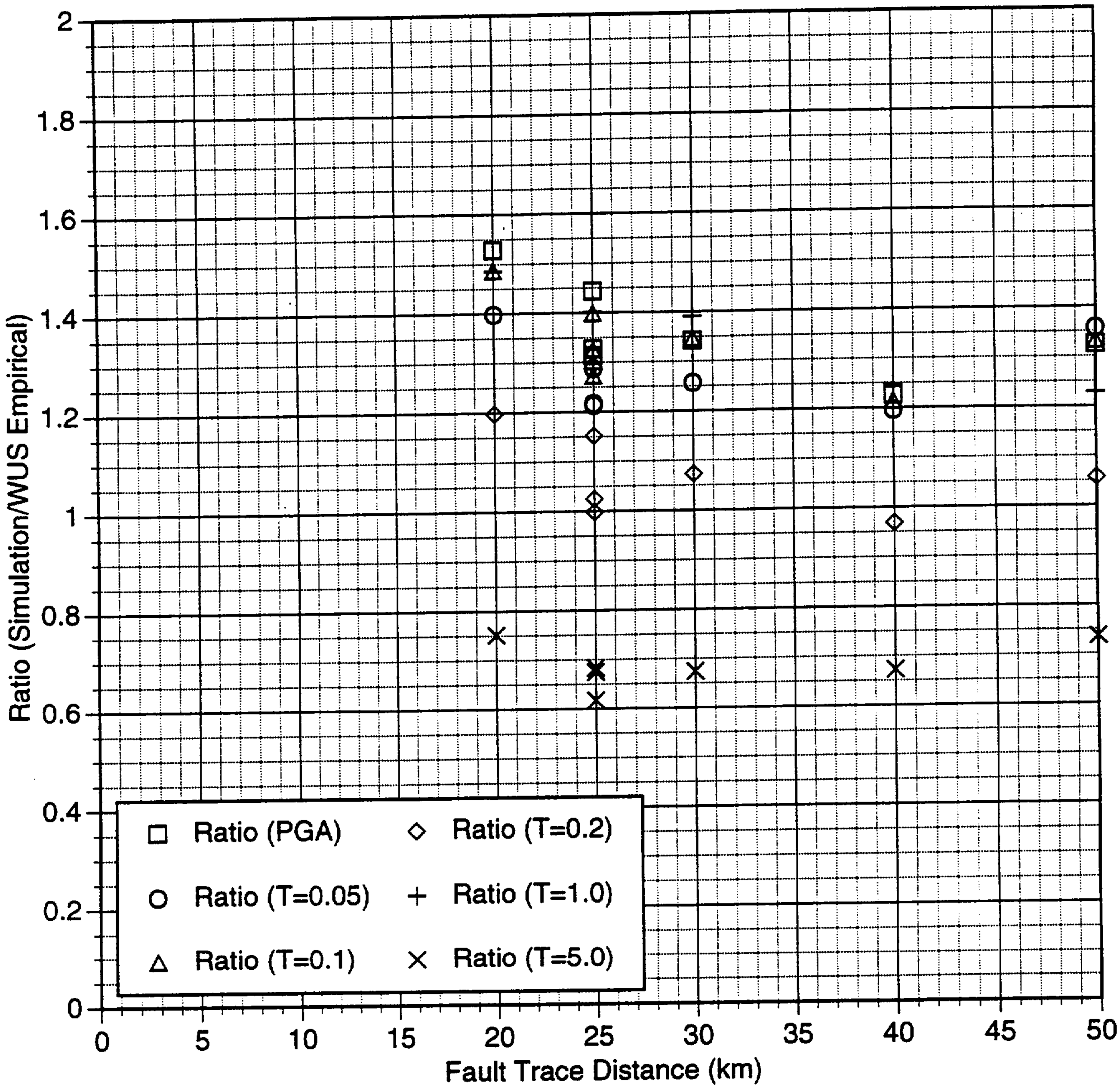
4-8a

Rock Valley M 6.7
Spectral Acceleration vs Distance (1.0 Hz)



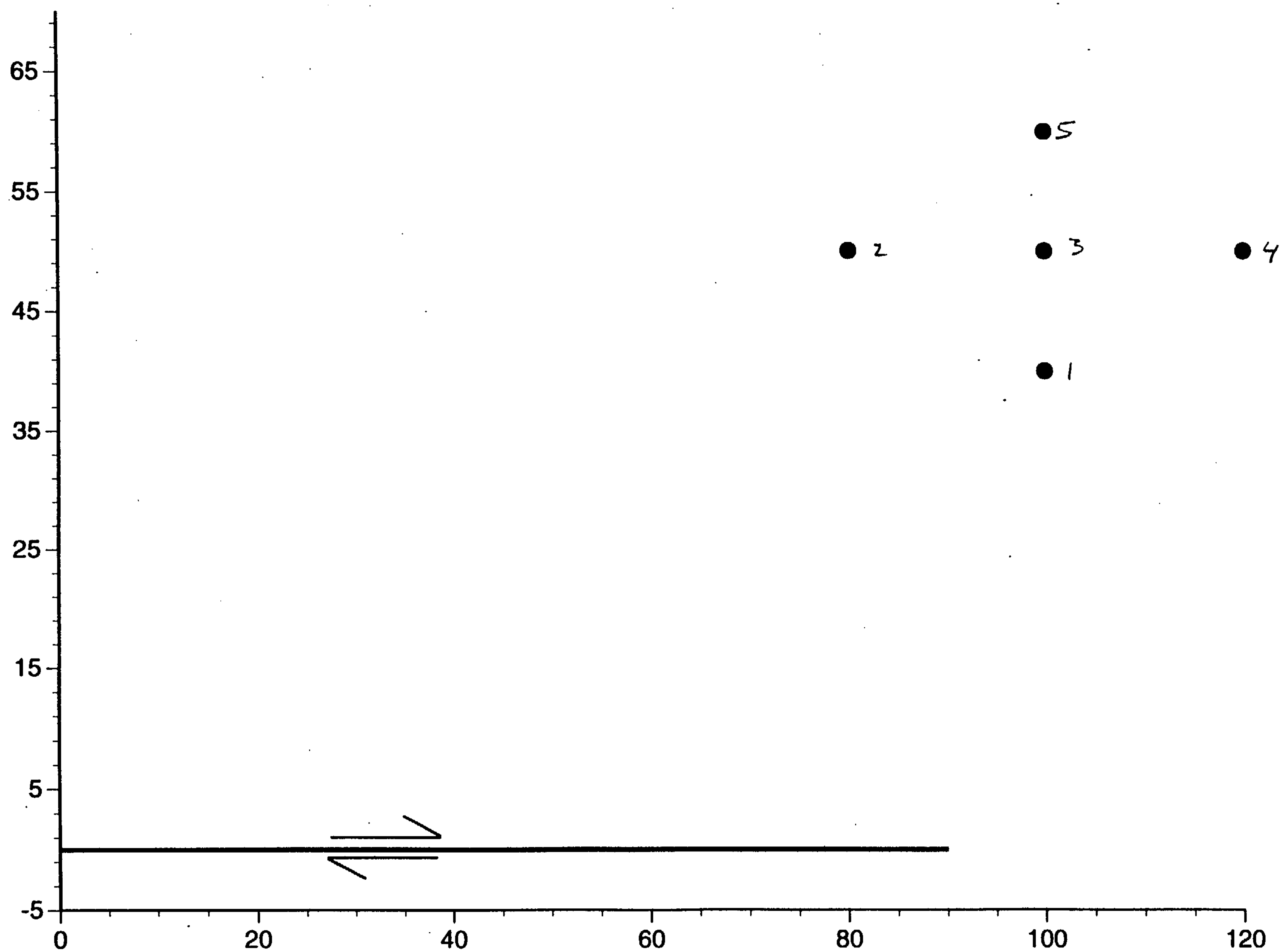
9.8e

Rock Valley



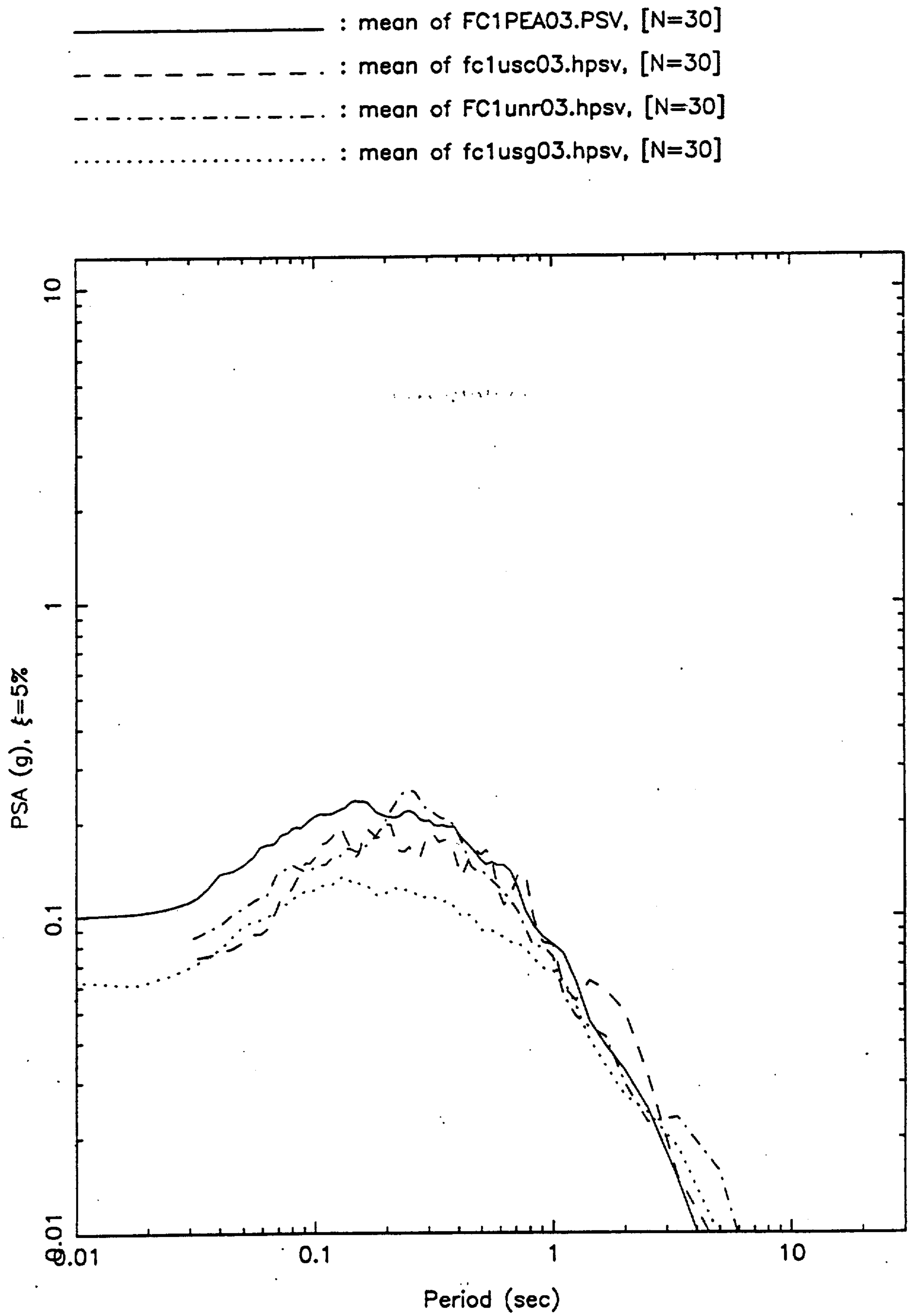
9.9

Furnace Creek



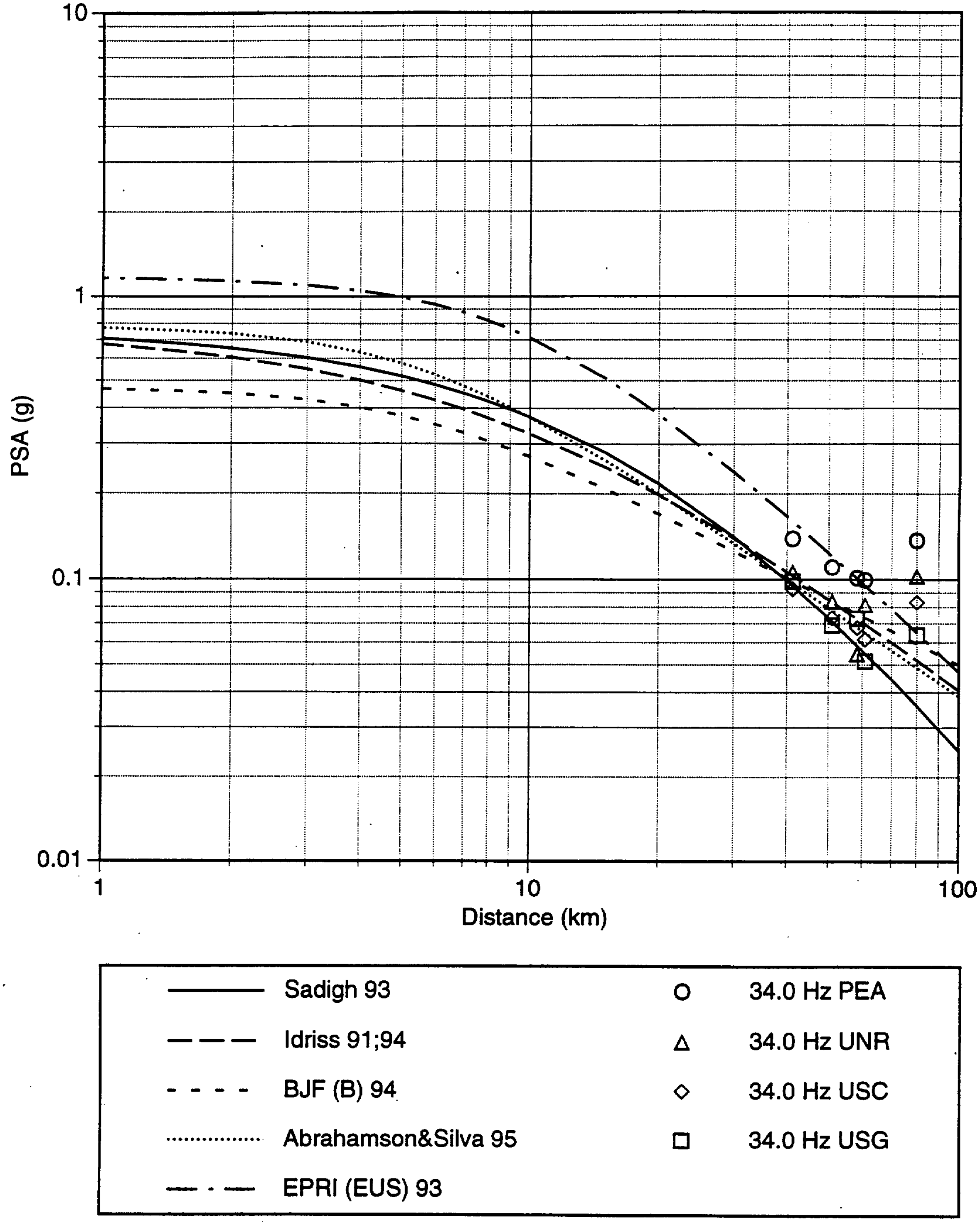
9-2

fc1, STATION # 3

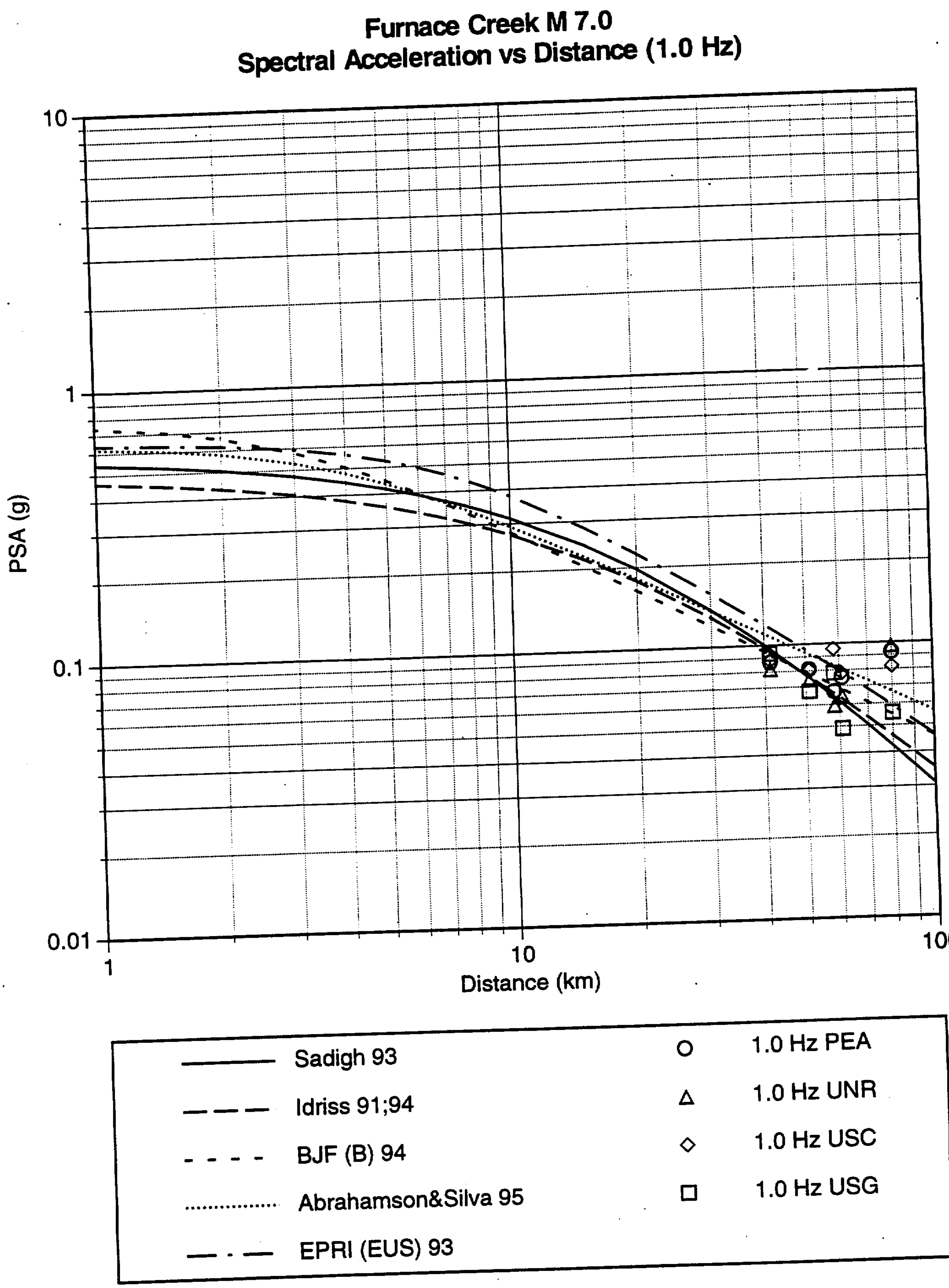


-3b

Furnace Creek M 7.0
Spectral Acceleration vs Distance (PGA)

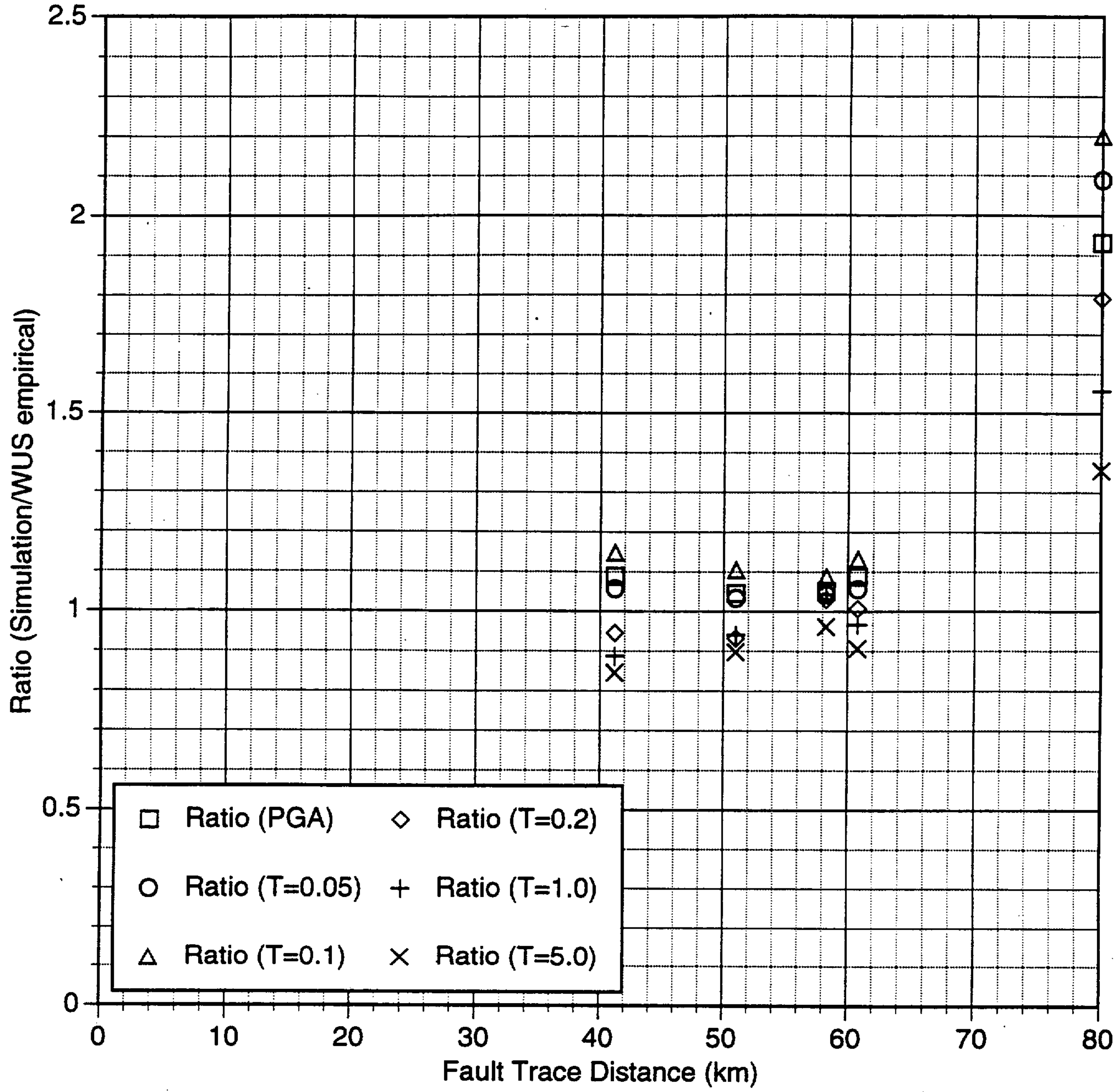


9.10 a

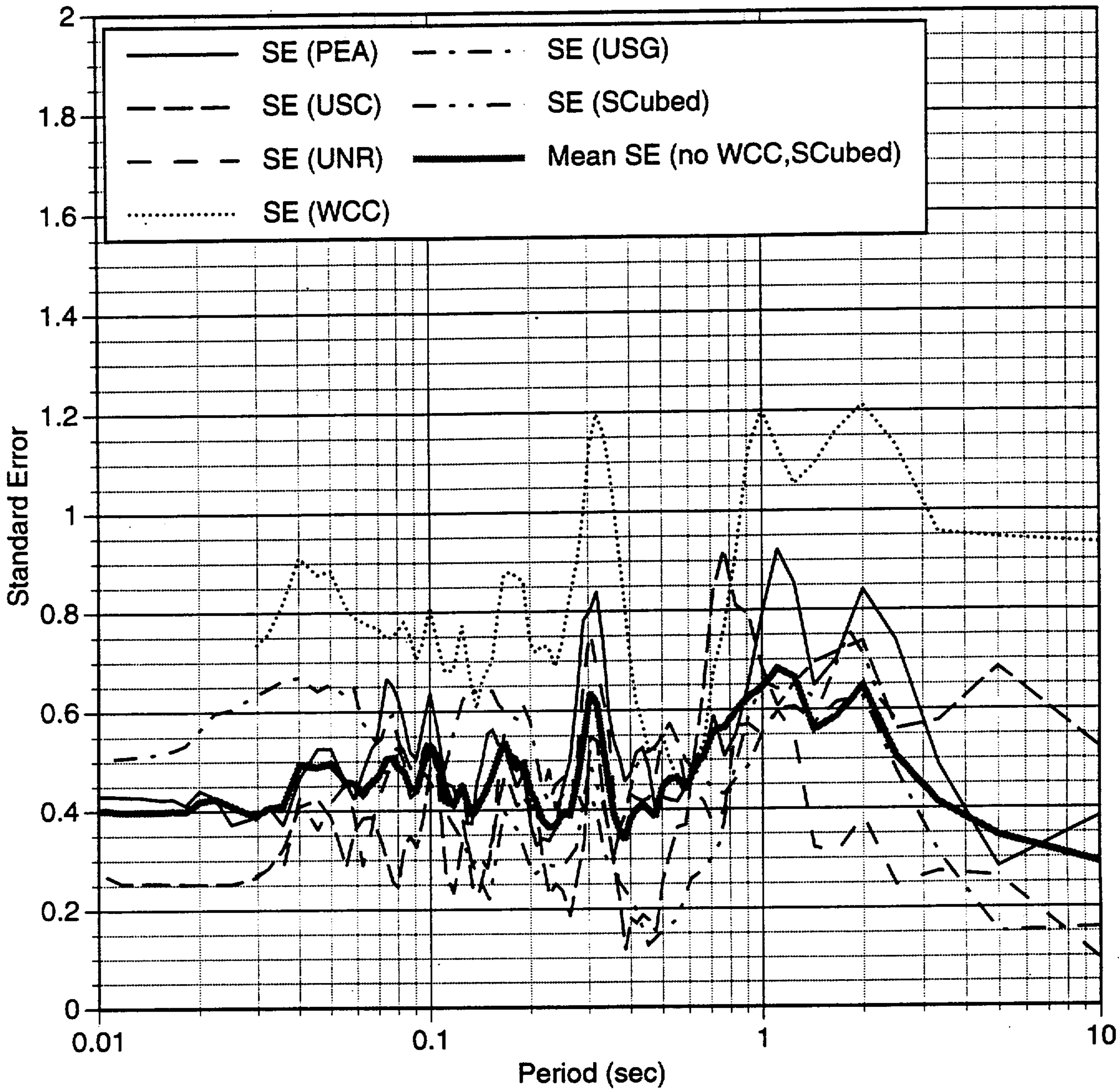

Furnace Creek M 7.0
Spectral Acceleration vs Distance (1.0 Hz)
10
1
0.1
0.01
PSA (g)
1
10
100
Distance (km)
Sadigh 93
Idriss 91;94
BJF (B) 94
Abrahamson&Silva 95
EPRI (EUS) 93
1.0 Hz PEA
1.0 Hz UNR
1.0 Hz USC
1.0 Hz USG

9.10e

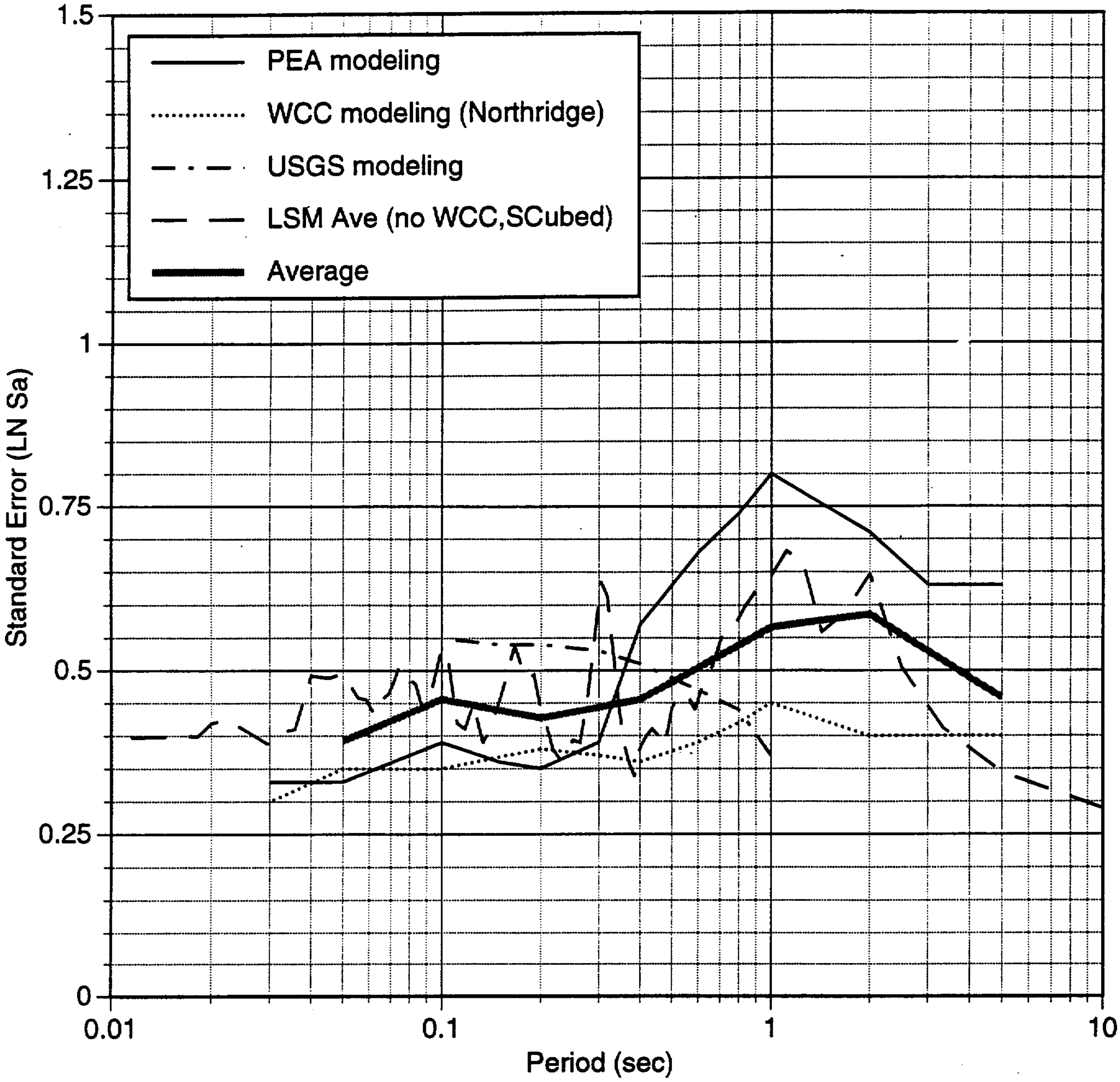
Furnace Creek



Standard Error: SM2

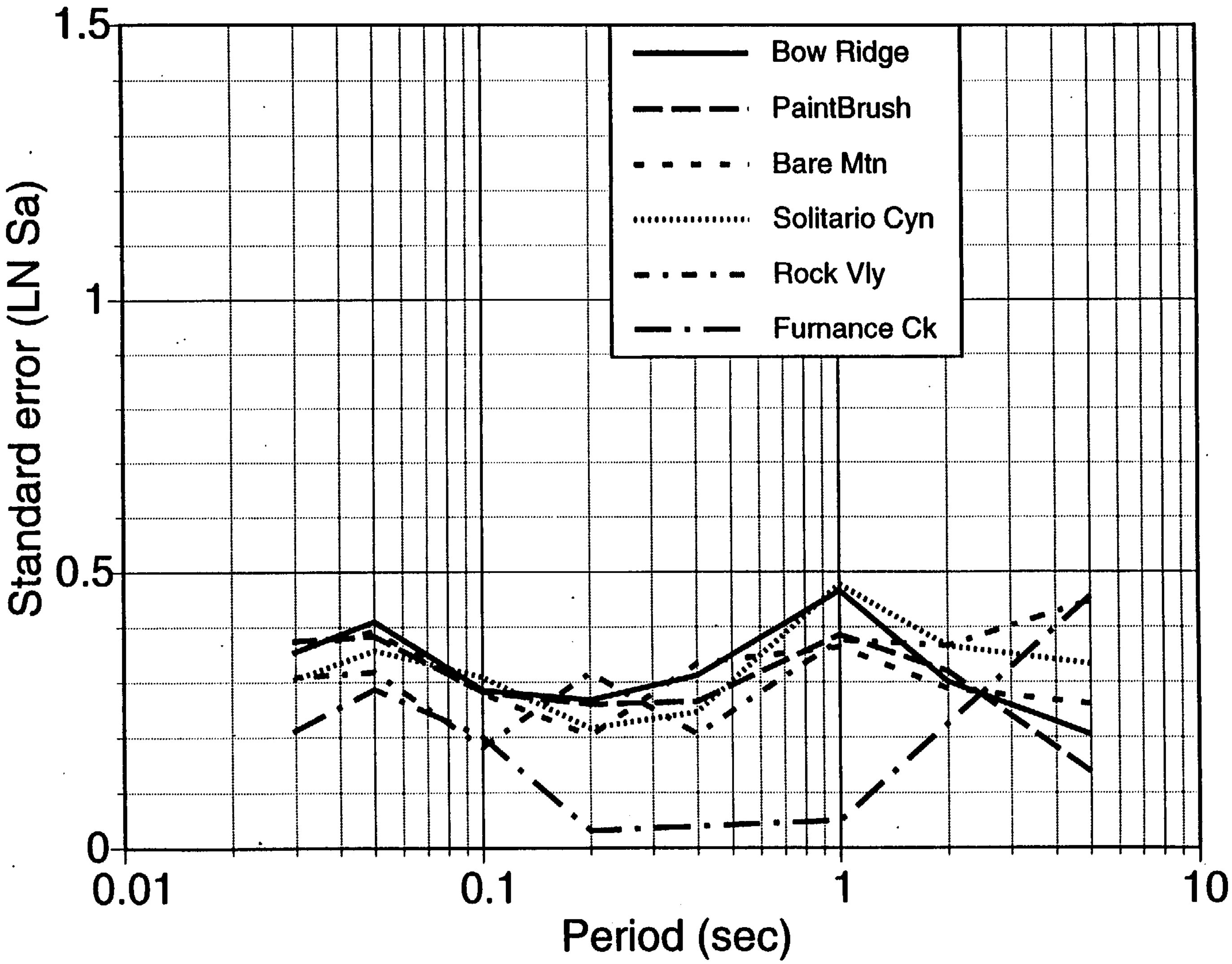


10.2

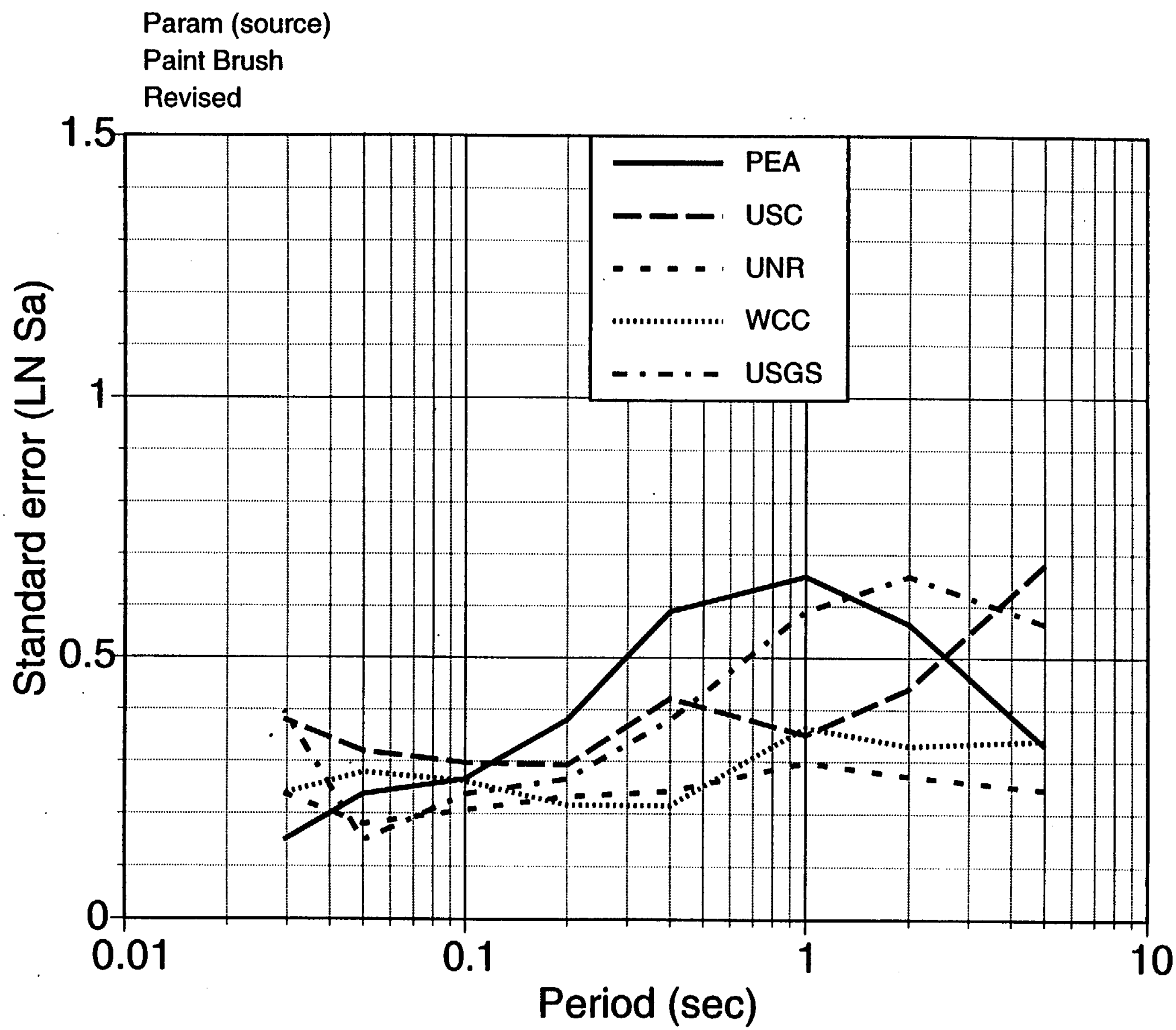

PEA modeling
WCC modeling (Northridge)
USGS modeling
LSM Ave (no WCC,SCubed)
Average
Standard Error (LN Sa)
Period (sec)
1.5
1.25
1
0.75
0.5
0.25
0
0.01
0.1
1
10

10.3

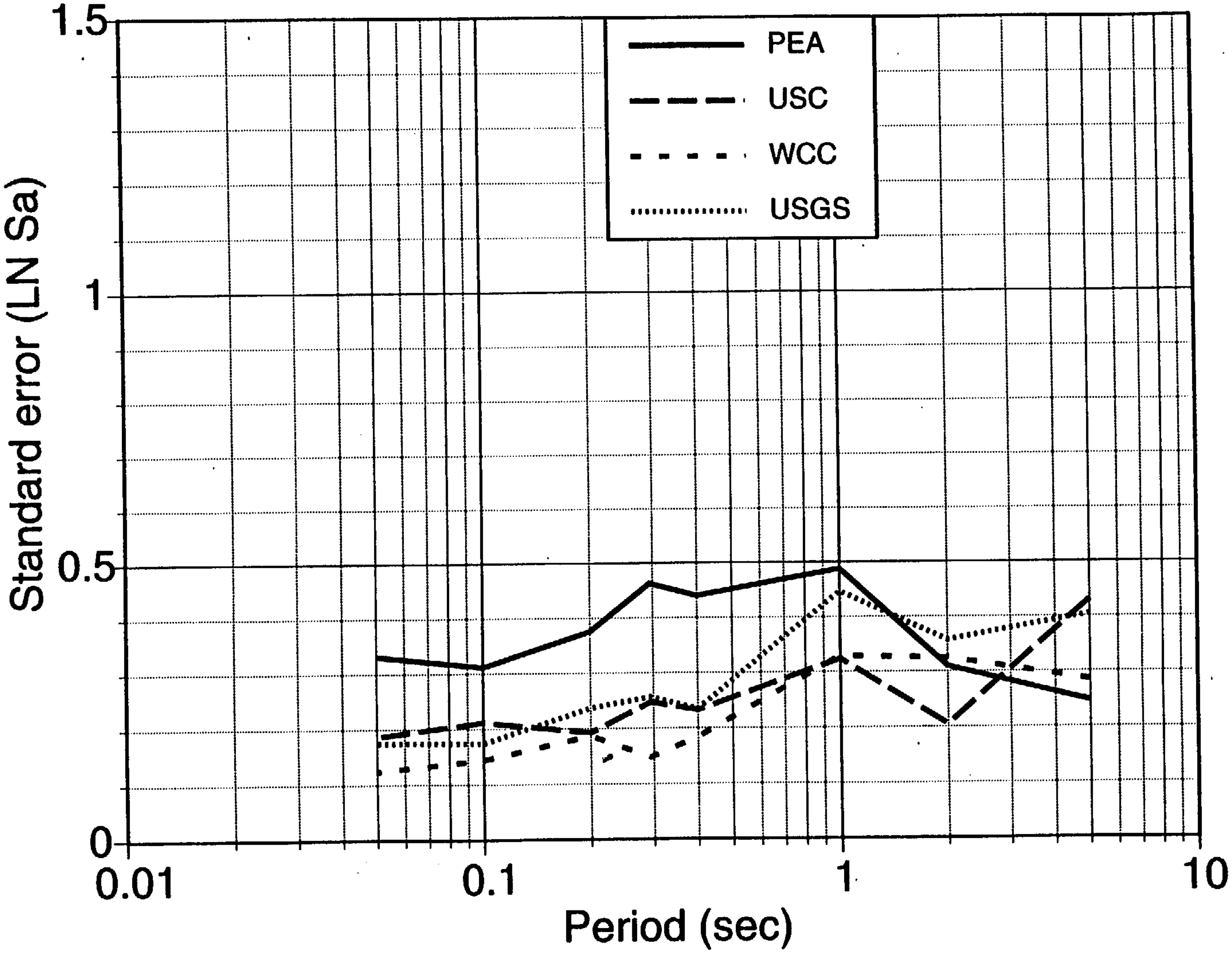
Sigma Method



10 4

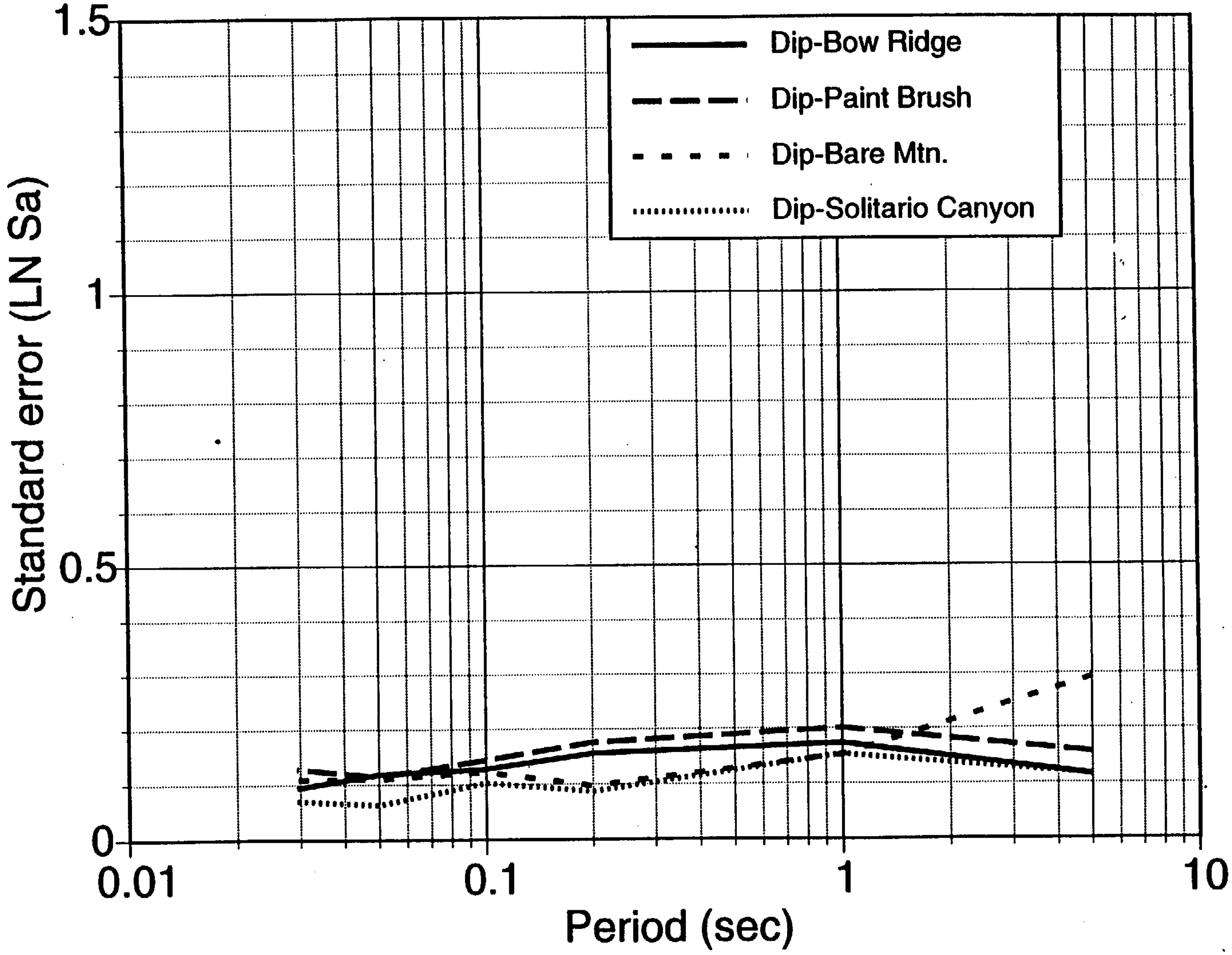

Param (source)
Paint Brush
Revised
PEA
USC
UNR
WCC
USGS
Standard error (LN Sa)
Period (sec)
1.5
1
0.5
0
0.01
0.1
1
10

Param (Source)
Rock Valley
Revised



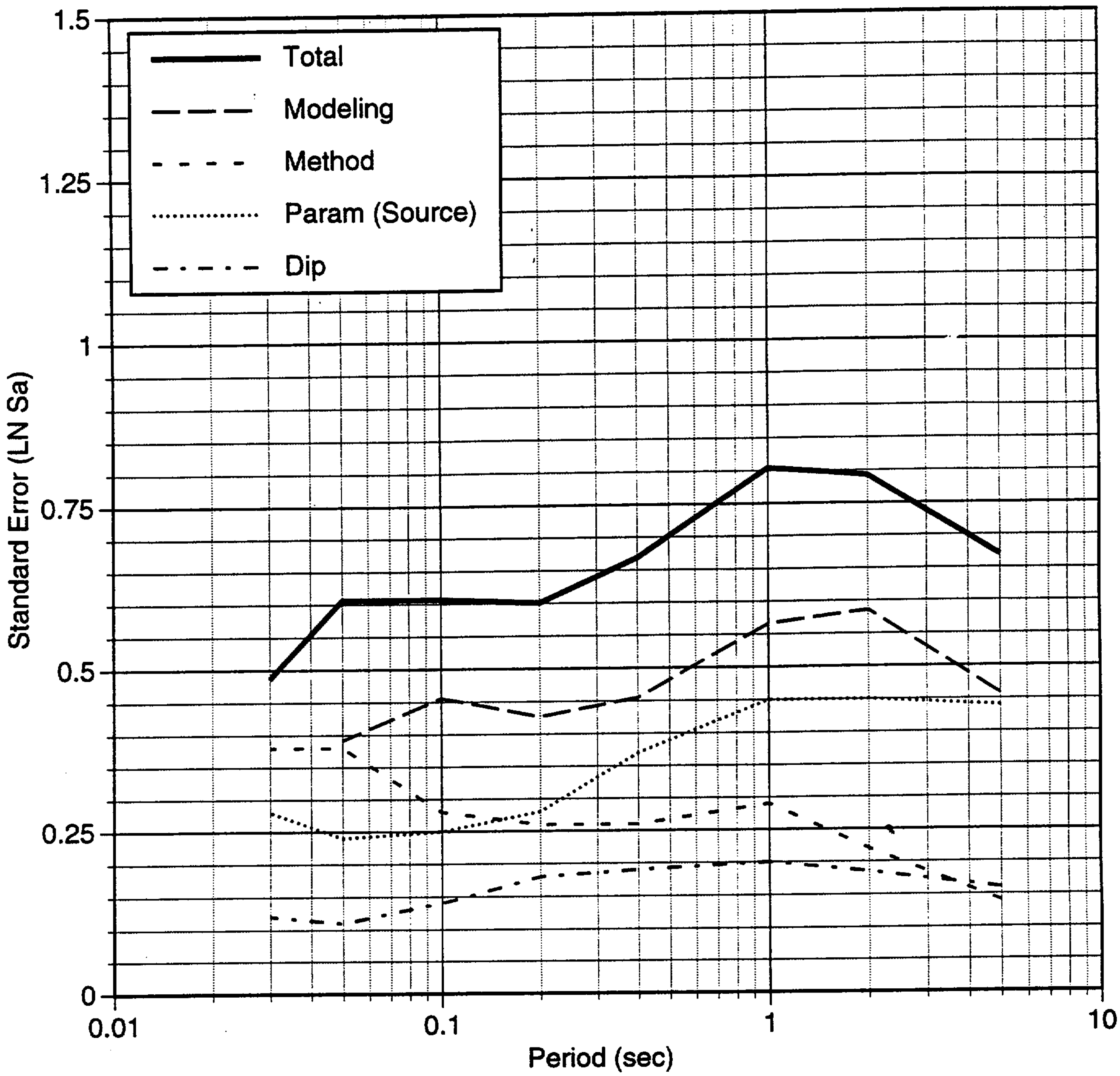
10-5e

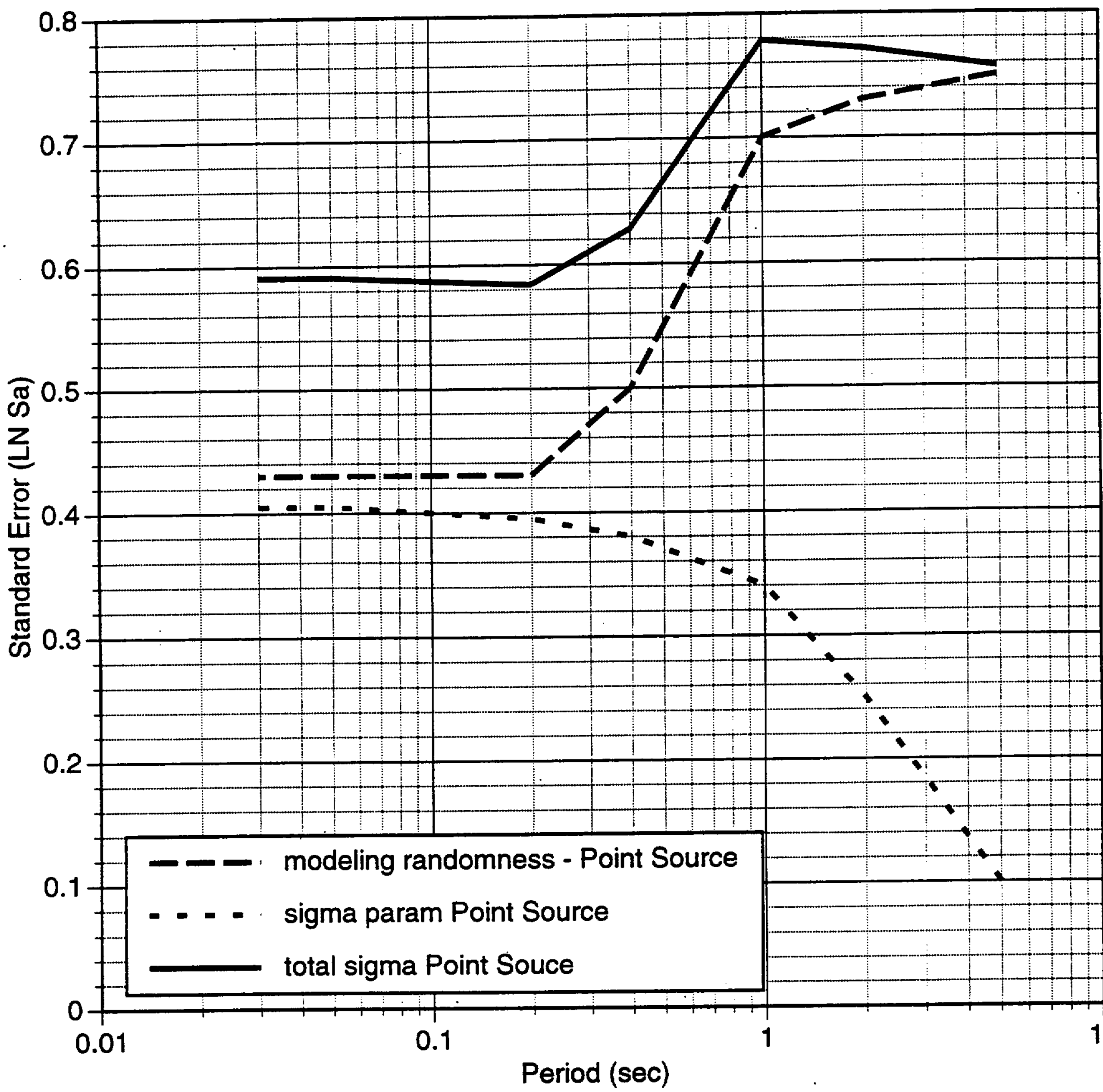
Dip
Revised



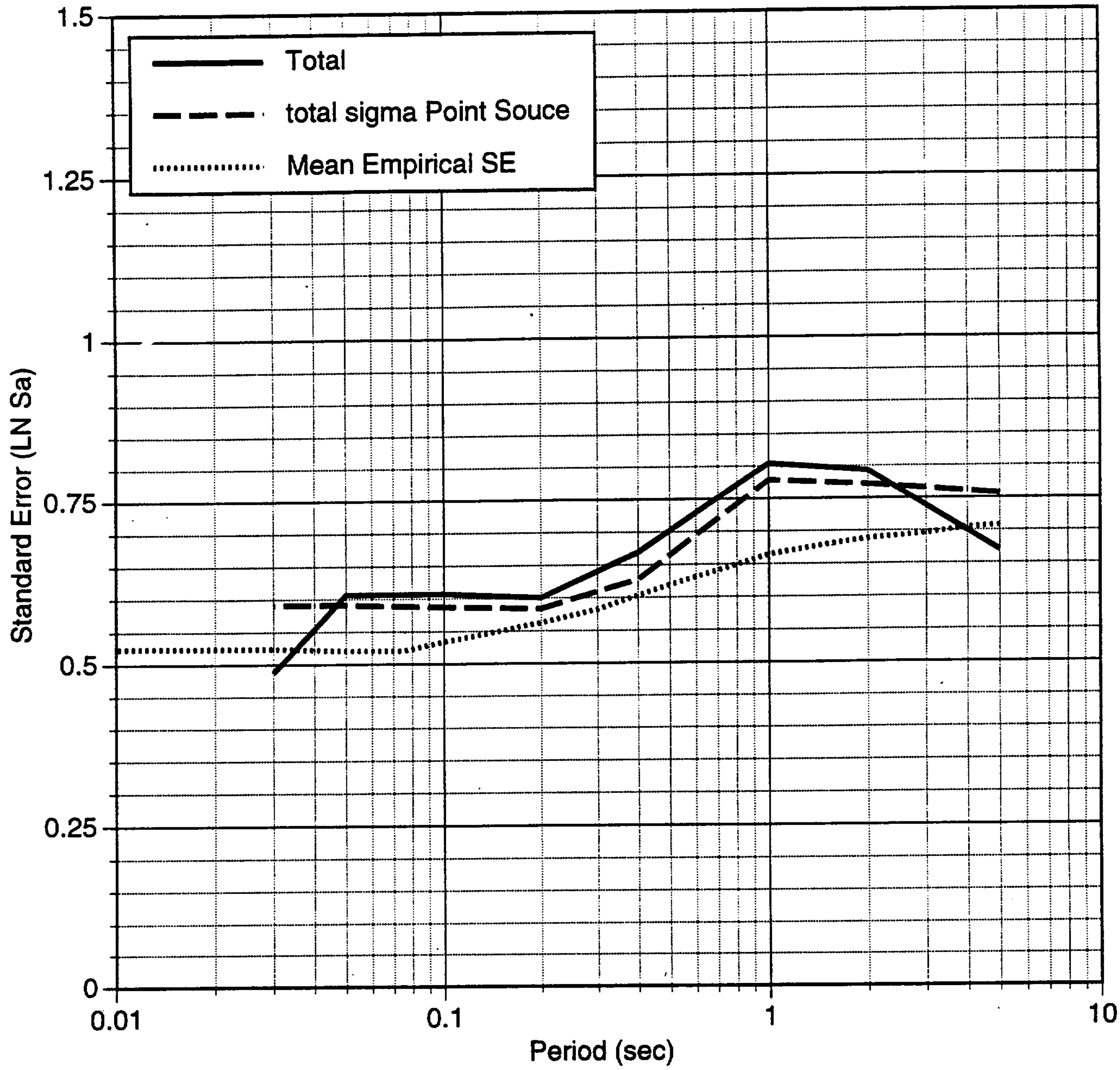
10-6

Standard Error: Paintbrush



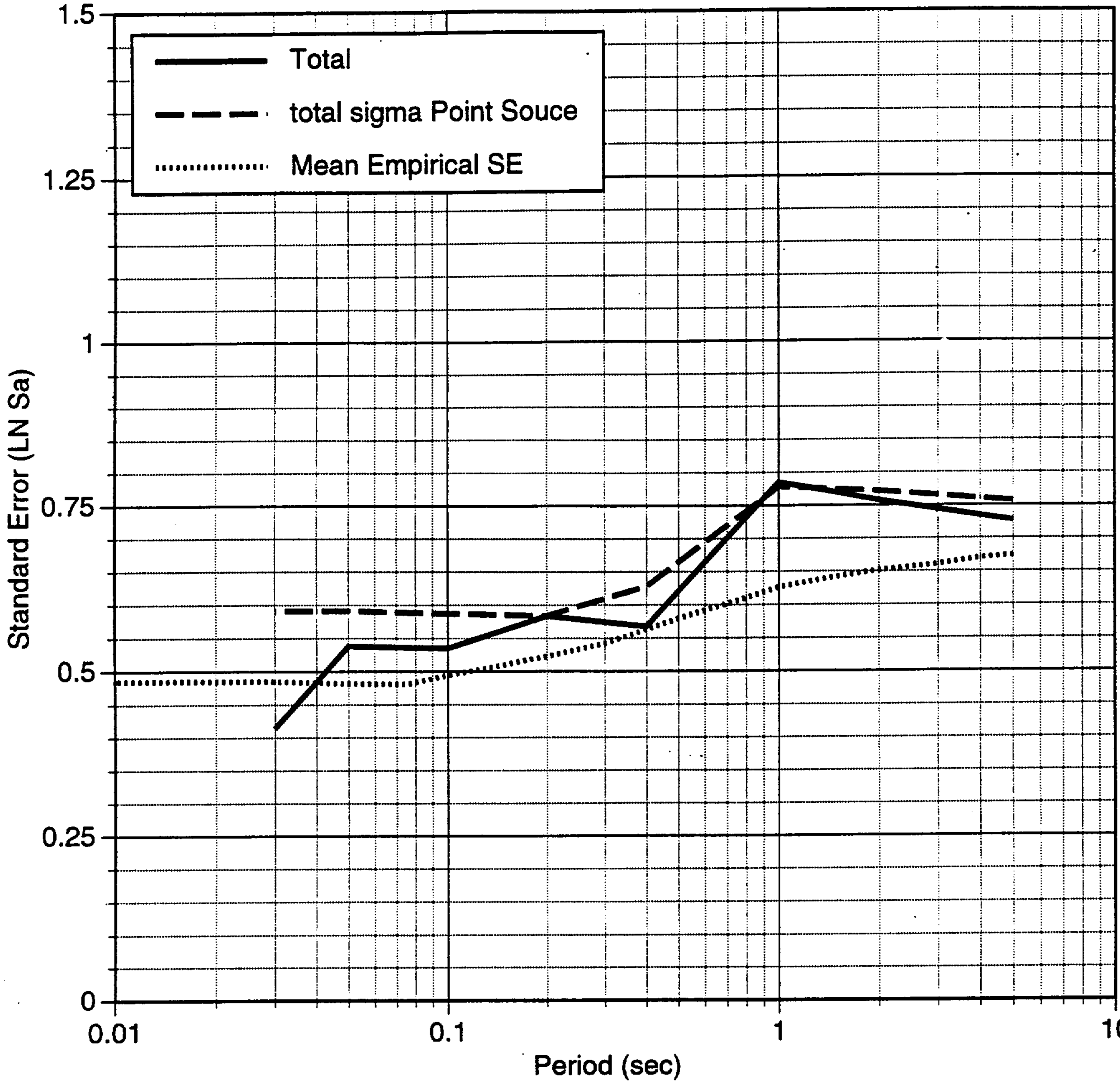

0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
Standard Error (LN Sa)
0.01
0.1
1
10
Period (sec)
modeling randomness - Point Source
sigma param Point Source
total sigma Point Souce

Standard Error: Paintbrush



10-9 b

Standard Error: Rock Valley



10-9 e

FINITE ELEMENT MODELS OF FAULT SLIP AND SEISMIC ATTENUATION PATTERNS FOR BARE MOUNTAIN AND YUCCA MOUNTAIN FAULTS

David A. Ferrill, Goodluck I. Ofoegbu, Kevin Smart, and John Stamatakos

Center for Nuclear Waste Regulatory Analyses

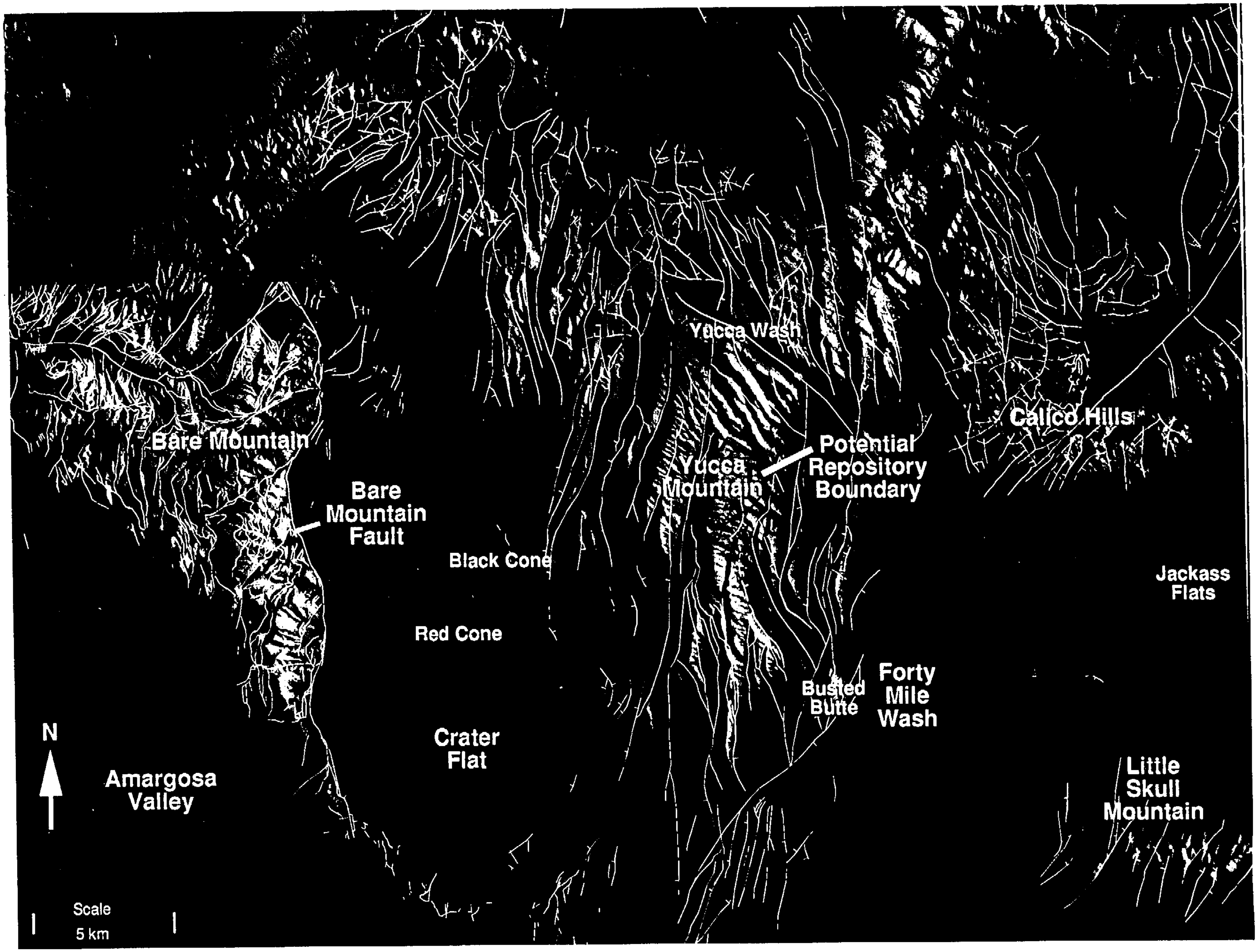
Presented at the

Ground Motion Characterization Workshop

9 & 10 January 1997

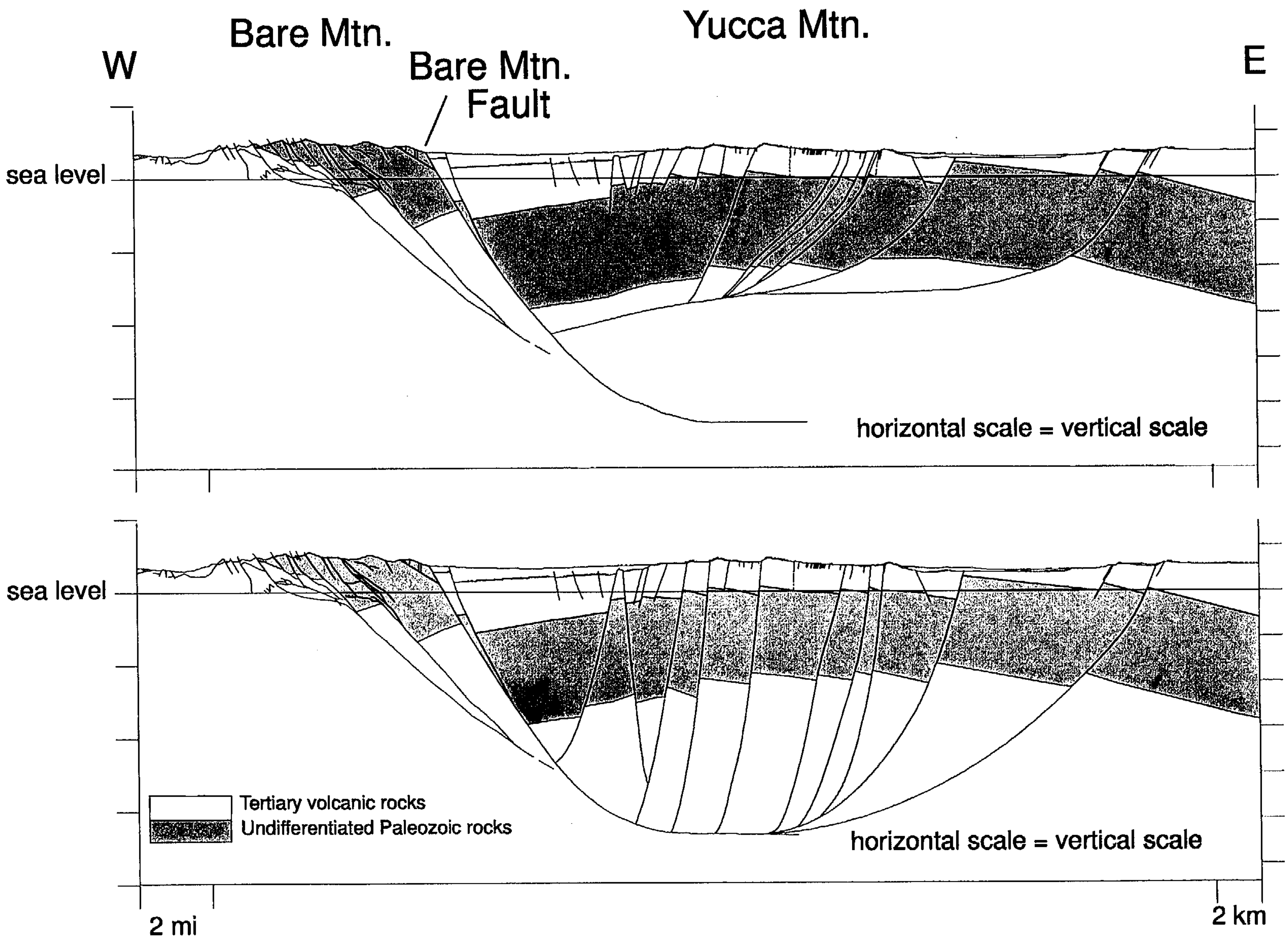
Salt Lake City, Utah

YUCCA MOUNTAIN TECTONIC SETTING

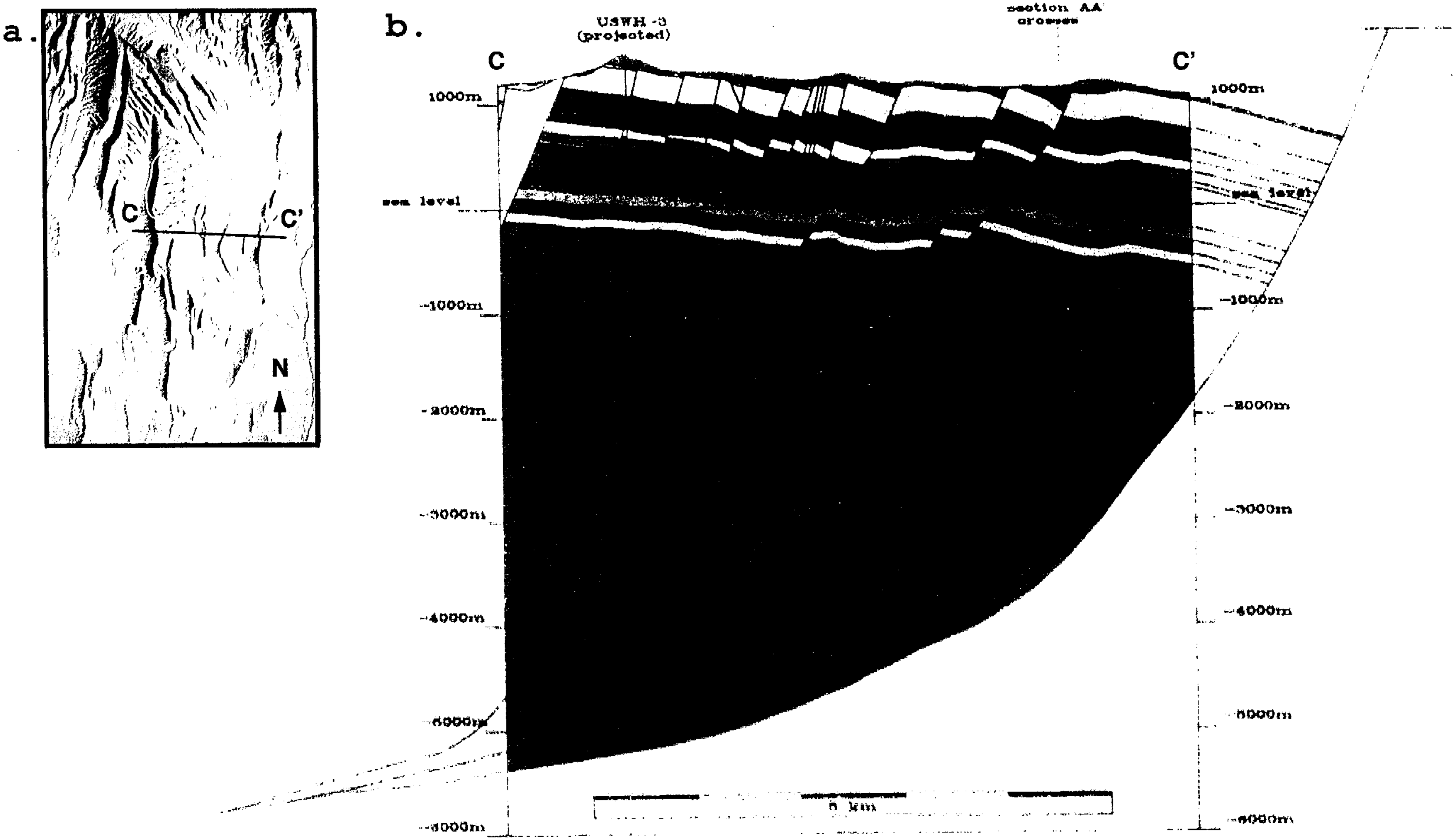


localDemAndFaults.sc 4-26-95

ALTERNATIVE MODELS FOR YUCCA MOUNTAIN FAULTS



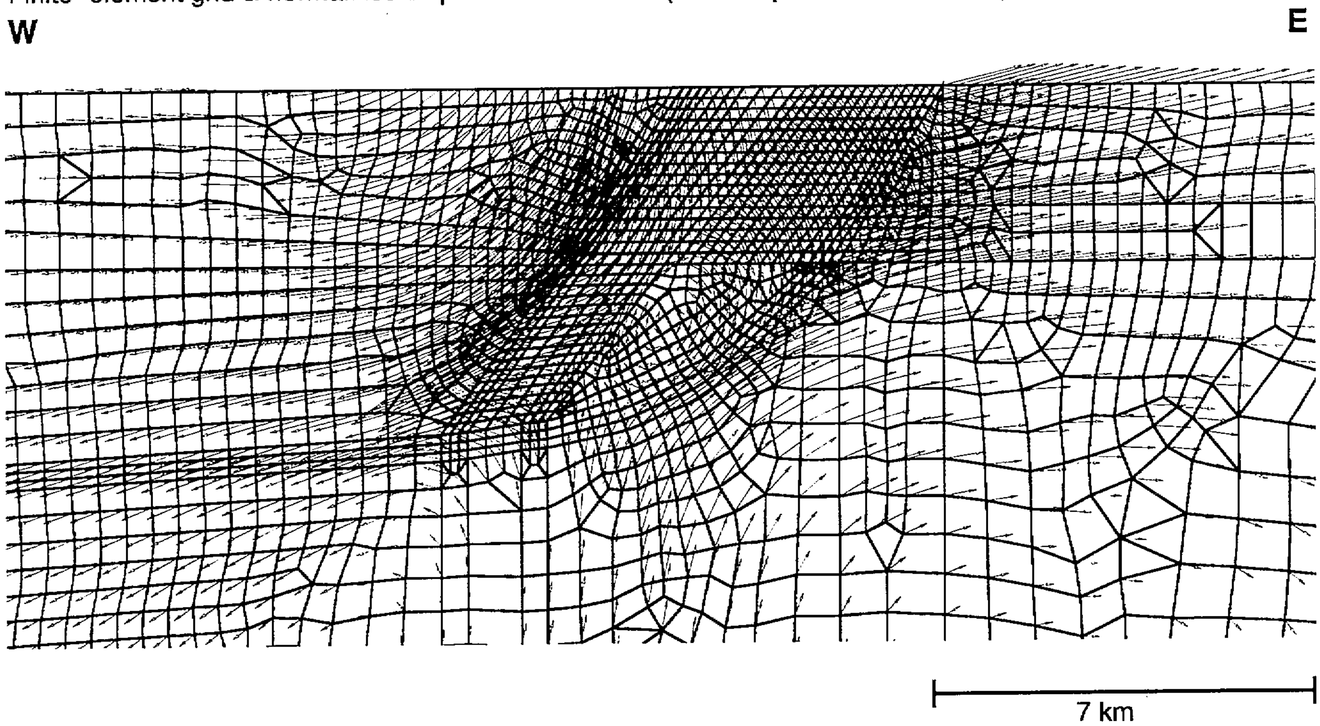
Yucca Mountain, Nevada, Cross–Section C–C'
(From Young et al. 1992)

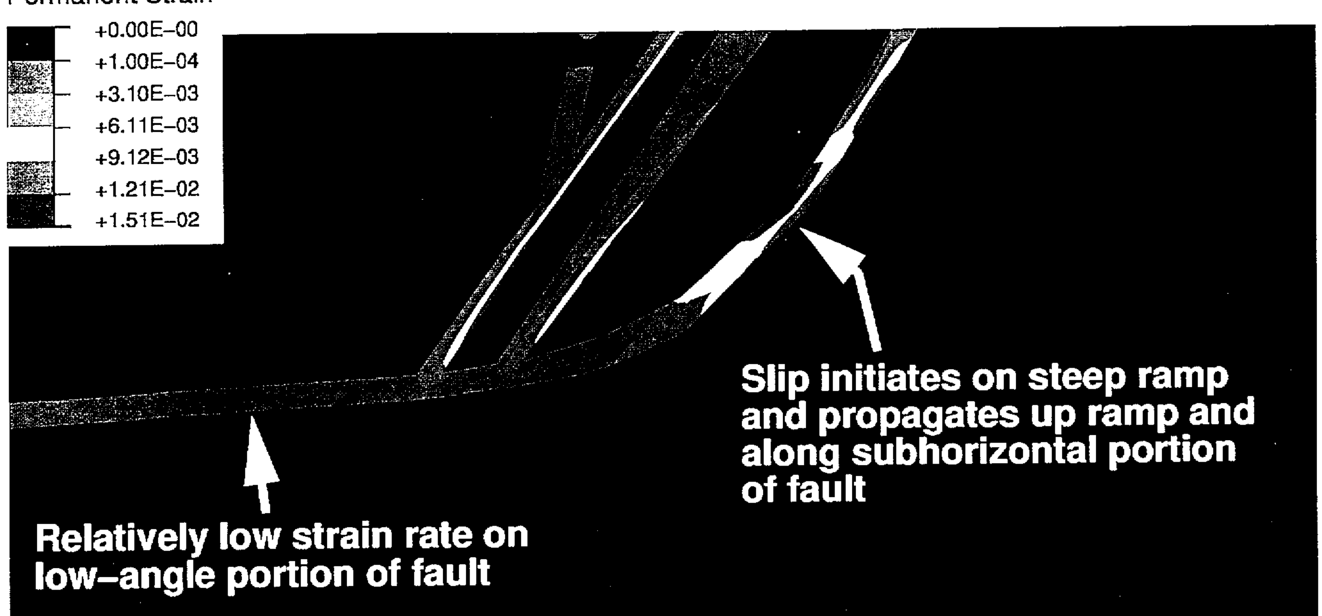


sectionCC.sc 4–3–95

Finite–Element Model of Hangingwall Deformation

Finite–element grid & normalized displacement vectors (max. displacement = 4.64m)





Model Parameters

Host Rock Linear Elastic Rheology:
Young's Modulus = 32.5 GPa
Poisson's Ratio = 0.33
Density = 2.5 g/cc
σ_v = 25 MPa/km
$\sigma_h = K \sigma_v$
$\sigma_{h1} = 0.9 \sigma_v$
$\sigma_{h2} = 0.26 \sigma_v$

Shear Zone Plastic Rheology:
Drucker–Prager failure criteria
Friction angle = 32 deg
Dilation angle = 10.7 deg
Unconfined Compressive Strength = 1 MPa
Damping Factor = 0.02

Initial Conditions

- Zero Strain
- Vertical Stress (σ_V): 25 MPa/km depth
- Horizontal Stress: 0.25 σ_V

Boundary Conditions

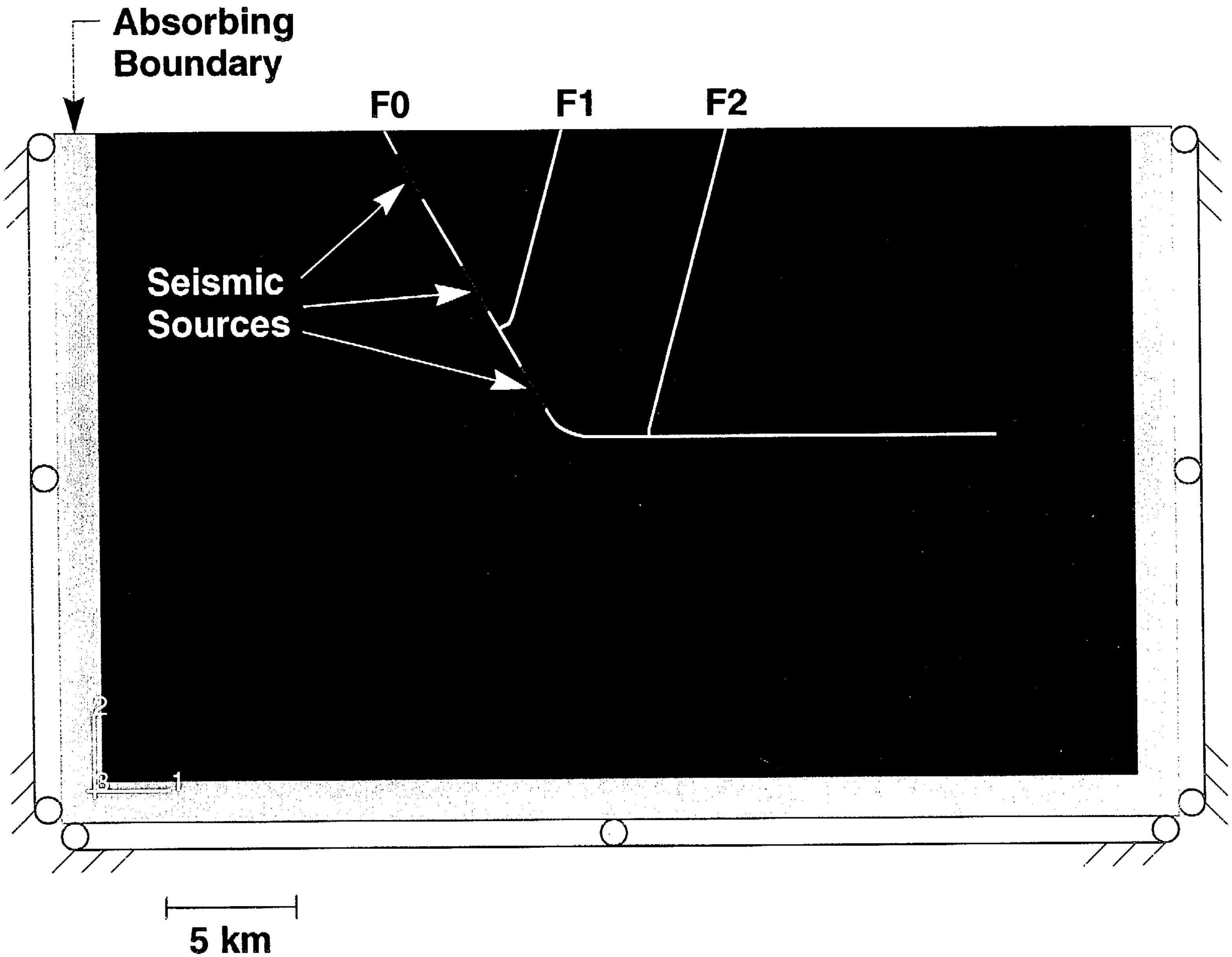
- Left, Right, and base boundaries
  - zero normal displacement
  - absorbing strip with high damping
- Top boundary
  - free surface

Material Properties

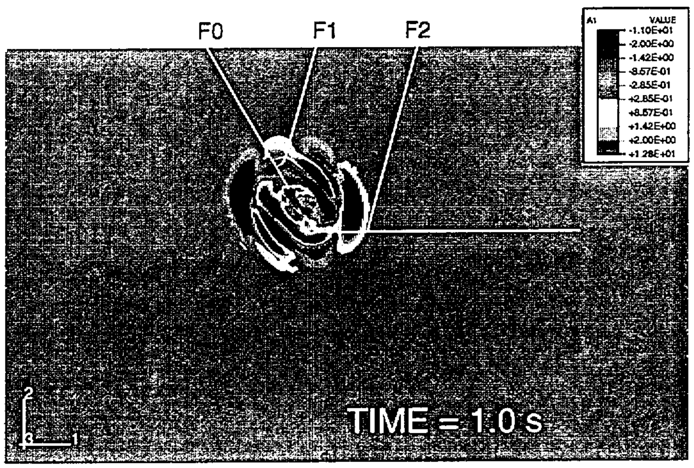
- Faults
  - 100 m thick solid
  - elastic-plastic behavior
  - E = 32.5 GPa, v = 0.25
  - friction angle = 47°
  - cohesion 2.7 MPa
  - damping factor: 0.025
- Rock Body
  - linear elastic
  - E = 32.5 GPa, v = 0.25
  - damping factor: 0.002

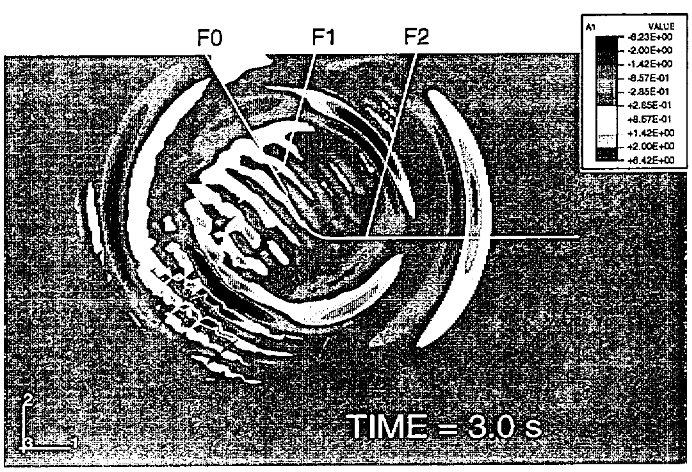
SIMULATION PROCEDURE

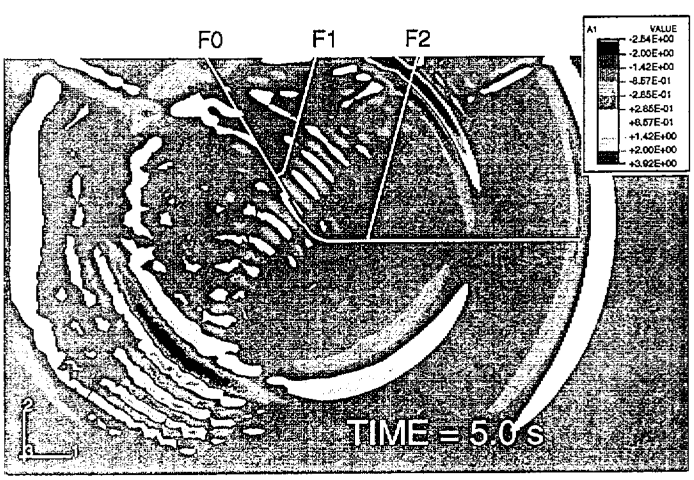
- Static analysis step to establish initial state
- Dynamic analysis step to induce fault slip
- Shear stress pulse applied over selected fault segment for about 4.0 s.
- Response monitored for about 12.0 s.


Absorbing
Boundary
F0
F1
F2
Seismic
Sources
5 km

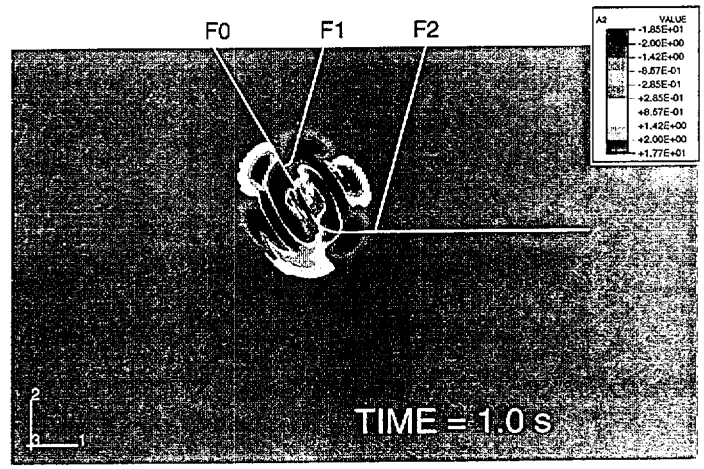
Horizontal Acceleration

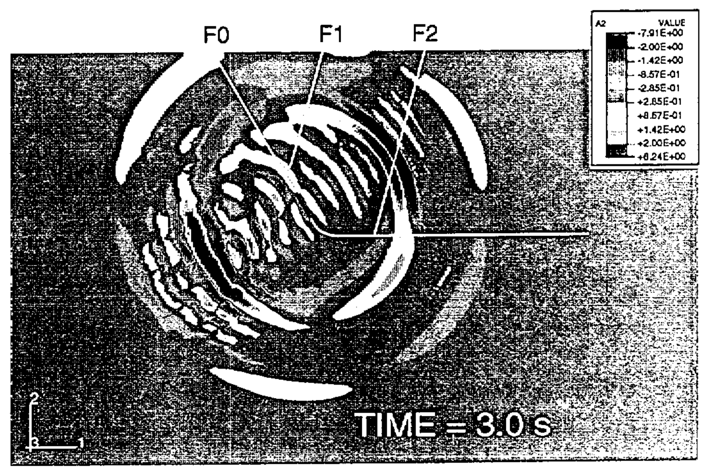


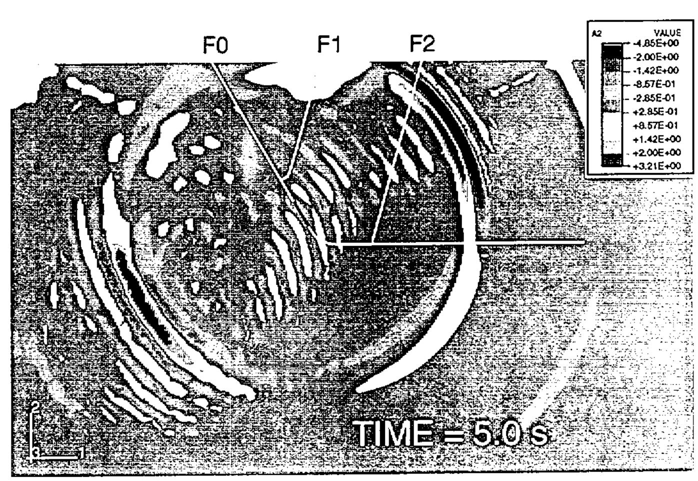




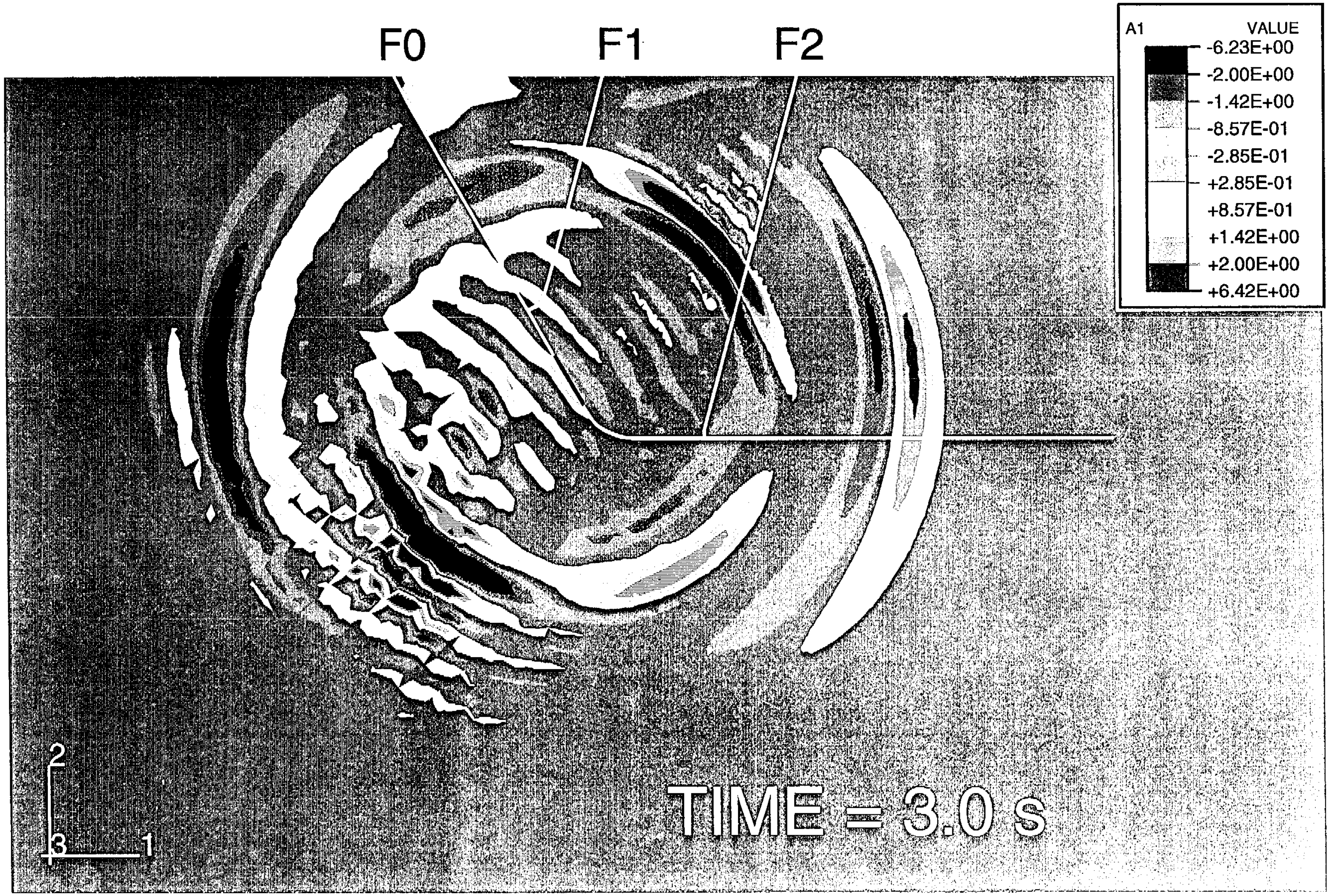
Vertical Acceleration



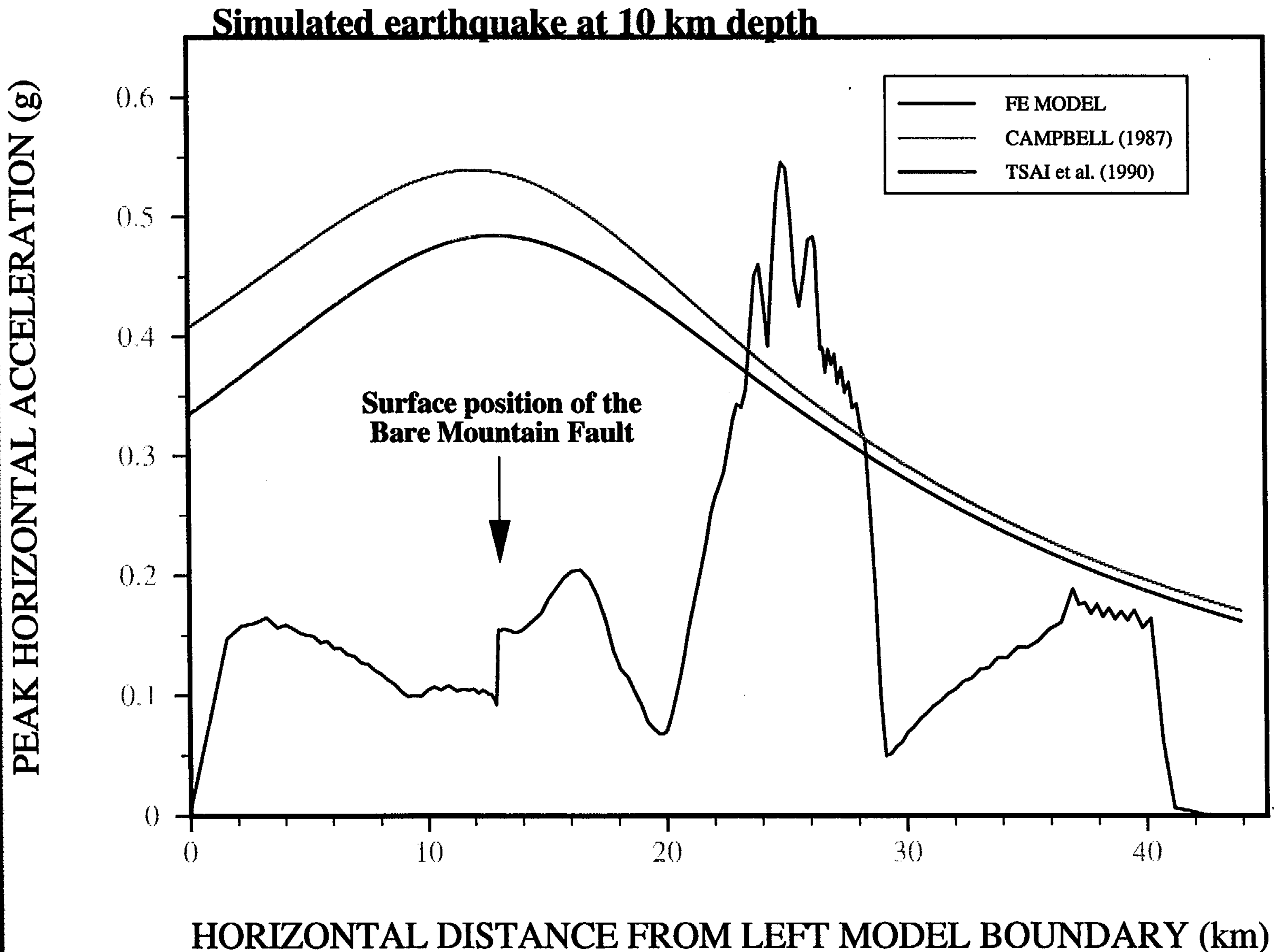




Horizontal Acceleration



GROUND ACCELERATION

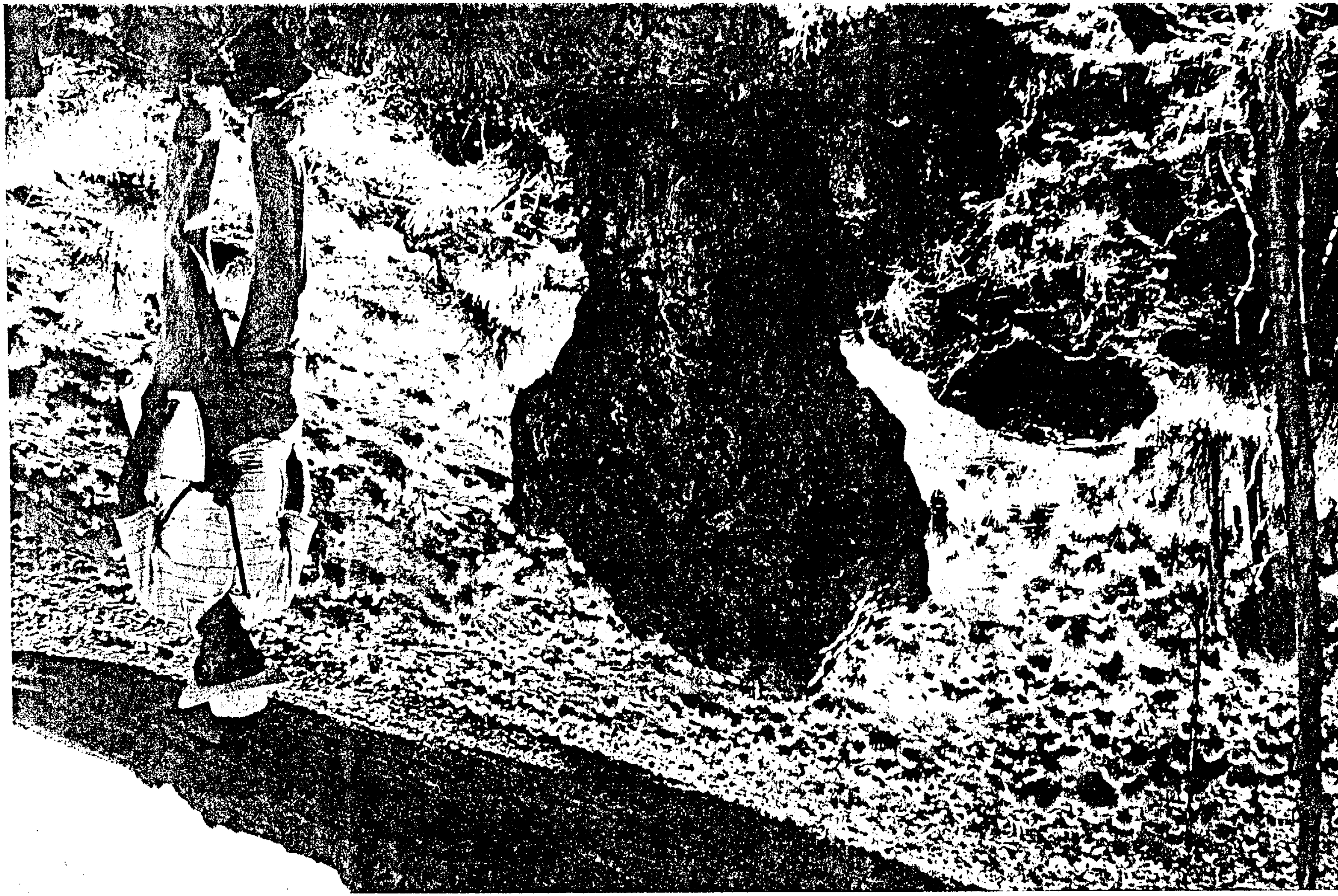


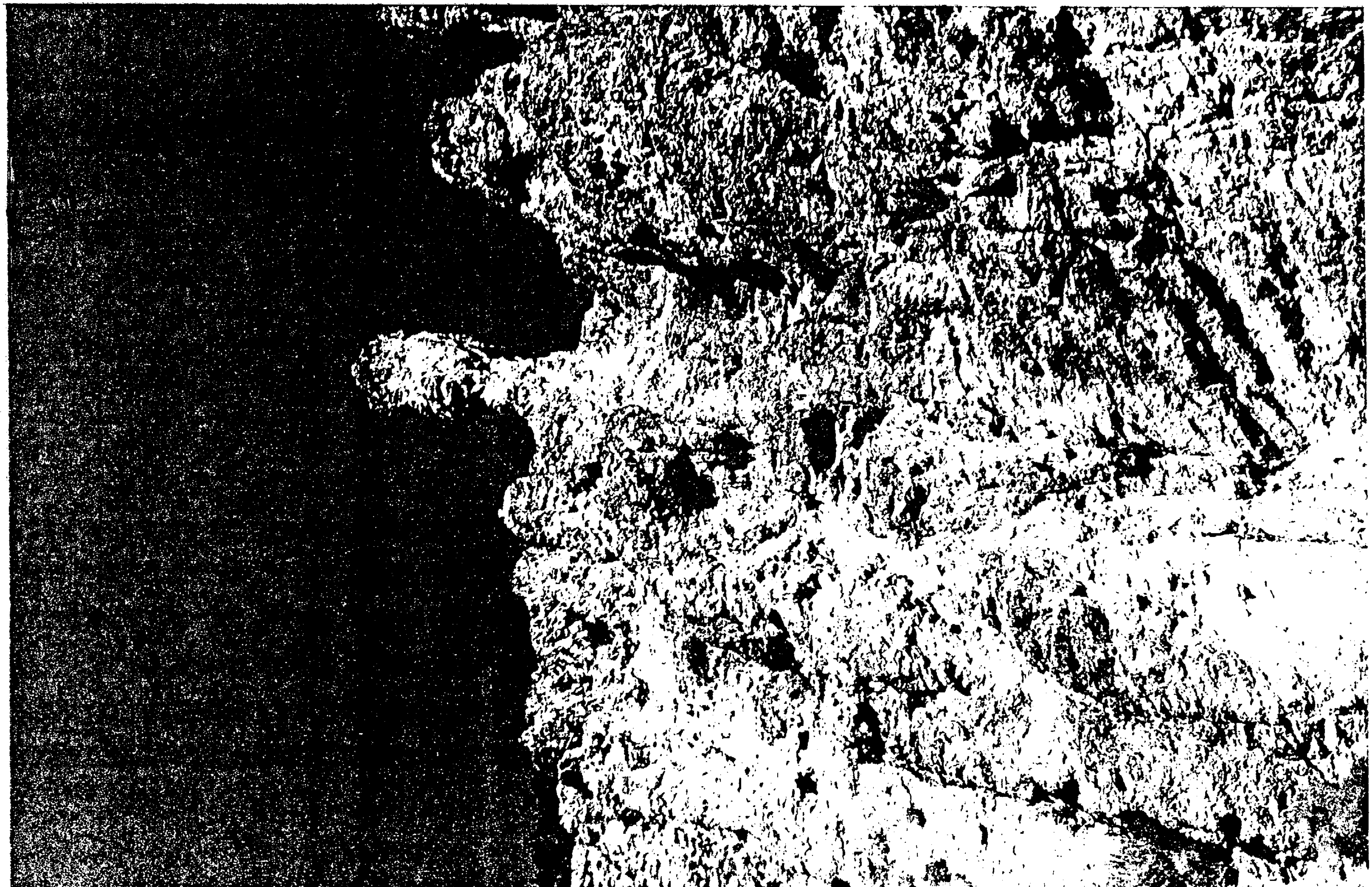
PRECARIOUS ROCKS AND SEISMIC SHAKING AT YUCCA MOUNTAIN, NEVADA

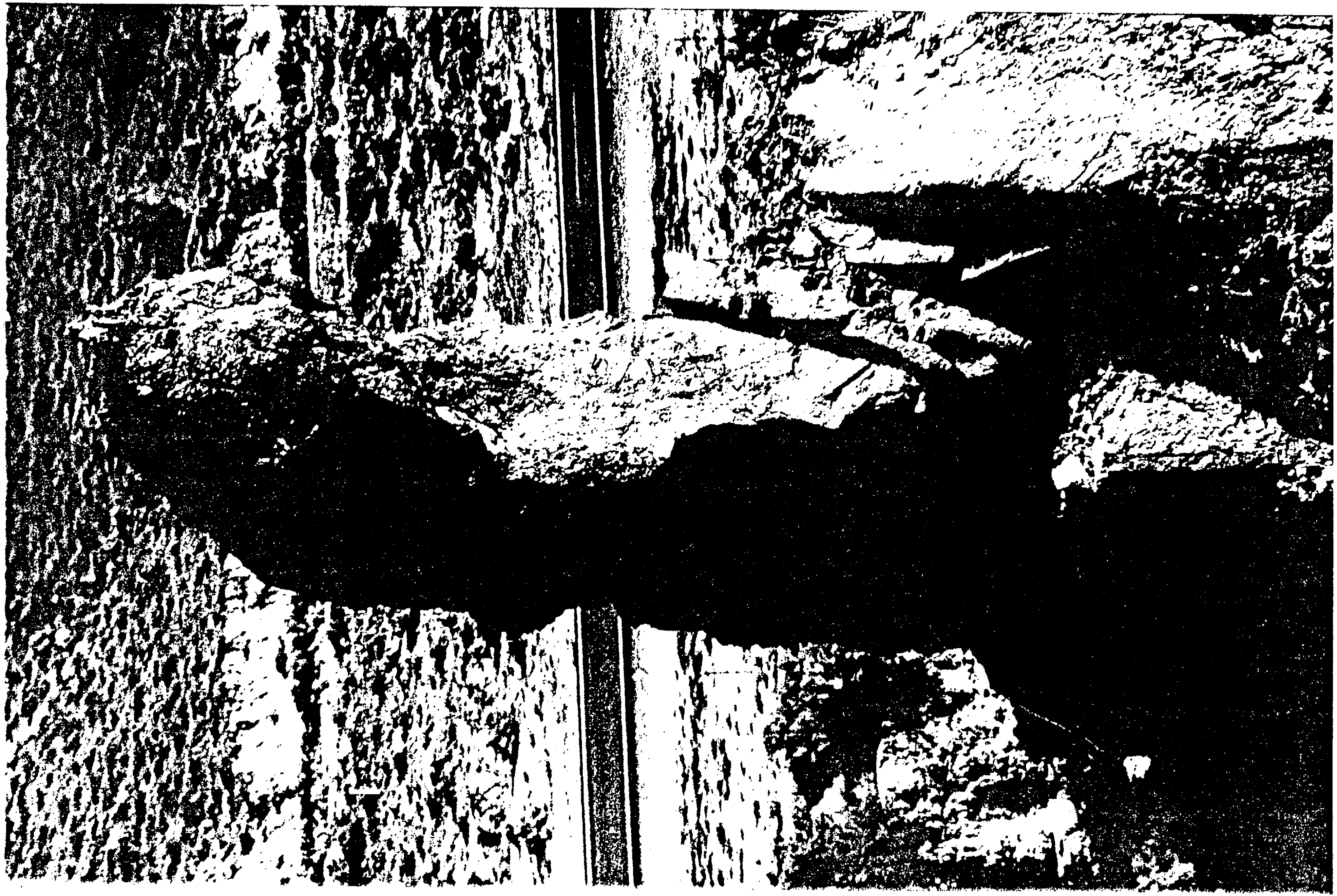
JAMES BRUNE
JOHN WHITNEY

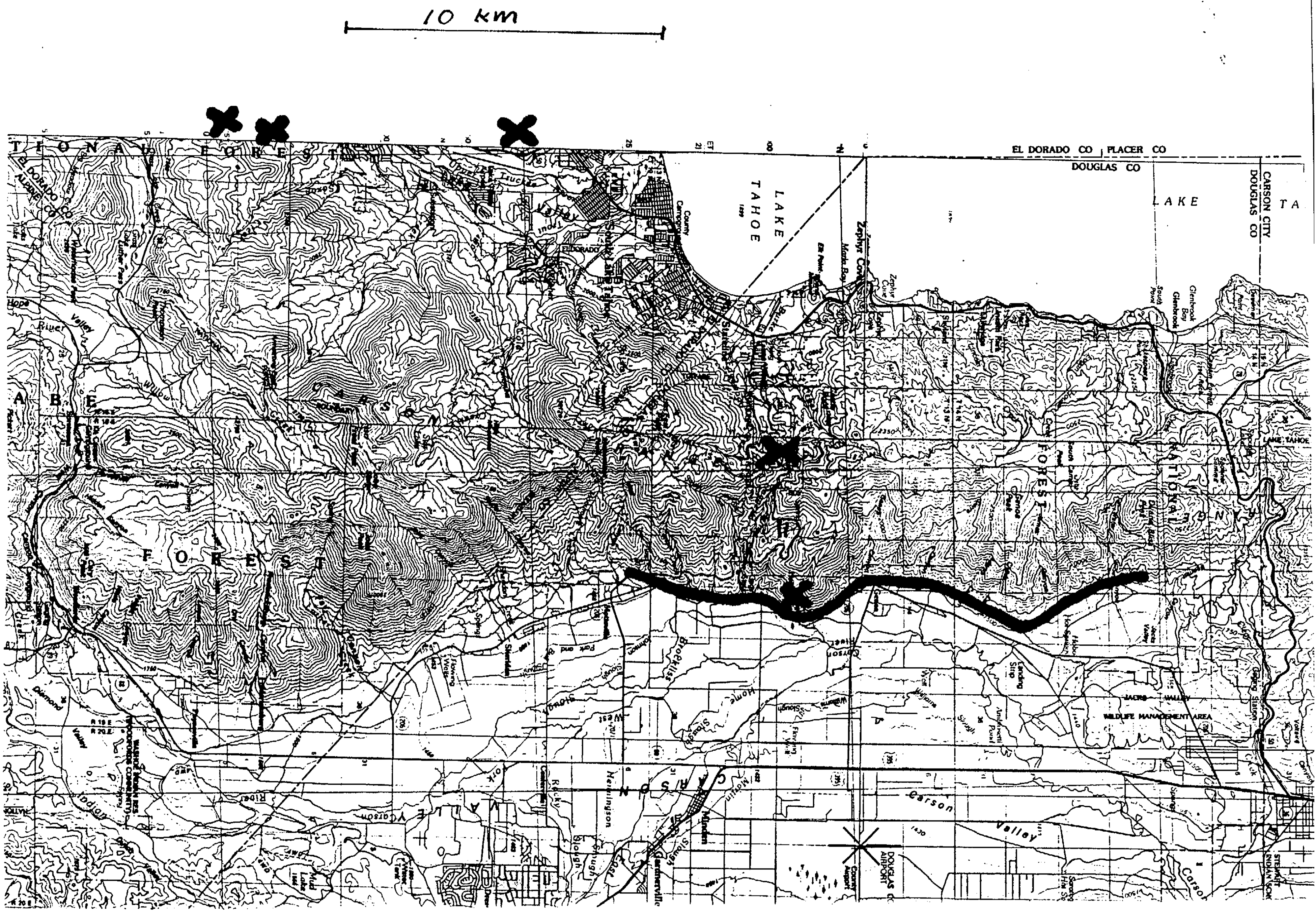
Presented at Salt Lake City
PSHA Conference

January 9, 1997

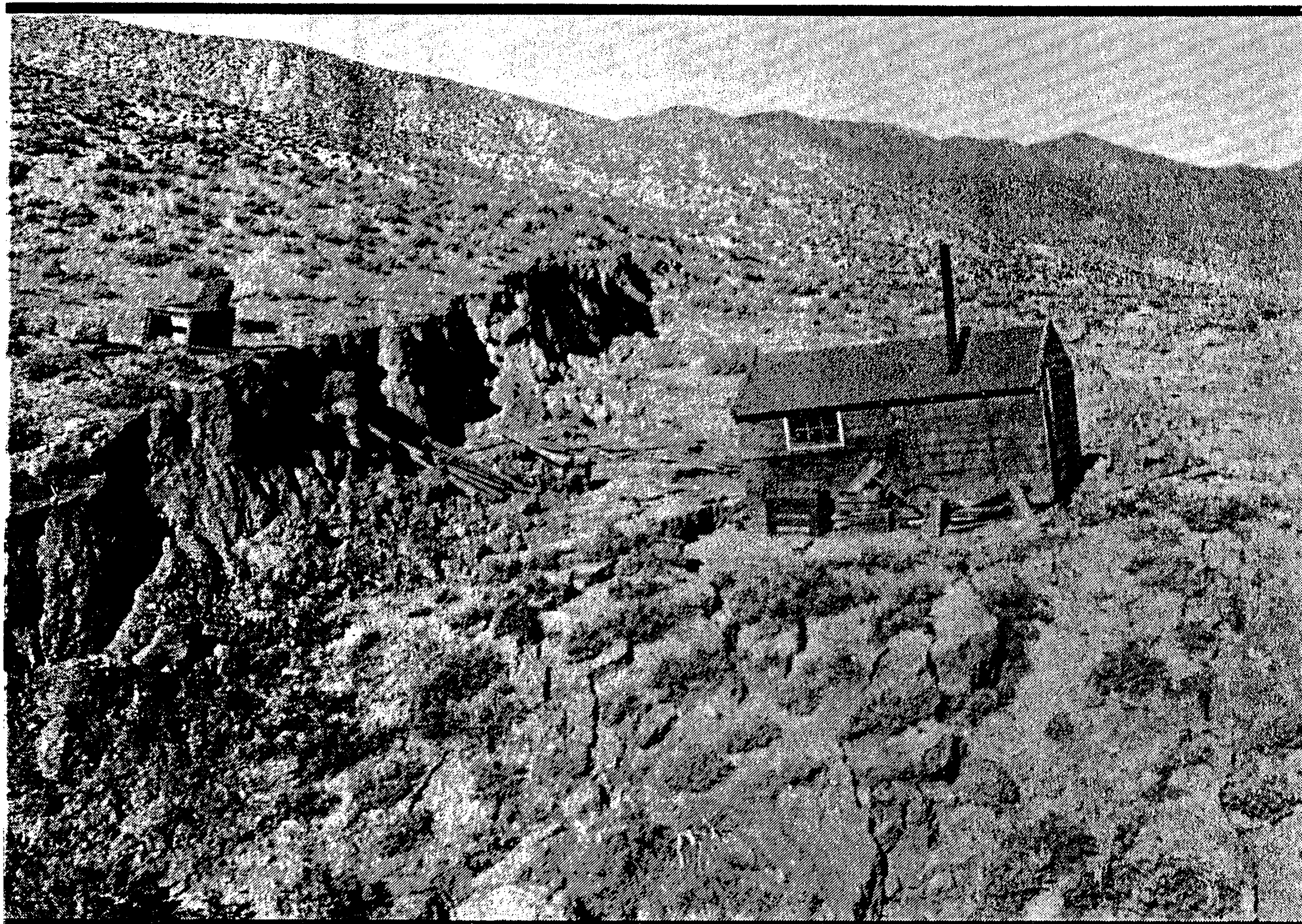







10 km
EL DORADO CO
PLACER CO
DOUGLAS CO
LAKE TAHOE
CARSON CITY
DOUGLAS CO
JACKS VALLEY
WILDLIFE MANAGEMENT AREA
Carson Valley
Minden
DOUGLAS AIRPORT

Catsup bottles on shelves not knocked over!



Ground Motion

Experts

John G. Anderson
David M. Boore
Kenneth W. Campbell
Art McGarr
Walter J. Silva
Paul Somerville
Marianne C. Walck

Attachment 8

JOHN G. ANDERSON

Professor Anderson received his Doctor of Philosophy degree in geophysics from Columbia University in 1976, where he specialized in seismology, and carried out research at the Lamont Doherty Earth Observatory. His undergraduate degree was earned in Physics, from Michigan State University. After earning his degree, Dr. Anderson held positions on the research faculty at the California Institute of Technology, the University of Southern California, and the University of California at San Diego. In 1988, he accepted a position of teaching and research at the University of Nevada.

Dr. Anderson's research has included a broad range of studies relating to seismic hazards. He has installed strong motion accelerograph networks in the eastern United States, in the Los Angeles metropolitan region, and in Guerrero, Mexico. He has carried out analysis of strong motion data from nearly every angle: data processing, interpretation of the seismic source, describing and understanding site effects, developing attenuation relations, and preparation of complete synthetic seismograms. These studies, combined, have helped to develop an understanding of the dominant effects that control the strong motion seismogram. Dr. Anderson has also been involved in research and applications of probabilistic seismic hazard analysis. One of the critical input parameters to hazard analysis is the seismic activity rate, where Dr. Anderson has studied how this can be developed from geological observations. Among other studies, he is currently involved in studies of state-of-the-art in ground motion attenuation for the southern California Earthquake Center. Dr. Anderson has published over 125 research articles and reports describing results of this research. Dr. Anderson has some personal experience with the Yucca Mountain project originating from studies of the Little Skull Mountain aftershock sequence and site effects in Midway Valley and the region around the southeastern portion of the Nevada Test Site.

Professional relationships have included membership on two panels for the National Academy of Science (Seismic Risk, and Base Isolation), member and chairman of the Nevada Earthquake Safety Council, associate editor for the Bulletin of the Seismological Society of America, and Associate Director and Acting Director of the Seismological Laboratory of the University of Nevada. He has served on advisory panels organized by the U.S. Geological Survey and National Science Foundation National Earthquake Hazard Reduction Program, and the California Division of Mines and Geology Strong Motion Instrumentation Program. He is a member of the Seismological Society of America, the Earthquake Engineering Research Institute, the American Geophysical Union, and the Royal Astronomical Society (London).

DAVID M. BOORE

Education

B.S. (Geophysics), Stanford University, 1964
M.S. (Geophysics), Stanford University, 1965
Ph.D. (Geophysics), Massachusetts Institute of Technology, 1970

Work Experience

Summer jobs with Shell Oil Company (seismic exploration: 1962, 1963, 1966), NASA (lunar cratering processes: 1965), Lincoln Laboratory (seismic verification: 1967).
1970-1972: National Research Council - USGS Post-Doctoral Research Associate
1972-1979: Assistant Professor of Geophysics, Stanford University
1979 - present: Geophysicist, U.S. Geological Survey

Research Interests

Prediction of strong ground shaking from earthquakes, making use of theoretical and empirical analysis of the source, wave propagation, and local site effects.

Non-research Contributions to the Profession

Associate Editor, *Bulletin of the Seismological Society of America*, 1975-1984.
Editor, *Bulletin of the Seismological Society of America*, 1985 1992.
Expert consultant, Lawrence Livermore National Laboratory Panels on seismic strong ground motion estimation in the eastern United States, 1980-present.
Chairman, Commission on Strong Motion Seismology, IASPEI, 1977-1983.
Member, Commission on Strong Motion Seismology, IASPEI, 1984-1991.
Member, Senior Seismic Hazard Analysis Committee, 1993 .
Consultant to Tank Seismic Expert Panel, 1994-

Invited Lectures

Invited participant, lecturer, or keynote speaker at more than 50 workshops, symposia, etc. in the U.S., Taiwan, China, Germany, Switzerland, Italy, Mexico, Venezuela, Canada, Yugoslavia, and Turkey.

Research Papers

Over 124 papers published, starting in 1969, most of which deal with predicting ground motion. The most publication is "Ground-motion relations for eastern North America," Bull. Seism. Soc. Am. (1995), p. 17-30 (coauthored with Gail M. Atkinson).

Biosketch - Ground Motion Expert
Probabilistic Seismic Hazard Analysis for Yucca Mountain
17 April 1995

BIOGRAPHICAL INFORMATION

Kenneth W. Campbell, Ph.D.
EQE *International*, Inc.

Dr. Campbell obtained his Ph.D. in 1977 in Geotechnical and Earthquake Engineering from the University of California at Los Angeles (UCLA). Since 1972, he has worked as an earthquake-engineering consultant for several engineering consulting firms and has served as a research civil engineer with the National Oceanic and Atmospheric Administration and U.S. Geological Survey. He is currently an Associate and Senior Technical Manager with EQE *International*, an engineering consulting firm with headquarters in San Francisco. Dr. Campbell has over 23 years of professional experience in technical management, consulting, and research in the areas of engineering seismology, strong ground motion, seismic hazards evaluation, and geotechnical and lifeline earthquake engineering. He has directed projects throughout the world to develop deterministically and probabilistically defined seismic design and evaluation criteria for the nuclear, oil, utility, and construction industries. Dr. Campbell has served as an expert witness at hearings to determine the seismic safety of several nuclear facilities in the United States and has been a member of several expert panels to assess ground motions for critical facilities. He has written over 100 publications in the fields of strong ground motion and seismic hazards evaluation and is an active member of the Seismological Society of America (SSA), the American Geophysical Union (AGU), the Earthquake Engineering Research Institute (EERI), and the American Society of Civil Engineers (ASCE). He currently serves on the Board of Directors of the Seismological Society of America and as a Vice-Chairman of the Seismic Risk Committee of ASCE's Technical Council on Lifeline Earthquake Engineering. He is widely known for his research on the analysis and prediction of near-source ground motion, which has led to the authorship of several well-known strong-motion attenuation relationships.

ART McGARR

Education
California Institute of Technology, B.S., Physics, 1962
California Institute of Technology, M.S., Geophysics, 1963
Columbia University, Ph.D., Geology, 1968

Professional History
U.S. Geological Survey, Menlo Park, CA, Geophysicist, 1978-present
University of Paris-Sud, Visiting Professor, 1981.
Bernard Price Institute of Geophysics, University of the Witwatersrand, Johannesburg, South Africa, Senior Research Officer, 1968-1978.
Lamont-Doherty Geological Observatory of Columbia University, Graduate Research Assistant, 1963-1968.
Texas Instruments, Inc., Dallas, TX, Seismological Research Assistant, June-Sept, 1963.

Affiliations
American Geophysical Union
Seismological Society of America
American Association for the Advancement of Science

Relevant Research and Publications
Dr. McGarr has published over 60 papers on seismology, tectonics and rock mechanics, including numerous articles on factors influencing the estimation of ground motion parameters.

WALTER J. SILVA

Dr. Silva is President and Senior Seismologist at Pacific Engineering and Analysis. Dr. Silva has over 20 years of experience in seismology with particular emphasis on strong ground motion estimation using both numerical modeling and empirical approaches. He has developed and thoroughly validated a numerical modeling methodology that accurately models strong ground motions at any distance (0-500 km) from small or large magnitude earthquakes. Validation exercises include magnitude 8 subduction zone earthquakes and earthquakes located in western and eastern North America. Over 50 earthquakes have been modeled resulting in the most thoroughly validated methodology available. The methodology incorporates source finiteness, crustal propagation effects, and nonlinear site response in one code.

In addition to source modeling, Dr. Silva also specializes in quantifying the effects of site conditions on strong ground motions using empirical and 1- and 2- dimensional modeling techniques. In this context, he has evaluated a number of nonlinear approaches as well as the widely used equivalent-linear methodology in applications to recorded motions. To augment his finite fault modeling to accommodate nonlinear site response in an accurate and computationally attractive manner, he developed and validated a frequency domain random vibration theory equivalent-linear formulation.

Dr. Silva has provided ground motion evaluations on a number of both large and small projects on a world-wide basis. He has provided site response predictions for over 30 nuclear power plants and numerous small projects, applied strong motion modeling techniques at four DOE facilities and at the ESF for the proposed high level nuclear repository at Yucca Mountain, Nevada, as well as numerous Reclamation dams and other small projects, and developed region specific attenuation relations for eastern and central North America, Colorado, Idaho, New Mexico, and Spain using the stochastic ground motion model. He has been a state-of-the-art speaker on site effects and continues to do applied research on source modeling and site effects for such agencies as NEHRP and DOE.

DR. PAUL SOMERVILLE
Woodward-Clyde Federal Services
566 El Dorado Street, Pasadena, CA 91101

Dr. Paul Somerville received his doctoral degree in Geophysics from the University of British Columbia in 1976. He spent two years as a Visiting Research Fellow at the Earthquake Research Institute, Tokyo University, during 1977 and 1978, and since then has participated in post-earthquake reconnaissance activities in Japan, most recently in the 1995 Kobe earthquake. He has 18 years' experience as an engineering seismologist with Woodward-Clyde and is manager of the Pasadena office. He is a member of the Seismology Committee of the National Research Council of the National Academy of Science, and is a member of the Earthquake Engineering Research Institute and an affiliate member of the Structural Engineers Association of California.

Dr. Somerville has participated in earthquake hazard evaluations for a large number and variety of engineering projects in many parts of the world. During the past ten years, he has developed and applied seismological methods for estimating ground motions for the seismic design of engineered structures. These include the use of strong motion simulation procedures to generate realistic ground motion time histories close to large earthquakes which include near-fault effects such as those due to rupture directivity. These procedures have been used to simulate ground motion time histories for structures such as Caltrans bridges in Northern and Southern California, and MWD's Domenigoni Valley Reservoir in Southern California. Dr. Somerville is currently participating with the SAC Joint Venture by providing ground motion time histories to represent the ground motions experienced by steel moment frame buildings during the Northridge earthquake as well as other possible events.

Multi-year projects that Dr. Somerville has directed include a program of numerical ground motion studies for the Long Term Seismic Program for PG&E's Diablo Canyon Power Plant; evaluation of earthquake source and ground motion characteristics in eastern North America for the Electric Power Research Institute and the Nuclear Regulatory Commission; estimation of strong ground motions in the Pacific Northwest from large subduction earthquakes on the Cascadia subduction zone for the U.S. Geological Survey; analysis of the characteristics of near-fault ground motions for the U.S. Geological Survey, and analysis of the ground motion characteristics of the 1989 Loma Prieta and 1994 Northridge earthquakes for the National Science Foundation.

Marianne C. Walck

Marianne Walck has been working with local-to-near-regional recordings of NTS underground nuclear explosions since 1984. She studied a signficant vertical acceleration anomaly that occurred at Jackass Flats, NTS for Pahute Mesa nuclear tests and presented the results at two Seismological Society of America meetings (1988 and 1992). This work involved siting acceleration stations on Jackass Flats, analyzing the resulting data for travel times and relative amplitude patterns, and modeling the shallow crustal structure at NTS using both 2-D raytracing and finite difference synthetic seismogram techniques. Marianne's involvement with the Yucca Mountain project began in 1988 with a study of 2-D crustal structure for three paths at NTS between nuclear testing areas and Yucca Mountain. Using UNE sources, she successfully reproduced absolute travel time, relative amplitude and waveshape data for the three paths, documenting signficant crustal structure differences at shallow depths near Yucca Mountain (Walck and Phillips, 1990; Phillips, Walck and Shephard, 1991). After a hiatus, Marianne resumed work on the Yucca Mountain project in 1992. She gave presentations on UNE ground motions at Yucca Mountain at the 1994 SSA Meeting and the Yucca Mountain Tectonics Workshop. Most recently, she and a contractor (Dr. Bashir Durrani of UTEP) have been employing propagator matrix techniques to model the very shallow structure at Yucca Mountain using UNE records from 4 borehole/surface pairs (Durrani and Walck, 1994; 1995) in order develop a predictive capability at depth near the site of the potential repository.

Marianne has also conducted research using nuclear explosion sources at teleseismic (Walck, 1988; Walck, 1989 and related abstracts) and at regional distances (Walck and Chael, 1990 (abs). The latter work used NTS explosions recorded at high-frequency stations in Nevada and California; the former used Soviet explosions recorded at NORESS to deduce path attenuation.

4 December 1996

PROBABILISTIC ANALYSIS OF FAULT DISPLACEMENT AND VIBRATORY GROUND MOTION AND THE DEVELOPMENT OF SEISMIC DESIGN BASES FOR YUCCA MOUNTAIN

PROJECT PLAN
(Revision 1)

In accordance with the Nuclear Waste Policy Amendments Act of 1987, the U.S. Department of Energy (DOE) is charged with the responsibility of evaluating Yucca Mountain as a potential geologic repository to site the nation's first permanent disposal facility for spent nuclear fuel and high-level radioactive waste. As part of this effort, the evaluation of seismic hazards at Yucca Mountain and the development of seismic design parameters is being carried out jointly by the U.S. Geological Survey (USGS) and the Civilian Radioactive Waste Management System (CRWMS) Management and Operations (M&O) contractor.

The work described in this project plan will be performed in four strongly integrated parallel activities (Figure 1) leading to the determination of fault displacement and vibratory ground motion levels for seismic design of the Yucca Mountain repository structures, systems, and components (SSCs) and to a full documentation of the technical bases for these determinations. Seismic design covers surface and subsurface SSCs. Both the pre-closure and post-closure performance periods of the repository (100 and 100,000 years, respectively) will be addressed in this project. The activities to be performed are: (1) evaluation and characterization of seismic sources; (2) evaluation and characterization of vibratory ground motion attenuation relationships, including earthquake source, wave propagation path and rock site effects; (3) probabilistic seismic hazard analysis (PSHA) for both fault displacement and vibratory ground motion; and (4) development of fault displacement and vibratory ground motion values appropriate for the seismic design of the proposed repository SSCs.

By necessity, evaluations of seismic source characteristics, earthquake ground motions, and fault displacement involve interpretations of data. These interpretations have associated uncertainties related to the ability of data to resolve competing hypotheses and models fully. The interpretations to be completed as part of this study will be based on seismological, geological, geophysical, and geotechnical data specific to the Yucca Mountain site and the surrounding area. Interpretations of the data sets will be fully integrated and coordinated to evaluate parametric variability and uncertainty in the interpretations. To evaluate scientific uncertainty, seismic source characterizations will be made by six teams consisting of three individuals each, who in composite are expert in the seismicity, tectonics, and geology of the Yucca Mountain site and region. Ground motion assessments will be made by seven individuals expert in evaluating the generation and attenuation of earthquake ground motion.

Interpretations for hazard assessment will be coordinated and facilitated through a series of workshops. Each workshop will be designed to accomplish a specific step in the overall interpretation and to assure that the relevant data are being fully considered and integrated into the evaluations. This process is designed to assure that all credible interpretations are considered in the fault displacement and vibratory ground motion hazard evaluations.

The seismic hazard computational procedures to be adopted or developed as part of this project will allow quantitative assessments of seismic hazard based on input interpretations provided by the evaluators. The quantification will incorporate uncertainty in the hazard due to scientific uncertainty in the input interpretations as well as to random variability in input parameters. The computational procedure and hazard results will provide that the needed information base relevant to seismic hazard and its uncertainty, as well as to seismic sources and the contribution of each source to the hazard, is available as a basis for determining the fault displacement and vibratory ground motion levels appropriate for seismic design of the proposed repository SSCs.

The methodology for determining seismic design inputs will be developed by the Seismic Design Basis Team through a series of meetings. The methodology and its implementation will be documented in a report.

PROJECT OBJECTIVE

The objectives of this project are to: 1) determine the fault displacement and vibratory ground motion hazards for the Yucca Mountain site; 2) develop seismic design parameters based on the hazard results; and 3) provide full documentation of the technical basis for determining these hazards and design parameters.

PROJECT ORGANIZATION

The major elements of the project organization include the Project Management Team, Review Panel, technical teams, and the expert panels (Figure 1). Members of the various teams and expert panels are shown on Figures 1 and 2.

Project Management

Management of the effort required to accomplish the objectives of this Project for Yucca Mountain will be provided by a Project Management Team. This team will provide overall management of the project, advise on technical issues relating to the project, and will oversee the efforts of the five technical methodology teams. The Project Management Team is comprised of a Project Director, assisted by two Deputy Project Directors (Figure 1). The Project Management Team will provide a direct interface between the USGS Project Chief, Dr. John Whitney, who is responsible for the seismic hazard studies at Yucca Mountain, and the Project Organization.

The major responsibility of the Project Management Team is to provide effective overall management of all efforts undertaken in the study. They will assure consistency with regulatory requirements, DOE policies and guidelines, and program needs. They will also provide logistical and organizational management of the workshops and the milestone products. Regarding the latter, the Project Management Team will provide that appropriate reviews are implemented, project schedules and milestones are met.

Project Director

The Project Director will be Dr. J. Carl Stepp who will provide overall direction and control of the project. He will provide the primary interface with the USGS and DOE, and on request, will participate in interactions with organizations such as the State of Nevada, the U.S. Nuclear Regulatory Commission, and the Nuclear Waste Technical Review Board. Overall cost management and control and scheduling of the project will be performed by the Project Director. Dr. Stepp will also be primarily responsible for managing development of the probabilistic hazard results and the Seismic Design Final Report and oversee the efforts by the Seismic Design Basis Team.

Because of the breadth of technical issues addressed by the five technical teams, the seismic source/fault displacement and ground motion efforts will be managed by two Deputy Directors.

Deputy Project Directors

Ivan Wong, Deputy Project Director, will oversee the efforts of the Seismic Source and Fault Displacement Characterization Facilitation Team. Mr. Wong will also manage the scheduling, logistical planning and support of all workshops. He will also oversee the efforts by the Data Management Team and the PSHA Calculations Team.

Dr. Jean Savy, Deputy Project Director, will oversee the Ground Motion Facilitation Team providing guidance, technical advice, and support as needed. He will be responsible for assuring that the project is conforming to regulatory requirements, and assist in other aspects of the project as directed by the Project Director.

Review Panel

The Review Panel (Figure 1) will consist of four individuals who are experts in the range of disciplines and topics which constitute seismic hazards and seismic design bases. Each member of the panel will be responsible for a specific technical scope of work of the project: Dr. Allin Cornell - PSHA methodology, process, and seismic design; Dr. Tom Hanks - vibratory ground motion; Dr. James Brune - seismic source characterization and vibratory ground motion; and Dr. David Schwartz - seismic source characterization and fault displacement hazard. The panel will attend the workshops and meetings relevant to their assigned scope of review. They will individually provide informal review comments and recommendations within their technical scope following each workshop, and will review draft reports and prepare comments and recommendations.

Technical Teams

To develop the technical evaluations necessary for this study, efficiency and project quality will be maximized by using the strengths of focused teams. Five teams will be responsible for data management, seismic source and fault displacement characterization facilitation, ground motion facilitation, PSHA calculations, and seismic design basis (Figure 1).

Seismic Source and Fault Displacement Characterization (SSFD) Facilitation Team

This team will facilitate development of the seismic source characterization and fault displacement input parameters for hazard analysis. They will provide the technical leadership required to facilitate expert interpretations by six separate groups of experts, composed of three individuals each, who will accomplish these interpretations. The Facilitation Team will organize, plan and lead all technical workshops related to characterization of the seismic sources and fault displacement evaluations. Their responsibilities include: (1) planning technical aspects and preparation of any necessary white paper documentation of the state-of-the-art in advance of the workshops; (2) conducting the workshops, preparing workshop agendas and reports summarizing the outcome of all workshops; (3) eliciting the interpretations of the experts; and (4) preparation of the Activity Report summarizing the process used to develop the expert's inputs and the inputs themselves. Further, they will participate in briefings and interact as required with DOE as well as with the NRC and any oversight groups. This six-member team will be led by Dr. Kevin Coppersmith (Figure 2). Dr. Peter Morris will assist in the expert elicitation as a normative expert.

Ground Motion (GM) Facilitation Team

This team will facilitate determining the attenuation relationships which will be used in the PSHA. These relationships describe the dependence of a measure of ground motion at any specific location on earthquake size and source distance. The team will prepare an Activity Report which will summarize the process used to develop the expert's inputs and the inputs themselves and provide parametric equations fit to each expert's estimates individually. The team will function in a manner analogous to the SSFD Facilitation Team, and it will consist of three individuals led by Dr. Norm Abrahamson (Figure 2).

Data Management Team

The Data Management Team will facilitate use of and access to common data sets by the expert panels. The team will compile data and provide derivative data products as specified by the data needs workshops. Additionally, the team will provide data and data products on a common scale and format to all participants. The goal will be to eliminate differences in interpretations caused by inconsistent data and knowledge bases. This team will be led by Dr. John Whitney assisted by Ivan Wong (Figure 2).

PSHA Calculations Team

The PSHA Calculations Team will perform both preliminary and final seismic hazard computations and document the latter in an Activity Report. The team will also modify the existing seismic hazards computation code for ground shaking to incorporate the code for calculating the hazard from fault displacement. The team will also take appropriate steps to bring the PSHA calculation software into compliance with the USGS Quality Assurance program. Because their activities are closely integrated with the activities of the Facilitation and Seismic Design Basis Teams, the Team Leader, Dr. Gabriel Toro, will participate in workshops and meetings as a technical resource (Figure 2).

Seismic Design Basis Team

The Seismic Design Basis Team will determine the vibratory ground motion and fault displacements for seismic design of the repository SSCs. They will prepare the Seismic Design Basis Report which will describe the seismic design values for ground motion and fault displacement. They will participate in the technical workshops as required and will provide guidance to the PSHA Calculations Team. Additionally, they will participate in briefings and interactions with the NRC and oversight groups. The team will be made up of engineers experienced in developing and applying seismic design methodology for nuclear facilities and earth scientists experienced in probabilistic seismic hazard assessments and deterministic assessments of fault displacement and vibratory ground motion. This team will be led by Dr. Robin McGuire (Figure 2).

Expert Panels

The uncertainty in scientific interpretations will be incorporated into the probabilistic hazard analysis by including multiple interpretations of scientists with complementary experience and knowledge. The expert panels will evaluate data and develop and document the interpretations used as input for the PSHA calculations. Their active participation in workshops, each of which will focus on an intermediate stage of the final interpretations, is key to the success of the project. Each GM expert or SSFD expert team will prepare and document their complete interpretations. For the seismic source and fault displacement characterizations, six three-person groups will be formed. The aggregate expertise of each group will cover the seismic geology, geology, and tectonics of Yucca Mountain and the Basin and Range province, seismology, and geophysics.

For ground motion attenuation, seven individual experts will be used to develop hazard inputs. The panel has been selected to cover the two principal approaches to estimating ground motions, empirical and numerical modeling, and includes one expert in nuclear explosion ground motions. Panel members' participation in briefings and other interactions with the NRC and oversight groups is also expected.

TASK DESCRIPTIONS

Selection of Experts

The panels of experts must represent the range of scientific disciplines required to perform the required evaluations and interpretations. Thus their professional expertise will cover the range of issues and technical understandings regarding the tectonic and seismic environment of the Yucca Mountain region as well as ground motion estimation. Experts will be chosen from a list of candidates nominated by knowledgeable individuals within the M&O, the USGS, and others working on the Yucca Mountain Project. A panel consisting of the Project Director, Deputy Project Directors, USGS Project Chief, and the facilitation team leaders will select the experts.

Expert selection will be based on the following criteria:

- Strong relevant expertise as demonstrated by professional reputation, academic training, relevant experience, and peer-reviewed publications and reports;
- Willingness to forsake the role of proponent of any model, hypothesis or theory and perform as an impartial expert who considers all hypotheses and theories and evaluates their relative credibility as determined by the data;
- Availability and willingness to commit the time required to perform the evaluations needed to complete the study;
- Specific knowledge of the Yucca Mountain area, the Basin and Range province, or ground motion characterization;
- Willingness to participate in a series of open workshops, diligently prepare required evaluations and interpretations, and openly explain and defend technical positions in interactions with other experts participating in the project; and
- Personal attributes that include strong communications skills, interpersonal skills, flexibility and impartiality, and the ability to simplify and explain the basis for interpretations and technical positions.

The panel will select (1) 18 individuals to form six three-person expert teams to perform the seismic source and fault displacement characterization; and (2) seven individual experts to perform the ground motion characterization for the Project (Figure 2). This process will be documented by letter reports accompanied by supporting documentation such as individual resumes of the selected experts and in the Final PSHA report.

Guidelines for Expert Teams

Each of the SSFD expert teams will be multi-disciplinary including an expert in Quaternary geology/ paleoseismology, seismology/geophysics, and regional geology/tectonics. Because of the interactions between members of the expert team are critical for the team to perform their responsibilities successfully, the following are guidelines each team should follow:

- Each team should act as a virtual individual expert; each team should identify and assess all approaches, tools, and data relevant to its evaluations.

- For some elements of the SSFD characterization, several data sets and/or overlapping discipline tools may apply; for others a single data set or discipline tool may dominate the evaluation; the full expertise/experience of the team will be drawn out to characterize uncertainty rather than deferring to a single team member for any element of this evaluation.

- All informed interpretations should be freely explored and properly considered; an extreme interpretation within a team should be reflected in the team's uncertainty.

- Within the team dynamic each expert should provide interpretations within his/her discipline across all models/evaluations recognizing that the resolving power of discipline tools and data may vary among models; the team integrates across disciplines and fully assesses uncertainty.

- Each team should achieve within-team aggregation through interactions, to permit across team aggregation using equal weights.

- All team members should be comfortable that their views are properly represented in the final team interpretation; acting together, they will be asked to defend and document their interpretations.

<u>Data Base Development</u>

The data base required for the study must be sufficient to characterize: (1) local and regional seismic sources having the potential to generate vibratory ground motions significant to the Yucca Mountain site; (2) the local faults which pose a potential surface faulting hazard; and (3) the attenuation of ground motion from the source to the site. These data requirements encompass a wide range of geoscience data sets including geology, seismology, and geophysics, as well as reduced data sets derived by applying data analysis methods.

Because the data form the basis for the expert interpretations, early in the Project the primary and derivative data needs will be assessed by the expert panels in a workshop. Summary presentations or background reports necessary to describe the data will be provided by prominent researchers, facilitation team members, or experts in the data needs workshops. Relevant data, including these developed outside the Yucca Mountain project, will be supplied by the DOE, M&O, USGS, and the Center for Nuclear Waste Regulatory Analyses and may be supplemented by the scientists involved in the Project. Data will be collated and distributed by the Data Management Team.

Workshops

A series of workshops (Figure 3) conducted by each facilitation team will provide the forum for discussion of technical issues by the experts. Five workshops will be held for seismic source characterization and three workshops for ground motion characterization. This format allows the experts to interact, explaining their own interpretations and questioning the interpretations of other experts. Through such interactions, hypotheses may be shown to be poorly supported by the data and scientifically indefensible models may or may not be eliminated or downweighted by the individual experts. The key purpose of the workshops is to provide a common information base for the required interpretations and to provide a forum for interaction among experts to achieve a common understanding of the data.

State-of-the-knowledge papers will be presented by facilitation team members, the experts, or other specialists who may have important relevant knowledge. Observers will be invited to attend and provide verbal comments at the workshops. Prior to each workshop, an agenda will be prepared to list the workshop goals and place the workshop in context with other aspects of the Project. Letter reports which summarize the workshops will be prepared by the facilitation teams and submitted to the Project Director and subsequently to the USGS.

Data Needs Workshops

Data needs workshops were held in April 1995 for both the seismic source and ground motion characterization. These workshops identified the tectonic, geologic, seismologic, and ground motion issues that must be evaluated as well as the primary data sets and derivative data products required to complete the evaluations. These workshops and the following workshops allow the experts to debate the significance of various technical issues and the relative resolving power of various data sets needed to evaluate them.

Hazard Methodologies Workshop

A Hazard Methodologies workshop will be held for seismic source and fault displacement characterization only (Figure 3). At this workshop, new data sets and derivative analyses will be presented together with a review of the technical interpretations that must be made by the expert panels. Once the data needs are prioritized, the primary data will be compiled by the Data Management Team and analyses performed as needed. The data and analyses results will be made available to the experts in common format. The purpose of this workshop is to provide the experts a common information base to perform their subsequent interpretations for fault displacement and vibratory ground motion analyses. For ground motion characterization, this workshop will be combined together with the Preliminary Interpretations (see below).

Models and Proponents Workshop/Field Trip

For seismic source characterization and the evaluation of fault displacement, a Models and Proponents Workshop will be held (Figure 3). Technical presentations will include a review of the competing models and hypotheses that the expert panels must evaluate. The experts will debate and challenge the models and hypotheses based on the data. They will be encouraged to formulate their own hypotheses. A field trip will also be conducted to provide the SSC experts an opportunity to observe the results of the paleoseismic and other geologic investigations that were performed at Yucca Mountain and the surrounding region. Following this workshop, the experts will assess the data and formulate their interpretations.

Methods and Models/Preliminary Interpretations Workshop

The second ground motion characterization workshop will focus on methods to be used in the PSHA similar to the SSFD Hazard Methodologies Workshop. In addition, the ground motion attenuation models to be considered in the PSHA will be presented, discussed, and preliminary interpretations made (see below). The Earthquake Scenario Modeling Project which took place in 1995 and involved several of the GM experts has provided a substantial foundation for the ground motion characterization activities and the results of that effort will be described and discussed in this workshop.

Each GM expert will provide for specified magnitude and distance pairs for strike-slip and normal faulting events, preliminary point estimates of the median and standard deviation (aleatory uncertainty) of spectral acceleration for about 10 periods. In addition, the experts will also provide estimates of the scientific uncertainty (epistemic uncertainty) for both the median and standard deviation for each point estimate. The experts will need to interpret ground motions from other regions (e.g., CA) and apply appropriate adjustment factors to account for differences between Yucca Mountain and the other regions. They will also be required to interpret ground motions from numerical simulations and judge their applicability to Yucca Mountain.

Preliminary Input Interpretations Workshop

The purpose of the Preliminary Input Interpretations Workshop for seismic source characterization (Figure 3) is to provide a mechanism for interaction among the experts regarding their preliminary interpretations. At this workshop, the SSFD experts will present some of their preliminary interpretations and show how these interpretations are supported by the data. It is expected that expert teams will provide alternative interpretations to reflect their assessments of data, model and process uncertainty. These aspects will be fully discussed to achieve a common understanding among experts and the facilitation team of the basis for all interpretations, including uncertainty assessments. With the experience of this workshop and full knowledge of the interpretations and uncertainty assessments of their peers, the expert teams will then be ready to have their judgments elicited formally.

Following this workshop, the SSFD expert teams will develop preliminary interpretations of all relevant seismic sources for input to the hazard computations through an elicitation interview (see following section). The experts' interpretations will focus on the issues of: (1) seismic source locations and geometries; (2) maximum earthquake magnitudes; (3) earthquake recurrence models; (4) assessment of displacement within the repository; and (5) assessment of displacement at particular points within the site area.

Feedback Workshops

The purpose of the Feedback Workshops (Figure 3) is to provide the experts feedback on the preliminary hazard results obtained using their input interpretations. To accomplish this, the PSHA Calculations Team will present aggregated hazard results: individual expert group (for seismic source and fault displacement characterization) and individual expert (for ground motion) results. In addition, the Calculations Team will present the results of an assessment of the sensitivity of hazard results to various input parameters. These analyses will be fully discussed in the workshops to provide the experts an understanding of how their interpretations contribute to the total seismic hazard results.

Following the Feedback Workshops, the experts will again review their interpretations in consideration of the knowledge gained from the additional information and workshop interactions. The experts are free to modify their interpretations or not, given this additional information. Any modifications will be provided to the facilitation teams in a final assessment.

Elicitation Process

The formal elicitations of the SSFD expert teams will be conducted through 1-1½ day interviews of each team. The elicitation team will consist of the following individuals: a *"specialist"* with specific experience in seismic source characterization and a detailed knowledge of the specific models, parameters, and uncertainties that need to be assessed; a *"generalist"* with hazard analysis experience to ensure that the assessments are properly expressed in a manner that is appropriate for the subsequent calculations; a *"normative expert"* with experience in the process of eliciting expert judgments and experience in applying techniques for avoiding cognitive biases; and a *"recorder"* to take detailed notes that will serve to document the assessments, their technical basis in the available data, and the associated uncertainties. Members of the SSFD Facilitation Team will fulfill each of these roles.

The normative expert is a decision analyst with specific experience in subjective probability elicitation, who will have provided the teams with elicitation training at SSFD Workshop #4. He will have alerted the experts to the potential for certain cognitive biases (e.g., anchoring, availability, uncertainty underrepresentation, etc.) and will be present at the elicitation to ensure that the experts are comfortable in properly expressing and documenting their uncertainties.

In the elicitation interview, the SSFD expert teams will be asked a series of questions that will lead them through the seismic source characterization. They will be asked to evaluate alternative models, interpretations, and parameter values and to provide their assessment of the relative credibility of alternative views. For each evaluation, the expert teams will be required to express the technical bases for their interpretations in terms of the available data. Uncertainties will be expressed in a form that is efficient (e.g., logic trees, continuous probability distributions). Pertinent data bases (e.g., maps, data syntheses) will be made available to the team at the interview for their review. During the interview, the evaluations will be documented by the recorder by taking detailed notes. It is anticipated that the teams will also develop mapped interpretations during the interview and base maps will be available for their use.

Following the interview, the notes will be formalized and provided to each team for their review and revision. This document, termed the "elicitation summary" will be the documentation that after several cycles of revision, including "Feedback Workshop #5, will be the ultimate documentation for each team's evaluation. The finalized elicitation summaries will be appended to the Seismic Source Facilitation Displacement Activity Report.

The elicitation process for the GM experts will be similar, although only a single GM expert will be elicited. The point estimates from the GM experts will be parameterized by the Facilitation Team to develop spectral attenuation relations for each expert for use in the hazard calculation. The experts will review the parameterization and, if needed, suggest changes to the models. The final parameterizations will be presented to the experts for their approval.

Aggregation of Expert Interpretations

The aggregation of the expert or expert team interpretations will occur through the direct combination of their final probability distributions using equal weights. The use of this approach is supported by deliberately developing a set of conditions throughout the entire project, as defined in SSHAC (1995). That is, the following steps ensure that an "equal-weighting" scheme is defensible:

1) The experts were selected using a formal selection process;

2) All the experts were provided with all applicable data bases;

3) Expert interaction was encouraged and required through the conduct of multiple workshops and/or field trips;

4) The experts were provided the opportunity to hear alternative interpretations of various proponents, to present their interpretations, and to challenge the interpretations of the other teams;

5) Sufficient feedback was provided to allow each team the opportunity to understand the implications of their evaluations relative to the hazard results; and

6) Throughout the process, the experts were reminded of their role as evaluators and to forsake the role of proponents of particular views or of institutional views.

Following the development of the aggregated hazard distribution, SSFD experts will be asked to provide their assessment that the final distribution properly represents the views of their particular team. No consensus across teams is required, nor is it expected. They should feel comfortable that their uncertainties have been represented properly and that the final probability distribution represents a reasonable representation of the total uncertainty across all of the teams.

Seismic Hazard Computations

The computer program, which will be used to perform the PSHA computations for vibratory ground motion, has been appropriately documented and meets DOE Quality Assurance standards for the Yucca Mountain Project. This existing code will be modified by the PSHA Calculations Team to compute the fault displacement hazard. As appropriate, all modifications will also be subjected to a Quality Assurance validation and verification. The fault displacement module to be added will be developed by the PSHA Calculations Team and will be based on a model selected by the SSFD experts. Hazard results based on the expert's interpretations, which are anticipated to be equally weighted, will be combined by simple mechanical aggregation. The results of the PSHA will be described and summarized in a report. The Activity Reports of the seismic source and fault displacement characterization and ground motion characterization will be summarized in the PSHA Report.

Determination of Fault Displacement and Vibratory Ground Motion Design Values

The determination of fault displacement and vibratory ground motion values appropriate for seismic design of the proposed Yucca Mountain SSCs will be based on probabilistic seismic hazard assessments which will also take into consideration other information including deterministic assessments. This is a key activity that integrates the seismic hazard results of fault displacement or vibratory ground motion, with engineering seismic design methodology, criteria and procedures. The Seismic Design Basis Team will assemble for four meetings (Figure 3) to perform this element of the project.

The seismic design methodology that will be followed will be developed by the Seismic Design Basis team. It is expected that procedures similar to those contained in Regulatory Guide, DG-1032, "Identification and Characterization of Seismic Sources and Determination of Safe Shutdown Earthquake Ground Motions" will be adopted. Deaggregation, to be carried out under the direction of the Seismic Design Basis Team, will result in a seismic hazard information base including significant earthquake sources for determination of vibratory ground motion loads and fault displacement values. Controlling earthquakes will be determined corresponding to the hazard values that meet the design basis hazard requirements of the proposed facility SSCs for the aggregate hazard.

Based on the above information base, the Seismic Design Basis Team will determine and define the fault displacement values and vibratory ground motions for seismic design of the proposed Yucca Mountain facility SSCs and provide supporting technical bases for the determinations. The seismic design of the repository will be described and summarized in the Seismic Design Report.

DOCUMENTATION

To comply with Quality Assurance requirements with regards to documentation of the Project process, all workshops will be summarized in letter reports. Activity reports which describe the input from each of the experts and expert teams, will be produced for both seismic source and ground motion characterization. Two other reports will also be produced to document the results of the project: the PSHA Final Report and the Seismic Design Final Report. A description and summary of the PSHA process will be provided in the former.

SCHEDULE

A Project schedule is shown on Figure 3.

REFERENCES

SSHAC (Senior Seismic Hazard Analysis Committee), 1995, Recommendations for probabilistic seismic hazard analysis: Guidance on uncertainty and use of experts, Lawrence Livermore National Laboratory, UCRL-ID-122160, 170 p.

PROJECT ORGANIZATION

Yucca Mountain Seismic Hazards Evaluation Project

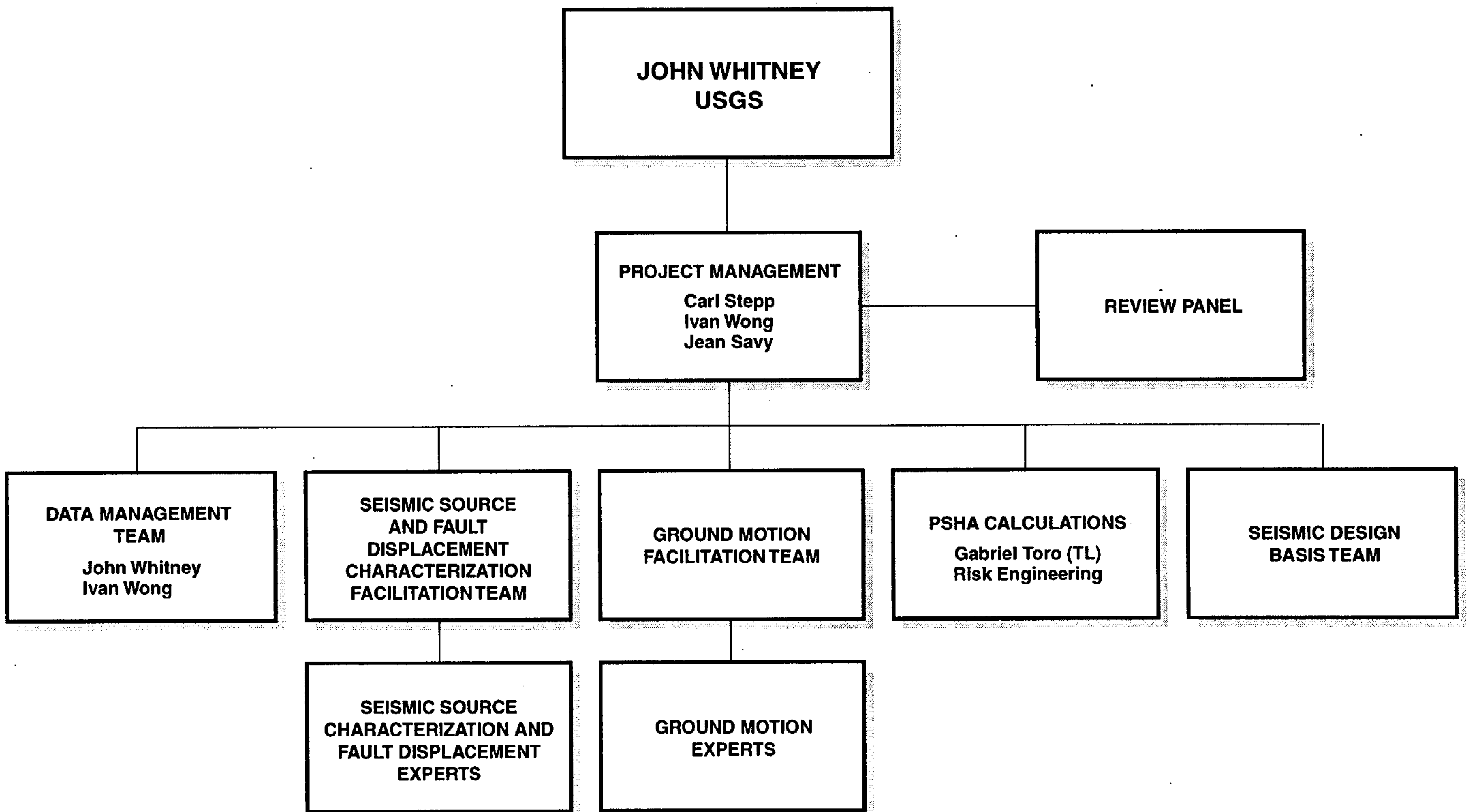


Figure 1

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TEAMS/EXPERT PANELS

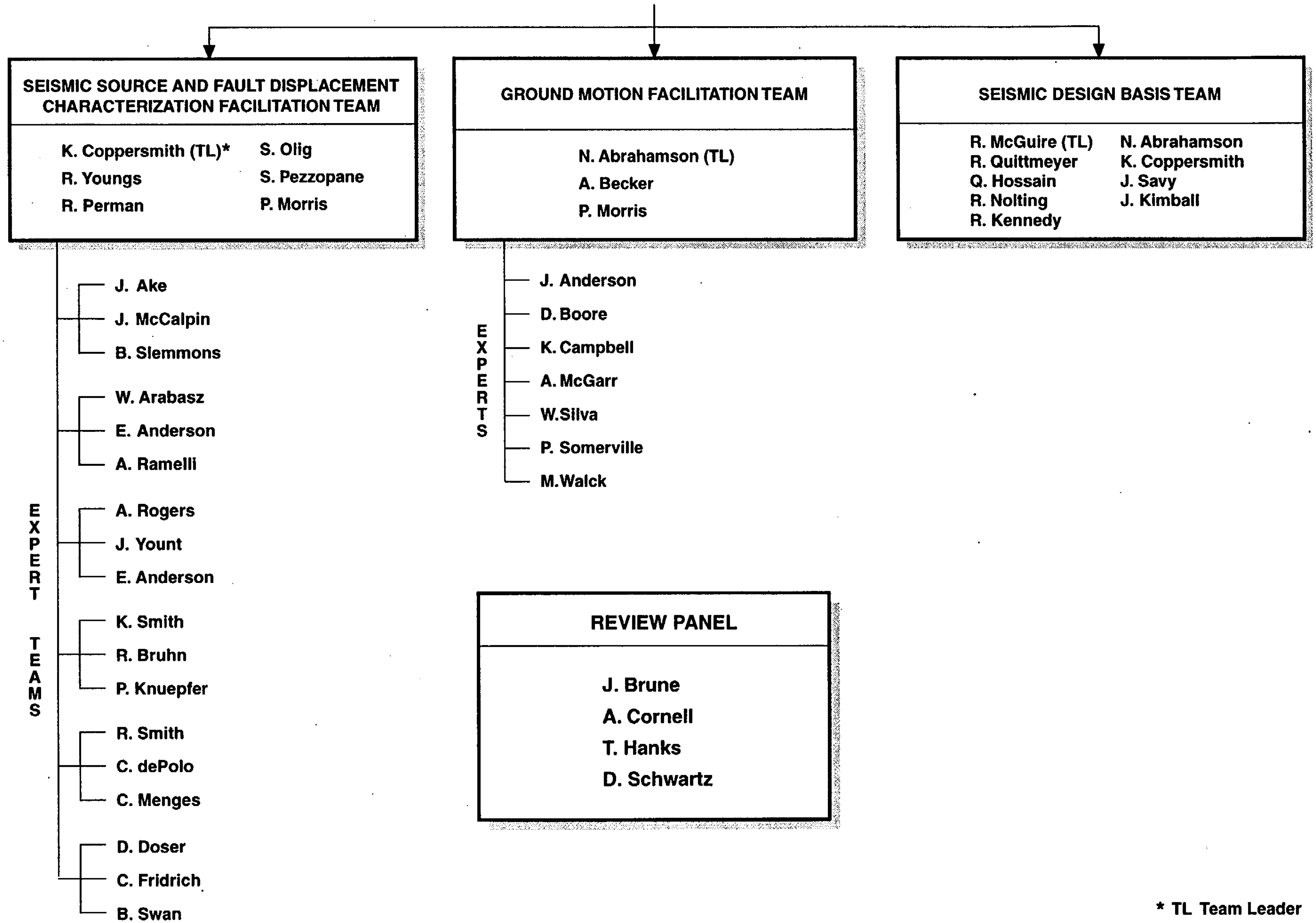

Figure 2

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PROPOSED SCHEDULE FOR YUCCA MOUNTAIN SEISMIC HAZARD EVALUATION

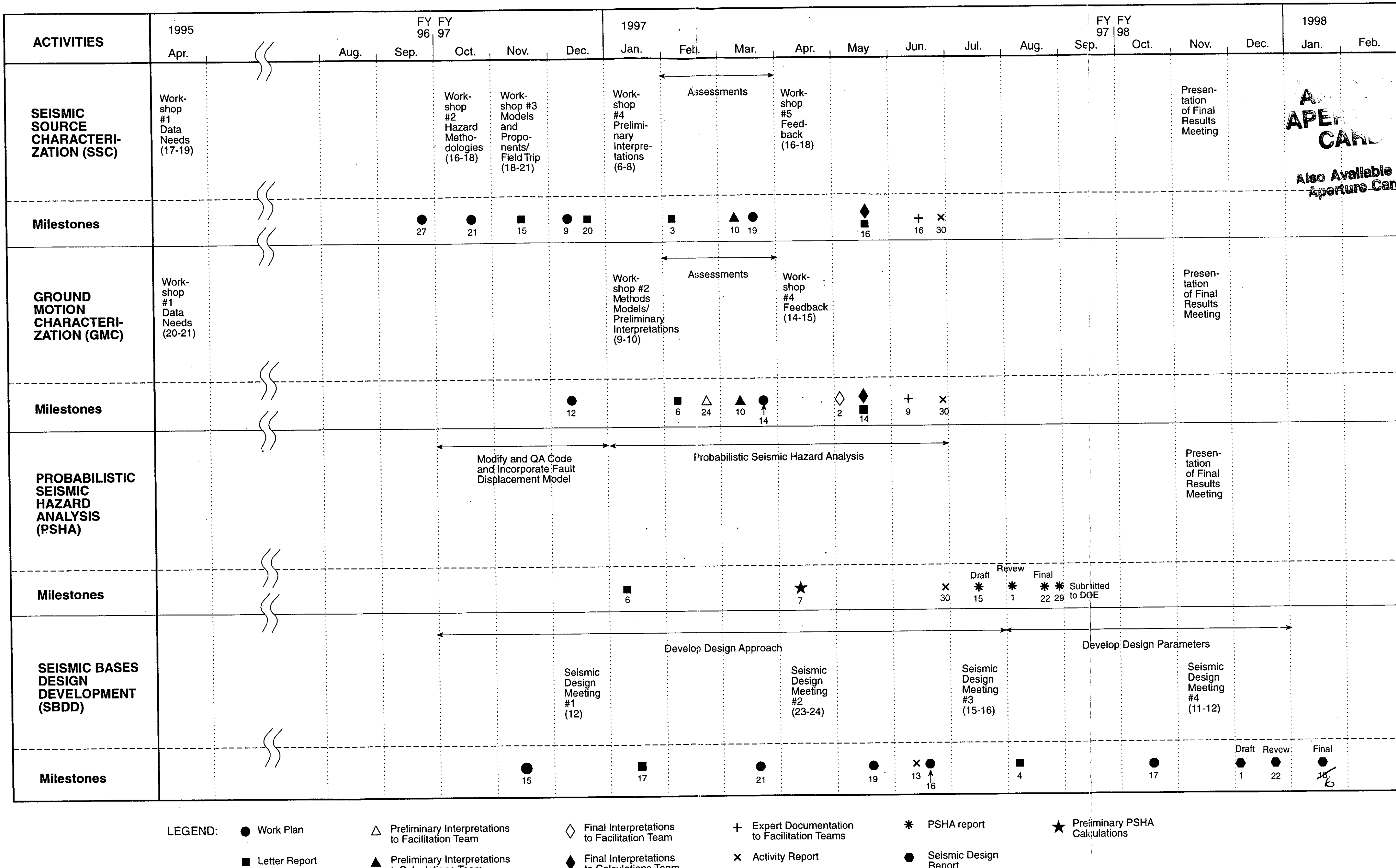

Figure 3

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Civilian Radioactive Waste Management System

Management & Operating Contractor

Summary of Seismic Source Characterization Preliminary

Interpretations Workshop

Salt Lake City, Utah

January 6-8, 1997

Prepared for:

U.S. Geological Survey

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January 31, 1997

Attachment 10

INTRODUCTION

The U.S. Geological Survey (USGS) is carrying out a probabilistic seismic hazards analysis (PSHA) for Yucca Mountain, Nevada as part of the Department of Energy's (DOE) project to characterize this site as a potential geologic repository for high-level radioactive waste. This study was initiated in April 1995 and resumed in June 1996. The aim of the analysis is to provide the annual frequency with which various levels of vibratory ground motion and fault displacement will be exceeded at the site. These results will be used as a basis for developing seismic design inputs and in assessing the waste isolation and containment performance of the site.

The PSHA involves development by two panels of experts of input interpretations and assessments of uncertainties required by the hazards calculations. One panel (consisting of six teams of three experts) addresses characterization of seismic sources and fault displacement, while the other (consisting of seven individual experts) deals with vibratory ground motion. Development of interpretations is being facilitated through a series of structured workshops to evaluate available data, to explore the range of interpretations allowed by the data, to examine critically the interpretations proposed by the experts, and to provide feedback on the implications of various interpretations for the seismic hazard at the site. This report summarizes the fourth workshop in the characterization of seismic sources and fault displacement: the Seismic Source Characterization (SSC) Preliminary Interpretations Workshop.

The primary goals of the workshop were to: (1) provide an opportunity for the expert teams to present and discuss their preliminary interpretations regarding key issues in SSC; (2) train the expert teams on the process of elicitation and uncertainty characterization; and (3) present and discuss additional information and interpretations of importance to SSC at Yucca Mountain. To accomplish these goals, a series of presentations (primarily made by the SSC expert panel members) and group discussion sessions were conducted, with emphasis on interaction among the SSC experts. Five key SSC issues were identified: (1) tectonic models; (2) potential seismic sources; (3) maximum magnitudes; (4) earthquake recurrence; and (5) fault displacement methodology. For each of these issues, two teams of experts were assigned to present their preliminary interpretations. These presentations were followed by group discussion of each issue, during which time the other teams were given the opportunity to present their preliminary interpretations. The focus of the presentations and discussions was on understanding the interpretations, their technical bases, their consistency or inconsistency with data, and the expression of uncertainty. Discussion was facilitated to ensure that each team understood the interpretations of others, including the degree to which they were supported by earthquake and faulting process models and observed data, and could then more knowledgeably re-evaluate their own team interpretations. The overall goal is for interpretations given at the upcoming elicitation interviews to be well-reasoned, technically-supported, and complete.

The workshop agenda is included as Attachment 1. Copies of overhead transparencies shown by presenters and additional material distributed during the workshop are included as Attachment 2. Table 1 is a list of participants and their affiliations.

MONDAY, JANUARY 6, 1997

The first day of the workshop included a series of presentations to provide additional information on a variety of specific issues outstanding from previous workshops. Kevin Coppersmith gave an introduction, describing the purpose and approach, and outlining the workshop agenda. He emphasized the overall goal was to prepare for the SSC elicitations such that the expert panel's interpretations were well-reasoned, technically-supported and complete. He also emphasized that team interpretations were still preliminary and experts should: feel free to explore the issues thoroughly, ask questions that will help them during the elicitations, and continually keep in mind the characterization of uncertainties. Miscellaneous questions about developing team assessments, scheduling elicitations, and the status of the historical seismicity catalogue were then discussed.

Next, Christopher Potter gave a presentation on the Sundance fault, reviewing previous studies from a historical perspective and discussing the evolution of interpretations as additional data were collected. In particular, he compared studies by Spengler et al. (1994) with those of Potter et al. (1995), describing in detail differences in scope, approach, products and results. He explained many differences in interpretations with site-specific examples from maps, highlighting one of the most significant differences was that although Spengler et al. (1994) interpreted the Ghost Dance fault to be offset by the Sundance fault by as much as 52 m, Potter et al. (1995) concluded that the Sundance fault did not even intersect the Ghost Dance fault based on mapping of continuous volcanic subunits. He pointed out probable causes for differences in interpretations, including the broader area covered by Potter et al. (1995), their emphasis on a geologic-based rather than engineering-based approach to defining rock units, and their mapping of several zones in the upper Tiva Canyon Tuff that provided good marker beds, which were not identified in the mapping used by Spengler et al. (1994).

Ernie Majer gave the next presentation on geophysical interpretations of the Yucca Mountain vicinity developed by Lawrence Berkeley National Laboratories (LBNL). Due to scheduling conflicts, Dr. Majer had not been able to attend earlier workshops to discuss the LBNL interpretation of these data. He described the data they used, including seismic reflection, gravity, magnetics, magnetotellurics, and vertical-seismic-profile well data. He pointed out that their studies were summarized in the Geophysical Synthesis Report, which has been made available to the experts. He reviewed the LBNL interpreted cross-sections, laid out seismic lines for the experts to review, and highlighted key differences with geophysical interpretations developed by Thomas Brocher and his colleagues at the USGS. Dr. Majer had met with Dr. Brocher during the last month to discuss these differences, and he had concluded that alternative interpretations are permitted by the data depending on the data sets emphasized and the approach to modeling. After extensive discussion during several meetings with USGS personnel, Dr. Majer still believes that smaller offsets of the top of Paleozoic rocks across the Ghost Dance fault are more reasonable based on the LBNL modeling of the gravity data and considering the data from a 3-D perspective. He pointed out, some ways that processing of seismic data could be improved, and discussed the uncertainties associated with each type of data. He emphasized the difficulties inherent in applying geophysical methods at Yucca Mountain and concluded that without additional drill-hole data, or perhaps simultaneous inversion of gravity and seismic data, multiple geophysical interpretations are permitted by the data and should be considered by the experts when they express their uncertainties.

John Stuckless gave the next presentation on some hydrological and geochemical considerations for evaluating movement on the Ghost Dance, Solitario Canyon, and Paintbrush Canyon faults. He discussed how spatial variations in temperatures, oxygen isotopes, and carbon isotopes of aquifers at Yucca Mountain suggest that block-bounding faults (such as the Solitario and Paintbrush Canyon faults) may be acting as conduits between aquifers, but the Ghost Dance fault does not. He pointed out that the relief on Paleozoic basement rocks, as interpreted from gravity data, has a northeast trend and probably is not related to offset on the Ghost Dance fault, but could be related to "sealed" pre-Miocene faults or erosional paleotopography and may not even be fault-related. He concluded that the hydrological and geochemical data suggests that offsets of the top of Paleozoic rocks across the Ghost Dance fault are not significant and are smaller than offsets across the Solitario and Paintbrush Canyon faults.

Next, Dennis O'Leary discussed the Yucca Mountain faults in a regional context, focusing on the southern extent of faults and their relation to surrounding tectonic features. He reviewed characteristics of the four classes of faults and constraints on spatial and temporal patterns of extension. He discussed the southern extent of the Bare Mountain fault, the southern margin of the Crater Flat basin, and the extent and role of the inferred fault, based on the Bouguer gravity field gradient, that strikes north-south along the eastern margin of the Amargosa trough. He also discussed the Spotted Range-Mine Mountain fault system, the caldera complex, the Kawich Range faults to the north of the caldera, and a faulted block of rocks on the southern flank of Mid Valley that may be an appropriate structural analog for Yucca Mountain. Dr. O'Leary's presentation stimulated much group discussion, including input from Burt Slemmons, John Whitney, Chris Fridrich, and Alan Ramelli on the southern extent of Yucca Mountain faults and faults east, west, and south of Bare Mountain.

The next presentation was given by Brian Wernicke on whether or not shallow-dipping normal faults (SDNF) generate significant earthquakes. He said his talk would largely follow the outline of a paper he recently published on this topic, and he provided reprints of the paper (Attachment 2). He described the apparent paradox about SDNF, that they are prominent and prevalent crustal-scale features that have accommodated significant amounts of brittle extension, and yet historical seismicity patterns and mechanical considerations suggest that SDNF are not seismically active and are not even capable of producing large earthquakes. He reviewed the limited number of historic, large normal-faulting earthquakes observed worldwide and presented kinematic and mechanical arguments as to why SDNF would have very long recurrence intervals. Thus, he argued that perhaps the general lack of observed large earthquakes on SDNF may be due to the historical record being too short. He also presented paleothermal interpretations for some SDNF in the Basin and Range province that suggest the faults initiated at a shallow dip, implying that they were active at a shallow dip and have not evolved from an active high-angle normal fault to an inactive SDNF. Dr. Wernicke then switched topics to review results from geodetic studies he worked on for the Center for Nuclear Waste Regulatory Analyses, which John Stamatakos had also presented at Workshop #2. At the end of Dr. Wernicke's presentation, there was discussion about the general lack of background seismicity on SDNF and the nature of a possible detachment under Yucca Mountain, which Dr. Wernicke believes is no longer active.

The final presentation of the afternoon was given by James Brune on studies of precarious rocks conducted by him, John Whitney, and associates at UNR, and their implications to paleoseismicity. He presented results from studies in southern California and Nevada of the spatial distribution of precarious rocks and their relation to (i.e. away from) major active faults and the area affected by NTS blasts. He showed examples of the many (~100) precarious rocks they had identified in the Yucca Mountain area and discussed age data that indicates all of the rocks they dated have likely been precariously balanced for longer than 10,000 years. He emphasized that these results have implications for longer recurrence of background earthquakes and the need to allocate some historical seismicity to faults in the area. He pointed out some new developments in thinking about ground motions since their report on precarious rocks was written, which was distributed to SSC experts (Attachment 2). He also presented results from a study of precarious rocks and ground motions from the Little Skull Mountain earthquake.

There were no comments from observers at the end of the day. Finally, the seismologists on the expert panel met to discuss issues related to the status of the seismicity catalogue. Ivan

Wong distributed handouts on preliminary magnitude conversions and completeness intervals for the catalogue (Attachment 2).

TUESDAY, JANUARY 7, 1997

Tuesday was devoted to team presentations and discussion of four of the key SSC issues: tectonic models, potential seismic sources, maximum magnitudes and earthquake recurrence. Dr. Coppersmith gave an introduction, outlining the issues.

Jim McCalpin gave the first presentation on tectonic models, representing the team of Jon Ake, Burt Slemmons, and himself. He said the models they considered were primarily based on Chapter 8 of the Yucca Mountain Seismotectonic Synthesis Report, which included caldera, detachment, volcanic, planar fault-block, and lateral shear models. He described the models, discussed their strengths and weaknesses based on tectonic processes, tectonic development of Yucca Mountain, and observed data; highlighted implications; and gave the team's preliminary assigned weights to the various models. He also discussed their preferred composite tectonic model which is based primarily on the planar fault model with integrated components of the lateral-shear and volcanic models. This stimulated discussion about one problem with the planar fault model; normal dip-slip on north-south striking faults does not appear to be consistent with strike-slip focal mechanisms and northwest-directed extension determined from historical seismicity data.

Robert Smith gave the next presentation, discussing his team's preliminary tectonic models. His other team members are Craig dePolo and Chris Menges. He outlined four classes of models prioritized by their preferability: half-graben (including planar and curved faults), detachment (not likely to be shallow), volcanism, and strike-slip. He highlighted relevant features of the Tertiary tectonic setting and relative variations in strain rates through time. He discussed necessary characteristics and considerations of seismotectonic models for Yucca Mountain, emphasizing constraints from geophysical and structural data, such as low contemporary strain rates (10^{-16}/s to 10^{-17}/s); seismogenic depths of 12 to 16 km; elastic thicknesses of 5 to 15 km, normal and strike-slip focal mechanisms that indicate northwest extension; and the closely-spaced complex, interconnecting nature of faults, many of which likely merge at depth and may be truncated by the Bare Mountain fault. He also discussed the transient aspects of the tectonic regime, which may be related to asperities in the lower crust causing transient loading rates on upper crustal faults. He also noted that stress-field rotations could lock-up structures, stimulating discussion about whether the stress-field is understood well enough to reliably conclude such structures are inactive.

During the discussion session that followed, Ernie Anderson presented a tectonic model, first proposed by Al Rogers to explain observed seismicity patterns, that relates oblique-slip on north-south-striking fault blocks to southward-directed translation of the blocks rather than dextral shear. As many teams seemed to favor the half-graben/planar fault block model, John Whitney next brought up some information relevant to a question raised earlier regarding whether the sum of late Pleistocene slip rates on Yucca Mountain faults was comparable to the late Pleistocene slip rate observed on the Bare Mountain fault. Dr. Whitney, Dennis O'Leary, and Alan Ramelli all discussed indirect geomorphic and geophysical evidence for additional buried traces of the Bare Mountain fault to the one that is visible and was trenched at the surface. Thus, although this trace has definitely been the most active during the late Quaternary, slip rates determined solely from this trace may still be minimums for the entire fault zone. David Ferrill then reiterated the higher longer-term slip rates that he and his associates have interpreted along the southern Bare Mountain fault based on 30 m of subsidence of a basalt flow inferred to be one million years old. Finally, Dr. Coppersmith reviewed the tectonic models presented and some of the key points that were discussed.

Chris Fridrich gave the first presentation on potential seismic sources, representing the team of Diane Doser, Bert Swan and himself. Dr. Fridrich described five types of seismic sources they had considered: 1) background sources; 2) regional fault sources based on mapped Quaternary faults identified in the Seismotectonic Synthesis Report; 3) local Quaternary faults, including a three-fault segment rupture model; 4) a strike-slip shear zone, which may truncate the southern end of some Yucca Mountain faults; and 5) a detachment fault. They defined seven domains for the background sources within 300 km and three domains within 100 km: the northeastern Walker Lane, the southeastern Walker Lane, and the northern Basin and Range. Bert Swan asked if there were any additional faults other teams had considered and Craig dePolo mentioned the buried fault inferred from the Bouguer gravity gradient bounding the Amargosa trough and buried faults in Crater Flat. Dr. Swan clarified that they considered the latter to be included with background sources and explained that they would zone the maximum magnitude for the background domains using a lower magnitude centered around Yucca Mountain where the resolution for identifying and characterizing potential fault sources is better because of more detailed study.

Jim Yount gave the next presentation on potential seismic sources, representing the team of Larry Anderson, Al Rogers and himself. He began by mentioning some additional buried faults under Jackass Flats that they had wondered about either characterizing explicitly or including them implicitly in the background source. Kevin Coppersmith said that the former approach was probably better for all nearby faults because the specific geometry of a source can be significant to the hazard, whereas details of geometry become less significant as sources become more distant. Dr. Yount then described the three types of seismic sources that his team considered: fault, hidden/background, and volcanic. He defined the criteria they used for considering faults as potential sources and then listed potential fault sources with their assigned probabilities of being sources and the bases for the probabilities. Next, he discussed whether volcanic sources need to be considered as potential sources of earthquakes.

He pointed out that although previous volcanic studies by Crowe et al. (1995) concluded that there is not a causative relation between structure and volcanism, paleoseismic evidence for the "ash event" (Event U in Chapter 5 of the Seismotectonic Synthesis Report) indicates some faulting events are synchronous with volcanism, suggesting that volcanic seismic sources may need to be considered.

Next, Larry Anderson presented another approach to characterizing potential sources that they were also considering in addition to the fault-specific approach. This approach was motivated by the apparent random pattern of paleoseismic events on faults through time. It would treat Yucca Mountain as a faulted volume with a composite recurrence of earthquakes uniformly distributed on faults. Finally, Al Rogers discussed the team's two models for background source zones, both of which include three zones. One model determines recurrence solely based on the historical seismicity in each zone and the other model attempts to first remove some seismicity that may be associated with mapped faults before calculating recurrence for each zone.

Peter Knuepfer started the discussion session off with questions about the Ghost Dance and Sundance faults as potential seismic sources, which stimulated discussion about general criteria for defining sources and the specific characteristics of these faults. Allin Cornell reiterated his concern about misusing the background earthquake as a crutch in characterizing sources and Burt Slemmons pointed out that it may be worthwhile to specifically consider some buried sources such as possible Quaternary faults in Crater Flat that are indicated on seismic lines. Dr. Cornell further stated that the background zone should be considered as the expression of a team's uncertainty in its seismic source interpretations; that is, its uncertainty that all sources have been included in the interpretation.

Jon Ake gave the first presentation on maximum magnitudes, representing the team of Slemmons, McCalpin and himself. He pointed out that maximum magnitudes are dependent on tectonic models and definition of seismic sources. For estimating maximum magnitudes on fault sources, his team chose to use regression relations by Wells and Coppersmith (1994) that relate average displacement, maximum displacement, or surface-rupture length to maximum magnitude. He discussed some assumptions and prejudices, and the reasoning behind their approach. He said they had only looked at closer fault sources so far, which had raised some questions about characterizing uncertainties and concerns about some possible inconsistencies. This initiated discussion about the shortcomings of using their approach for closely-spaced, short faults with long recurrence intervals. Difficulties in assessing displacements with limited data were also discussed, along with apparent discrepancies between short fault lengths and larger than expected displacements. Kevin Coppersmith pointed out that of the three sources of uncertainty (statistical, process, and parameter), the latter was probably the greatest, but all need to be considered.

Craig dePolo gave the next presentation on maximum magnitudes, representing the team of Robert Smith, Chris Menges, and himself. He outlined the different approaches his team would use to estimate maximum magnitudes depending on the type of data available for each seismic source. Types of data included surface and possibly subsurface rupture length, average and maximum displacement, down-dip width (to determine area), and slip rate. He discussed many different regression relations they might use and the factors they would consider in weighting the different relations. Next, he discussed their approach to assessing the maximum background earthquake, which would likely be about M_w 6.3 (+0.3, -0.1). He also discussed the problem of potentially double-counting seismic moment when characterizing fault and background sources in the same area. Finally, Robert Smith brought up concerns about uncertainties in magnitude conversions to M_w, and possible systematic biases introduced during declustering of the seismicity catalogue.

Next, two unscheduled presentations were given by David Ferrill and James Brune. Dr. Ferrill presented results of laboratory deformation studies used as a physical analog for the development of pull-part basins. He discussed similarities and differences of features in the lab experiments to those observed at Yucca Mountain. He also reiterated results from their slip-tendency analysis of Yucca Mountain faults (presented by John Stamatakos at Workshop #2), emphasizing implications for a low-slip tendency on shallow-dipping faults. Dr. Brune also discussed results from laboratory modeling experiments. He pointed out that implications from his foam rubber models are that SDNF are much more mechanically stable than shallow-dipping reverse faults because of different dynamic effects, implying that SDNF are not likely seismogenic. Following the presentations was considerable discussion about complexities in using displacement data to estimate maximum magnitudes.

Diane Doser gave the first presentation on earthquake recurrence, representing the team of Chris Fridrich, Bert Swan and herself. She discussed how they planned to use the seismicity catalogue to calculate earthquake recurrence for their background source zones. She emphasized that there were many issues in preparing the catalogue and making the calculations and she highlighted some of these. Bert Swan then discussed how their team would characterize recurrence for fault sources. He said they would use a seismic moment rate approach, explaining how they would estimate slip rates for each of three different structural/behavioral models. He pointed out that they would try to calculate average net slip rates, using ratios of vertical to net slip of between 1:1 and 1:1.4. He also noted they would use three different recurrence models: models developed by Wesnousky et al. (1983), Schwartz and Coppersmith (1984), and an exponential model. Paleoseismic data on recurrence intervals would only be used as a "sanity check."

Larry Anderson gave the next presentation on recurrence, representing the team of Rogers, Yount, and himself. He focused on fault sources and had compiled a space-time diagram of paleoseismic events on Yucca Mountain faults to assist in evaluating synchroneity of rupture behavior and estimating earthquake recurrence. He discussed estimated recurrence intervals for different structural and behavioral models, pointing out ambiguities and associated uncertainties in the paleoseismic record. Al Rogers then discussed their approaches to estimating earthquake recurrence for each of their two background earthquake models, outlining the steps they used in processing the seismicity catalogue and explaining how they would allocate seismicity to faults for one of the models.

During the following discussion session, Allin Cornell asked if any team had considered using a real-time approach, stimulating discussion about advantages and disadvantages of doing so and the data needed. Next, Tom Hanks expressed concern that some of the maximum magnitudes assigned to sources would result in forcing high stress-drop events to occur in a low stress-drop regime. He urged the experts to at least keep implications for stress drop in mind when developing their characterizations. Finally, Kevin Coppersmith asked for comments from observers. Clarence Allen pointed out that the relation of historical seismicity to mapped faults is problematic in many other areas in addition to Yucca Mountain. He also cautioned experts about the uncertainties in extrapolating observations of small earthquakes to make inferences about large earthquakes. Bakr Ibrahim expressed concern about whether triggered events were adequately being considered. Leon Reiter suggested to confirm whether or not results will be used for both pre-closure design and post-closure performance assessments, the latter making it especially important that low probability scenarios be included and carried through the analysis. Jerry King suggested that additional guidance regarding which faults at what distance needed to be considered would help the experts.

WEDNESDAY, JANUARY 8, 1997

The entire morning session was devoted to addressing the last SSC issue, developing methodologies for characterizing the fault displacement hazard. Walter Arabasz gave the first presentation on their approach to characterizing fault displacement, representing the team of Ernie Anderson, Alan Ramelli, and himself. He outlined premises to their approach and discussed their two types of sources, primary and non-primary. Their approach is to directly use displacement per event data wherever it exists and for other faults to use various scaling relations to estimate slip per event. He pointed out how fault aspect ratios generally observed for moderate to large earthquakes have implications for expected fault rupture lengths at Yucca Mountain, given a certain depth of rupture penetration and vice versa. He discussed scaling relations to estimate slip per event from length and cumulative slip, including some examples developed specifically for Yucca Mountain faults. He said they were considering both recurrence interval and slip rate approaches to incorporate the frequency of displacement events into the assessment. Finally, he mentioned how scaling relations from Chapter 9 of the Seismotectonic Report can be incorporated into the methodology developed by Coppersmith and Youngs (1992) to assess displacement within the repository, particularly various characteristics of secondary displacement.

Next, Alan Ramelli discussed the spatial distribution of faulting within the proposed repository. He focused on issues of how does the potential for secondary faulting vary and what areas of different potential can be defined. Both he and Ernie Anderson described similarities of the Clover Mountain area, which they believe provides a structural analog to Yucca Mountain and may have implications for the shallow depth of penetration of some faults, particularly non-primary faults. Discussion followed about possible problems with using some of the scaling relations in an area where deformation rates are transient and much of the total throw occurred during the Miocene. Finally, Kevin Coppersmith emphasized that the methodologies developed by the experts need to be appropriate for the entire Controlled Area, not just the proposed repository.

Ron Bruhn gave the next presentation on their team's fault displacement methodology, representing the team of Ken Smith, Peter Knuepfer, and himself. He said that there would be two parts to their presentation, he would focus on the displacement aspects and Ken Smith would discuss assessing rates using historical seismicity and paleoseismic data. Dr. Bruhn then outlined the conceptual framework of their approach, which is based on statistical analyses used in mining engineering. He emphasized that their goal was to develop an algorithm for estimating the probability of exceedance of a specified displacement at a point within a rock mass without prior knowledge of the point, but given that certain statistical and structural properties of observed faults in the rock mass are known or can be estimated. He provided details of the technical description of his method in a handout. He outlined the general steps in his talk, highlighting assumptions and the data needed for each of the three steps. He discussed application to an analog repository in Leagerdorf, Germany. Finally, he emphasized they were still working on incorporating recurrence into the assessment and he discussed some of the issues and considerations related to both direct and indirect approaches. David Schwartz offered suggestions on using paleoseismic data from primary faults to provide maximum constraints on recurrence rates. Ken Smith then discussed their preliminary analysis of the seismicity catalogue and resulting recurrence curves both with and without the incorporation of paleoseismic data for Yucca Mountain faults.

After the break, Jim McCalpin presented an approach to characterizing fault displacement that entails developing probability density functions for fault density. He discussed issues and considerations in using available data to construct the curves for Yucca Mountain faults. Next, Robert Youngs, representing the Fault Displacement Working Group, presented what he referred to as the earthquake approach to characterizing fault displacement, which uses a displacement attenuation function for secondary faulting. He discussed how scaling relations and data presented in Chapter 9 of the Seismotectonic Synthesis Report could be used to perform this type of analysis.

Throughout the morning session, there were questions raised about more specifically defining the fault displacement objective. During the discussion session, Carl Stepp emphasized that the primary need from the SSC teams is a methodology to predict fault displacement at any point in the Controlled Area given that a particular feature exists. Kevin Coppersmith elaborated by listing four things that the Seismic Design Team were looking for regarding fault displacement: (1) fault displacement hazard curves at selected locations; (2) fault dip and sense of slip; (3) the width over which displacement occurs on a fault; and (4) recommended methodologies for assessing displacements at other locations. Silvio Pezzopane presented a "strawman" selection of points and classes of features that should be represented by the points . John Whitney suggested adding a point in Midway Valley. After some discussion, it was decided that a list of the classes of features and a map of the selected points would be distributed to the experts shortly after the workshop (Attachment 2). Other topics discussed included aspect ratios of fault ruptures at Yucca Mountain, available displacement data for tunnels and mines elsewhere in the world, availability and access to ESF fault and fracture data, and the likelihood of future displacement on intrablock and other Tertiary bedrock faults which show no evidence for Quaternary faulting but for which Quaternary movement cannot be precluded. Also discussed were problems in predicting slip for future events based on a long-term displacement record (in some cases Miocene) in an area where displacement rates have varied significantly through time.

Just before lunch, Kevin Coppersmith outlined upcoming steps in the SSC elicitation process, which had already begun with each team's preparation of preliminary interpretations for this workshop. Next would be the elicitation interview and follow-up, with draft assessments due to the Calculations Team by March 10. Preliminary results would be presented at the Feedback Workshop, which was originally scheduled for April 16-18 but was moved up to April 14-16. After this last workshop, elicitation summaries would be finalized. Dr. Coppersmith emphasized that elicitations and development of the team's interpretations were an ongoing process that would continue until the final summary was written. He then asked for comments from observers. Leon Reiter commented on the need to know the resolution for all types of data and the importance of considering this in the assessments. He also reiterated a point he had made earlier that it would be helpful to the experts if a minimum threshold of engineering concern for displacement could be defined at some level above 0 cm. He believed this would help experts to better focus on characterizing the displacements of main concern to design. Carl Stepp responded that the Management Team advised against doing this because they wanted to avoid any possible conditioning of the experts' interpretations. Kevin Coppersmith then added that in terms of guidance on the distance of interest for SSC characterization for ground motion hazard, experts needed to characterize sources out to 100 km, with detailed characterization of sources out to 50 km from Yucca Mountain.

The final afternoon session was devoted to elicitation training, conducted by Peter Morris. Ivan Wong introduced members of the ground motion panel, who had arrived to also participate in the elicitation training (participants in the Ground Motion Workshop on Methods and Models are not included in Table 1, but will be included in a separate report). Peter Morris referred to the training as a workshop in probability assessment. The topics covered included using probability to quantify uncertainty, representing and manipulating probabilities, and assessing probabilities. The information presented followed his handout closely (Attachment 2), with the addition of many real-life examples and interactive exercises with the experts. The workshop was adjourned after the elicitation training, at about 5:00 pm.

TABLE 1. YUCCA MOUNTAIN SEISMIC SOURCE CHARACTERIZATION WORKSHOP #4 - PRELIMINARY INTERPRETATIONS

January 6 to 8, 1997

Attendance List

Name	Affiliation
1. Ake, Jon	U.S. Bureau of Reclamation (USBR)
2. Allen, Clarence	Nuclear Waste Technical Review Board (NWTRB)
3. Anderson, Ernie	U.S. Geological Survey (USGS)
4. Anderson, Larry	USBR
5. Arabasz, Walter	University of Utah (UU)
6. Bell, John	UNR
7. Bruhn, Ron	UU
8. Brune, James	UNR
9. Chaney, Tom	USGS
10. Coppersmith, Kevin	Geomatrix
11. Cornell, Allin	Consultant
12. dePolo, Craig	UNR
13. Doser, Diane	University of Texas, El Paso
14. Ferrill, David	Center for Nuclear Waste Regulatory Analysis
15. Fridrich, Chris	USGS
16. Hanks, Tom	USGS
17. Ibrahim, Bakr	U.S. Nuclear Regulatory Commission (NRC)
18. Justus, Phil	NRC
19. King, Jerry	M&O/SAIC
20. Knuepfer, Peter	State University of New York at Binghamton
21. Lui, Christiana	NRC
22. Majer, Ernie	Lawrence Berkeley National Laboratories
23. McCalpin, Jim	GEO-HAZ Consulting, Inc.
24. McGuire, Robin	Risk Engineering
25. Menges, Chris	USGS
26. Morris, Peter	Applied Decision Analysis, Inc.
27. O'Leary, Dennis	USGS
28. Olig, Susan	Woodward-Clyde Federal Services (WCFS)
29. Parks, Bruce	USGS
30. Penn, Sue	WCFS
31. Perman, Roseanne	Geomatrix
32. Pezzopane, Silvio	USGS

33. Pomeroy, Paul	Advisory Committee on Nuclear Waste
34. Potter, Chris	USGS
35. Quittmeyer, Richard	WCFS
36. Ramelli, Alan	UNR
37. Reiter, Leon	NWTRB
38. Rogers, Al	EQE International
39. Savy, Jean	Lawrence Livermore National Laboratory
40. Schwartz, David	USGS
41. Sheaffer, Patricia	USGS
42. Slemmons, Burt	WCFS
43. Smith, Ken	UNR
44. Smith, Robert	UU
45. Stamatakos, John	CNWRA
46. Stepp, Carl	WCFS
47. Stuckless, John	USGS
48. Sullivan, Tim	DOE
49. Swan, Bert	Geomatrix
50. Toro, Gabriel	Risk Engineering
51. Wernicke, Brian	Cal Tech
52. Whitney, John	USGS
53. Wong, Ivan	WCFS
54. Youngs, Robert	Geomatrix
55. Yount, Jim	UNR

ATTACHMENT 1

Workshop Agenda

FINAL AGENDA
SEISMIC SOURCE CHARACTERIZATION
PRELIMINARY INTERPETATIONS WORKSHOP
JANUARY 6-8, 1997
WASATCH ROOM, DOUBLETREE HOTEL
SALT LAKE CITY, UTAH

PURPOSE OF WORKSHOP

- To provide an opportunity for the expert teams to present and discuss their preliminary interpretations regarding key issues in seismic source characterization
- To train the expert teams on the process of elicitation and uncertainty characterization
- To present and discuss additional information and interpretations of importance to source characterization

APPROACH

- For each of the five key issues assigned, two teams will present their interpretations; all of the teams will discuss the issue and will be prepared with summary slides
- Focus on understanding the interpretations, their technical bases, consistency with data, and expression of uncertainty
- Each team should feel that they understand the interpretations of others and should be prepared to re-examine their thinking in light of what they hear
- The goal is for interpretations given at the elicitation interviews to be well-reasoned, technically-supported, and complete.

MONDAY, JANUARY 6, 1997

1:00-1:15	Introduction and Purpose (K. Coppersmith)
1:15-2:00	The Sundance Fault (C. Potter)
2:00-2:30	Hydrologic and Geochemical Considerations Relating to Evaluation of Faulting at Yucca Mountain (J. Stuckless)
2:30-3:15	Geophysical Interpretation of Yucca Mountain and Vicinity (E. Majer)
3:15-3:30	**Break**
3:30-4:15	Yucca Mountain Faults in a Regional Context (D. O'Leary)
4:15-5:00	Subhorizontal Detachments and Seismicity (B. Wernicke)
5:00-5:30	Precarious Rocks and Their Implications to Prehistorical Seismicity (J. Brune, J. Whitney)
5:30-5:45	Comments from Observers
5:45	**Adjourn for Dinner**

TUESDAY, JANUARY 7, 1997

8:00	**Continental breakfast in Wasatach #4**
8:30-8:35	Introduction to Key Issues (K. Coppersmith)
8:35-10:30	**Issue #1: Tectonic Models**
8:35-9:05	Presentation of Team Interpretation (Ake, Slemmons, McCalpin)
9:05-9:35	Presentation of Team Interpretation (Smith, dePolo, Menges)
9:35-10:15	Discussion of Issue #1 (All Teams)
10:15-10:30	**Break**
10:30-12:30	**Issue #2: Potential Seismic Sources**
10:30-11:00	Presentation of Team Interpretation (Doser, Fridrich, Swan)
11:00-11:30	Presentation of Team Interpretation (Rogers, Young, Anderson)
11:30-12:30	Discussion of Issue #2 (All Teams)
12:30-1:30	**Lunch (on your own)**
1:30-3:15	**Issue #3: Maximum Magnitudes**
1:30-2:00	Presentation of Team Interpretation (Ake, Slemmons, McCalpin)
2:00-2:30	Presentation of Team Interpretation (Smith, dePolo, Menges)
2:30-3:15	Discussion of Issue #3 (All Teams)
3:15-3:30	**Break**
3:30-5:30	**Issue #4: Earthquake Recurrence**
3:30-4:00	Presentation of Team Interpretation (Doser, Fridrich, Swan)
4:00-4:30	Presentation of Team Interpretation (Rogers, Yount, Anderson)
4:30-5:30	Discussion of Issue #4 (All Teams)
5:30-5:45	Comments from Observers

WEDNESDAY, JANUARY 8, 1997

8:00	**Continental Breakfast in Wasatch #4**
8:30-10:30	**Issue #5: Fault Displacement Methodology**
8:30-9:00	Presentation of Team Interpretation (Arabasz, Anderson, Ramelli)
9:00-9:30	Presentation of Team Interpretation (Smith, Bruhn, Knuepfer)
9:30-10:30	Discussion of Issue #5 (All Teams)
10:30-10:45	**Break**
10:45-11:30	Additional Guidance on Fault Displacement Hazard (Fault Displacement Working Group)
11:30-12:00	General Discussion
12:00-1:00	**Lunch**
1:00-3:00	Elicitation Training (P. Morris)
3:00-3:15	Break
3:15-4:30	Elicitation Training (Continued)
4:30-4:45	Where We Go From Here (K. Coppersmith)
4:45-5:00	Comments from Observers
5:00	**Adjourn**

Civilian Radioactive Waste Management System
Management & Operating Contractor

Summary of Methods, Models, and Preliminary Interpretations
Workshop on Ground Motion at Yucca Mountain

Salt Lake City, UT
January 9 and 10, 1997

Prepared for

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February 4, 1997

INTRODUCTION

The United States Geological Survey (USGS) is currently performing a probabilistic seismic hazards analysis (PSHA) of the proposed high-level radioactive waste repository at Yucca Mountain, Nevada. The study is an element of the Department of Energy's (DOE) site characterization activities. The PSHA will result in the annual probability of exceedance of various levels of vibratory ground motion and fault displacement.

Input to the PSHA is being developed by two panels of experts: one characterizes seismic sources and fault displacement and the second estimates vibratory ground motion. Their interpretations are being facilitated in a series of structured workshops. The goal of the process is to have differences in experts' interpretations result from true differences in judgment and not differences in access to data, definition, or lack of full understanding of each other's interpretations. This report summarizes the second in the series of workshops for characterizing ground motion: the Methods, Models, and Preliminary Interpretations Workshop.

The Workshop proceedings included discussions of Yucca Mountain and site-specific issues as they relate to ground motion modeling. An understanding of these issues is necessary to evaluate whether and to what extent existing models of ground motion may require modification to adequately estimate motions at the proposed repository. Several models have been developed or revised since the first Workshop (Data Needs, April 1995) and these were presented in detail. Finally, results of a preliminary modeling exercise (posed to the Experts in advance of the Workshop) was discussed. Each speaker provided copies of presentation materials and these are included as an Attachment to this Summary.

The Workshop was attended by a representative of the DOE, Tim Sullivan, and members of the Project Management Team, John Whitney, Carl Stepp, Ivan Wong, and Richard Quittmeyer. All Ground Motion Team Experts were present: John Anderson, David Boore, Kenneth Campbell, Art McGarr, Walter Silva, Paul Somerville, and Marianne Walck. Members of the Ground Motion Facilitation Team in attendance were: Norman Abrahamson and Ann Becker. Also present were Robin McGuire, Seismic Design Team Leader; Gabriel Toro, PSHA Calculations Team Leader; and Review Panel members Allin Cornell, Tom Hanks, and James Brune. Technical Observers included representatives from the NRC, NWTRB, ACNW, and the CNWRA.

THURSDAY, JANUARY 9, 1997

The full scope of the Experts' involvement was detailed by Norman Abrahamson, the Ground Motion Facilitation Team Leader. They must develop ground motions as a series of point estimates for specified magnitudes and source - site geometries. Both strike-slip faulting on a vertical surface and normal slip on a moderately dipping fault are to be considered. The site is representative rock with dynamic properties equivalent to the existing conditions at repository level (called "repository outcrop"). The repository outcrop is based on the velocity profile with the top 300 m removed. Horizontal and vertical motions will be estimated for peak ground acceleration, peak ground velocity, and spectral acceleration at frequencies of 0.5, 1, 2, 5, 10, and 20 Hz. The Experts must document in detail the reasoning underlying their interpretations. The median ground motion, aleatory uncertainty, and the epistemic uncertainties of both are to be provided. The importance of quantifying uncertainty was discussed in the context of the elicitation process by an expert in these techniques (Peter Morris, Wednesday joint session with Seismic Source Characterization Team). This was elaborated on (Gabriel Toro, Thursday) and the partitioning of uncertainty as parametric or modeling and (orthogonally) as aleatory or epistemic was discussed. Several relevant examples of the partitioning as it relates to ground motion modeling were presented to thoroughly inform the Experts of the process.

A fundamental question which the Experts must address is whether ground motions at Yucca Mountain differ from the motions represented by the data set which forms the basis for empirical models. Differences could be caused by source effects (extensional vs. compressional regimes and normal vs. strike-slip faulting), path effects (crustal differences), or site effects (site response). It was shown that significant differences in near fault ground motions for normal and reverse faults are observed in foam rubber models (James Brune). The propagating wavefront in dip-slip faulting is greatly affected by normal stresses. In reverse faulting, the surface reflected wave is dilatational and reduces normal stress on the slip surface. Foam rubber models show the reflected wave destabilizes the fault and results in increased particle motions in the hanging wall and at the fault tip. In normal faulting, the reflected wave is compressional, which stabilizes the fault and results in weak motions. Additionally, 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 motion radiated from near-surface layers.

The USGS (Paul Spudich) has compiled a data base of strong ground motion records in extensional tectonic regimes. The criteria for inclusion were that the data were: (1) available in digital form; (2) recorded in the free field or in structures less than 3 stories high; (3) triggered before the S-wave arrival; (4) resulted from earthquakes with moment magnitude at least 5; and (5) recorded at distances no greater than 105 km. Nine normal faulting events in the data base were inverted for stress drop and kappa using a Brune ω^2 spectral form with a single corner frequency (Ann Becker). The median stress drop was about 30 bars for several cases using site transfer functions developed by Silva and about 60 bars using site transfer functions by Boore and Joyner. The median kappa obtained was about 0.04 to 0.06 sec for all sites and the inversion results confirmed that the Little Skull Mountain recording sites have particularly low kappas (about 0.015 sec). This compares with stress drops for western North American events of 70 to 100 bars (Boore-Joyner, using Boore-Joyner amplifications) and for six California earthquakes of about 37 bars (Silva, using Silva's amplifications).

The faults in the Yucca Mountain region are generally characterized by low slip rates. However, slip rate has not been included in regressions of fault length on magnitude (John Anderson). Comparisons between regressions including and excluding slip rate show that ignoring slip rate may underestimate the magnitude. Or, for a given rupture length, larger earthquakes occur on faults with lower slip rates than on faults with high rates implying a larger static stress drop for low slip-rate faults. Anderson also presented the composite source model and showed how it can be used to estimate energy and several stress parameters. The key stress parameters for ground motion are dynamic stress drops, not the static stress drop. Anderson noted that lower ground motions from extensional regimes can be modeled by lower than average dynamic stress drops even if the static stress drop is larger than average. Anderson also briefly summarized the Dinar, Turkey M 6.4 normal faulting earthquake (1 Oct 1995) which caused surface rupture. Records were obtained at close distances to the fault plane and an analysis of the event has been initiated. The results should be available in February.

Site response issues were discussed in terms of measured nonlinear response of tuff samples obtained from Yucca Mountain (Kenneth Stokoe). Resonant column and dynamic torsional shear testing was performed on two welded and one unwelded tuff specimens. The specimens are not homogeneous and results of the resonant column testing are robust whereas the torsional shear tests are less so. The modulus degradation with increasing shear strain is less nonlinear than granular samples, but the low-strain modulus is significantly greater than granular soils. Similarly, material damping is low. Measured low-strain shear wave velocities are 4200, 5800, and 8100 fps (1300, 1800, 2500 m/sec) for the unwelded and welded tuffs, much greater than the approximately 600 m/sec measured in-situ (Schneider et al., Ground Motion Modeling of Scenario Earthquakes at Yucca Mountain, Final Report for Activity 8.3.1.17.3).

The effect of source, site, and regional crustal differences was evaluated using the point-source Band-Limited-White-Noise (BLWN) source model combined with Random Vibration Theory (RVT) (Kenneth Campbell). Ratios of synthetic motions (horizontal motion; response spectra ratios) for California- and Yucca Mountain-type sites showed the largest sensitivity to site kappa at frequencies higher than about 10 Hz and to stress drop at all frequencies. Regional effects other than event stress drop also cause significant amplification at high frequency for Yucca Mountain-type sites. At high frequencies, significant differences between Campbell's results and a similar analysis by Silva were noted. These differences were primarily due to different site amplifications models developed by Boore and Silva. Differences in Q models also contributed to the differences. Campbell and Silva are working to resolve these differences.

The empirical data base at Yucca Mountain consists of data recorded from underground nuclear tests. The records have been interpreted by Walck (Workshop #1) for two-dimensional crustal structure. The very shallow blasts result in large surface waves. There are also unusual wave propagation effects observed at some locations in NTS (not Yucca Mountain) which are not well understood (Paul Somerville). Confined shallow sources, such as the blasts, are not common in large earthquakes so the variability from typical earthquake depths may be much less than observed in the blast data.

Existing empirical relationships were next examined. The USGS extensional regime study (Paul Spudich) 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 include a bias correction and a standard deviation correction for all distances and also for distances less than 20 km. Many of the factors show a period dependence. Spudich also presented the new attenuation relation developed using extensional regime data only. This model should be applicable to Yucca Mountain without changes to the source.

FRIDAY, JANUARY 10, 1997

The second day of the Workshop continued with discussions of proponent models arising from empirical data. The Abrahamson and Silva (1996) relationship was not available at the time of the USGS study; style-of-faulting modification factors were provided (Norman Abrahamson) as well as a discussion of the regression procedure.

An advantage to numerical simulations is the ability to modify input parameters to evaluate the sensitivity of ground motions to the parameters (and thus uncertainties) and compute scaling factors. Walter Silva presented results using the point source RVT model, and Kenneth Campbell for the hybrid empirical model. (The attached notes for Dr. Silva's presentation are not complete; much of his work was performed under separate contract to the DOE and was not authorized for release in print form.) Silva has calibrated the point source model using data from 16 earthquakes. This calibration exercise also provides estimates of the modeling uncertainty term. Silva's point source model will be presented to the experts with variable stress-drop so the experts can select their own estimate of the stress drop in applying the model.

Campbell's approach is to estimate ground motions by scaling existing empirical relationships. He develops the scaling factors from comparisons of California motion estimates to Yucca Mountain motion estimates, both developed using the BLWN RVT point source model. The examples he presented correspond to a postulated M 6.5 earthquake at 10 km distance and considered both strike-slip and normal faulting. The correction factors for peak ground acceleration were presented for three discrete values of stress drop and ranged from 1.053 to 1.832. Campbell will provide a complete set of estimates for other magnitudes, distances, and periods as part of his proponent model.

A third class of proponent models arises from the blast data base consisting of thousands of recordings at NTS (T. Joseph Bennett). Three alternative methods were presented for defining the attenuation relationship using information from the blast data. The first model uses the NTS data directly with a conversion from explosion yield to earthquake magnitude. The second model uses the attenuation rates from the blast data but with the spectral shape defined by California empirical attenuation models. This second method addresses the issue of different spectral content in explosions and earthquakes. The third method uses the attenuation rate from explosions but with a spectral shape from the Little Skull Mt. earthquake.

Because of the lack of an empirical earthquake ground motion data base at Yucca Mountain, the relevance and applicability of numerical models was the focus of the USGS report Ground Motion Modeling of Scenario Earthquakes at Yucca Mountain (Schneider et al., 1996). Predictions from six methods were included in the study (Abrahamson) which covered the range of modeling methods commonly used in ground motion estimation. In the Scenario exercise, the investigators calibrated their models to data recorded in the 1992 Little Skull Mountain event and then computed motions for scenario earthquakes occurring on tectonic sources which could potentially affect Yucca Mountain. The suite of scenario earthquakes consist of five normal faulting sources and two strike-slip. The simulated motions for the normal faulting case were higher than attenuation relations derived from western U. S. data by about 60% at distances less than about 5 km and by about 20% at 15 km. The variation at short distance was attributed to differences in kappa and at longer distance due to crustal amplification and directivity. For the strike-slip event, the computed motions exceeded existing attenuation relationship predictions by about 30 % at 25 km, again attributed to kappa, but were consistent with predictions at 50 km distance.

Recent results from finite element modeling of a postulated rupture on the Bare Mountain fault beneath the repository region was presented (David Ferrill). The model assumes the regional faults are connected at depth along a subhorizontal detachment. Slip on an initially rupturing segment is transferred up-dip towards the surface and down-dip to the detachment. The modeling indicates that the rupture can trigger slip on other faults and result in higher accelerations than if it were confined to a single faulting surface. At distances approximating the location of the proposed repository, peak horizontal ground accelerations at the surface may exceed predicted values from empirical attenuation relationships by about 50%.

Although the Yucca Mountain region has not experienced a major earthquake in historic times, the western boundary of the Basin and Range has and clues to ground motion attenuation may be found in studies of the numerous precariously balanced rocks found region-wide (James Brune). The distance of balanced rocks from the ruptures combined with the acceleration required to topple these rocks provide physical evidence of the attenuation of motion surrounding an historic earthquake. This information is currently being collated to provide a constraint on ground motion attenuation in the region. Near the repository itself, balanced rocks could be toppled by about 0.3 g accelerations, and semiprecarious rocks by about 0.4 g. Age-dating the rock varnish indicates that they have been precariously positioned for about 40,000 to 80,000 years, suggesting a bound on these acceleration levels.

At the conclusion of the Workshop, the Experts presented trial estimates of median ground motion (and uncertainties) for a M 6.5 earthquake occurring 10 km from both strike-slip and normal faulting earthquakes. The purpose of this exercise was to familiarize the experts with the process and the form of the estimates that they will have to provide. Several of the experts only presented proponent models rather than evaluating the suite of alternative models. As a result there was a large variability in their estimates; their estimates of the median peak ground acceleration varied by about a factor of 2 for the strike-slip case, up to 3 for the hanging wall of the normal case, and over 3 for the footwall.

In the comments by observers, Jerry King indicated that the seismic design will include tall structures whose natural periods are beyond 1.0 sec. It was decided that this observation needed to be verified given the fact that the planned period range to be characterized by the Experts only went to 2.0 sec (0.5 Hz). Attached is a memorandum addressing this issue; the requested period range extends to 3.0 seconds.

To:	Alden Segrest
cc:	Richard Nolting, Matthew Gomez, John Salchak, Daniel McKenzie, Kalyan Bhattacharya, cstepp @ aus.computize.com at pmdfpo @ YMPGATE, IGWONGXO @ wcc.com at pmdfpo @ YMPGATE, mcguire @ riskeng.com at pmdfpo @ YMPGATE, nabraham @ holonet.net at pmdfpo @ YMPGATE, Jerry King
From:	Richard Quittmeyer
Date:	01/16/97 05:39:51 PM
Subject:	Frequency Range of Interest for Seismic Design

Alden,

During a recent ground motion workshop being carried out in support of the Probabilistic Seismic Hazard Assessment for Yucca Mountain, a question was raised concerning what frequency range is of interest to the designers with respect to seismic design. In evaluating ground motion at Yucca Mountain, we want to have the members of our expert panel provide assessments for ground motion at frequencies that span the range of natural periods that will be associated with the various structures, systems, and components making up the repository facilities. I would appreciate a formal response to this inquiry via an IOC or e-mail so that it can be incorporated into the proceedings of the ground motion workshop. If you have any questions concerning this request, please contact me at 794-7765. Thanks for your attention to this request.

Richard

To:	Richard Quittmeyer
cc:	Alden Segrest, Kalyan Bhattacharya, Fei Duan, Matthew Gomez, John Salchak
From:	Richard Nolting
Date:	01/24/97 10:50:36 AM
Subject:	Re: Frequency Range of Interest for Seismic Design

A preliminary assessment has been made of natural frequencies based on a few examples of repository structures. More accurate values depend on a more complete analysis and more complete designs.

The attached table lists structures considered typical of the repository and estimates of their natural frequencies. Natural period, the inverse of the frequency, is also given. Values for subsurface structures, for example, are based on a simple relationship using mass and an assumed spring constant. Values for surface structures are also based on simple formulas, for example, those given in the Uniform Building Code for steel, reinforced concrete, and shear wall structures. The number for the waste handling building is an approximation based on estimates that ranged from 2 to 20 Hz.

Based on these approximate values, and considering that the subsurface ground support structures are not susceptible to amplified ground motions, the range of natural frequencies of most interest is about 0.3 to 20 Hz (3 to 0.05 sec).

For questions regarding this information please contact Richard Nolting (702/295-4450) or Fei Duan (702/295-4538).

Frequency Range of Interest for Seismic Design

Selected repository structures and estimated natural frequencies (or natural periods):

Subsurface	Frequency (Period)
Drift support linings (concrete or steel components)	100 to 600 Hz (0.01 to 0.0017 sec)
Drift attachments (e.g., utility support structures)	10 Hz (0.1 sec)
Surface Structure (height)	
Waste Handling Building (25 meters ±)	2 Hz (0.5 sec)
Shaft Head Frame structure (17 meters ±)	1 Hz (1 sec)
Shaft Ventilation and Filter structure (30 meters ±)	0.5 Hz (2 sec)

PLEASE NOTE:

The presentation materials handed out during the Seismic Source Workshop #4 and Ground Motion Workshop #2 and mentioned in these summaries are NOT included with this mailing. If you require copies of any handouts, please contact Sue Penn at 510-874-3122 or Patricia Sheaffer at 303-236-0516, x231.