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2/11

PROBABILISTIC SEISMIC HAZARD ANALYSIS: ELEMENTS OF CONSIDERATION

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ABSTRACT

Considerable recent interest in probabilistic seismic hazard analysis (PSHA) has resulted from detailed analysis of nuclear facilities. The analyses often employ multiple expert opinions in an attempt to capture a measure of uncertainty in the present state of knowledge. PSHA are based on historical seismicity, paleo-seismicity derived from measured and dated offsets observed in trenched faults, attenuation functions for ground motion, probability distributions for the parameters used, and site-to-ground-motion-source distances. Yet uncertainties in these inputs are seldom fully captured by the PSHA. Because of long term earthquake clustering, historic seismicity may under- or over-estimate seismicity expected in the future. Paleo-offset fault dating often underestimates paleoseismicity. The choice of recurrence relationships (the relative numbers of earthquakes of different magnitudes) can produce internal inconsistencies in PSHA which may lead to incorrect results. The effects of these uncertainties are examined in this paper with particular emphasis on the earthquake hazard and its effect on homes, workplaces, transportation, water supplies and other necessities of civilization. Design codes or laws governing such structures usually allow energy to be dissipated by the structure through inelastic degradation short of failure, when subjected to a probabilistic design earthquake. The effect of non-linear recurrence (e.g., clustering attributed to the fractal nature of earthquake recurrence) on the likelihood of failure for inelastically degrading structures, is estimated. It is found to be higher than if earthquakes are assumed to occur perfectly randomly. The input parameters to PSHA are examined and current practices summarized. Potential failure could be reduced with elastic rather than inelastic designs, and close attention to code construction detail to preclude catastrophic failure should probabilistic estimates be exceeded. Costs of proceeding on such a basis must be weighed against the costs of broad scale economic disruption and recovery, such as recently observed in California with presently used PSHA and associated inelastic design methods.

PROBABILISTIC SEISMIC HAZARD ANALYSIS (PSHA)

PSHA is a process by which earthquake generated ground motion accelerations (or response spectral bands), which are used to design buildings or other structures, are determined probabilistically. Such analyses were first published in Canada (Milne and Davenport, 1969) using extreme value statistics and were later incorporated in the Canadian National Building Code. Cornell (1968) provided the mathematics to calculate a mean, median and various percentile curves of potential earthquake accelerations at a particular site. This process was put in the form of computer programs, EQRISK and later FRISK (McGuire, 1976 and 1978). Algermissen and Perkins (1976) describe the program SEISRISK (now superseded by versions II and III) and provided a map of earthquake acceleration probabilities for the United States which was incorporated in the U.S. Uniform Building Code (e.g., ICBO 1991 or SEOC, 1990). In the zoning maps accompanying the Uniform Building Code (UBC), accelerations are given as having a ten percent chance of occurring in 50 years, a nominal lifetime of most modern structures. This approach to building code zoning maps is now used in Canada and the United States.

More recently, concern over the possibility that an earthquake of the type experienced at Charleston, South Carolina could occur anywhere in the eastern United States (e.g., Rankin et al., 1977), inspired development of multiple expert PSHA computer codes that use opinions where data are absent or insufficient. Two such codes are SEISM or SHC (Bernreuter et al., 1984) and EQHAZARD (Toro et al., 1988 for the Electric Power Research Institute).

The analyses of aggregated hazards from individual experts or expert teams, in addition to probability distributions about empirical data, permit an estimate of total uncertainty. Multiple expert PSHA is in essence a combination of single expert PSHAs. In practice, however, the input from various experts may be applied in a single PSHA calculation which keeps track of the spread in opinion at each step of the process. These techniques, although technically efficient, result in an analysis that is difficult to understand or review. This characteristic of multiple expert PSHA is termed "lack of transparency." To assist in understanding such PSHA, hazard curves developed by multiple experts or groups of experts may be disaggregated to find the acceleration produced by the principal earthquakes contributing to the hazard. Strong motion records may then be sought, scaled or synthesized for use in dynamic design analyses.

Selection of experts and the manner of elicitation is a controversial topic. This controversy is well summarized in Kotra et al. (1996) who make recommendations for expert selection and elicitation for topics of interest in relation to the storage of high level nuclear waste.

A very brief description of the PSHA process is given in Reiter (1990) after TERA Corporation (1978), from which **Figure 1** is derived. Step 1 shows two faults which may be sources of earthquakes. Step 2 shows choices in recurrence curves depicting the numbers of earthquakes with different magnitudes that have occurred on one of the faults. The other fault in the illustration would also be assigned one of these curves. In practice, many faults and/or seismic source regions would be included in a PSHA conducted in a seismically active area.

For all but a few very-large very-active faults, not enough earthquakes will have been observed to determine the shape of a recurrence curve. The shape of the recurrence curve has often been assumed to be the same as observed for large regions. The assumption has been that activity on many faults in a region is similar to the activity of the fault in question. At times historical earthquake data is supplemented with geologic age dating of fault offsets to obtain the numbers of large earthquakes which may have occurred on the fault over a known geologic time period. Step 3 depicts how earthquake ground motions attenuate as a function of distance from the source; a topic that also may be subject to expert opinion. From these inputs, the probability that a given acceleration will be exceeded in a given time period may be estimated. Experience with this process has led to additional understanding about each of the topics in **Figure 1**. This experience is summarized in the following paragraph.

RECURRENCE

In Step 2 of **Figure 1** is a Gutenberg and Richter (G-R) recurrence, (Gutenberg and Richter, 1956). A G-R recurrence represents the numbers of earthquakes of different magnitudes observed globally or in broad earthquake generating regions. Insufficient historical earthquake data at the time of development of the G-R recurrence precluded making estimates for individual faults. However with nearly an additional 50 years of instrumentally recorded earthquakes, Schwartz and Coppersmith (1984) attempted to construct recurrence curves for sections of the San Andreas fault in California (comparable to the Queen Charlotte fault offshore from British Columbia and its northward continuation called the

Fairweather fault). They found that there were an unusually large number of similar magnitude earthquakes corresponding to the lengths of San Andreas fault sections demarcated by offsets, bends or simply sections whose seismicity was distinctly different from other sections. They called the recurrence produced by these sections of the fault a "characteristic" recurrence (also in **Figure 1**, Step 2) and the earthquake magnitude which was seen much more frequently than anticipated, the "characteristic" earthquake. They theorized that this form of recurrence might also apply to entire faults, not just segments. The "knee" in the Schwartz and Coppersmith (1984) characteristic recurrence is two magnitude units wide. Other studies suggest a less wide "knee," as little as three quarters of a magnitude unit. Jackson and Kagan (1995), for example, state that the characteristic recurrence predicts up to 5 times too many characteristic earthquakes for some Pacific Rim faults. Davidson and Scholz (1985) pointed out that for the Aleutian Islands thrust, a characteristic recurrence was observed until a very large earthquake (larger than the characteristic earthquake) occurred. Afterwards, a G-R recurrence provided a better fit to the earthquake data. This suggests that a characteristic recurrence may be limited in time and applies only until one or more fault barriers or asperities are broken by a large earthquake fault rupture.

Wesnowsky (1994), measured recurrence, again on the entire San Andreas fault, and on three major associated faults. He found that two of the associated faults demonstrated a characteristic recurrence during the historic record of seismicity, but that recurrence of one of the associated faults and of the entire San Andreas fault were better fit by a G-R recurrence. Wesnowsky included earthquakes in a band 20 km wide on either side of these faults, a point that may be of importance because smaller ancillary faults are contained in this band.

Hofmann and Ibrahim (1995) and Hofmann (1996) point out that a region enclosing several faults, one of which generates the maximum magnitude for the region, imposes limits on the recurrence that can be assigned to individual faults. If the number of maximum magnitude earthquakes for the region is correctly estimated, and the fault, which is large enough to cause them, is assigned a G-R recurrence, that fault then describes the entire recurrence for the region enclosing it and other faults. Therefore, individual faults within the region can not each have a G-R recurrence because the resulting regional recurrence will not be a G-R recurrence. It will be a non-linear recurrence which predicts many more small earthquakes than observed.

An additional problem is that although there are good statistics on the numbers of earthquakes of various sizes that occur in a region where a G-R recurrence is observed, there are seldom enough earthquakes to accurately determine recurrence on an individual fault. The arbitrary assignment of a G-R recurrence to each fault within a region may lead to excessive numbers of smaller earthquakes and distort acceleration probabilities of exceedance expected at a site. Because actual recurrence is not known for individual faults, candidate recurrences for PSHA which have produced fewer small earthquakes than a G-R recurrence, could be a characteristic recurrence, a maximum-magnitude-only recurrence (Wesnowsky et al., 1982), or recurrences which vary with time. It is possible that faults may be inactive or have any of the recurrences discussed during a given time span. The only recurrence we know with some degree of certainty is that regional recurrence, consequent to the recurrences assigned to individual faults within the region, follows the G-R recurrence.

CLUSTERING

Earthquakes do not usually occur regularly or perfectly randomly in time; they cluster. For example, Lee and Brillinger (1979), and Xiwei and Quidong (1996) present evidence for clustering in China. Goes (1996) and Bell (1994) document earthquake clustering in several seismic regions. Main (1995) proposes three types of clustering behavior depending on tectonic driving velocity, the size of the seismic source area and other factors, and that these types can be incorporated in PSHA through modifications of a Gamma distribution of recurrence. Turcott (1992) states that clustering may be represented by the fractal dimension of earthquake recurrence. Smalley et al. (1987) provides an example by estimating the fractal dimensions of earthquake recurrence in the New Hebrides. The intervals given on the San Andreas appear to be too few to reliably exploit this concept but work with smaller earthquakes may be possible. Seih et al. (1989), Fumal et al. (1993), and Grant and Seih, (1994) demonstrate clustering from dated movements of the San Andreas fault at Pallett Creek, Wrightwood and in the Carrizo Plain of California, respectively, **Table 1.** For Grant and Seih (1994), several interpretations are given in their text. The one in **Table 1** was derived with aid of correlation with paleo-earthquakes observed on other sections of the fault. There are hundreds of years between clusters (150-337) and only tens of years between earthquakes within clusters (45-54). A time window, equal to the average recurrence of 120 years, that is moved along the recurrence dates in **Table 1**, will include two major earthquakes about 5 times in 1,186 years, 2 times in 650 years and 2 times in 387 years, respectively as reported by these authors.

These recurrences can be converted to the number of times that two major earthquakes will occur during the average recurrence interval of 120 years, reduced to an annual basis, or chance per year. The annual chance of two occurrences of a major earthquake during its average recurrence interval is .0042, .0031, and .0052 respectively from the data of the authors cited in Table 1, or an average of .0041 times per year. For 500 years, a major earthquake, occurring 2 times in 120 years, is likely to happen twice. This corresponds to about a 10 percent chance in 50 years.

If adequate earthquake statistics are available for a region, a probability of multiple events during the lifetime of a facility may be estimated. This probability becomes important when design methods, that take advantage of inelastic behavior or ductility are used. For example, building codes commonly used in the United States assume that structural degradation can take place without resulting in failure using methods which permit elastic design to as little as 1/12th the expected probabilistic acceleration corresponding to a ten percent chance of occurrence in 50 years. There is a further assumption that accelerations will not exceed the 0.4g of a seismic zone map. The seismic zone map is roughly based on the PSHA by, for example, Algermissen and Perkins (1976) and Algermissen et al. (1982), but has been modified by committee. Recent California earthquakes (e.g., Northridge 1994), suggest that failure of code designed structures may occur more frequently than expected, based on the number and distribution of red-tagged buildings as illustrated in Holmes and Krawinkler (1994). In both the 1971 San Fernando and the 1995 Northridge earthquakes, substantial areas appear to have been shaken at higher levels than 0.4g, and shaken 2X at those levels within 24 years, **Figure 2**, after Chang et al. (1996) and Maley and Cloud (1971). During the 1994 Northridge earthquake, damage to structures which survived the 1971 San Fernando earthquake may have resulted from a continuation of largely hidden structural degradation initiated in the earlier event.

To quantify temporal clustering as the likelihood of two or more events exceeding a given acceleration in a given area, adequate statistics on acceleration experienced by various mapped locations are needed. These data are dependent on a high density of strong motion accelerographs. Such data is sparse, particularly for damaging acceleration levels. Many more strong motion accelerographs were available in 1994, however, than in 1971 in the Los Angeles area.

If a probabilistic peak acceleration is most frequently caused by one fault system or source region, clustering of a particular acceleration level at a site should be similar to clustering of earthquakes in a fault zone or single source region. If several independent sources contribute to the probabilistic

6/17

acceleration of interest at a site, their aggregate acceleration recurrence would be expected to appear less clustered and more random.

For the Los Angeles metropolitan area, two occurrences of greater than 0.4g would not be expected in 25 years considering that typical building code seismic zone maps predict a 10% chance of one occurrence in 50 years (the equivalent of exceeding one 0.4g occurrence in 500 years). This observation suggests that clustering may be an important factor.

Paleoseismic observations of near maximum offsets on the San Andreas fault could be considered to represent an expected degree of clustering for less than near maximum earthquakes by scaling the time of observation to match a lower magnitude. However, the area about the San Andreas fault in which smaller associated magnitude earthquakes may occur is unknown. Another way of looking at the problem is to scale the number of near maximum fault offsets (assuming they represent an average magnitude of 8.2) to a lower magnitude, (e.g., 6.7) assuming that earthquake clustering is scale invariant. The number of earthquakes found in the California catalogue may then be compared to the estimate. The Gutenberg and Richter (1954) world catalogue of earthquakes indicates that there are about eight times as many earthquakes for each succeedingly lower magnitude. This relationship is approximately followed in seismically active regions including California.

To determine the rate of M=6.7 earthquakes in the Los Angeles Basin associated with M=8.2 earthquakes on the San Andreas fault, several reasonable but uncertain assumptions can be made. The expected number of magnitude 6.7 earthquakes (18) over approximately 200 years associated with the San andreas magnitude 8.2 earthquakes is about half the number of magnitude 6.7 earthquakes in the California catalogue for the entire state from 1769 to 1989 (30). Many of the early earthquakes in Stover and Coffman (1993) were assigned Richter local magnitudes (M_L) derived from Modified Mercalli damage intensities. M_L saturates at about magnitude 6.5, so some of these earlier pre-instrumental recording earthquakes may have had higher M_S or M_W magnitude which were assigned to recent instrumentally recorded earthquakes. Therefore, it is possible that a smaller area than half of the state of California may be appropriate for assigning magnitude 6.7 earthquakes associated with magnitude 8.2 earthquakes on the southern half of the San Andreas fault.

The probability of two accelerations exceeding a given value (e.g., the 0.4g maximum in U.S. building code seismic zone maps, such as ICBO, 1990 and SEOC, 1990 as adopted fully or partially by various communities) at a particular place can be very crudely estimated by assuming that M=6.7 earthquakes associated with M=8.2 earthquakes on the San Andreas fault may occur in a zone 100km wide on either side of the fault. This zone width for associated earthquakes does not include the Sierra Nevada fault which may also generate magnitude 8 earthquakes, but is large enough to include numerous faults capable of generating earthquakes in the magnitude 6 to 7 range. The sampling of offsets cited represents about 300 km of the San Andreas fault. Therefore the total area is about 60,000 km^2. The Los Angeles Basin and its bounding buried faults represent an area of about 100 by 50 km or 5,000 km^2. The ratio of the two areas is 1 to 12. The 0.09 times per year (18/200 years) that a magnitude 6.7 earthquake is expected to occur over the entire 60,000 km^2 area can be divided by 12 yielding .0075 occurrences of M=6.7 earthquakes per year in the Los Angeles Basin as described. For 500 years then, M=6.7 earthquakes should occur 3.75 times. The 500 year return period is roughly equivalent to a 90 percent chance of non-exceedance in 50 years: the same basis as building code zoning map accelerations.

The average interval between the presumed magnitude 8+ earthquakes on the San Andreas fault is 120 years. Eighteen divided by 12 is 1.5 times as many M=6.7+ earthquakes in the Los Angeles basin as there are M=8.2+ earthquakes on 300 km of San Andreas fault. The interval between M=6.7+ earthquakes in the 60,000 km^2 area will be one eighteenth of the 120 yr interval for M=8.2+ earthquakes, or 6.7 years; 12 times that interval is about an 80 year interval for M=6.7+ earthquakes in the Los Angeles basin.

Using the .0041 times per year that two earthquakes are expected during a 120 year average recurrence period for an assumed M=8.2 earthquake, clustering for an M= 6.7 may be roughly estimated for an 80 year period in the Los Angeles basin. No pairs of 6.7 magnitude earthquakes, within 80 years of each other, had been observed for about the 220 years of record until the 1971-1994 pair. Two hundred years of record times the 0.0041 rate of M=6.7 earthquakes within 80 years of each other, is about once for the Los Angeles basin. Perhaps fortuitously, such an event has occurred once, the 1971-1994 pair. Although the historical earthquake record is not long enough to observe a statistically significant number of earthquakes in this magnitude range, results are not greatly different than the singular observation. There is a question concerning whether M=6.7 earthquakes on thrust faults, that are now known to be large enough to support earthquakes in the M=7+ range, are "characteristic" earthquakes and therefore, are not representative of those associated with San Andreas large events. However, the phenomena of apparently time-limited characteristic recurrences and characteristic earthquakes may be just one manifestation of the fractal nature of earthquakes.

PALEOSEISMICITY

Historical seismicity in North America is limited to about 200 years for most localities. Age dating of paleo offsets on faults can provide additional information concerning the recurrence of earthquakes and their maximum magnitudes. In parts of California where faults are vertical and the crust is shallow, almost all damaging level earthquakes will rupture the surface. However, in the adjacent Basin and Range tectonic province the crust is thicker and faults have dips in the 45 to 70 degree range or less. The distance from the surface to the elastic-plastic interface at the base of the crust along the potential fault slip surface is greater than for near vertical California strike-slip faults. Therefore rupture areas of fairly large earthquakes may not necessarily intercept the surface. For example Smith and Arabasz (1991) point out that historic earthquakes below magnitudes 6 to 6.5 have not produced surface ruptures in the Basin and Range. Theoretically, assuming fault rupture areas as defined by Wyss (1979) or by Wells and Coppersmith (1994), some earthquakes larger than the 6.0 to 6.5 magnitude range may not intercept the surface on typical dip slip faults in the Basin and Range. Most Basin and Range tectonic province faults are capable of maximum magnitudes of 7 or less. Therefore, it is likely that only a partial record of paleo-seismicity is captured by paleo-fault offsets dated from surface trenching. Larger Basin and Range tectonic province earthquakes typically produce surface offset that is distributed over small semi-parallel faults and in distortion of wide areas of surficial material. For example, Ferrill et al. (1995, 1996) and Stamatakos (1996) find slip rates on the Bare Mountain fault in Nevada that are higher than those determined from age dated fault offsets. Their procedures included fission track thermochronometry to estimate rate of exhumation of crystalline meta-sedimentary rocks and studies of the distribution of alluvial fan deposits. Under these circumstances, age dating of surficial paleo-fault offsets may produce an unconservative earthquake recurrence and a consequent unconservative PSHA.

TECTONIC MODEL EXAMPLE

The Death Valley - Furnace Creek fault in California and Nevada (**Figure 3**), has considerable Holocene movement but no associated historical earthquakes, Reheis (1994). The 1992 Landers, California earthquake, east of the San Andreas fault, caused several very distant aftershocks along the California -

8/17

Nevada border including the Little Skull Mountain earthquake within the Nevada Test Site just south of Yucca Mountain. The fault slip to the east of the San Andreas fault appears to be caused by the lock in the fault at the "big bend" which was last broken with a great earthquake in 1857. Strain is now being manifested by earthquakes on thrust faults perpendicular to the San Andreas and on strike slip faults to the east of the San Andreas. Should the lock on the "big bend" continue, it appears likely that the Death Valley - Furnace Creek fault system will eventually accommodate a significant part of the plate boundary strain previously relieved by the San Andreas system during historic times. Such tectonic model considerations may have a significant impact on long term PSHA. Kagan (1993) argues that ". . . earthquakes do not occur on a simple . . . surface but on a fractal structure of many closely related faults." Certainly long term PSHA requires consideration of the system of faults in or near which the site is located.

POTENTIAL EFFECT ON BUILDING AND LIFELINE FAILURE

PSHA results are influenced by knowledge (or lack of knowledge) about locations, sizes and activity states of seismically active faults. Recent experience with previously unknown or unrecognized faults in California suggests a serious deficiency in the PSHA concept. Alternatively, deterministic methods are also limited by lack of knowledge. Earthquake ground motion specifications using results from both methods are being considered (e.g., Reiter, 1995). In highly seismic regions there are many known faults. Deterministic methods, which assume a potential near-maximum earthquake on each such fault with demonstrated activity over a specified time period, are likely to produce more conservative results than probabilistic methods. This conclusion is itself uncertain, but setting design input to the highest acceleration which results from using both methods will result in a more conservative design than if only one method is used.

Building codes currently limit this input to an unrealistically low 0.4g, although strong motion measurements and seismological theory suggest higher values, for example the 2.0g of Brune (1970) and of Weichert (1986). In addition to the 0.4g limitation, reductions permitted in the building codes through the use of R_W and F_μ reduce the 0.4g by 4 to 12 times (e.g., Bertero, 1991) to near trivial levels. One acceleration near 1.8 g and nine or ten values higher than 0.4 g were recorded in the 1994 Northridge earthquake (e.g., Abrahamson and Somerville, 1996). Hall et al. (1995) state that failure mechanisms are not very well understood. The large number of red tagged buildings following the moderate M=6.7 Northridge earthquake confirm that higher measured g values are real and destructive and indicate that the combination of reduction factors and the 0.4g limitation is unwarranted.

Total costs caused by the Northridge earthquake are still not fully evaluated. Loss of roadways for automobile transportation caused a significant period of lost work and business income, in addition to repair and rebuild costs only partially replaced by insurance. De Pineres (1995) pointed out the costs of construction for a completely elastic design (R_W or F_μ = unity) of the Latin American tower in Mexico City built in 1948 was only 9.3% higher than others. This structure has withstood several earthquakes which caused failures of structures designed less conservatively. Consequently, its design criteria were recommended for earthquake prone areas.

Another factor to be considered is that although truly great earthquakes, M=8+, may not produce greatly higher peak accelerations than moderate earthquakes, they clearly have much longer durations and are more likely to drive structures to their maximum response. Nelson et al. (1995) state that they ". . . don't believe that simply mandating that structures be designed for forces 10 times higher is the answer." It indeed may not be the complete answer but bringing earthquake design criteria up to non-trivial levels is certainly a needed step that would reduce problems inherent in allowing structures to absorb large amounts of energy through inelastic structural degradation. The inelastic degradation may exceed the amounts assumed if a structure survives a design earthquake and requires only cosmetic repair, but is shaken a second time by another earthquake, or if shaken once by a larger longer-duration earthquake than anticipated. Code levels of ductile hysteresis are sometimes argued to not exceed levels at which strength degradation occurs. Bases for such arguments have been difficult to quantify because there were not sufficient numbers of strong motion instruments to accurately define contours of peak acceleration in earthquake stricken areas. The 1994 Northridge earthquake may be an exception. Extensive damage data have been collected by C. Kircher for the California Governor's Office of Emergency Services but is not yet publicly available. Future analyses of this data may better quantify whether clustering of earthquakes has affected structural failure rates and whether typical building code criteria result in hysteresis above or below material strength reduction levels.

CONCLUSIONS

There are three principal conclusions:

- Conventional treatment of uncertainties in input to typical probabilistic seismic hazard analyses often tend to cause a reduction in conservatism

- Clustering of earthquake recurrence results in a significant probability that a particular site may be subjected to a design earthquake more than once during its projected nominal lifetime

- The 0.4g limit in building codes should be reconsidered now that extensive strong motion records from moderate earthquakes indicate much higher values and extensive damage to code designed buildings correlate with them

Recommendations to lessen the impact of these conclusions are to:

- Consider deterministic seismic analyses as well as probabilistic analyses in the development of seismic design criteria

- Use elastic designs without reductions for inelastic behavior because designs using such reductions are potentially sensitive to multiple events or larger longer-duration events than anticipated

There is evidence that elastic designs are not greatly more expensive than inelastic designs, and may well provide large long-term savings in life cycle costs.

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10/17

REFERENCES

Abrahamson, N.A., and P.G. Somerville. 1996. Effects of hanging wall and footwall ground motions recorded during the Northridge earthquake. *Bulletin of the Seismological Society of America* 86-1B: S93–S99.

Algermissen, S.T., and D.M.Perkins. 1976. *A Probabilistic Estimate of Maximum Acceleration in Rock in the Contiguous United States*, U.S. Geological Survey Open-File Report 76-416. Washington DC: Department of Interior.

Algermissen, S.T., D.M. Perkins, P.C. Thenhaus, S.L. Hanson, and B.L. Bender. 1982. *Probabilistic Estimates of Maximum Acceleration and Velocity in Rock in the Conterminous United States*, U.S. Geological Survey Open File Report 82-103. Washington DC: Department of the Interior.

Bell, J.W. 1994. Temporal clustering of paleoearthquakes, in *Evaluation of the Geologic Relations and Seismotectonic Stability of the Yucca Mountain Area Nevada Nuclear Waste Site Investigation (NNWSI), Center for Neotectonic Studies* Progress Report to the Nevada Nuclear Waste Project Office of the Department of Energy. Reno NV: Mackay School of Mines, University of Nevada, Reno.

Bernreuter, D.L., J.B. Savy, R.W. Mensing, and D.H. Chung. 1984. *Seismic Hazard Characterization of the Eastern United States: Methodology and Interim Results for Ten Sites*, NUREG/CR-3756. Washington DC: Nuclear Regulatory Commission.

Bertero, V.V. 1991. Structural engineering aspects seismic zonation. *Proceedings of the Fourth International Conference on Seismic Zonation*, August 25-29, Stanford University, 1: 261–321. Oakland, CA: Earthquake Engineering Research Institute.

Brune, J.N. 1970. Tectonic stress and the spectra of seismic shear waves. *Journal of Geophysical Research* 75B: 4,997–5,009.

Chang, S.W., J.D. Bray, and R.B. Seed. 1996. Engineering implications of ground motions from the Northridge earthquake. *Bulletin of the Seismological Society of America* 86: S270–S287.

Cornell, C.A. 1968. Engineering seismic risk analysis. *Bulletin of the Seismological Society of America* 58: 1,583–1,606.

Davidson, F.C. Jr., and C.H. Scholz. 1985. Frequency-moment distribution of earthquakes in the Aleutian arc: A test of the characteristic earthquake model. *Bulletin of the Seismological Society of America* 75: 1,349–1,361.

De Pineres, O.G. 1995. A safer earthquake design code after Northridge. *Civil Engineering* 6: 72–73.

Ferrill, D.A., G.L. Stirewalt, D.B. Henderson, J.A. Stamatakos, A.P. Morris, B.P. Wernicke and K.H. Spivey. 1995. *Faulting in the Yucca Mountain Region: Critical Review and Analysis of Tectonic Data from the Central Basin and Range*. CNWRA Report 95-017. San Antonio, TX: Center for Nuclear Waste Regulatory Analyses.

Ferrill, D.A., J.A. Stamatakos, S.M. Jones, B. Rahe, H.L. McKague, R.H. Martin, and A.P. Morris. 1996. Quaternary slip history of the Bare Mountain fault (Nevada) from morphology and distribution of alluvial deposits. *Geology* (in press).

Fumal, T.E., S.K. Pezzopane, R.H. Weldon II, and D.P. Schwartz. 1993. A 100-year average recurrence interval for the San Andreas fault at Wrightwood, California. *Science* 259: 199–203.

Goes, S.D. 1996. Irregular recurrence of large earthquakes: An analysis of historic and paleoseismic catalogs. *Journal of Geophysical Research*, 101B: 5,739–5,749.

Grant, L.B., and K. Seih. 1994. Paleoseismic evidence of clustered earthquakes on the San Andreas fault in the Carrizo Plain, California. *Journal of Geophysical Research* 99B: 6,919–6,841.

Gutenberg, B., and C.F. Richter. 1954. *Seismicity of the Earth and Associated Phenomena*. Princeton, NJ: Princeton University Press.

Gutenberg, B., and C.F. Richter. 1956. Earthquake magnitude, intensity, energy and acceleration. *Bulletin of the Seismological Society of America* 32:163.

Hall, J.F., T.H. Heaton, M.W. Halling, and D.J. Wald. 1995. Near-Source Ground Motion and its effects on flexible buildings. *Earthquake Spectra* 11: 569–605.

Hofmann, R.B., and A.K. Ibrahim. 1995. Background zones for long term PSHA at Yucca Mountain. *Proceedings of FOCUS '95 Methods of Seismic Hazards Evaluation*, Sept 19, Las Vegas, NV. 81–85.

Hofmann, R.B. 1996. Opinion paper: Individual faults can't have a Gutenberg-Richter Recurrence. *Engineering Geology*, (in press).

Holmes, W.T., and H. Krawinkler. 1994. Chapter 4 - Buildings, in *Northridge Earthquake of January 17,1994 - Preliminary Reconnaissance Report*, J.F. Hall editor. EERI Publication 94-01. Oakland, CA: Earthquake Engineering Research Institute.

ICBO. 1990. *Uniform Building code*. Whittier, CA:International Conference of Building Officials.

Jackson, D.D., and Y.Y. Kagan. 1995. Implications of characteristic earthquakes (Abstract S32A-4). *EOS* 76:S199, April 24 Supplement.

Kagan, Y.Y. 1993. Statistics of characteristic earthquakes. *Bulletin of the Seismological Society of America* 83:7–24.

Kotra, J., M.P. Lee, N.A. Eisenberg, and A.R. DeWispelare. 1996. *Branch Technical Position on the Use of Expert Elicitation in the High-Level Radioactive Waste Program*, NUREG Public Comment Draft. In Federal Register, February 28, 1996, Vol. 64, No. 41, Page 7,568.

Lee, W.H., and D.R. Brillinger. 1979. On Chinese earthquake history - An attempt to model an incomplete data set by point process analysis. *Pure and Applied Geophysics* 117: 1,229–1,257.

12|17

Maley, R.P., and W.K. Cloud. 1971. Strong motion accelerograph records, in *Strong Motion Instrumental Data on the San Fernando earthquake of February 9, 1971*, D.E. Hudson, ed. California Institute of Technology and U.S. Coast and Geodetic Survey publication.

McGuire, R.K. 1976. EQRISK: *Evaluation of Earthquake Risk to Site, FORTRAN Computer Program for Seismic Risk Analysis*, U.S. Geological Survey Open File Report 76-67. Washington DC: Department of the Interior.

McGuire, R.K. 1978. *FRISK-Computer Program for Seismic Risk Analysis Using Faults as Earthquake Sources*, U.S. Geological Survey Open File Report 78-1007. Washington D.C.: Department of the Interior.

Main, I.G. 1995. Earthquakes as critical phenomena: Implications for probabilistic seismic hazard analysis. *Bulletin of the Seismological Society of America* 85: 1,299–1,308.

Milne, W.G., and A.G. Davenport. 1969. Distribution of Earthquake risk in Canada. *Bulletin of the Seismological Society of America* 59: 729–754.

Nelson, R., R.E. Bachman, and T.A. Sabol. 1995. Design code 'opinions'. *Civil Engineering* 11:26.

Rankin, D.W., editor. 1977. *Studies Related to the Charleston Earthquake of 1886 - A Preliminary Report.* U.S. Geological Survey Open File Report 1028. Washington DC: Department of the Interior.

Reheis, M.C. 1994. Holocene faulting along the central Fish Lake Valley fault zone, California and Nevada (Abstract). *Abstracts with Programs 90th Cordilleran Section of the Geological Society of America Meeting*, March 21-23, San Bernardino, California. Boulder, CO: Geological Society of America.

Reiter, L. 1990. *Earthquake Hazard Analysis, Issues and Insights.* New York, NY: Columbia University Press.

Reiter, L. 1995. Combining probabilistic and deterministic seismic hazard analysis. *Proceedings of FOCUS 95, Methods of Seismic Hazards Evaluation*, September 18-20, 1995, Las Vegas, NV. LaGrange Park, IL: American Nuclear Society.

Schwartz, D.P., and K.J. Coppersmith. 1984. Fault behavior and characteristic earthquakes: examples from the Wasatch and San Andreas faults. *Journal of Geophysical Research*, 89: 5,681–5,698.

Seih, K.E., M. Stuiver, and D.R. Brillinger. 1989. A more precise chronology of earthquakes produced by the San Andreas fault in Southern California. *Journal of Geophysical Research* 94: 603–623.

SEOC. 1990. *Recommended Lateral Force Requirements and Commentary.* Sacramento, CA: Seismology Committee, Structural Engineers Association of California.

Smalley, R.F. Jr., J.-L. Chatelain, D.L. Turcott, and R. Prévot. 1987. A fractal approach to the clustering of earthquakes: Applications to the seismicity of the New Hebrides. *Bulletin of the Seismological Society of America* 77: 1,368-1,381.

Smith, R., and W. Arabasz. 1991. Seismicity of the intermountain seismic belt, in D.B. Slemmons, E.R. Engdahl, M.D. Zoback, and D.D. Blackwell, ed. *Neotectonics of North America*. Boulder, CO: Geological Society of America.

Stamatakos, J.A., D.A. Ferrill, K.H. Spivey, A.P. Morris, R.A. Donelick, and R.A. Ketchum. 1996. New constraints on Neogene exhumation of Bare Mountain, Nevada from apatite fission-track thermochronometry. *Tectonics* (in review).

Stover, C.W., and J.L. Coffman. 1993. *Seismicity of the United States, 1568-1989 (Revised)*. U.S. Geological Survey Professional Paper 1527. Washington DC: Department of the Interior.

TERA Corporation. 1978. *Bayesian Seismic Hazard Analysis, A Methodology*. TERA report to Lawrence Livermore National Laboratory. Berkeley, CA: TERA Corporation.

Toro, G.R., R.K. McGuire, and W.J. Silva. 1988. *Engineering Model of Earthquake Ground Motion for Eastern North America*. EPRI Report NP-6074. Palo Alto, CA: Electric Power Research Institute.

Turcott, D.L. 1992. *Fractals and Chaos in Geology and Geophysics*. London, U.K.: Cambridge University Press.

Weichert, D.H. 1986. Vertical acceleration exceeding 2 g? The case of the missing peak. *Bulletin of the Seismological Society of America* 76: 1,473-1,478.

Wells, D.L., and K.J. Coppersmith. 1994. Updated empirical relationships among magnitude, rupture length, rupture area, and surface displacement. *Bulletin of the Seismological Society of America*, 84: 974-1,002.

Wesnowsky, S.G. 1994. The Gutenberg-Richter or characteristic earthquake distribution, which is it? *Bulletin of the Seismological Society of America* 84: 1,940-1,959.

Wesnowsky, S.G., C.H. Scholz, and K. Shimazaki. 1982. Deformation of an island arc: Rates of moment release and crustal shortening in intraplate Japan determined from seismicity and Quaternary fault data. *Journal of Geophysical Research* 87: 6,829-6852.

Wyss, M. 1979. Estimating maximum expectable magnitude of earthquakes from fault dimensions. *Geology* 7: 336-340.

Xiwei, X., and D. Quidong. 1996. Nonlinear characteristics of paleoseismicity in China. *Journal of Geophysical Research*, B101: 6,209-6,231.

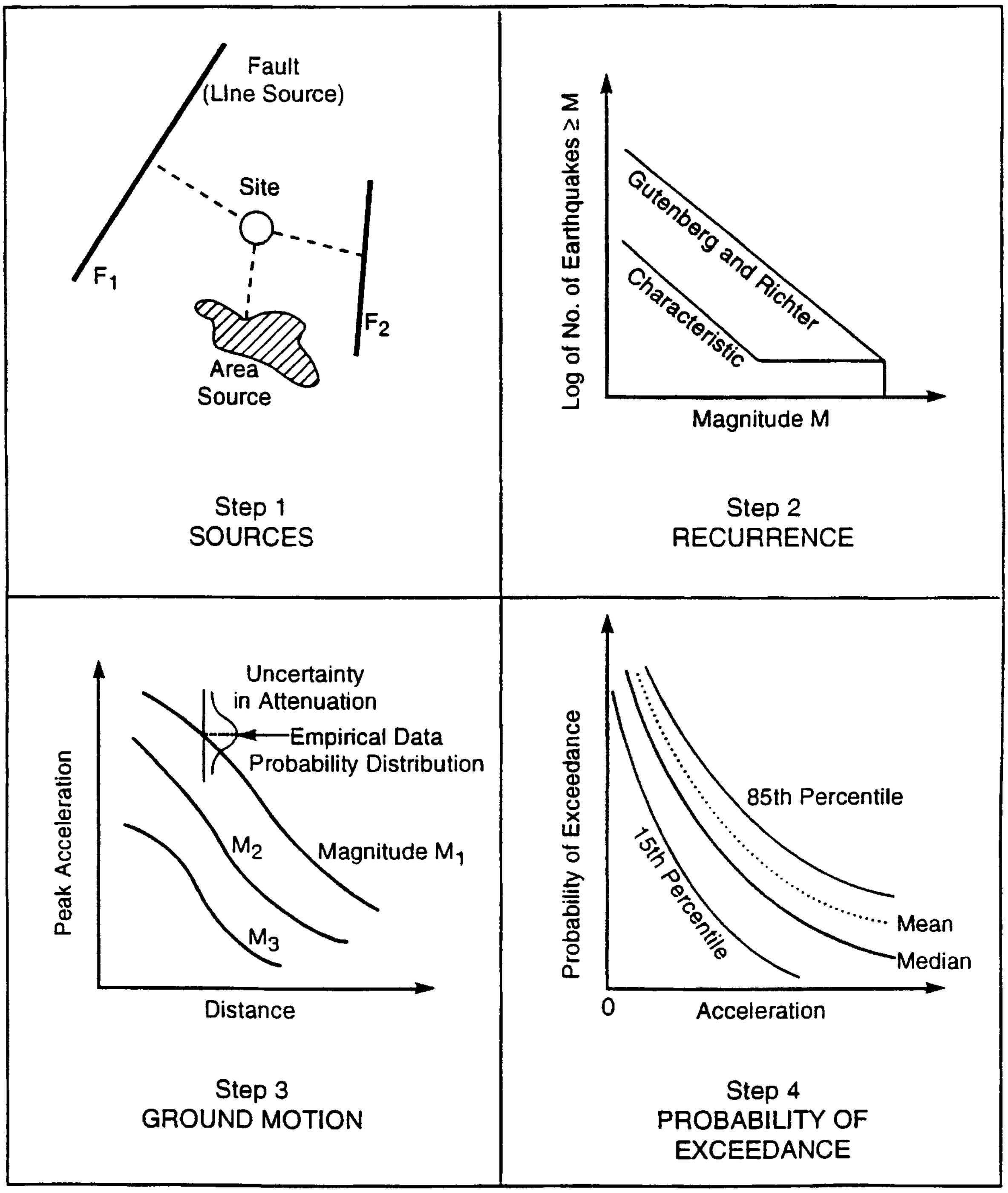
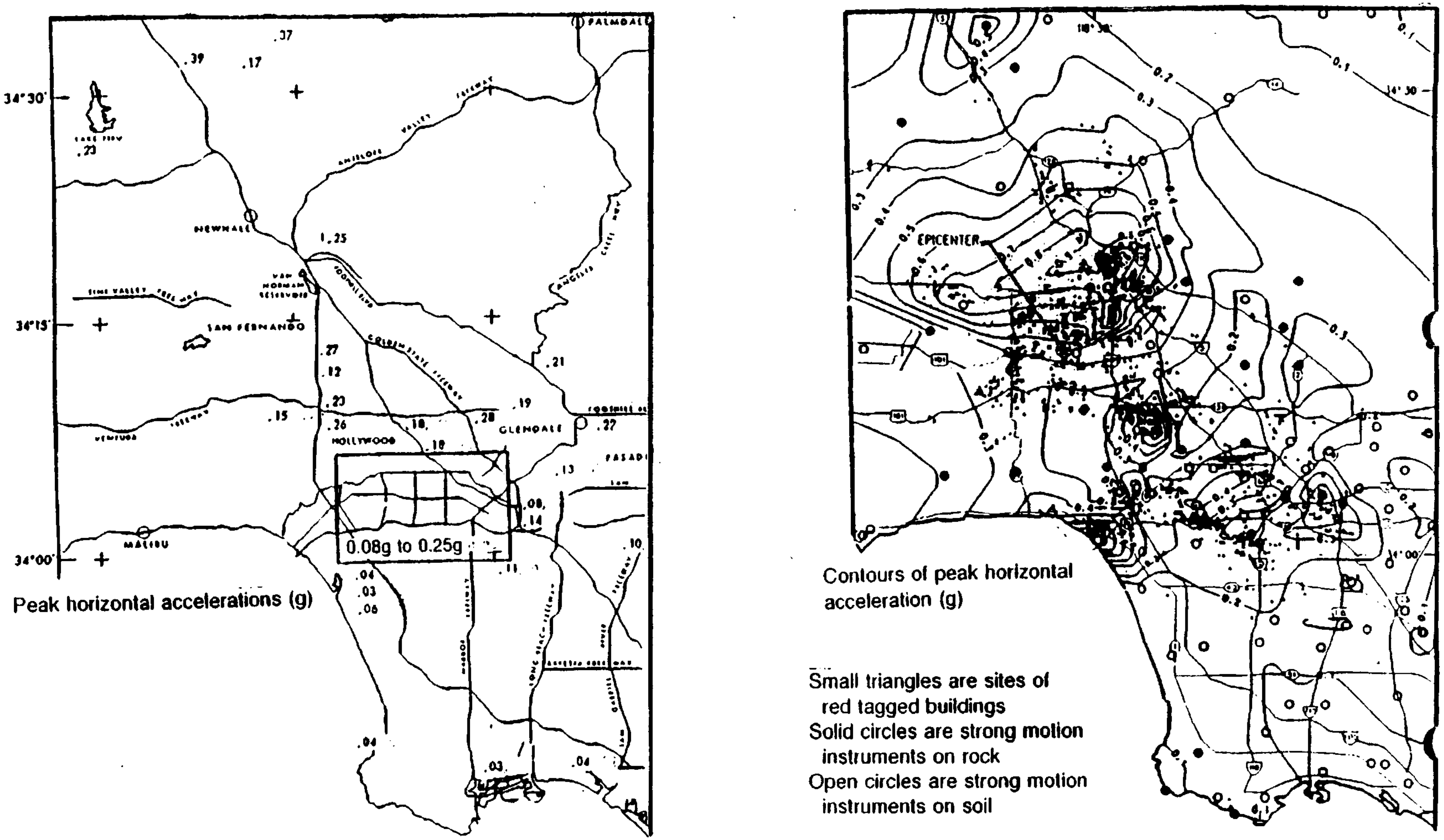


Figure 1. Elements of PSHA [after TERA Corporation (1978) and Reiter (1991)]



Peak horizontal accelerations (g)

Contours of peak horizontal acceleration (g)

Small triangles are sites of red tagged buildings
Solid circles are strong motion instruments on rock
Open circles are strong motion instruments on soil

After Maley and Cloud (1971)

After Chang et al. (1996)

Figure 2. Peak Horizontal Accelerations for the Los Angeles Area 1971 and 1994 M=6.7 California Earthquakes

16/17

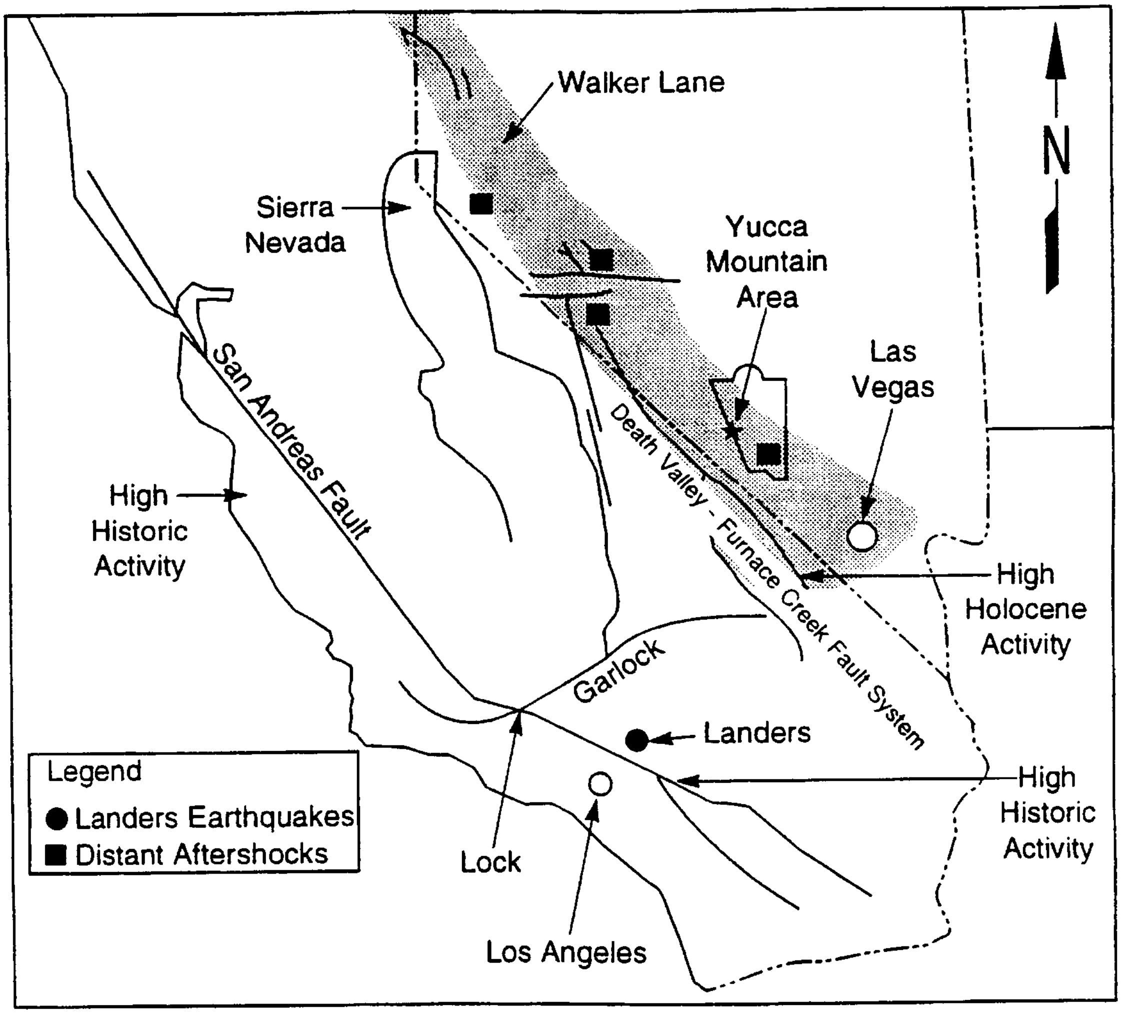


Figure 3. Sketch Map of California-Eastern Nevada Faults

Table 1. Intervals of Age Dated Offsets on the San Andreas Fault, California.

	Event	Year	
Pallet Creek	C	677	Seih et al. (1989) 5 (2 events in 120y) over 1,180 y. .0042/y. Avg. interval = 111 years.
	D	734	
	F	797	
	I	947	
	N	1046	
	R	1100	
	T	1346	
	V	1480	
	X	1812	
	Z	1857	
Carizzo Plain	E	date? 1218 to 1247	Grant & Seih (1994) 2 (2 events in120y) over 639 .0031/y. Avg. Interval = 153 years.
	B	1346	
	C	1394	
	D	1480	
	A	1857	
Wright-wood		1470	Fumal et al.(1993) 2(2 eventsin 120y) over 387 y. .0052/y. Avg. Interval = 97 years.
		1610	
		1700	
		1812	
		1857	
			Avg. rate of 2 events in 120 y is .0041/y. Avg. of Intervals = 120 years