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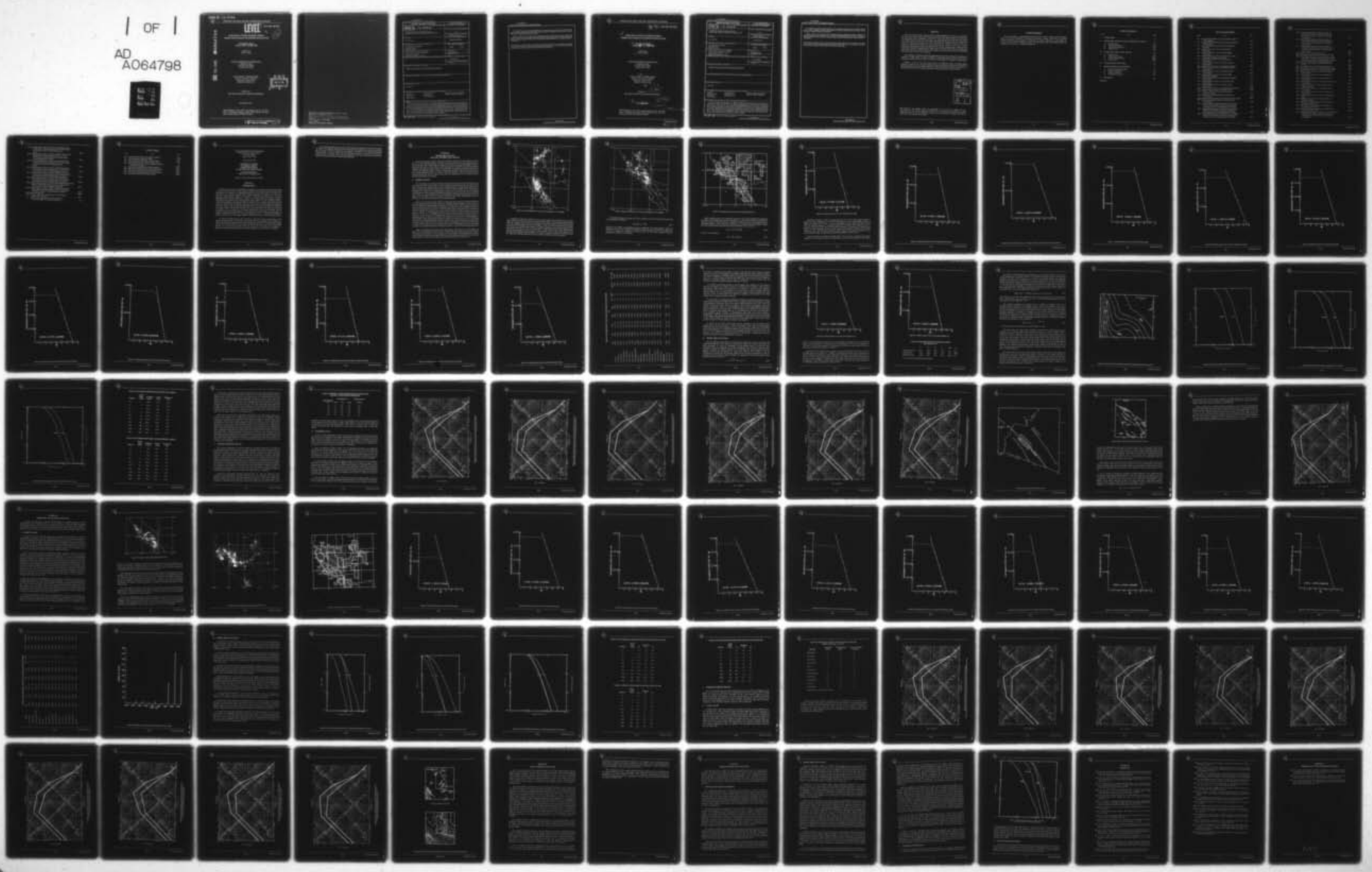

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GEOPHYSICAL STUDIES FOR MISSILE BASING: SEISMIC RISK STUDIES IN THE WESTERN UNITED STATES

Final Scientific Report
1 March 1978–31 October 1978

Prepared by
James C. Battis

TEXAS INSTRUMENTS INCORPORATED
Equipment Group
Post Office Box 226015
Dallas, Texas 75266

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20 December 1978

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SECTION I

INTRODUCTION

For the past 3 years, Texas Instruments Incorporated has conducted research that attempts to evaluate the seismic risk at certain military facilities in the western United States. This work was initiated as a response to two significant geophysical events that occurred in 1975 and 1976. The first of these was the Pocatello Valley, Idaho, earthquake of 28 March 1975. This event produced ground motions which were sufficient to disturb instruments located at military installations near Cheyenne, Wyoming, a distance of 6 degrees from the earthquake epicenter. The second event was the report of a geologically sudden uplift of an area of southern California centered near Palmdale. This regional uplift was thought to be a possible premonitory indicator of seismic activity within the affected region and the occurrence of a large-magnitude earthquake within the uplifted zone constituted a significant risk to the operational status of Edwards Air Force Base, which is located near Palmdale. Thus, the initial studies were directed at evaluating the likelihood of a recurrence of the seismic disturbances at Cheyenne, Wyoming, and the estimation of ground motion parameters at Edwards Air Force Base caused by seismic activity in southern California. The tasks have since been expanded, however, to include the estimation of seismic risk at several of the military facilities which might be used in the MX missile program.

In previous scientific reports, the methods by which the seismic characteristics of the regions surrounding each site of interest are estimated and the techniques used to evaluate the seismic risk at a given location have been presented along with the results for several sites (Battis and Hill, 1977; Battis, 1978). For this report, the last two site studies, for Luke Air Force Base, Arizona, and the Nevada Test Site, have been carried out. In addition, the feasibility of generating a regionally independent ground motion attenuation equation has been examined.

In the following sections, the results of these studies are presented. In Sections II and III, the results of the regional seismicity studies and seismic risk evaluations for Luke Air Force Base and the Nevada Test Site, respectively, are presented. A discussion of the problems associated with generating a universal ground motion attenuation equation is presented in Section IV. Finally, Section V contains a brief review and summary of the results which have been obtained under the Geophysical Studies for Missile Basing Program.

SECTION II

SEISMIC RISK ANALYSIS FOR LUKE AIR FORCE BASE, ARIZONA

Interest in the seismic risk for Luke Air Force Base is derived from the possible use of this facility as an MX missile installation. The base is located in southwestern Arizona and lies mostly in the tectonically stable Sonoran Desert subregion of the Basin and Range Physiographic Province (Fenneman and Johnson, 1946). However, the closeness of the seismically active zones of southern California, especially the Salton Trough–Gulf of California Rift, suggests a significant hazard at this facility from earthquake activity. Using the methods and computer program that have previously been described (Battis and Hill, 1977; Battis, 1978; Hill and Battis, 1978), the necessary regional seismicity studies and the risk evaluation were made for southwestern Arizona. In this section, the results of these studies are presented.

A. SEISMICITY STUDY

It is the purpose of the regional seismicity study to identify the zones of seismic activity that could affect the level of seismic risk at a site of interest and to estimate the level of activity within each of these source regions. Based on the experience gained in evaluating the seismic risk at Cheyenne, Wyoming, and White Sands Proving Ground, New Mexico (Battis, 1978), both stable and reasonable risk curves can be generated for a given site with knowledge of the seismicity characteristics of a region within an 800-kilometer radius of the site of interest. Thus, as the initial step of this study, the National Oceanic and Atmospheric Administration Earthquake Data File (Meyers and Von Hake, 1976) was searched; all events located within 800 kilometers of Yuma, Arizona were entered into the data base for this seismicity study.

Because of the extremely large number of earthquakes with epicenters in southern California and data storage limitations associated with the seismicity analysis programs, it was necessary to edit the initial data set substantially. Examination of the data base revealed two facts which were used to develop the method by which the data base was edited. First, the majority of events in the catalogue had epicenters to the west of 115°W longitude. Second, using only events of magnitude 4.0 m_b or greater, it was possible to generate accurate estimates of seismic activity in the source regions to the west of 115°W longitude. Therefore, the data base has edited so that all events with epicenters to the east of 115°W longitude were used in the final data base but only events of magnitude 4.0 m_b or greater were passed if the epicenter lay to the west of 115°W longitude. A total of 4992 events remained in the data base, of which 1255 were from east of 115°W. In Figures II-1 and II-2, the reported epicenters of these events are plotted. The earthquakes used in this study occurred between 1852 and 1975, with the earliest event reported to the west of 115°W having occurred in 1916. Of the 1255 events located to the east of 115°W longitude, only 473 earthquakes had either an associated magnitude or intensity and could be used in the regional seismicity study.

Using this earthquake data base tectonic flux contour plots (Ryall, et al., 1966; Battis and Hill, 1977) were generated for the study area. Together with the epicenter plots shown in Figures II-1 and II-2, these maps were used to identify any concentrations or spatial alignments of seismic activity within the region under analysis. These zones were designated as seismic source regions and the boundaries of the set of source regions used in this study are shown in Figure II-3.

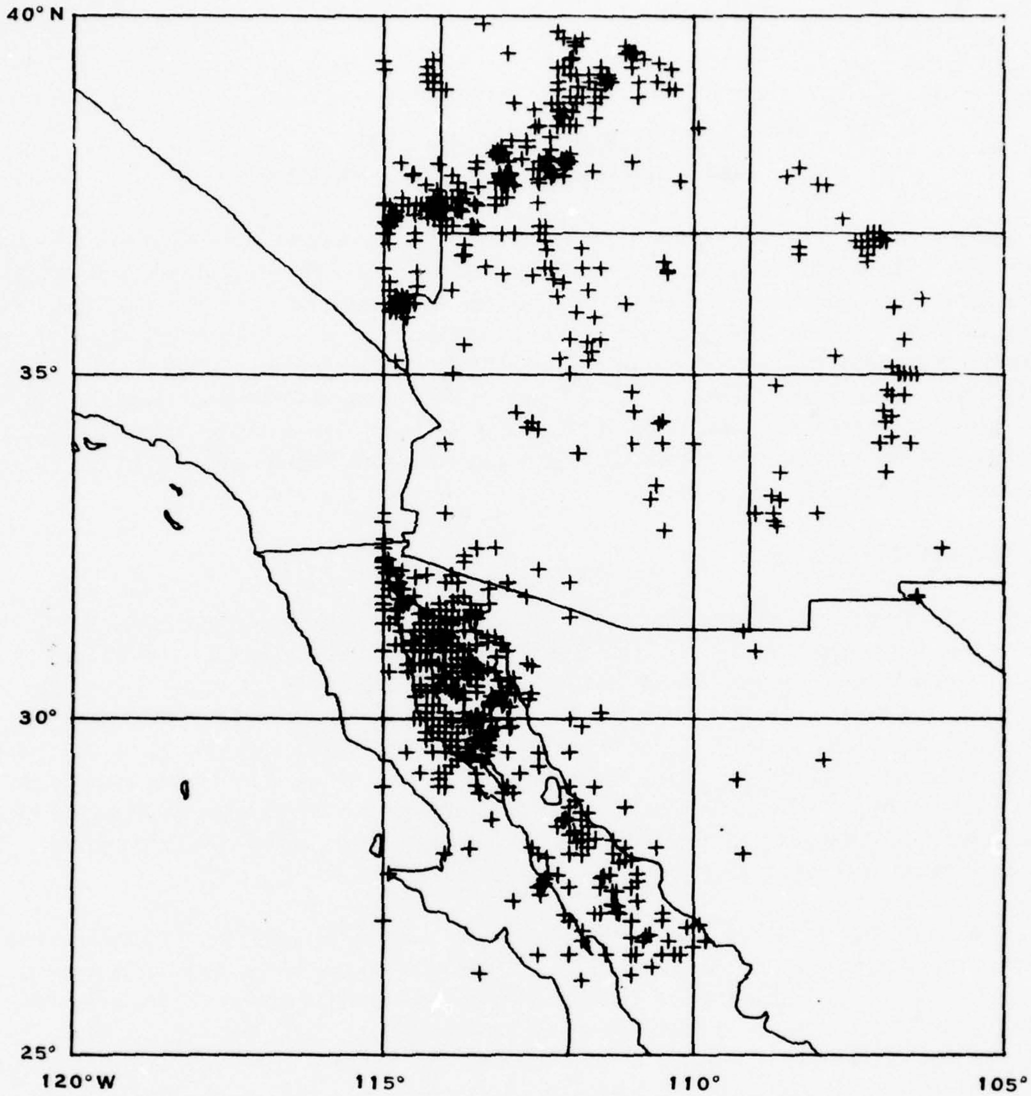

Figure II-1. Epicenters within 800 km of Luke Air Force Base and East of 115°W Longitude

It should be noted that, while some of the source regions bear identical names to source regions defined for previous studies, the exact boundaries might not be duplicated in each seismicity study. An example of this is the Gulf of California source region used in both this study and that conducted for White Sands Proving Ground (Battis, 1978). In the White Sands Proving Ground study, the Gulf of California source region encompassed a smaller area than does the present study. This resulted from the fact that the distance limit of 800 kilometers from White Sands Proving Ground passes through this source region, cutting a portion of the complete source region out of the White Sands Proving Ground evaluation. As would be expected, an alteration of this sort could also change any statistical estimates in the rate of seismic activity for such source regions.

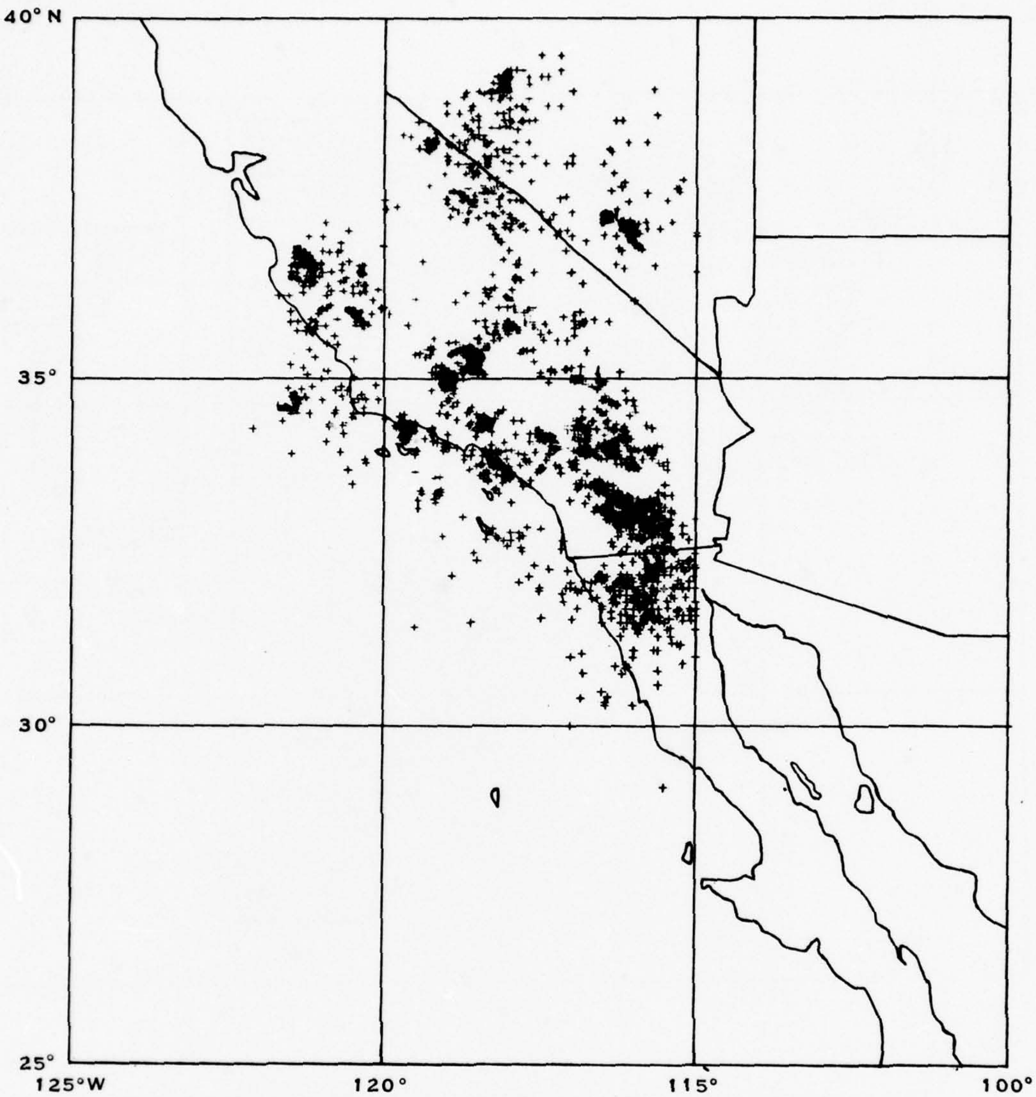

Figure II-2. Epicenters Within 800 km of Luke Air Force Base and West of 115°W Longitude

The standard measure of seismic activity for a seismic source is the recurrence function that can be defined by the relation:

$$\text{Log}_{10}(N) = A - bM \qquad \text{(II-1)}$$

where N is the number of earthquakes per year of magnitude M or larger (Richter, 1958). The parameters A and b are then obtained by fitting this curve to the data for a given source region. The value of N can also be normalized to some unit area. For this study, recurrence functions normalized to 1,000 km^2 are calculated.

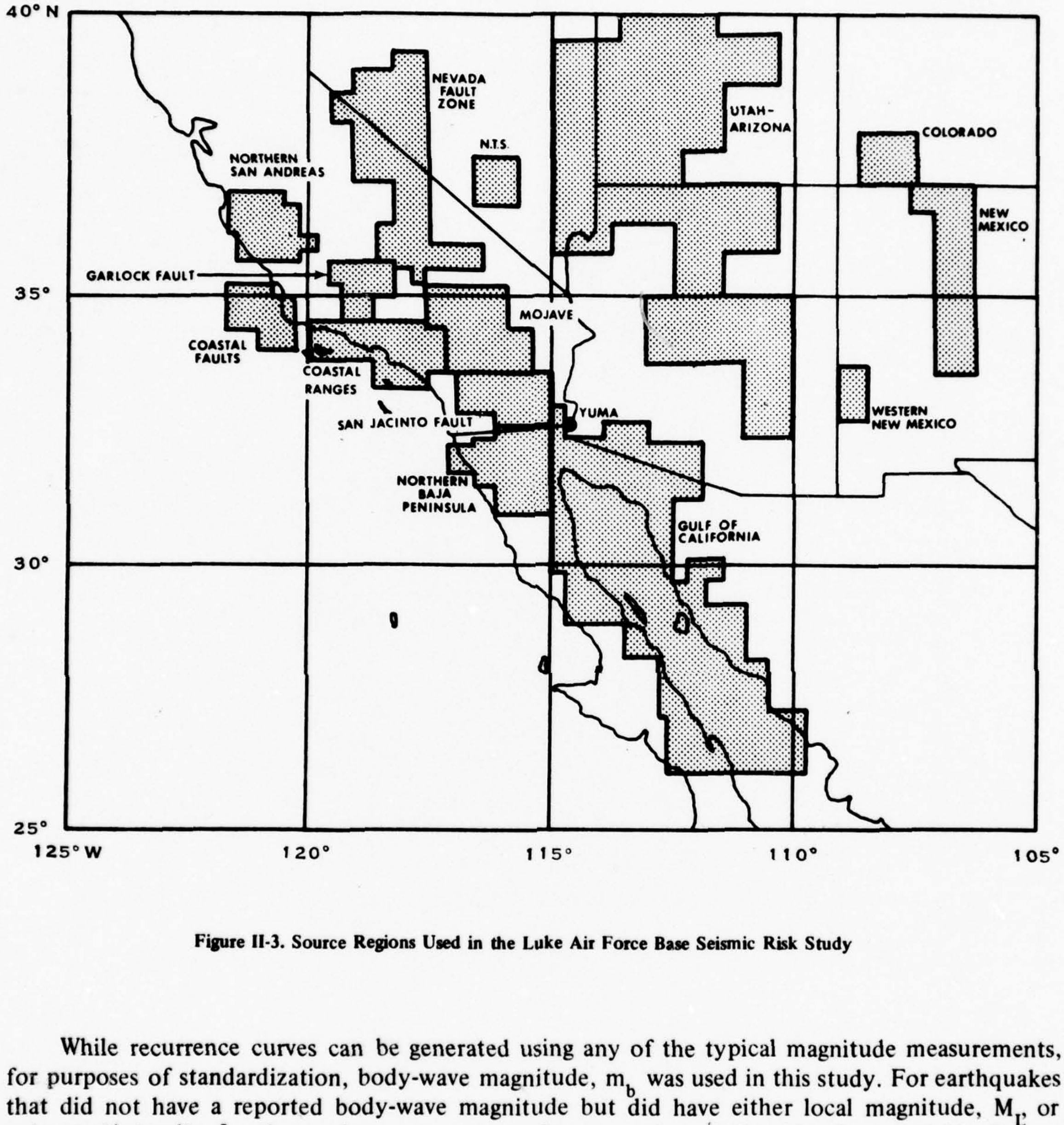

Figure II-3. Source Regions Used in the Luke Air Force Base Seismic Risk Study

While recurrence curves can be generated using any of the typical magnitude measurements, for purposes of standardization, body-wave magnitude, m_b was used in this study. For earthquakes that did not have a reported body-wave magnitude but did have either local magnitude, M_L, or epicentral intensity, I_o, these values were converted to m_b, using relationships formulated by Brazee (1976) for California and western Nevada. The transformation for M_L is given by:

$$m_b = 1.276 + 0.749\ M_L \qquad \text{(II-2)}$$

and for I_0 by the equation

$$m_b = 2.886 + 0.365\ I_0 \qquad \text{(II-3)}$$

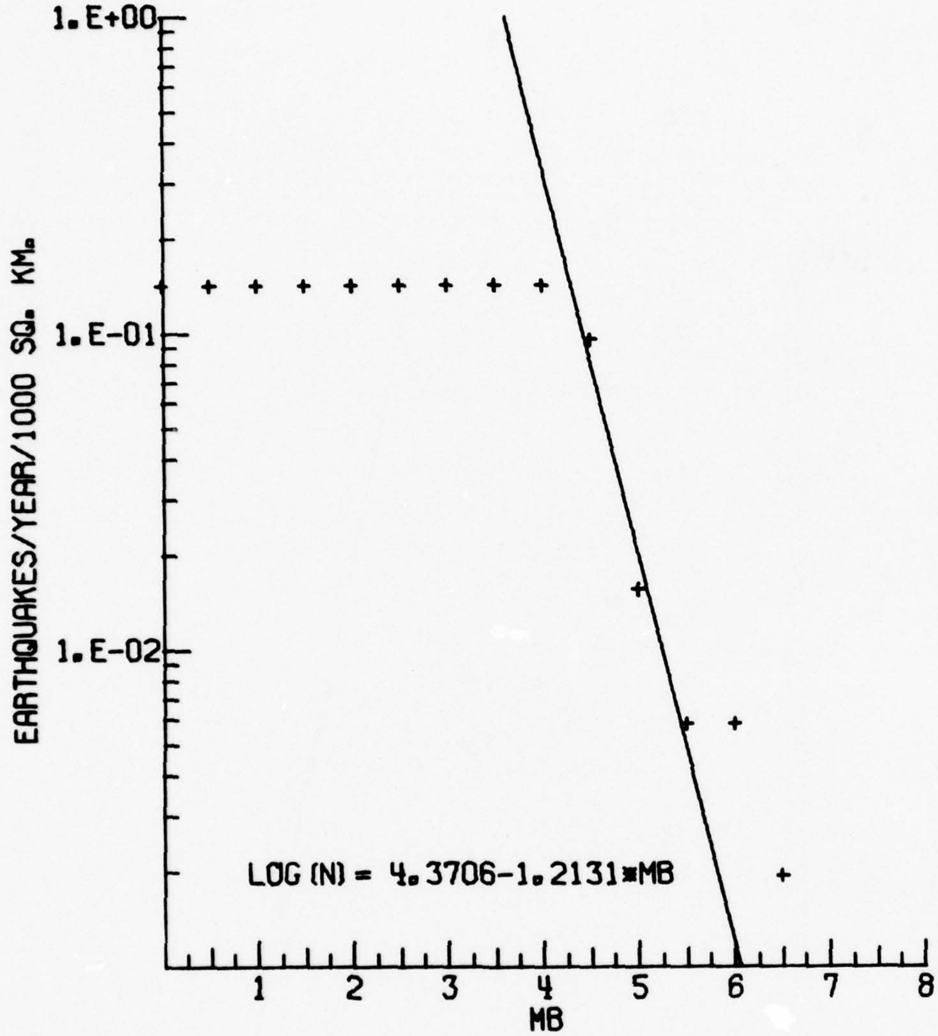

Figure II-4. Cumulative Recurrence Curve for the Coastal Faults Source Region

Cumulative recurrence curves were generated for each of the source regions derived in Figure II-3. These recurrence curves and the associated recurrence relationships are given in Figures II-4 through II-15. These recurrence relationships are also restated in Table II-1 along with the necessary parameter conversions required for the seismic risk evaluation process. It should be noted that, in the case of the Colorado, New Mexico, and western New Mexico source regions, the event catalogues of these source regions were combined to produce one common recurrence curve. This was done because the small number of earthquakes reported in each source region separately would result in statistically unreliable recurrence curves.

Stepp's method of completeness analysis (Stepp, 1972) was used to evaluate the temporal stability of rate of seismic activity, or completeness, for each of the designated source regions.

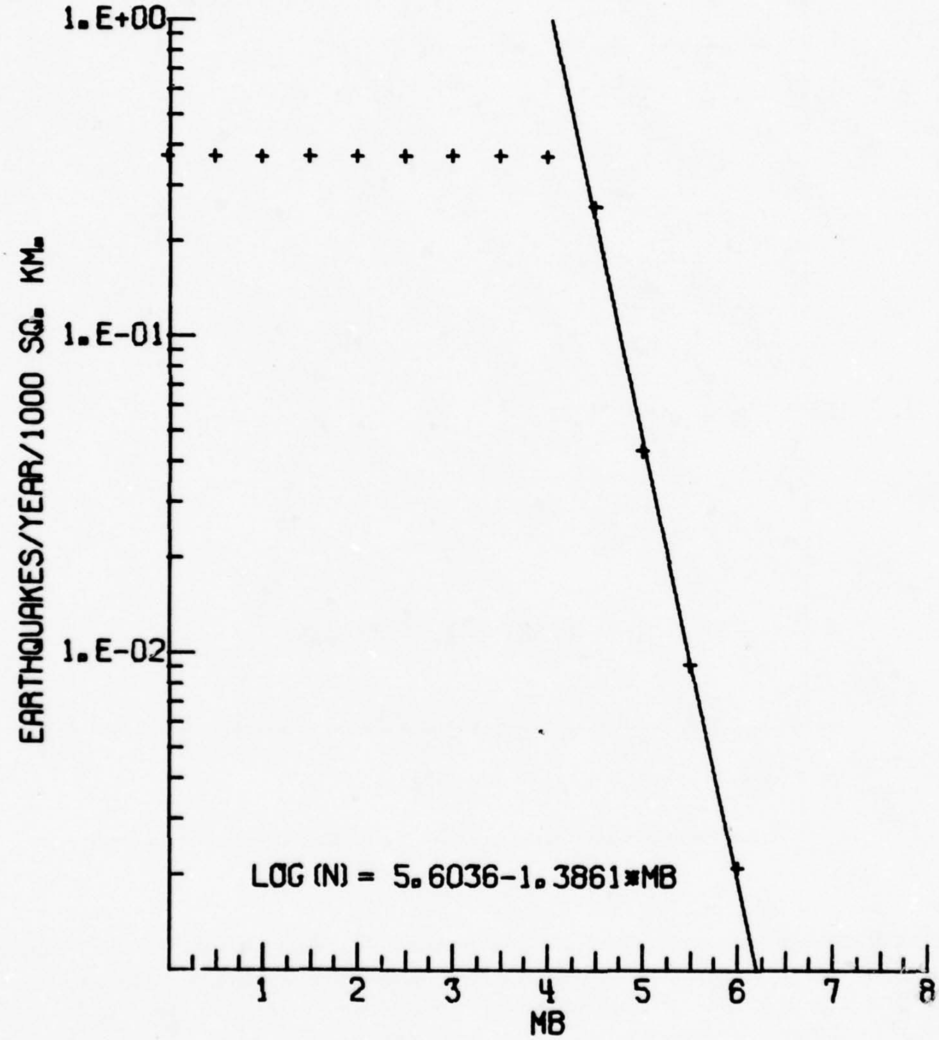

Figure II-5. Cumulative Recurrence Curve for the Coastal Ranges Source Region

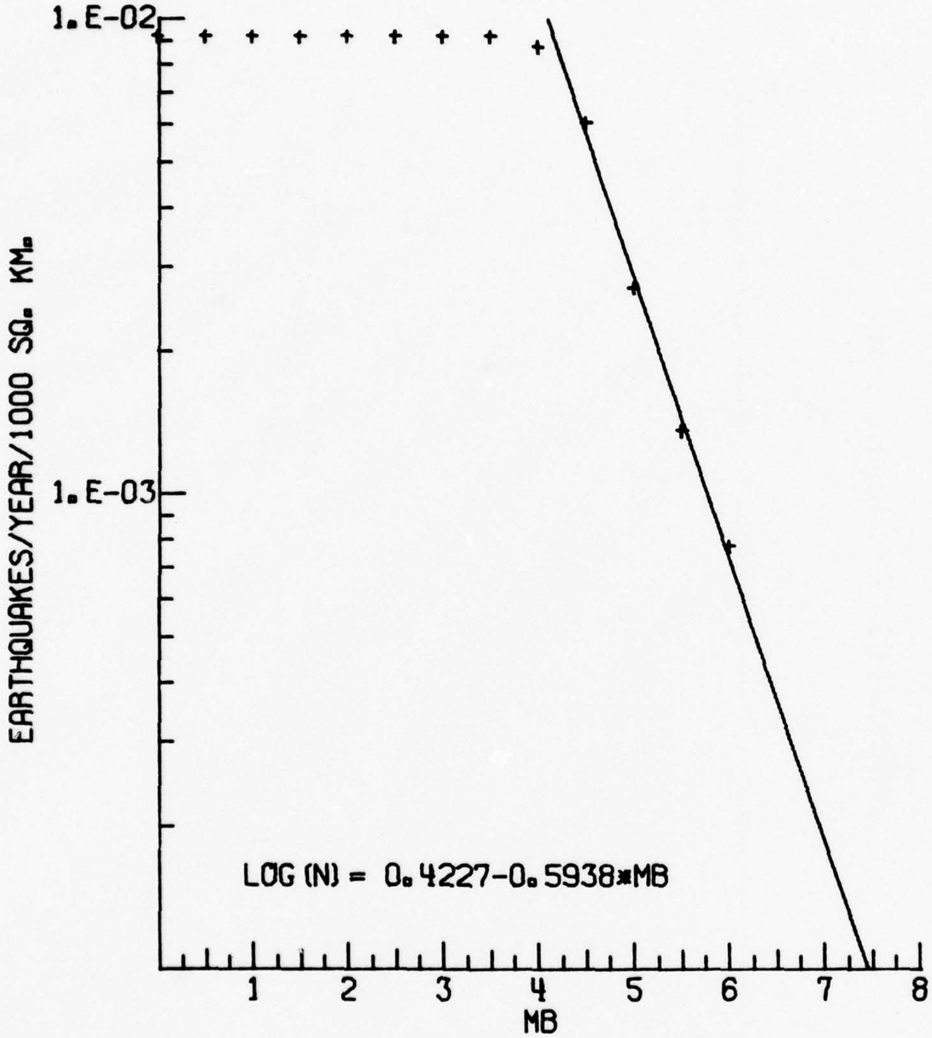

Figure II-6. Cumulative Recurrence Curve for the Colorado, New Mexico, and Western New Mexico Source Region

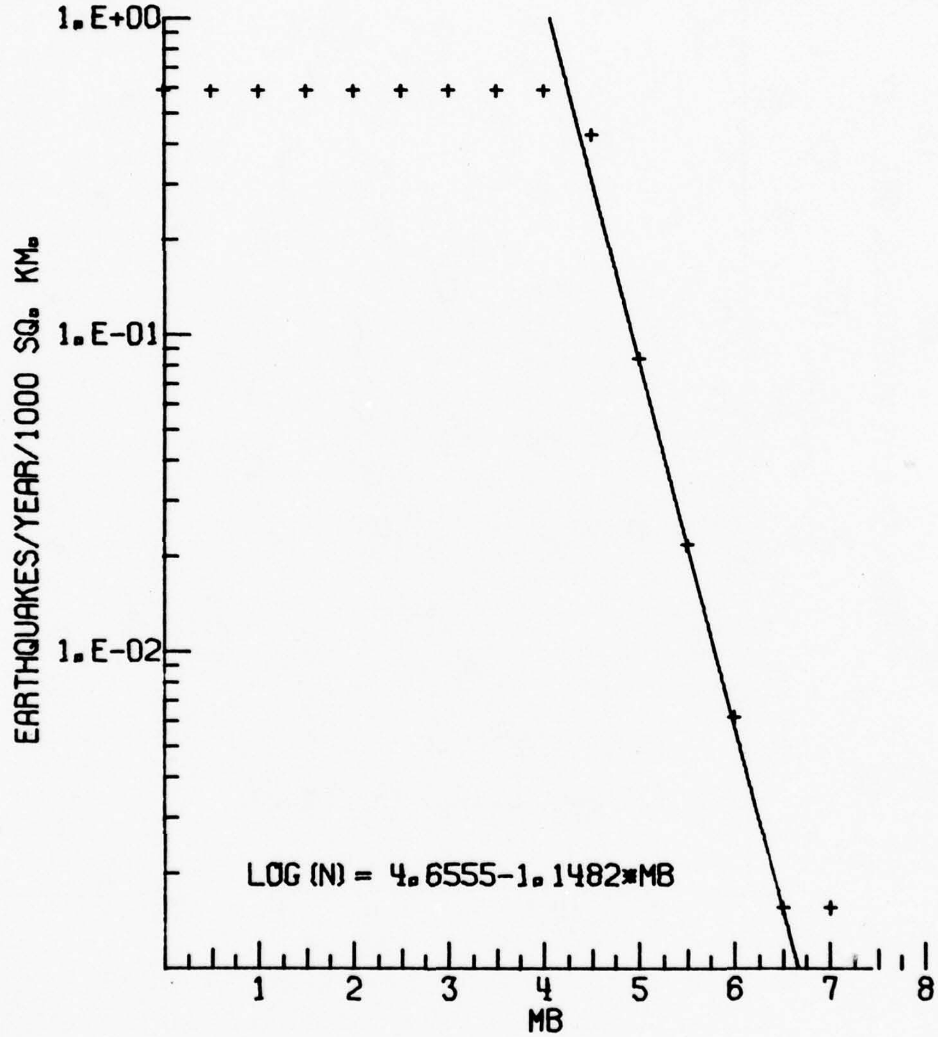

Figure II-7. Cumulative Recurrence Curve for the Garlock Fault Source Region

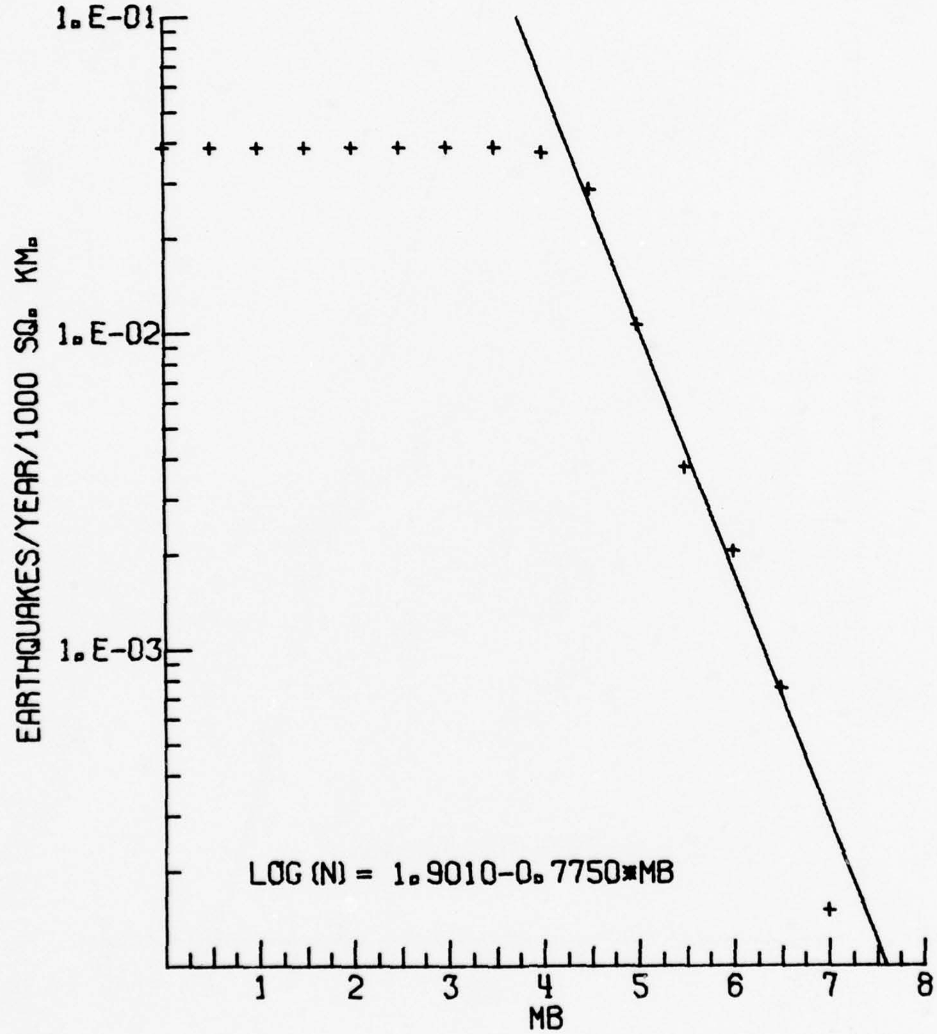

Figure II-8. Cumulative Recurrence Curve for the Gulf of California Source Region

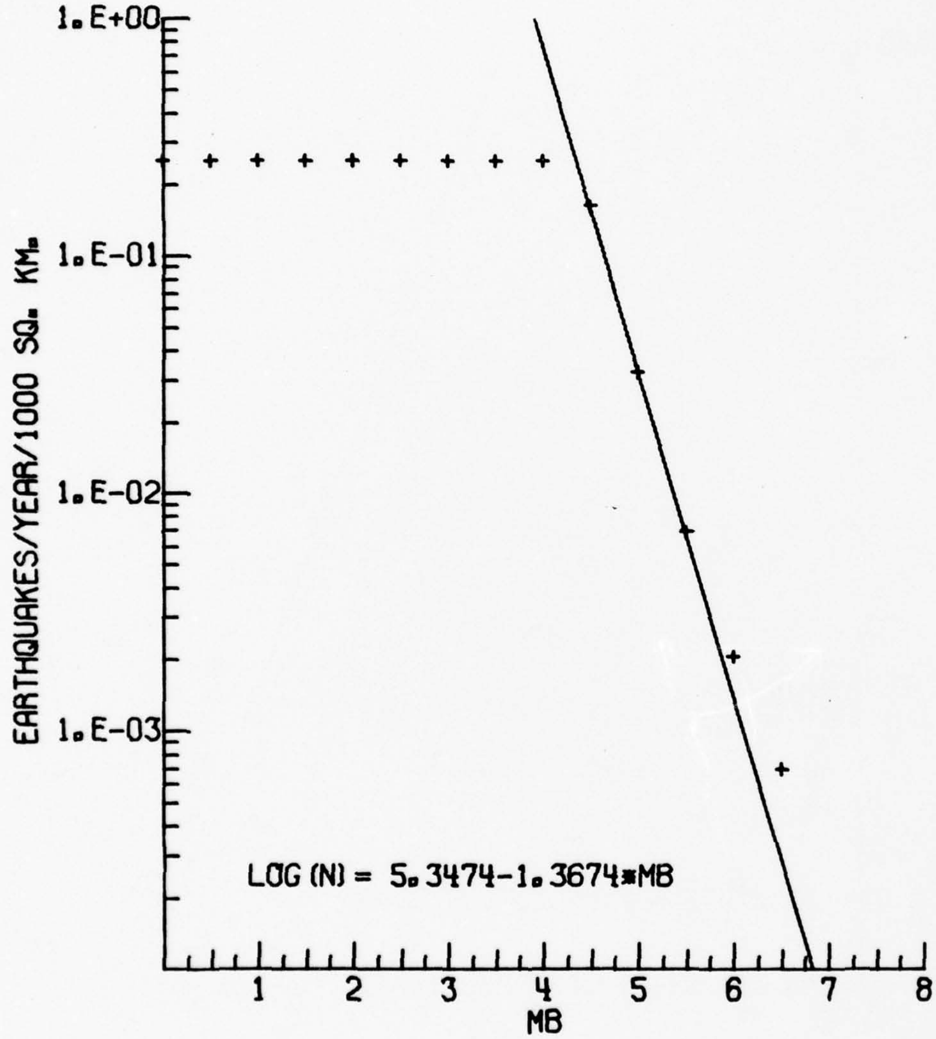

Figure II-9. Cumulative Recurrence Curve for the Mojave Source Region

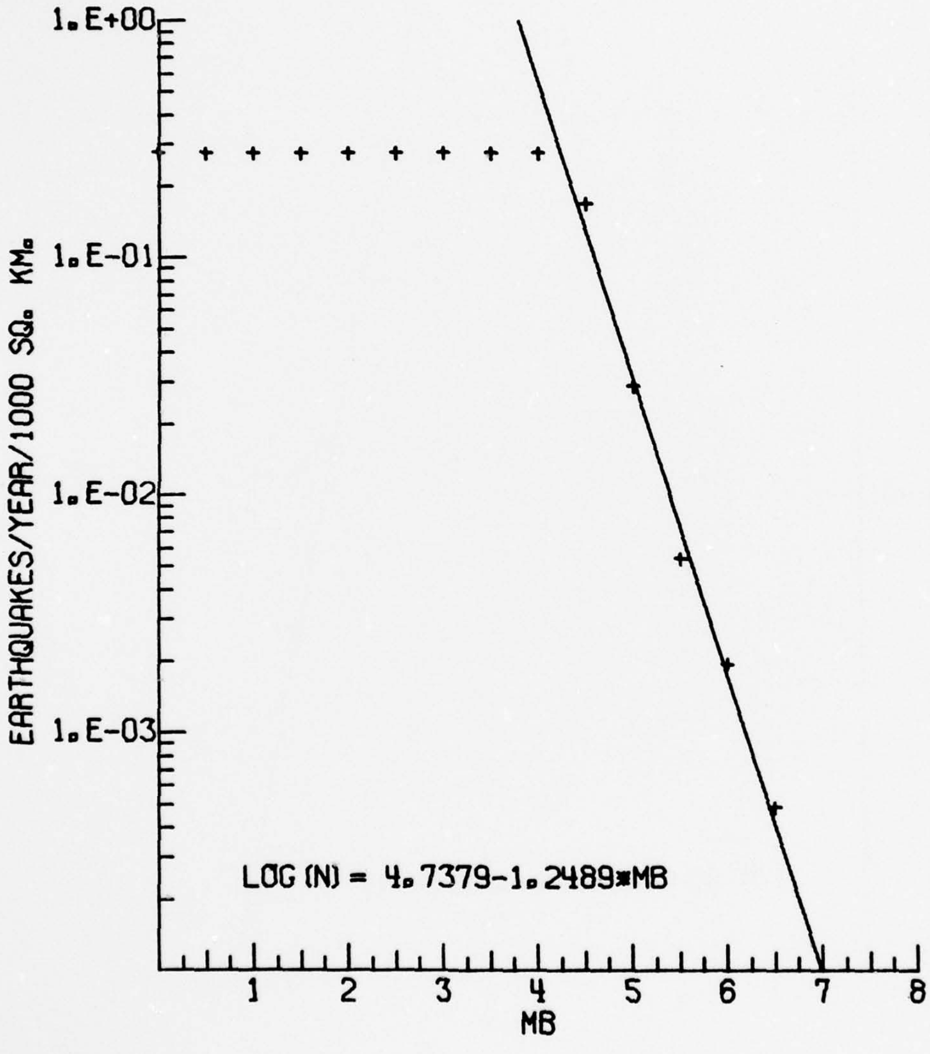

Figure II-10. Cumulative Recurrence Curve for the Nevada Fault Zone Source Region

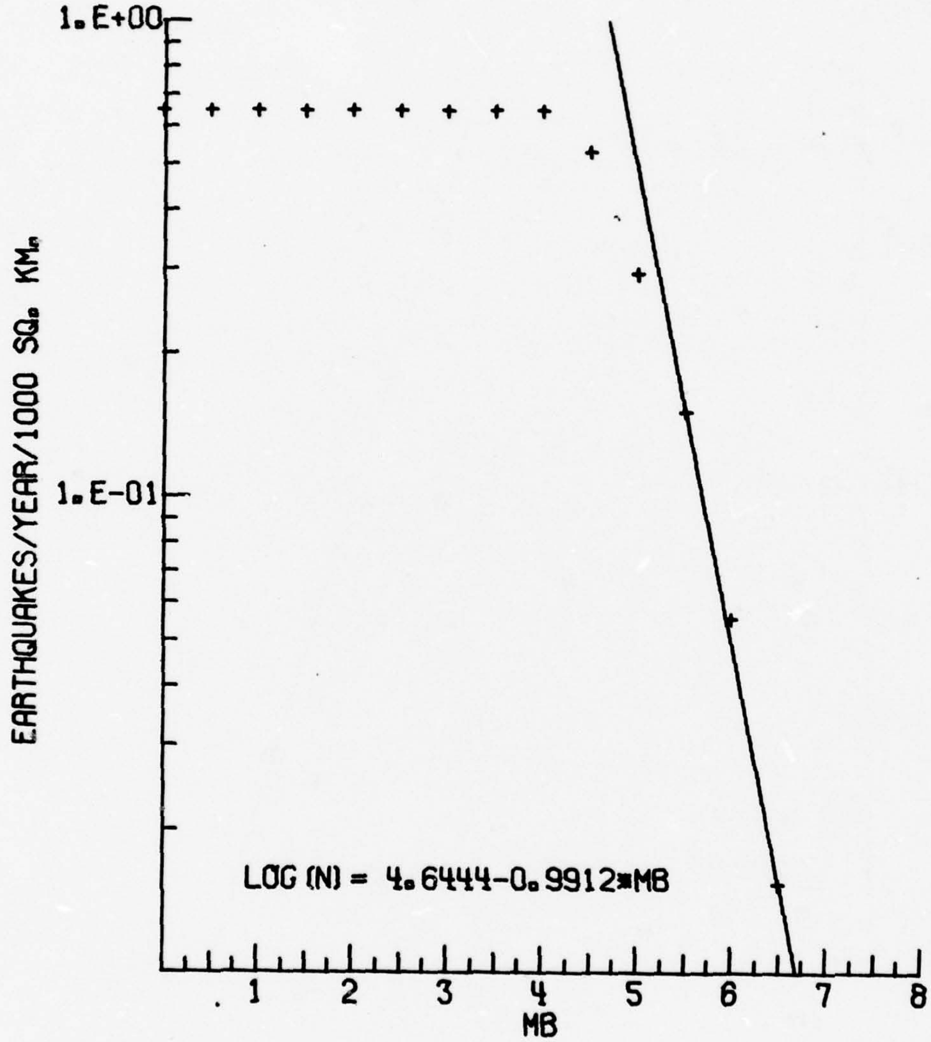

Figure II-11. Cumulative Recurrence Curve for the Nevada Test Site Source Region

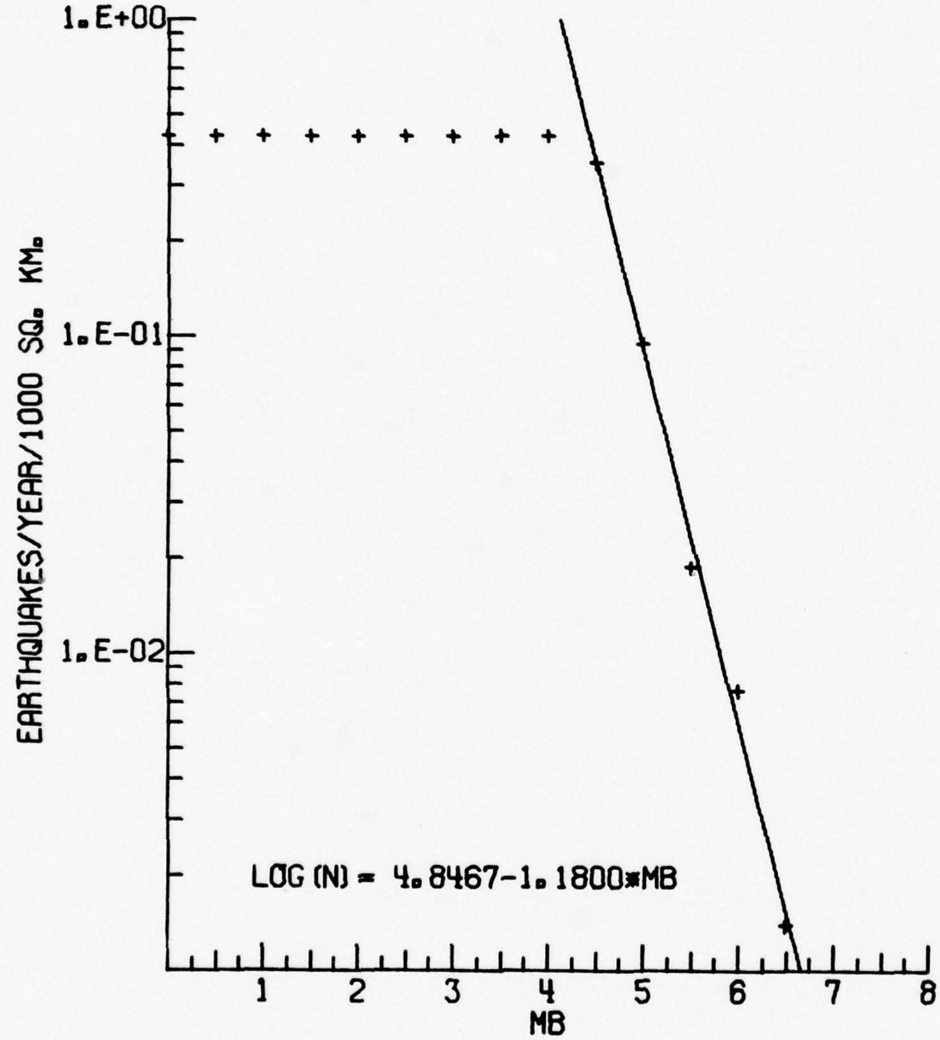

Figure II-12. Cumulative Recurrence Curve for the Northern Baja Peninsula Source Region

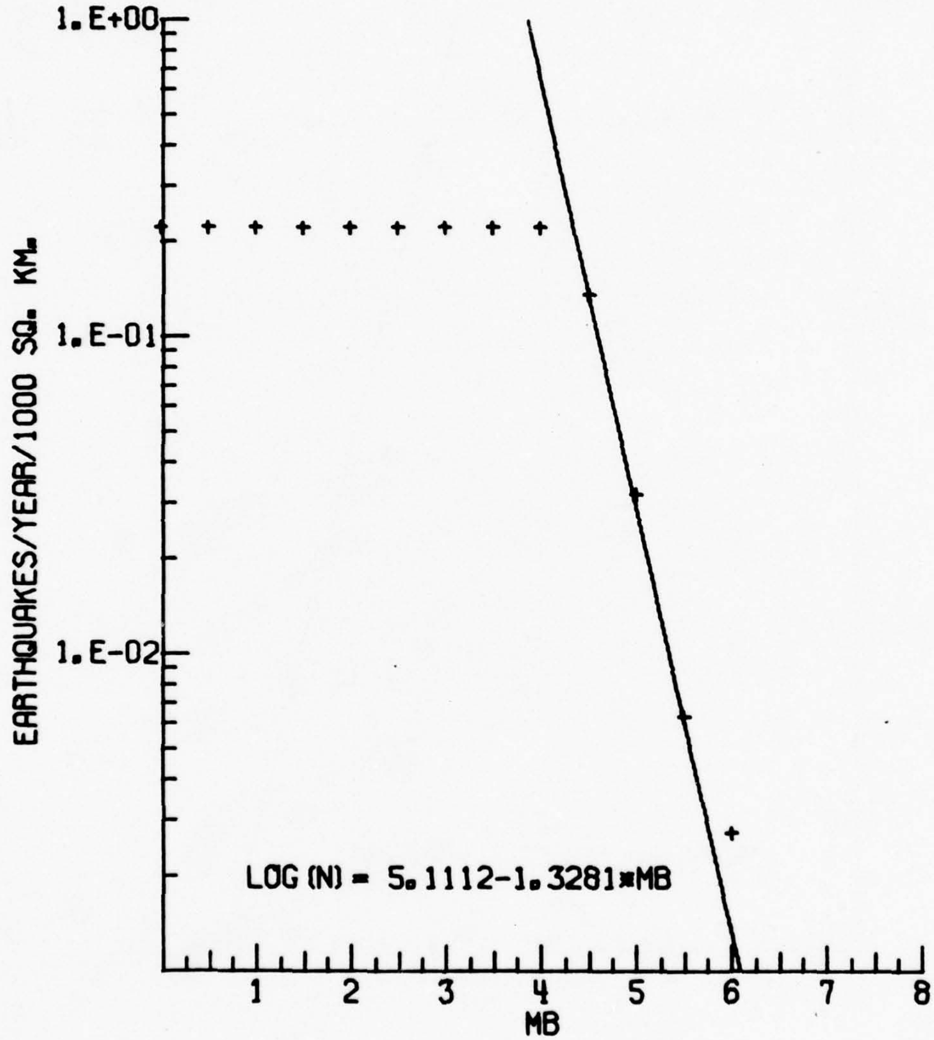

Figure II-13. Cumulative Recurrence Curve for the Northern San Andreas Source Region

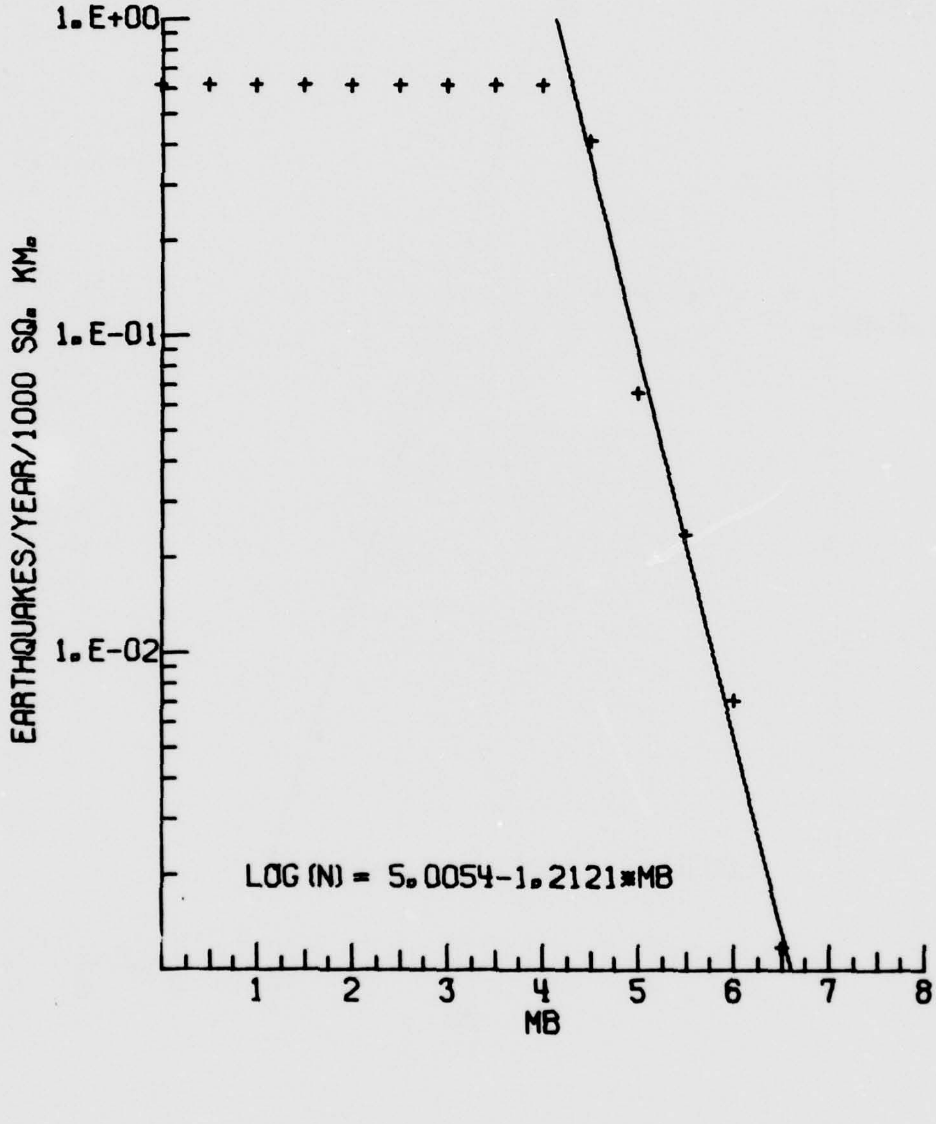

Figure II-14. Cumulative Recurrence Curve for the San Jacinto Fault Source Region

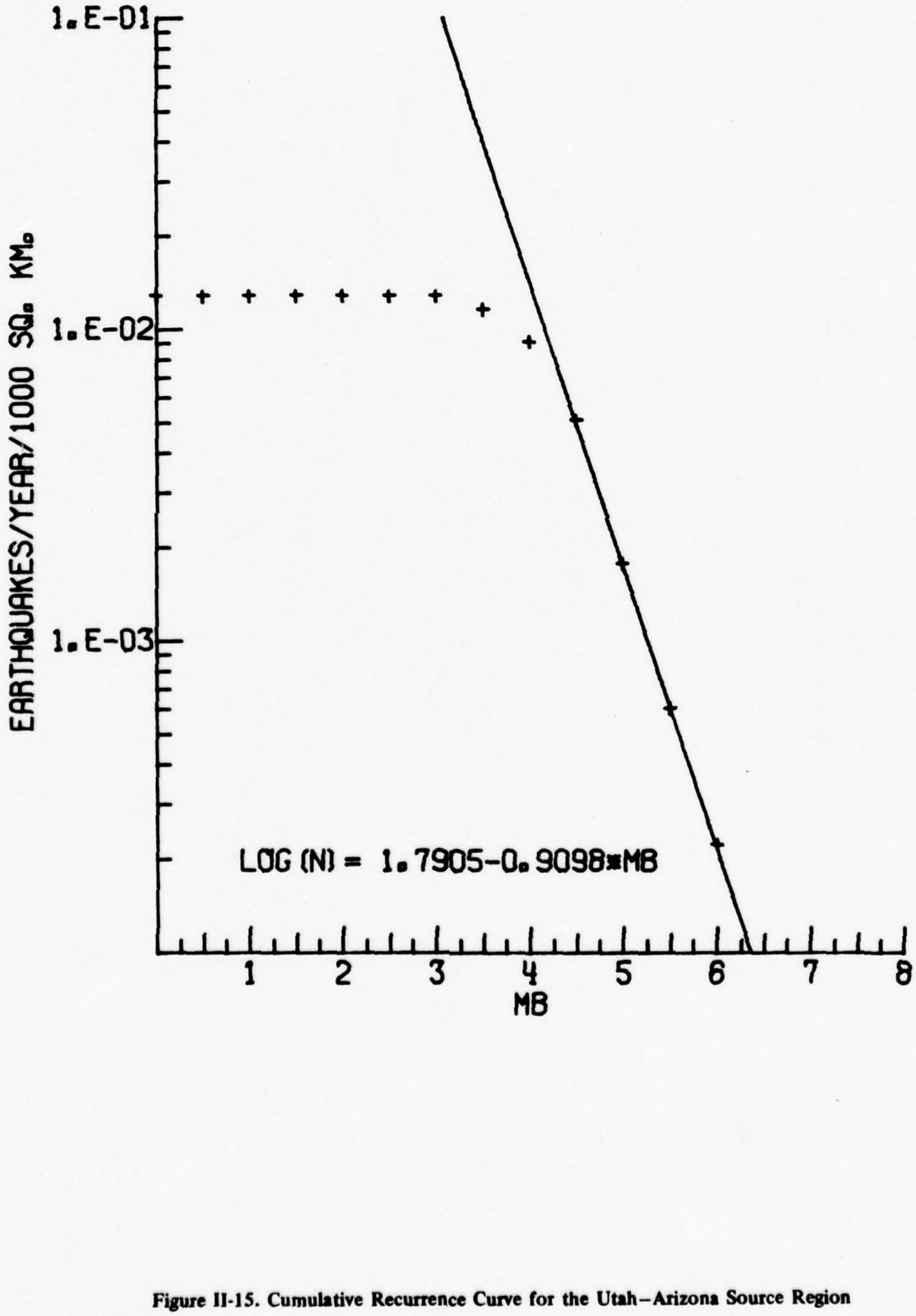

Figure II-15. Cumulative Recurrence Curve for the Utah–Arizona Source Region

TABLE II-I. SOUTHWESTERN UNITED STATES SOURCE REGION PARAMETERS

	A_{m_b}	B_{m_b}	Area	M_L: A_{M_L}	B_{M_L}	M_L^o	M_L^{max}	$B_{M_L} \ln 10$	N/Yr at M_L^o
Colorado	0.4227	0.5938	5.9×10^3	0.4346	0.4448	3.9	6.1	1.0241	0.0503
New Mexico	0.4227	0.5938	4.5×10^4	1.3135	0.4448	3.9	6.1	1.0241	0.3803
New Mexico W	0.4227	0.5938	1.86×10^3	–0.0650	0.4448	3.9	6.1	1.0241	0.0159
Gulf of California I	1.901	0.7750	1.44×10^5	3.0714	0.5805	3.9	6.9	1.3366	6.4410
Gulf of California II	1.901	0.7750	3.35×10^4	2.4369	0.5805	3.9	6.9	1.3366	1.4944
Utah–Arizona I	1.7905	0.9098	9.38×10^4	2.6020	0.6814	3.9	6.1	1.5691	0.8832
Utah–Arizona II	1.7905	0.9098	4.37×10^4	2.2697	0.6814	3.9	6.1	1.5691	0.4710
Northern Baja Peninsula	4.8467	1.1800	2.86×10^4	4.7971	0.8838	3.9	6.9	2.0351	22.5144
San Jacinto	5.0054	1.2121	1.77×10^4	4.7061	0.9079	3.9	6.5	2.0904	14.7128
Mohave Desert	5.3474	1.3674	2.24×10^4	4.9528	1.0242	3.9	6.5	2.3583	9.1416
Coastal Range	5.6036	1.3861	2.44×10^4	5.2226	1.0382	3.9	6.1	2.3905	15.0048
Coastal Faults	4.3706	1.2131	9.61×10^3	3.8053	0.9086	3.9	6.5	2.0922	1.8364
Northern San Andreas	5.1112	1.3281	1.97×10^4	4.7110	0.9947	3.9	6.1	2.2905	6.8222
Garlock Fault	4.6555	1.1482	1.09×10^4	4.228	0.8589	3.9	6.9	1.9776	7.0149
Nevada Fault Zone I	4.7379	1.2489	9.74×10^3	4.1329	0.9354	3.9	6.5	2.1539	3.0693
Nevada Fault Zone II	4.7379	1.2489	3.72×10^4	4.7154	0.9354	3.9	6.5	2.1539	11.7381
Nevada Test Site	4.6444	0.9912	8.67×10^3	4.3176	0.7414	3.9	6.5	1.7072	26.9506
Backgrounds:									
East of 115°W	–1.8676	0.5968	4.05×10^6	0.9783	0.4464	3.9	6.1	1.0279	0.0015*
West of 115°W	2.7619	1.2584	4.05×10^6	4.7636	0.9413	3.9	6.1	2.1674	0.0144*

*per 10^4 Km^2

As would be expected from the number of events in the data base, none of the source regions lying to the east of 115°W longitude had sufficient earthquake reporting to generate a data set that could be considered temporally stable. The opposite was true for those sources located to the west of 115°W longitude. Owing to both higher rates of activity and levels of instrumentation, the earthquake catalogue for this region is much closer to being complete; thus, the recurrence curves were found to represent stable rates of activity.

It is possible, using Stepp's method, to edit incomplete data catalogues so as to produce a data set that appears to be stable in terms of the annual rate of occurrence. This is done by restricting the time periods from which data are accepted for a number of given magnitude ranges (Stepp, 1972). This was attempted for source regions having incomplete data bases. However, because of the extremely short time gates necessary to produce complete data bases for these sources, the results from these edited data catalogues were believed to be no more reliable than the original incomplete data bases.

It is important to understand the implications of having an incomplete data base for a given source region. In general, incompleteness of the data catalogue results from insufficient reporting of low-magnitude earthquakes. Thus, the recurrence relation generated on the basis of these data will have a slope, or b factor, which is too shallow. Then, when this relationship is used in the seismic risk evaluation, both too few low-magnitude and too many high-magnitude earthquakes will be predicted in a given time span. As the magnitude of an earthquake is directly proportional to predicted peak ground motion at a site resulting from that event the likelihood of lower amplitude ground motions is underpredicted while large peak ground motion is overpredicted. In general, the seismic risk is underestimated for the short term but overestimated for the longer return periods. It is practically impossible to quantize this error, however, because of the complex manner by which the levels of activity and location of each source region combine to produce the final seismic risk estimate for a given site.

In addition to the seismic source region analysis, estimates of the background seismic activity levels to the east and west of 115°W were calculated. These values were calculated by eliminating (from the event catalogue) all events whose epicenters lie within one of the defined source regions. Because of the additional magnitude restriction imposed on events that lie to the west of 115°W longitude, activity levels were calculated separately for these two zones. The recurrence curves are shown in Figures II-16 and II-17. The recurrence relationships are stated in Table II-1 along with the necessary parameter conversions.

B. SEISMIC RISK EVALUATION

Once the seismicity study defines the likely locations and levels of seismic activity for the region surrounding the site of interest, it is necessary to evaluate the effects of this activity. Of prime importance is a means for estimating the peak ground motion at a given site when epicentral distance and magnitude are known. Throughout these studies, the ground motion prediction equations developed by McGuire (1974) were used. The case developed for using the McGuire equations was presented in an earlier report (Battis, 1978); however, it can be summarized by stating that the McGuire equations tend to predict values that are near the average value for the other available equations. The general form of the peak ground motion prediction equation is given by:

$$g = a_1 e^{a_2 M_L} (R + a_3)^{-a_4} \qquad \text{(II-4)}$$

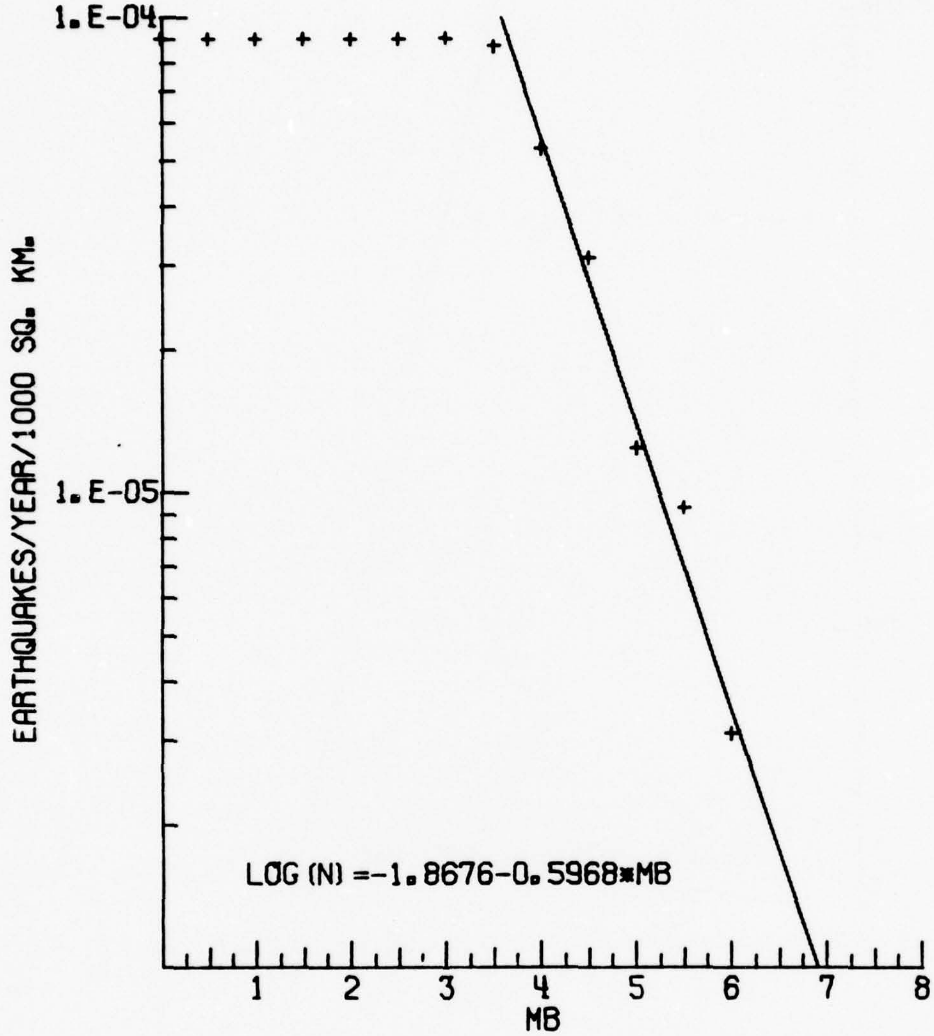

Figure II-16. Cumulative Recurrence Curve for the Eastern Background Area

where g is the desired ground motion, M_L is the earthquake local magnitude, R is the epicentral distance, and the values of a_1 through a_4 have been determined on the basis of available data. The values for the fitting parameters, as determined by McGuire for peak ground acceleration, velocity, and displacement, are given in Table II-2.

Knowledge of the dominant source regions, their associated activity levels, and a means for predicting peak ground motion as a function of earthquake magnitude and epicentral distance can be combined to estimate the annual likelihood of attaining a given ground motion level at the site of interest. This, in other words, is the seismic risk. Various methods have been proposed to carry out this assimilation of information. The specific formulation used in this study is that proposed by Cornell (1968) and Mertz and Cornell (1973). This method has been implemented in a FORTRAN computer program by McGuire (1976).

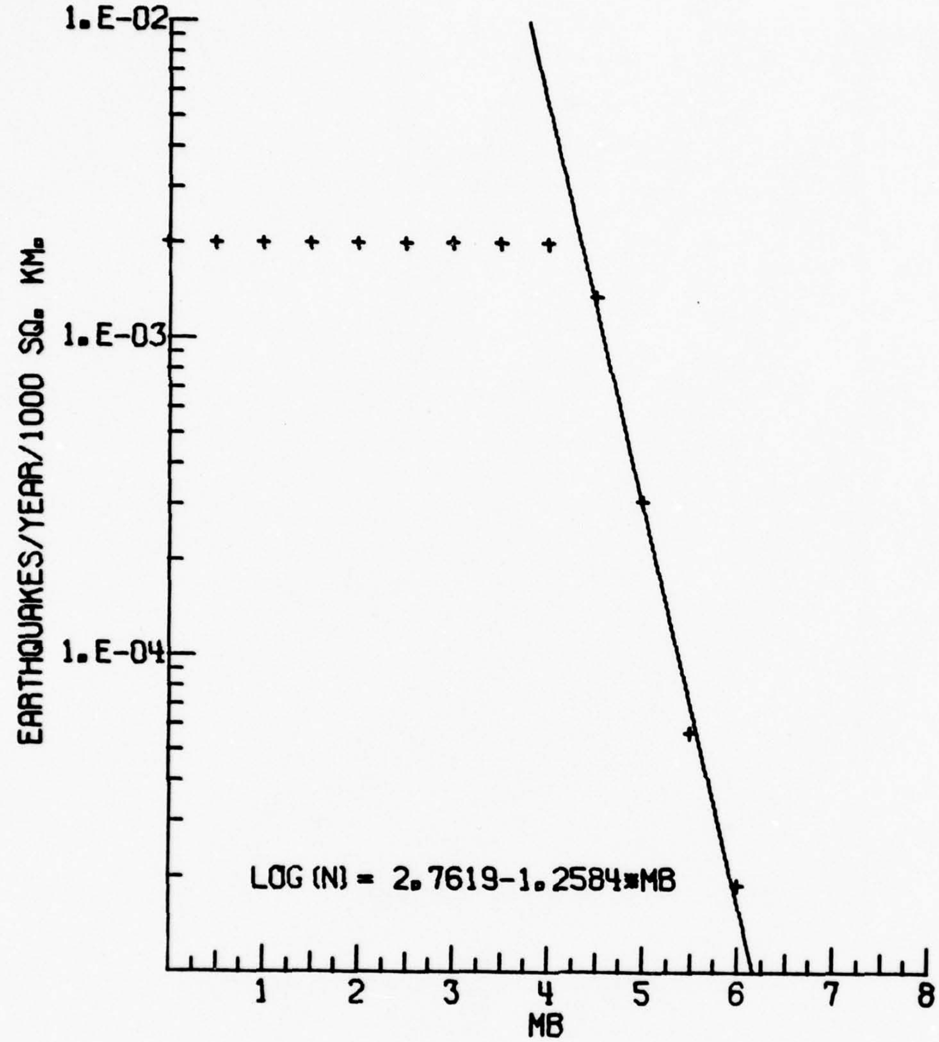

Figure II-17. Cumulative Recurrence Curve for the Western Background Area

TABLE II-2. PEAK GROUND MOTION ATTENUATION CURVES (After McGuire, 1974)

	a_1	a_2	a_3	a_4	$\ln a_1$	σ*
Acceleration (cm/s^2)	472.0	0.645	25.0	1.30	6.16	0.511
Velocity (cm/s)	5.64	0.921	25.0	1.20	1.73	0.629
Displacement (cm)	0.393	0.99	25.0	0.88	–0.934	0.76

*σ is for the Log_e of the ground motion parameter.

The details of this method have been discussed in a previous report (Battis, 1978); however, a brief statement of the problem follows. For any given earthquake, the peak ground motion parameters at some specified location are functions of epicentral distance and earthquake magnitude. Neglecting other considerations (e.g., source radiation pattern effects), the probability that the peak ground motion will reach or exceed a specified level can be defined as the integral of the product of the independent probability density functions for magnitude, f_S and distance, f_R, and the conditional probability of reaching or exceeding the specified ground motion level, given magnitude s and r. This integral is evaluated over all possible values of s and r. This can be expressed in terms of the 'Total Probability' Theorem by:

$$P[M_g \geqslant m_g] = \int\int P[M_g \geqslant m_g | s \text{ and } r] \; f_S(s) \; f_R(r) ds dr \qquad \text{(II-5)}$$

where $P[M_g \geqslant m_g]$ denotes the probability of the event ground motion, M_g, of being greater than a specified value, m_g, and $P[M_g \geqslant m_g | s \text{ and } r]$ is the conditional probability given event magnitude and distance (McGuire, 1976).

The condition probability in Equation (II-5) is a function of Equation (II-4) and its associated standard deviation. The probability density function for magnitude, $f_S(s)$, can be derived from each of the known source region recurrence curves. The function $f_R(r)$ incorporates the spatial relationship between each source and the site of interest. Evaluation of the integral gives the probability of reaching or exceeding m_g for one event from one source area. By multiplying the integral by the expected number of events in the source region and accumulating over all source areas, the total expected number of events meeting the condition at the site of interest can be calculated. Finally, assuming the earthquake occurrence is modeled by a Poisson distribution, the annual risk can be evaluated as

$$R[M_g \geqslant m_g] = 1 - e^{-E[M_g \geqslant m_g]} \qquad \text{(II-6)}$$

where R denotes risk and E denotes the expected number of events.

The initial step in the seismic risk evaluation for Luke Air Force Base, Arizona, was the evaluation of the 100-year return period acceleration levels for a grid of points located in southwestern Arizona. Evaluations were carried out at 0.5-degree intervals between 32°N to 34°N and 112°W to 115°W and a contour map of the 100-year return period acceleration level for this zone was generated. This map is shown in Figure II-18. This contour map shows the characteristics that could be expected, given the seismic setting of the site of interest. At the western and southern edges of the plot, the contours are closely spaced and of high amplitude because of the nearness of several very active source regions. These include the Gulf of California, the northern Baja Penninsula, and the San Jacinto source regions. The contours are much less steep and of much lower amplitude as one moves away from the seismically active areas of southern California.

From Figure II-18, it can be seen that Yuma, Arizona, represents one of the higher risk locations near Luke Air Force Base while Phoenix, Arizona, is a low seismic risk site. To demonstrate the extremes of seismic risk that might occur over the area of Luke Air Force Base, peak ground acceleration, velocity, and displacement risk curves were generated for these two sites. These curves are given in Figures II-19 through II-21. In addition, ground motion levels associated with specific levels of annual risk for Yuma, Arizona, are given in Table II-3 and similar values for Phoenix are given in Table II-4.

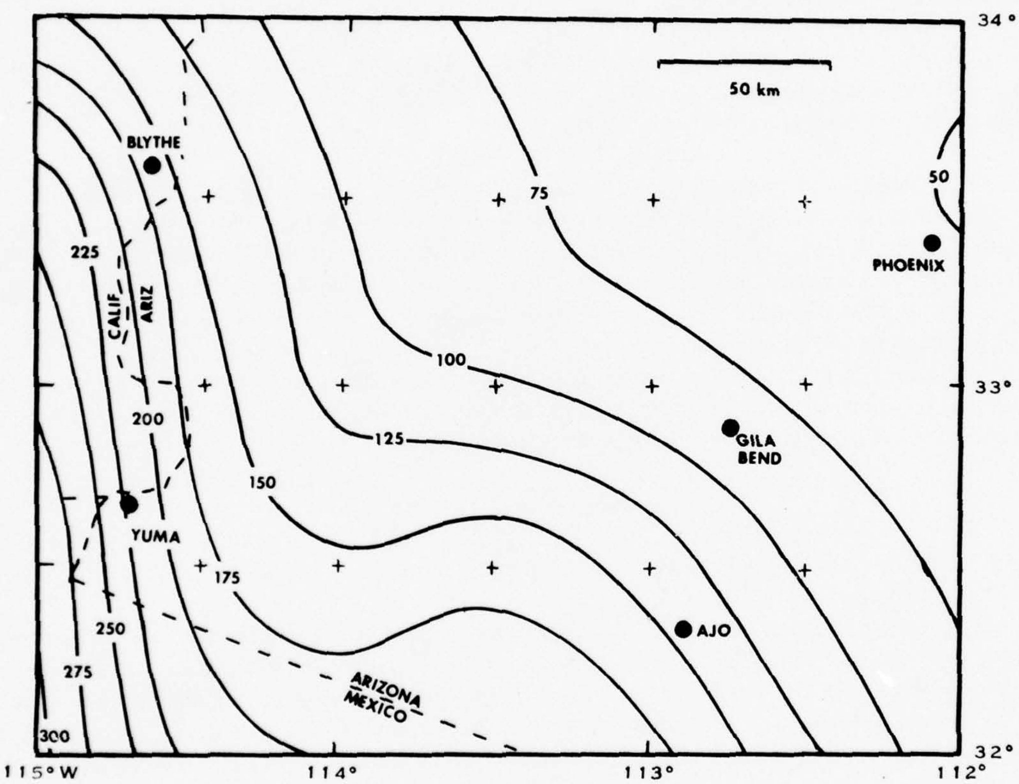

Figure II-18. Contours of 100-Year Return Period Accelerations in Southeastern Arizona (Contours in cm/s^2)

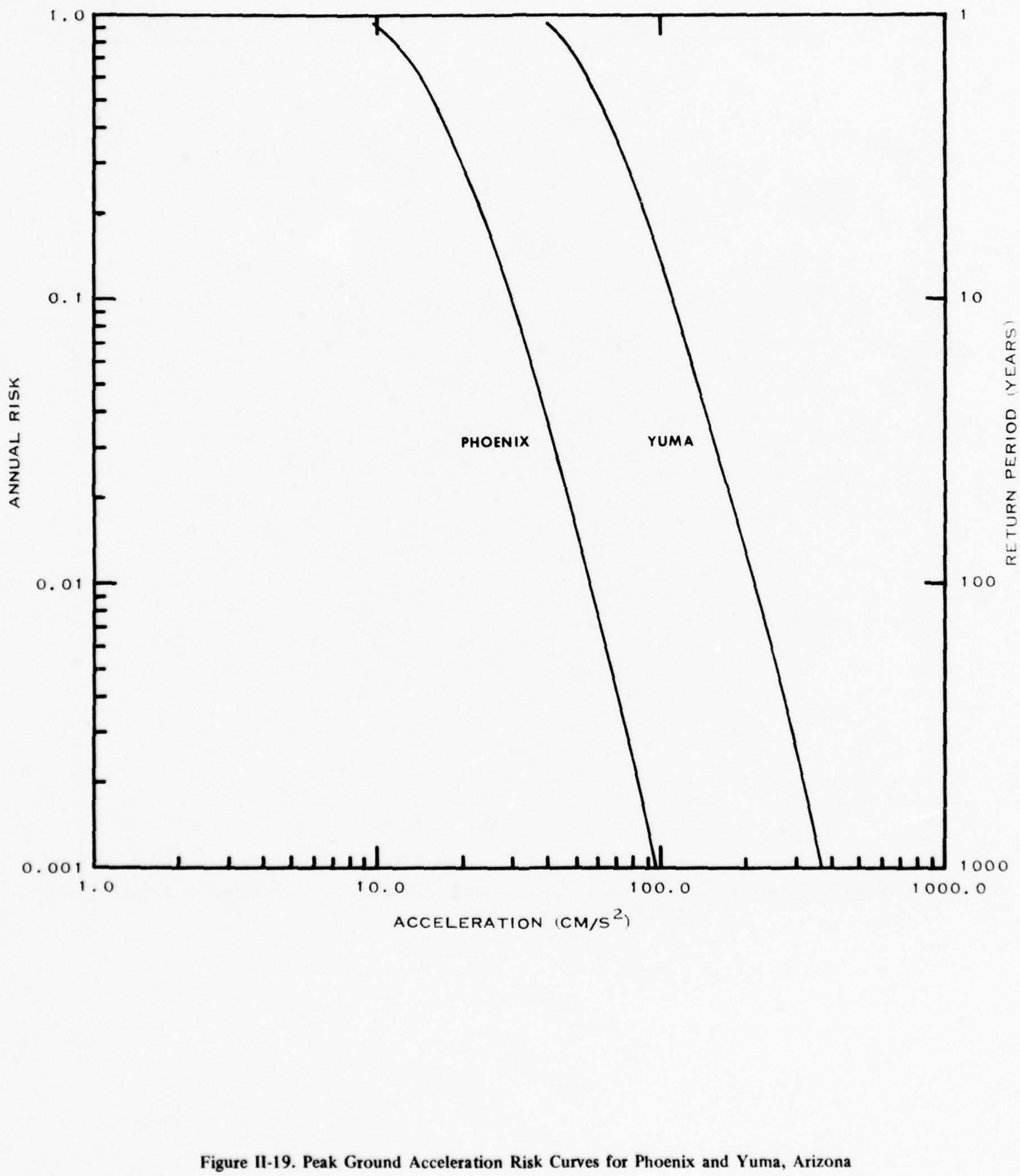

Figure II-19. Peak Ground Acceleration Risk Curves for Phoenix and Yuma, Arizona

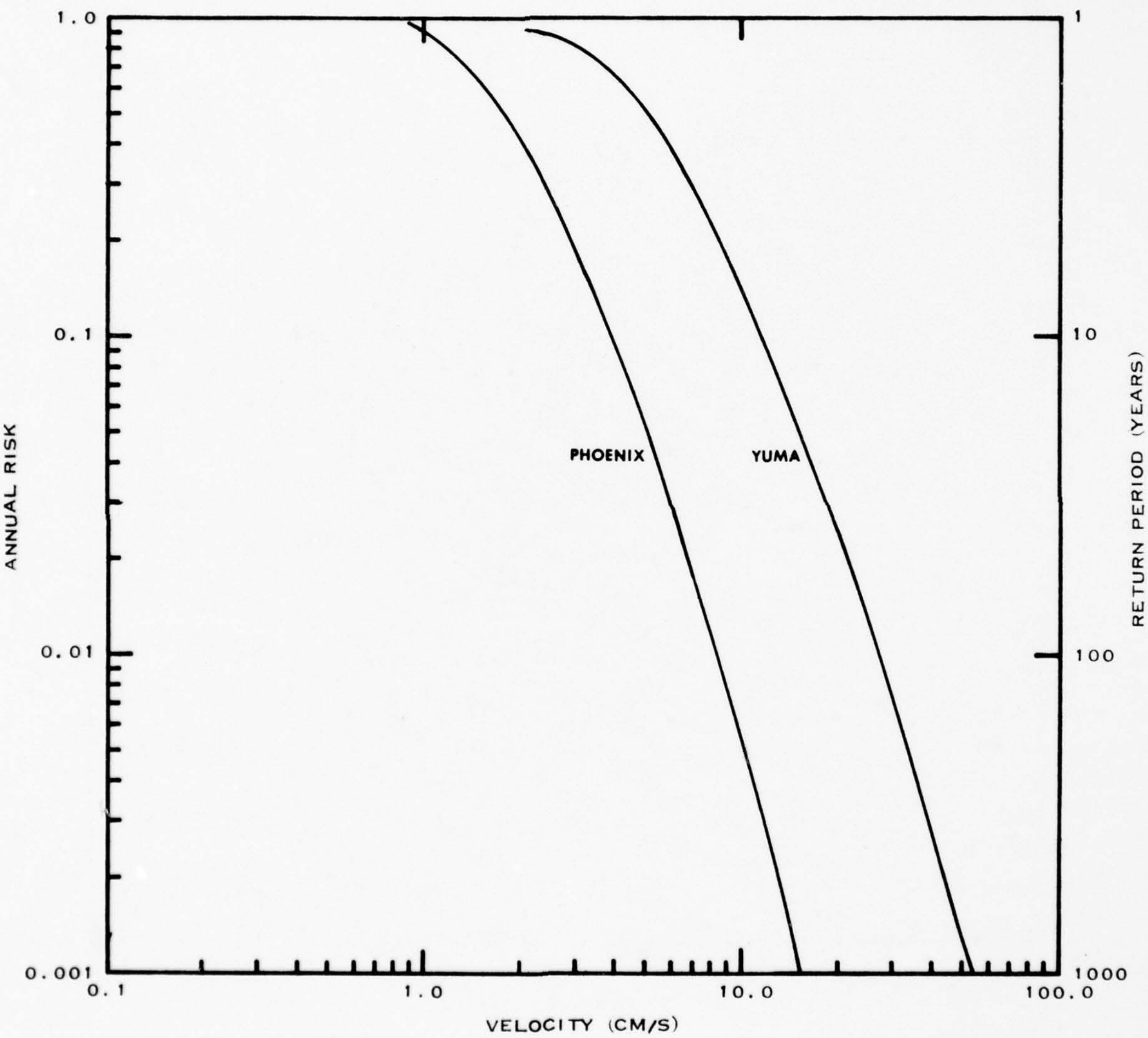

Figure II-20. Peak Ground Velocity Risk Curves for Phoenix and Yuma, Arizona

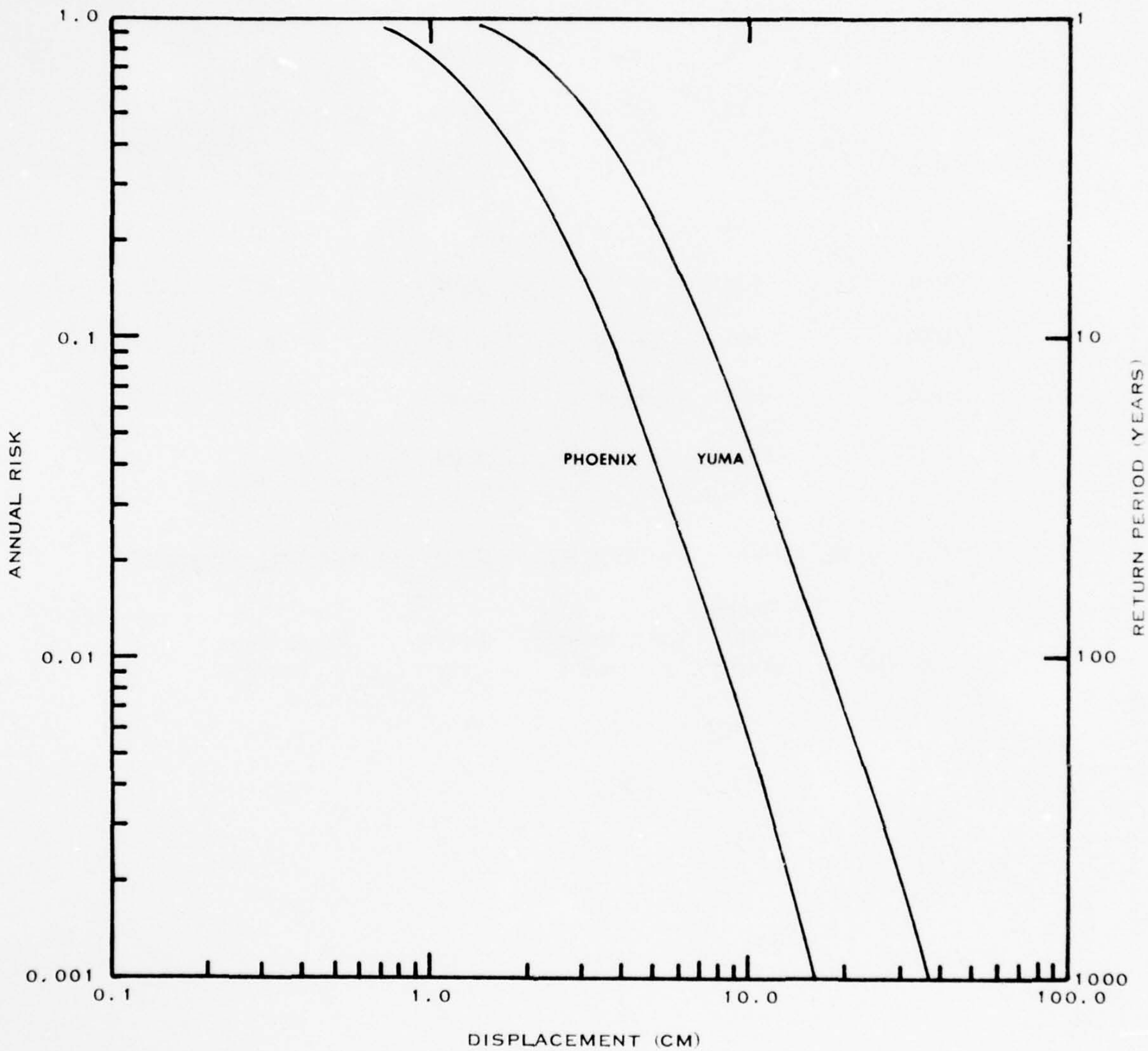

Figure II-21. Peak Ground Displacement Risk Curves for Phoenix and Yuma, Arizona

TABLE II-3. PEAK GROUND MOTION RISK VALUES FOR YUMA, ARIZONA

Risk/Year	Return Period (Years)	Acceleration (cm/s^2)	Velocity (cm/s)	Displacement (cm)
1.0	1	25.04	1.04	0.60
0.5	2	59.93	5.18	3.06
0.2	5	85.61	8.52	5.26
0.1	10	107.28	11.61	7.19
0.05	20	132.74	15.25	9.62
0.02	50	173.25	21.33	13.68
0.01	100	209.61	26.96	17.44
0.005	200	251.77	33.63	21.96
0.002	500	316.54	44.09	29.17
0.001	1000	372.71	53.31	35.69

TABLE II-4. PEAK GROUND MOTION RISK VALUES FOR PHOENIX, ARIZONA

Risk/Year	Return Period (Years)	Acceleration (cm/s^2)	Velocity (cm/s)	Displacement (cm)
1.0	1	5.01	0.50	0.16
0.5	2	15.11	1.81	1.52
0.2	5	23.52	2.89	2.58
0.1	10	29.73	3.98	3.55
0.05	20	36.44	5.10	4.71
0.02	50	46.95	6.91	6.55
0.01	100	56.11	8.51	8.23
0.005	200	66.71	10.32	10.17
0.002	500	83.05	13.07	13.18
0.001	1000	97.81	15.45	15.83

At this point, a brief discussion of the reliability of these seismic risk estimates should be made. It can be expected that the primary source of error in the evaluation process involves assigning levels of activity to the various source regions and to the background activity. In this study, sources west of 115°W longitude essentially controlled the level of risk, with some significant contribution from the Gulf of California source area. As was stated earlier, all sources that lie to the west of 115°W longitude had complete data bases, implying that accurate evaluations of seismic activity levels had been made. The Gulf of California source region data catalogue was not complete and any error in assigning an activity level would affect the final risk evaluation. While it is impossible to estimate the error that might result, it has already been noted that the effect would be to overestimate the ground motion levels associated with lower annual risk. The effect would be to the conservative side.

The results of work done by Algermissen and Perkins (1972) and refined in Hays, et al. (1975) can be compared to the results in this report to give some idea of reliability. Using a different risk evaluation process, Algermissen and Perkins constructed a 50-year return period acceleration contour map for Arizona and Utah. Their work predicts a 50-year return period acceleration at Yuma which is approximately 50 percent of the value given in Table II-3 for Yuma and 25 percent of the value for Phoenix. Some of the discrepancy can be explained by differences in the boundaries of the source regions or activity levels. However, it would appear that the most important variation between the studies is the peak ground motion attenuation curves. Algermissen and Perkins used those derived by Schnabel and Seed (1972), which have a much higher rate of attenuation than do those given in Table II-3. For example, at just 20 kilometers epicentral distance, McGuire's equations predict a peak ground acceleration of 150 cm/s^2 compared with approximately 125 cm/s^2 from the Schnabel and Seed curve. Variations of this degree could easily explain the differences in predicted risks found between these two studies. As neither attenuation curve can be considered innately superior to the other, the choice of which to use is subjective.

C. COMPOSITE RESPONSE SPECTRA

The spectral characteristics of ground motion are typically represented in the form of response spectra. The response spectrum is typically calculated from accelerograms and represents the maximum response of a simple, viscous-damped harmonic oscillator over a range of natural periods for a specific percentage of critical damping. This form is useful in the study of structure response to strong seismic motion. Methods have also been developed to estimate upper limit response spectra, given levels of peak ground motion at the site of interest (Hays, et al., 1975), known as design response spectra. One set of commonly used amplification factors is that proposed by Newmark, et al. (1973) and is given in Table II-5. These values are used to calculate the responses at the specified frequencies, based on given peak ground acceleration and displacement values at a site of interest. The different levels of critical damping correspond to variations in foundation soil conditions at the site. The lower percentages of critical damping are representative of hard rock sites. An increase in the percentage of critical damping correlates to decreasing material rigidity at the site for which the response spectra is calculated.

Using the ground motion parameters associated with 10-, 100-, and 1,000-year return periods at Yuma and Phoenix, composite response spectra were evaluated. The curves representing 0.5-percent and 10-percent critical damping are shown in Figures II-22 through II-27. These two curves represent the upper and lower limits, respectively, of normally expected site conditions. It should be noted that these curves are composite in nature because they do not

TABLE II-5. HORIZONTAL DESIGN RESPONSE SPECTRA AMPLIFICATION FACTORS AT CONTROL POINT FREQUENCIES

Critical Damping (%)	Acceleration (% g)			Displacement (In)
	33 Hz	9 Hz	2.5 Hz	0.25 Hz
0.5	1.0	4.96	5.95	3.20
2.0	1.0	3.54	4.25	2.50
5.0	1.0	2.61	3.13	2.05
7.0	1.0	2.27	2.72	1.88
10.0	1.0	1.90	2.28	1.70

represent the design response spectra for any one earthquake. This is because the peak ground motion parameters upon which they are based, while having the same return periods, might not be generated by the same earthquake (Battis, 1978). Thus, it is more correct to view these spectra as predicted upper limit responses at each frequency, individually, than as upper limit spectra.

D. ALGODONES FAULT

As stated in the introduction to this section, the area of interest for this study lies along the border of the seismically active Salton Trough–Gulf of California rift zone. In fact, the region near Yuma, Arizona, is crossed by several faults that define the boundary between the Salton Trough and Sonoran sections of the Basin and Range Province. The location of these faults is shown in Figure II-28. In evaluating the seismic risk for this region, it is apparent that the likelihood of activity along these faults must be considered.

Based on qualitative geologic evidence, the last significant movement on the Algodones Fault, seemingly the principal fault in this region, could have been no more recent than late Pleistocene, or at least 10,000 years ago (Mattick, et al., 1973; Howard, et al., 1978). This estimate is based on the lack of disturbance of more recent alluvial deposits along the fault trace. The parallel or en echelon faults associated with the Algodones Fault are inferred to be even older. Unequivocal data on the amount and sense of motion along these faults are unavailable.

It is mostly likely. however, that the Algodones Fault is an extension of the San Andreas Fault system of southern California. The Algodones Fault can be inferred to connect to the southernmost segment of the San Andreas Fault proper through the Sand Hills Fault (Figure II-29), a southern extension of the San Andreas Fault system that is inferred from geophysical evidence. The San Andreas Fault system is the major interface between the Pacific and North American plates and seismic activity along the fault is the result of differential motion between the plates. This, in turn, suggests that the Algodones Fault should be considered a fault with relatively high risk of seismic activity.

There is evidence to suggest, however, that the role of the San Andreas Fault, in the area shown in Figure II-29, as an active interface between the plates is being replaced by the Elsinore and San Jacinto Faults (Benioff, 1955). This concept would seem to be supported by the higher

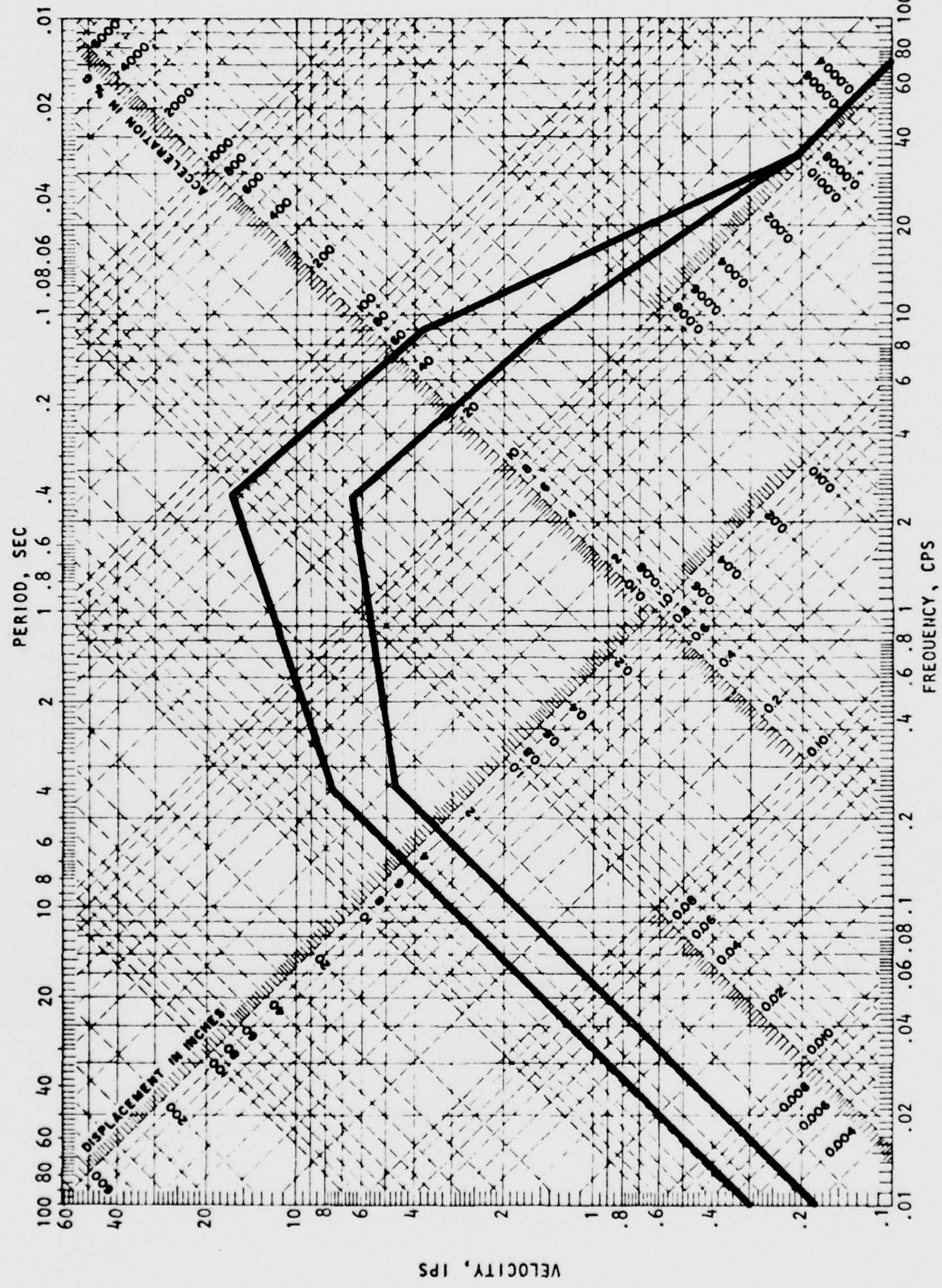

Figure II-22. Composite Response Spectra for Yuma, Arizona, for 10-Year Return Period Ground Motions [0.5 Percent (Upper) and 10 Percent (Lower) of Critical Damping Curves Shown]

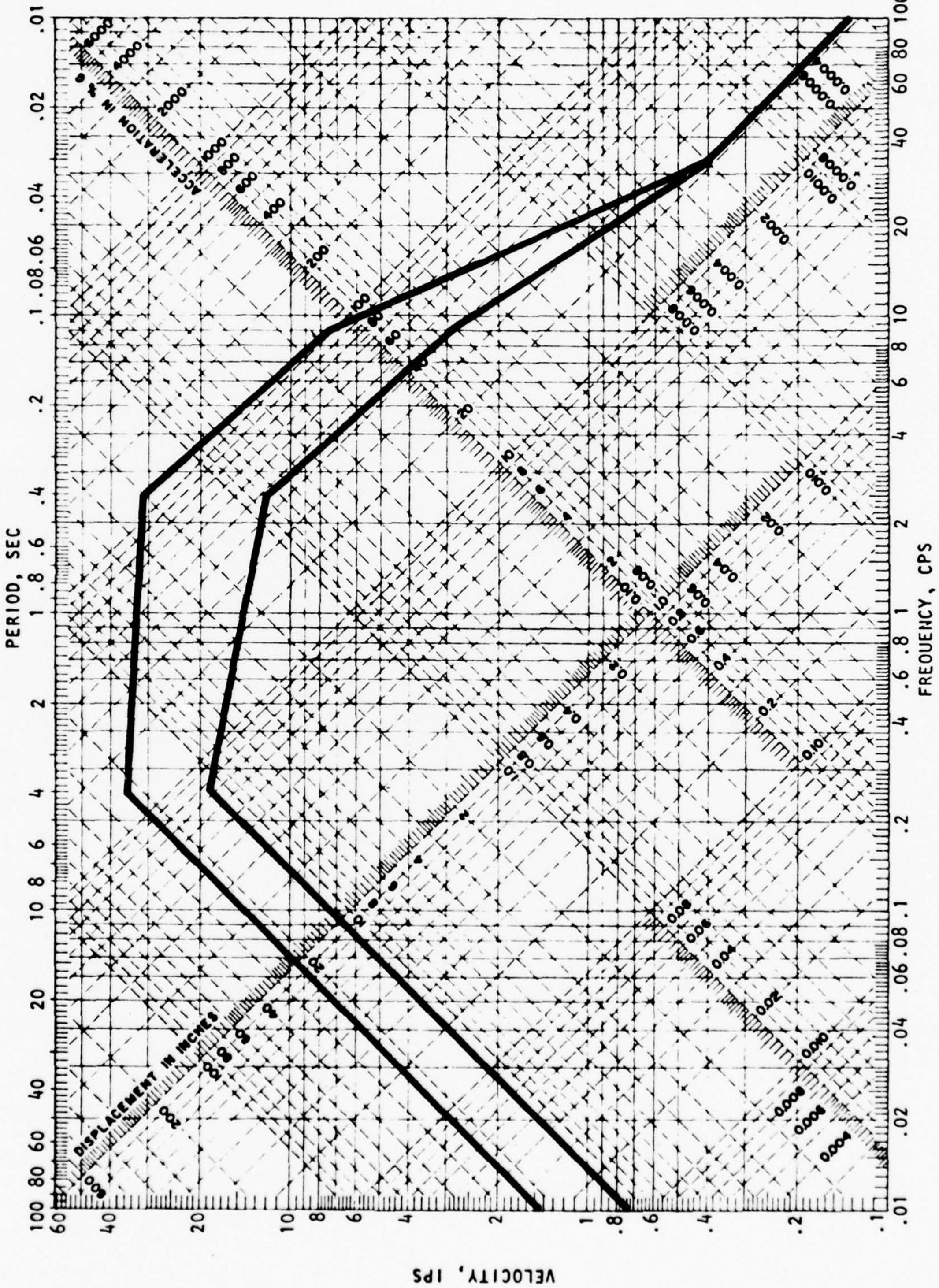

Figure II-23. Composite Response Spectra for Yuma, Arizona, for 100-Year Return Period Ground Motions [0.5 Percent (Upper) and 10-Percent (Lower) of Critical Damping Curves Shown]

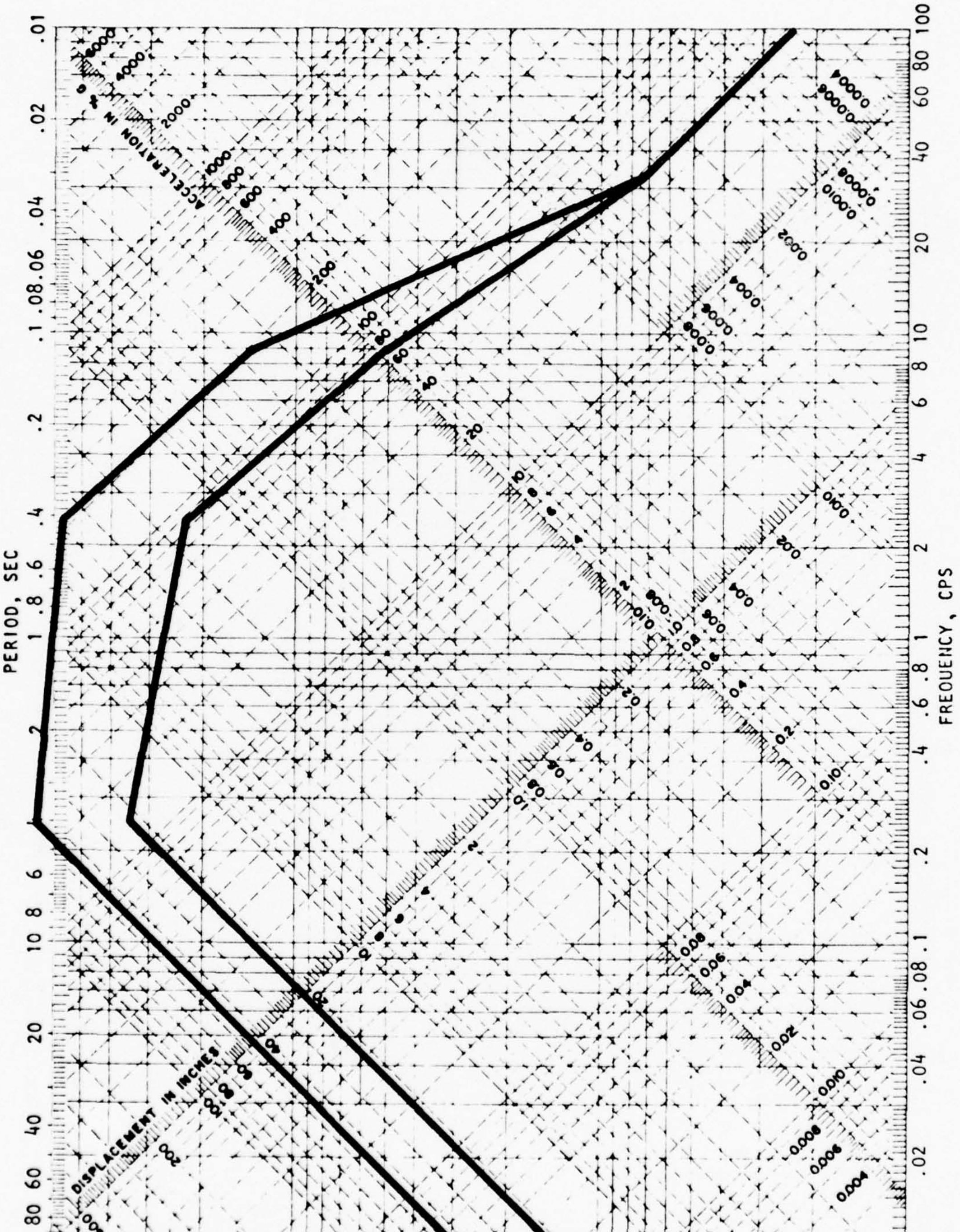

Figure II-24. Composite Response Spectra for Yuma, Arizona, for 1,000-Year Return Period Ground Motions [0.5 Percent (Upper) and 10 Percent (Lower) of Critical Damping Curves Shown]

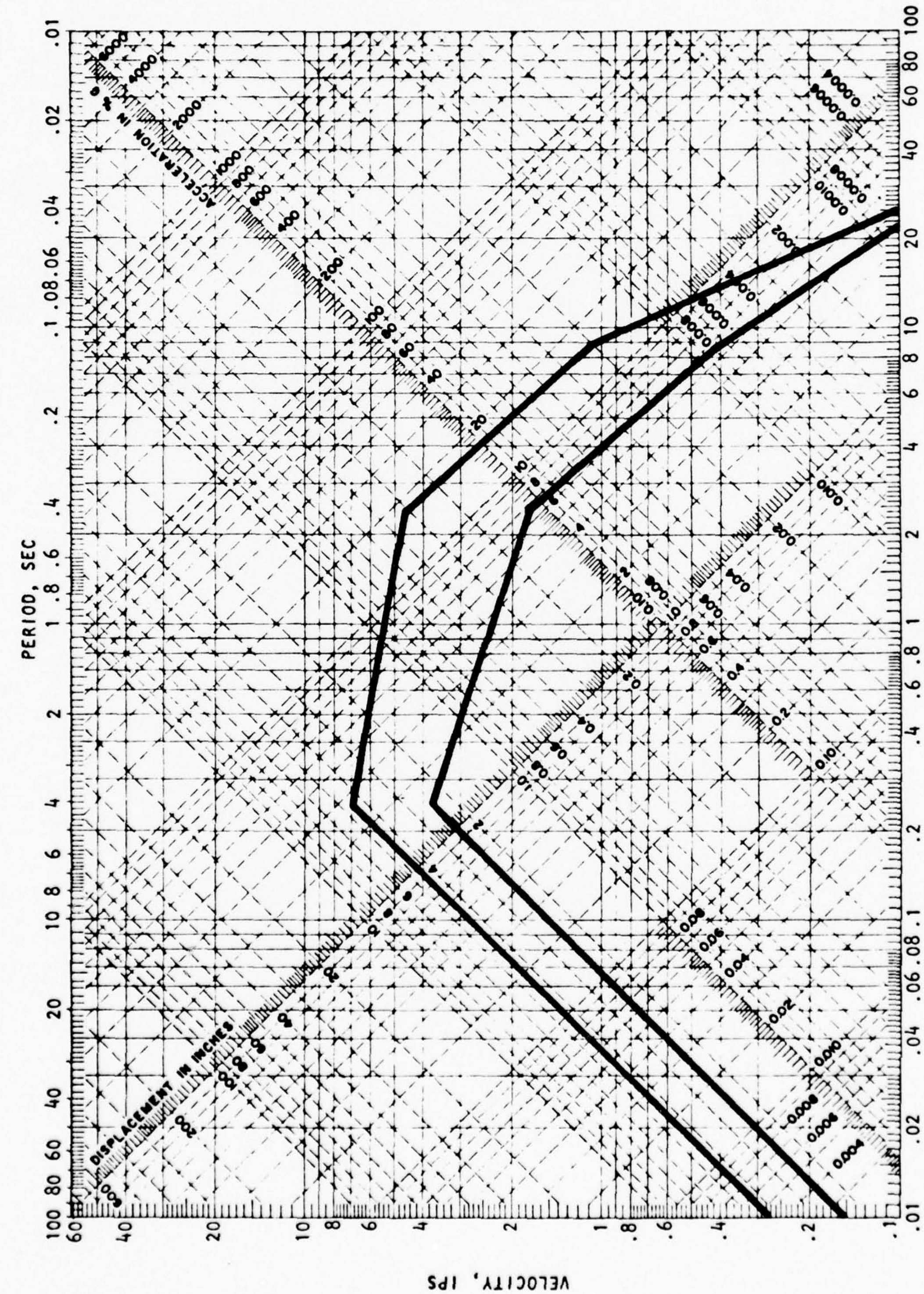

Figure II-25. Composite Response Spectra for Phoenix, Arizona, for 10-Year Return Period Ground Motions [0.5 Percent (Upper) and 10 Percent (Lower) of Critical Damping Curves Shown]

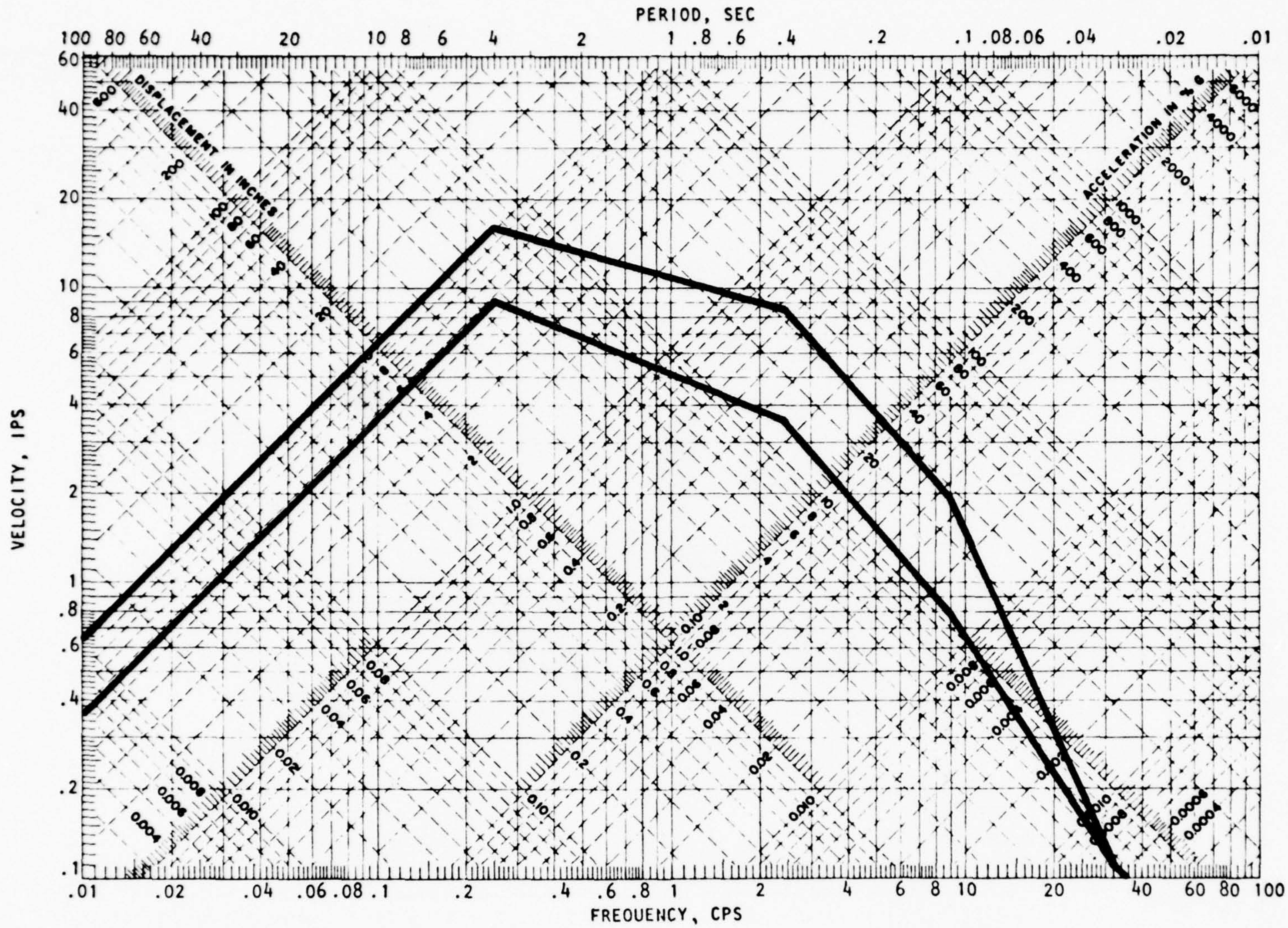

Figure II-26. Composite Response Spectra for Phoenix, Arizona, for 100-Year Return Period Ground Motions [0.5 Percent (Upper) and 10 Percent (Lower) of Critical Damping Curves Shown]

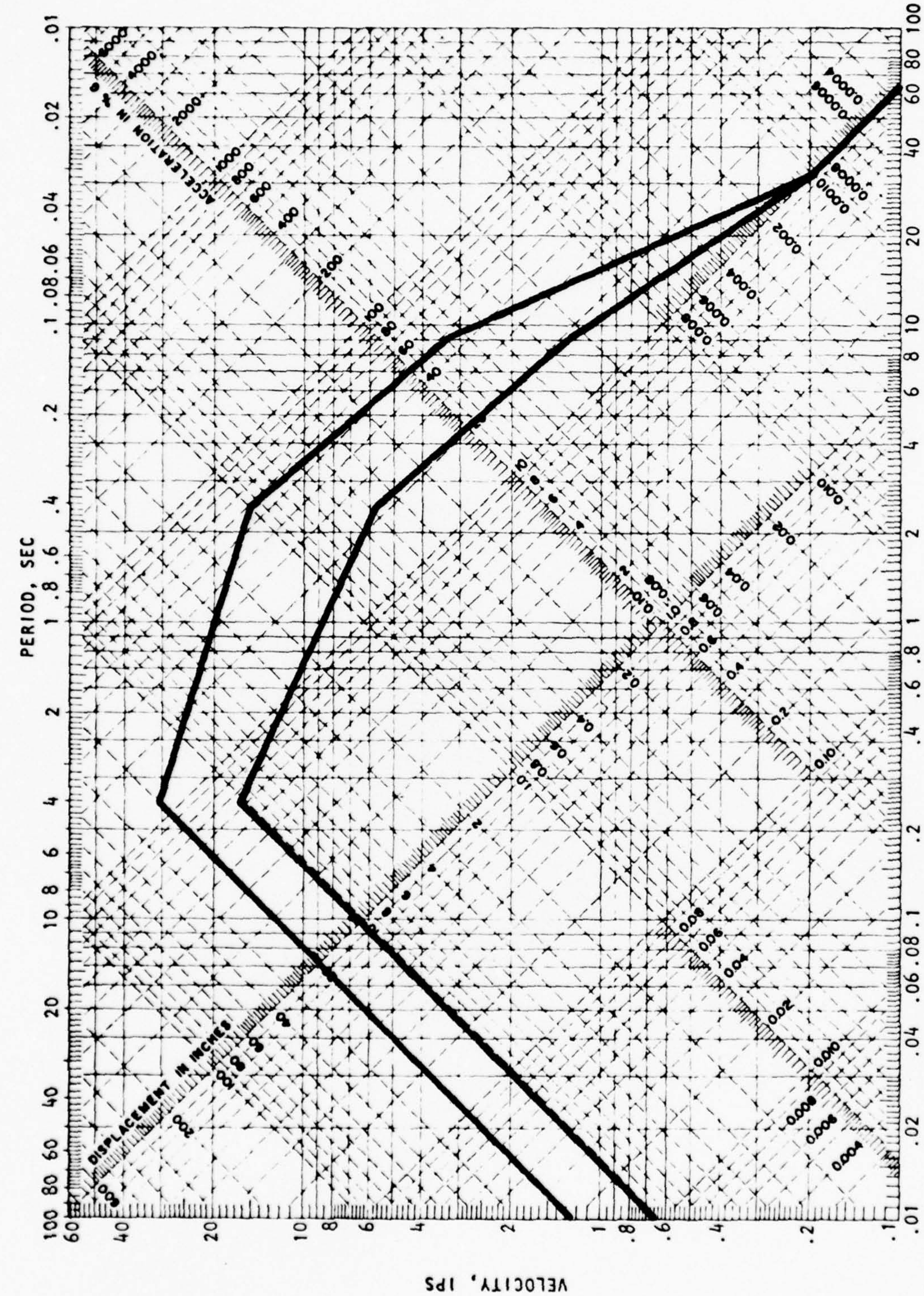

Figure II-27. Composite Response Spectra for Phoenix, Arizona, for 1000-Year Return Period Ground Motions [0.5 Percent (Upper) and 10 Percent (Lower) of Critical Damping Curves Shown]

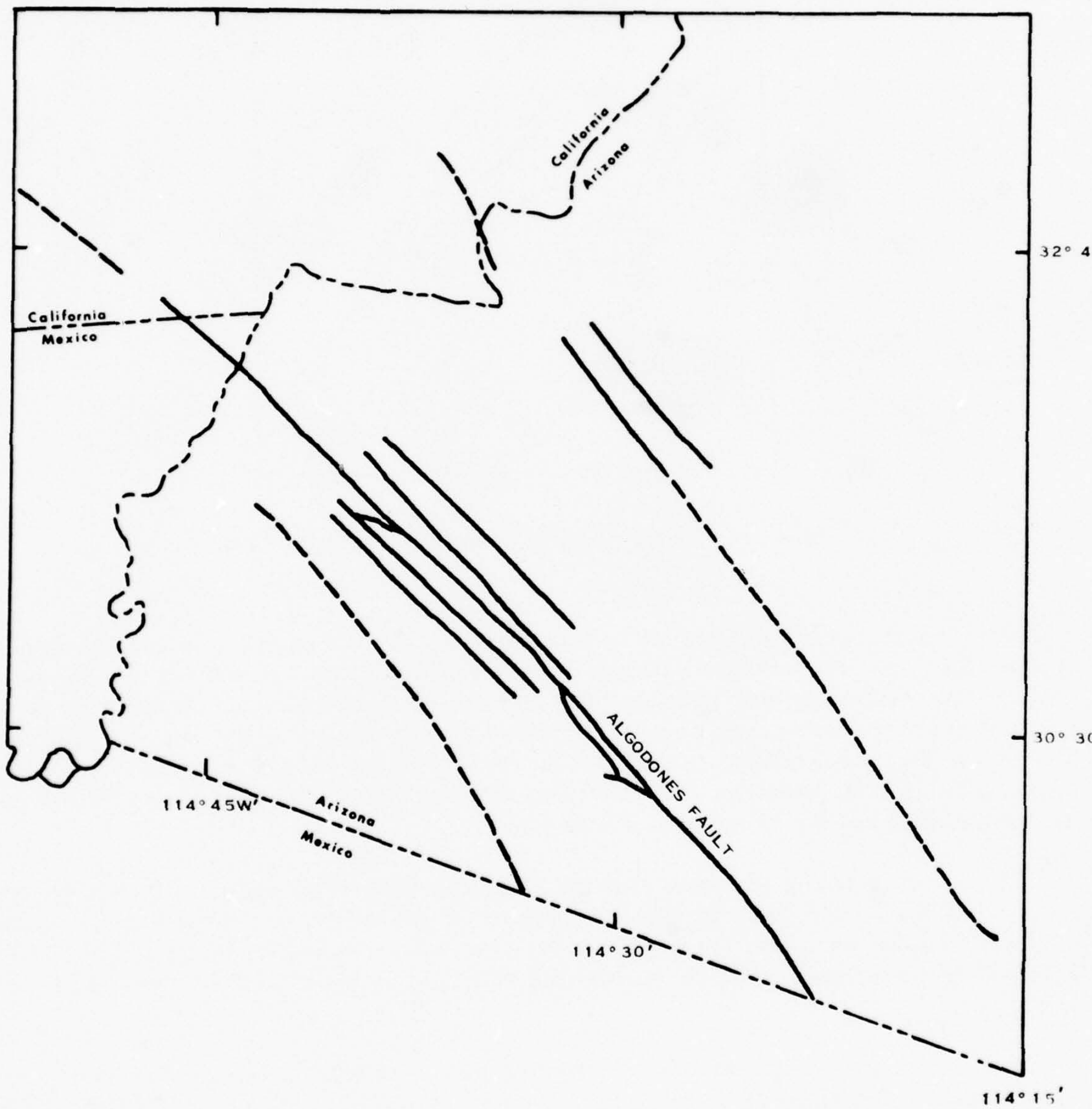

Figure II-28. Location of Faults in Southwestern Arizona

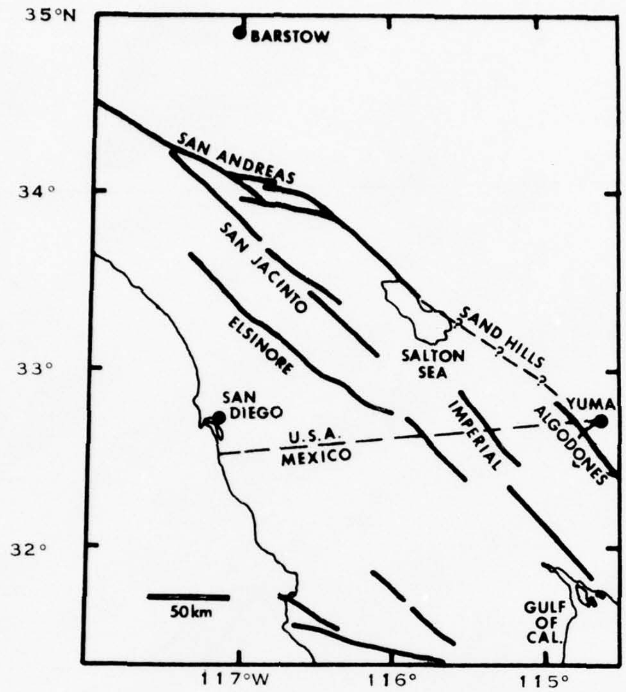

Figure II-29. Major Faults and Fault Systems Near Luke Air Force Base

number of earthquakes associated with these faults than found on the southern San Andreas system (Hileman, et al., 1973). However, seismic activity has not completely ceased on the southern San Andreas system. Jennings (1975) reports both coseismic fault displacement on the southern San Andreas Fault and possible creep along a short segment of the Sand Hill Fault near the Salton Sea. And finally, Hileman, et al. (1973) located several earthquake epicenters, including two 5.0 M_L events in 1935, very near the Sand Hills Fault. The Algodones Fault does not seem to have any similar recorded seismic activity.

Thus, there is reason to believe that the Algodones Fault is associated with an active fault system and that other faults in the same branch of the system demonstrate recent seismic activity. It follows, then, that the Algodones Fault has some potential for future seismic activity. It should be emphasized, however, that the risk of significant activity would appear to be very low.

It is of interest to estimate the maximum creditable earthquake for the Algodones Fault. This estimate of the largest earthquake likely to occur on the fault can be calculated on the basis of maximum rupture length on the fault. In the case of the Algodones Fault, this distance is not exactly known because the fault has not been traced beyond the Arizona-Mexico border. However, if the known segment is assumed to be most of the fault, a total length is approximately 45 miles. Using a relation derived by Greensfelder (1974) to estimate the maximum magnitude of an earthquake for a given fault length in miles, L, given by

$$M_L = 5.0 + 1.4 \text{ Log } (L) \pm 0.26 \qquad \text{(II-7)}$$

the Algodones Fault is found to have a maximum creditable earthquake of 7.3 M_L. This value is similar to that found by Greensfelder for the Sand Hills and southern segment of the San Andreas Faults and is, therefore, probably a reasonable value.

Design response spectra at Yuma for this earthquake were evaluated under the assumption that the event epicenter was located on the fault at the point closest to Yuma, approximately 10 kilometers away. These spectra are shown in Figure II-30. The same amplification factors were used as for the composite response spectra shown earlier (Table II-5). Again, as for the composite spectra, only the 0.5 percent and 10 percent of critical damping response spectra are shown, as these represent the upper and lower limits, respectively, for most site soil conditions. The peak ground motion parameters used to evaluate these curves were calculated using the attenuation equations developed by McGuire (1974) and are given in Table II-2.

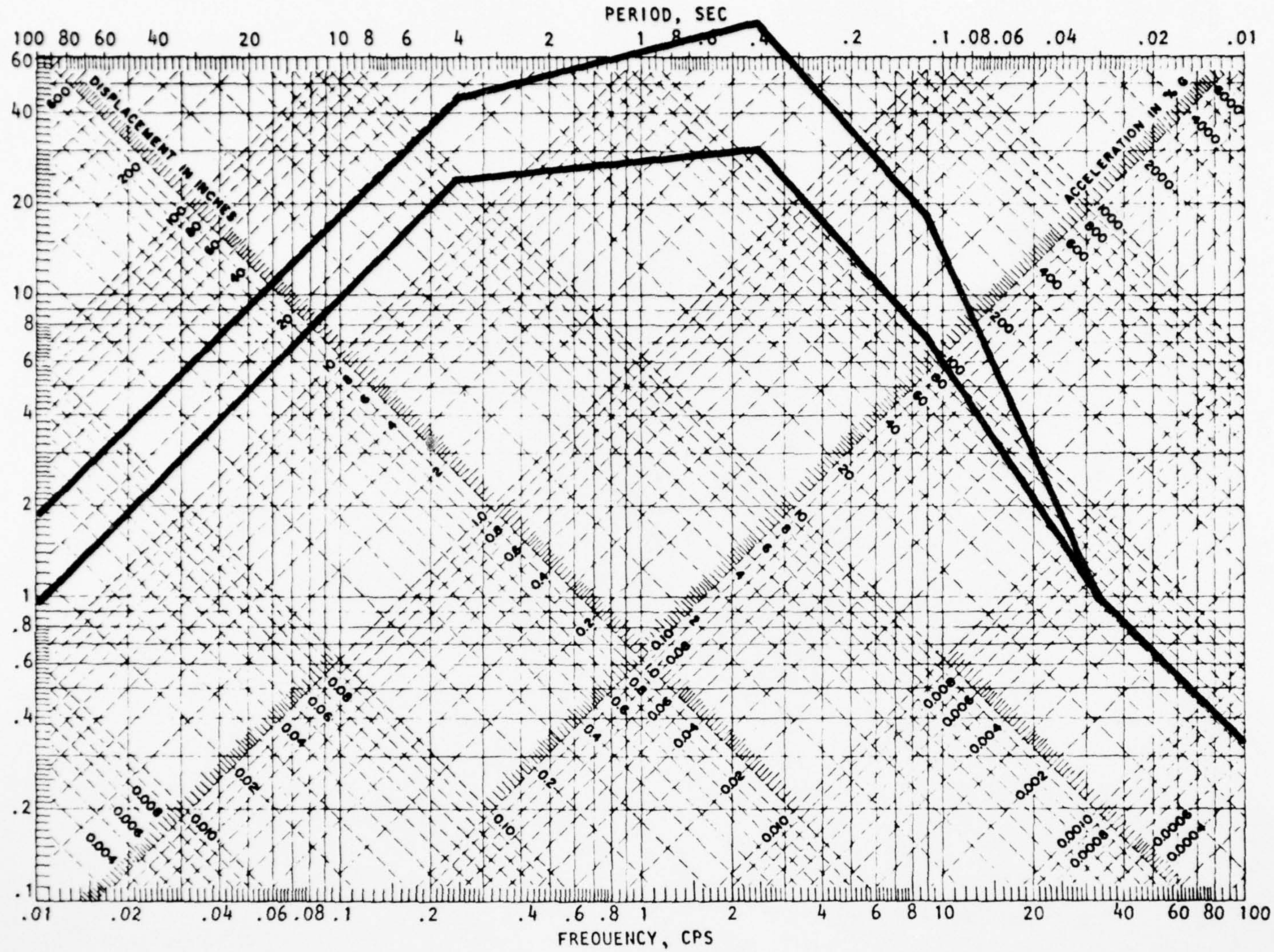

Figure II-30. Design Response Spectra for *Yuma, Arizona, for a* 7.3 M_L Earthquake on the Algodones Fault
[0.5 Percent (Upper) and 10 Percent (Lower) of Critical Damping Curves Shown]

SECTION III

SEISMIC RISK AT THE NEVADA TEST SITE

Like Luke Air Force Base, the Nevada Test Site (NTS) is a potential location for an MX missile facility. This installation, situated in southern Nevada, is within the Basin and Range Physiographic Province and is very close to several active sources of seismic activity. Using the same method described in the previous section of this report, both seismicity and seismic risk evaluations were conducted for the NTS. The results of that work are presented in this section.

A. SEISMICITY STUDY

As with the previous seismic risk evaluations, the seismicity study conducted for the NTS risk evaluation was made on the area within 800 km of the site of interest. Once again, the volume of earthquake data from the southern California area required that the data base be edited. As in the previous analysis, editing was best done by dividing the region under study into two sections. The first of these consisted mainly of southern California and was the area to the west of 116°W longitude south of 36°N and to the west of 120°W longitude south of 38°N latitude. The second study region contained the remaining study area. The division was so selected that all activity at or near NTS was entirely within one data base.

In the first of these regions, all earthquakes having a magnitude of 4.0 m_b or greater reported on the Earthquake Data File (Meyers and von Hare, 1976) were used to form the data base. The epicenters of these events are shown in Figure III-1. A total of 3183 earthquakes formed this data set. The catalogue ranged between 1906 and 1975, with the San Francisco Earthquake of 1906 being the largest reported event in the data set with a magnitude of 8.3 M_L. Because of the much lower level of both seismic activity and earthquake reporting in the second study area, the data catalogue for the seismicity study was composed of all earthquakes in the area without regard to magnitude. A total of 6410 earthquakes have been reported in this region between 1852 and 1975. The epicenters of these events are shown in Figure III-2. Of the 6410 earthquakes, 4743 events had associated magnitude or epicentral intensity estimates and could be used in this seismicity study. For conversion of local magnitudes or epicentral intensity to bodywave magnitude, the functional relationships found by Brazee (1976), and given in Equations (II-2) and (II-3), were used.

Based on the locations and alignments of these epicenters, 15 seismic source regions were identified within 800 km of NTS. The approximate boundaries of these source areas are shown in Figure III-3. Many of the source areas in southern California are defined identically to those used in the Luke Air Force Base seismicity study and the seismicity analysis was not redone for these regions. For source areas not previously analyzed or where the boundaries have been altered for this study, cumulative recurrence curves were evaluated and are shown in Figures III-4 through III-13. The recurrence functions and the appropriate parameter conversions required for the seismic risk evaluation process are given in Table III-1.

Of particular importance to this study is the estimation of the level of seismic activity near NTS, because activity at close range tends to dominate the risk estimation for a site. At NTS, however, the process of evaluating the activity level is complicated by the use of this facility as a nuclear test site. Since 1957, when the first underground explosion was set off (Bullen, 1963),

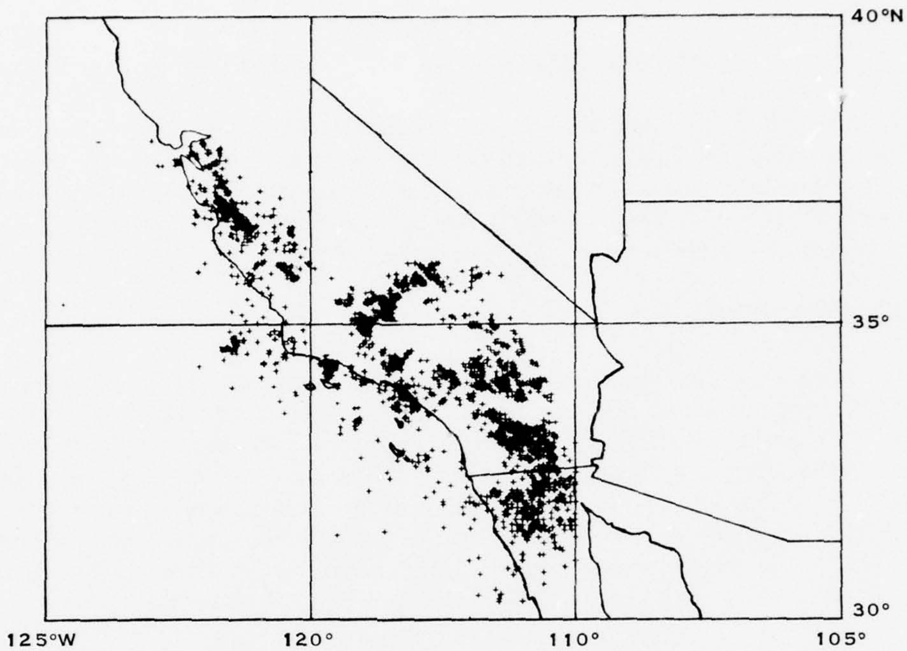

Figure III-1. Epicenters in Southern California Within 800 km of NTS

NTS has been the site of numerous announced and unannounced nuclear tests. While one can remove the announced explosions from the event catalogue, this still leaves both the unannounced shots and associated aftershock activity of nuclear tests. Each of these phenomena could substantially alter the estimate of seismicity for this area.

The significance of this fact can be seen in Figure III-14 which is a histogram of all events reported in the NTS source region between 1930 and 1970, broken into 5-year segments. Of the 673 reported epicenters in this area, only 41 of them occurred before 1957. While it is apparent that the NTS does have some level of seismic activity unrelated to the nuclear testing, the earthquake catalogue for NTS is quite incomplete and no reliable estimate of the level of activity can be made. The means by which this situation was handled in the seismic risk process will be discussed later.

To a large degree, the areas of study for the Luke Air Force Base and the NTS seismicity evaluations are the same. Therefore, the background seismicity levels found in Section II of this report, based on the Luke Air Force Base data set, would be satisfactory for use in this study. These recurrence functions were given in Table II-1.

Once again, completeness of the earthquake catalogues was found for all of the source regions to the west of 115°W longitude and incompleteness for the sources to the east of this longitude. This is the same result as found in the previous seismicity study and suggests the possibility of overestimating the occurrence of large earthquakes while, conversely, underestimating the smaller magnitude events in source regions to the east of 115°W longitude.

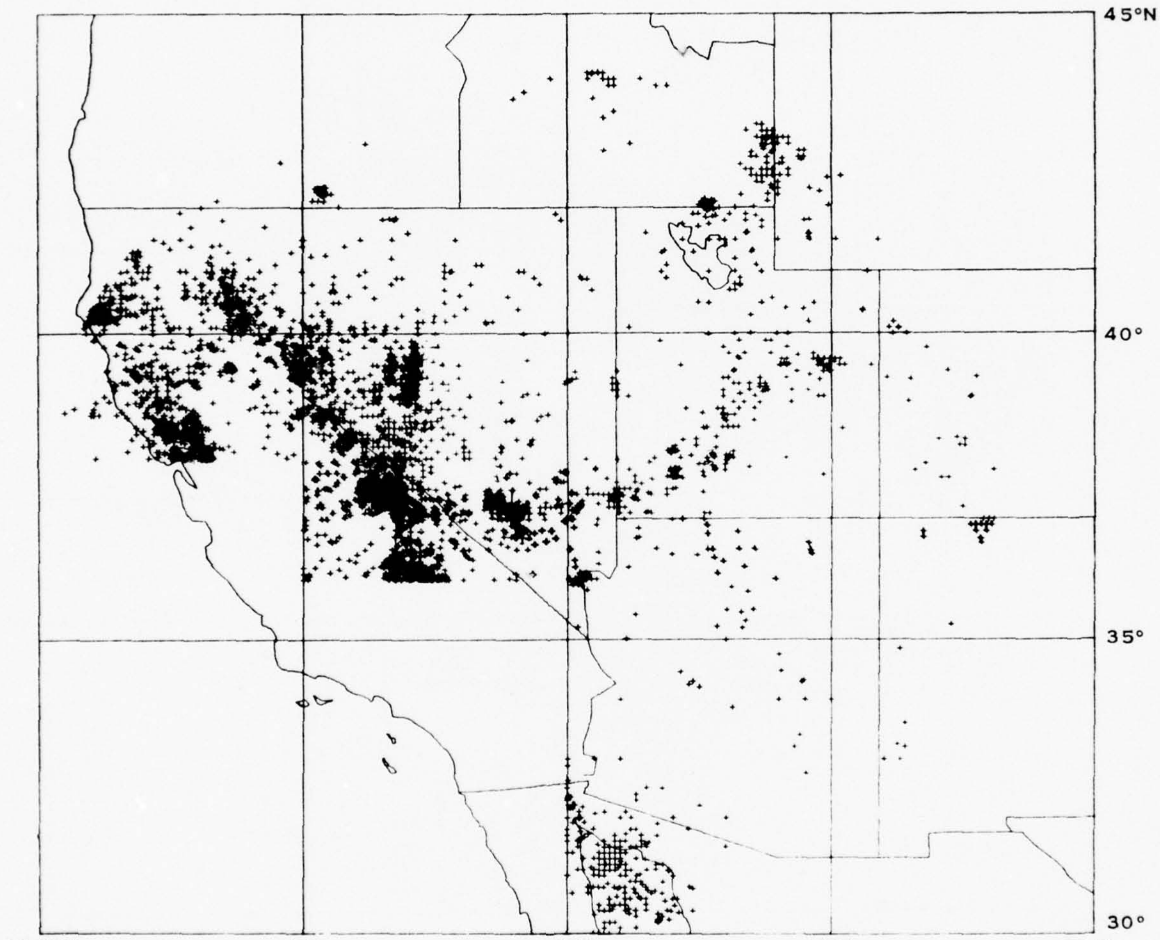

Figure III-2. Epicenters Outside Southern California Within 800 km of NTS

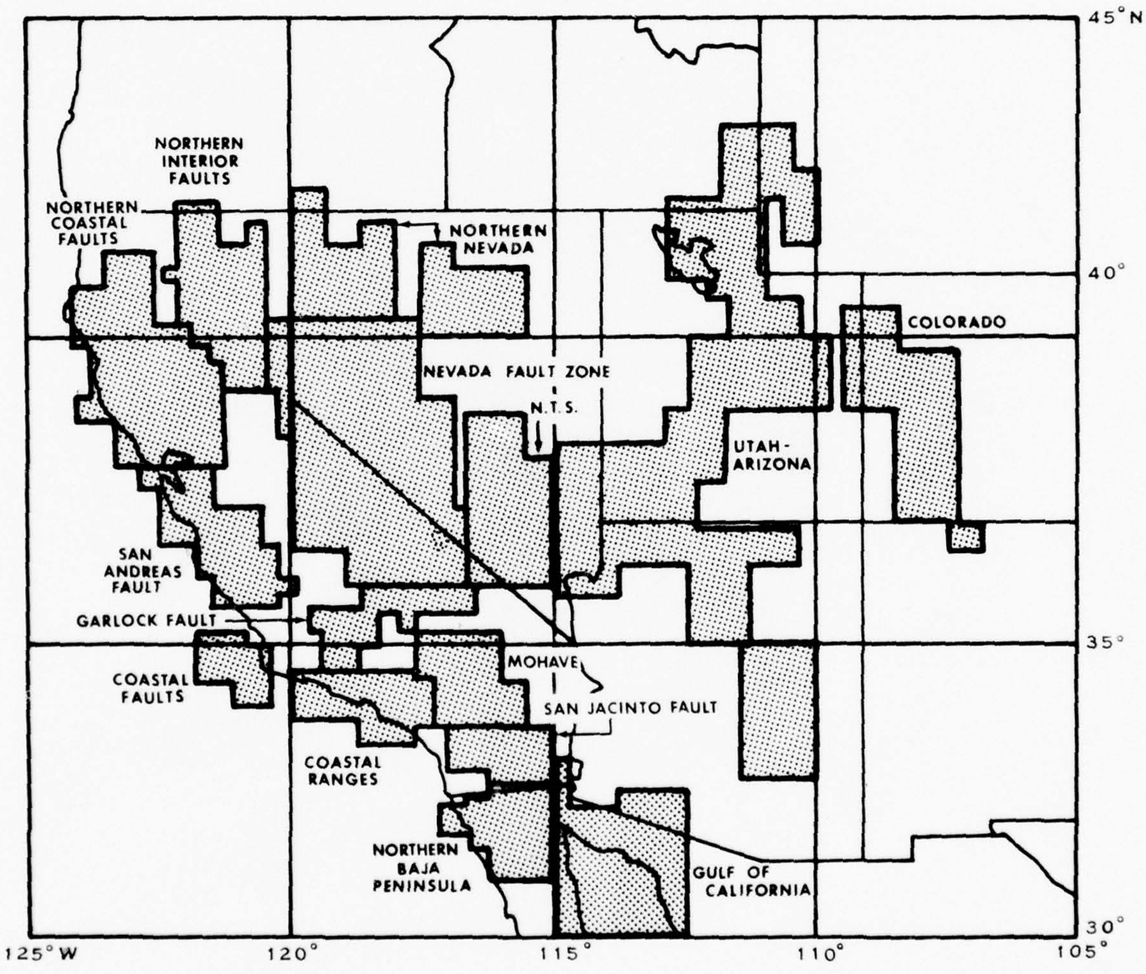

Figure III-3. Source Regions Used in the NTS Seismic Risk Analysis

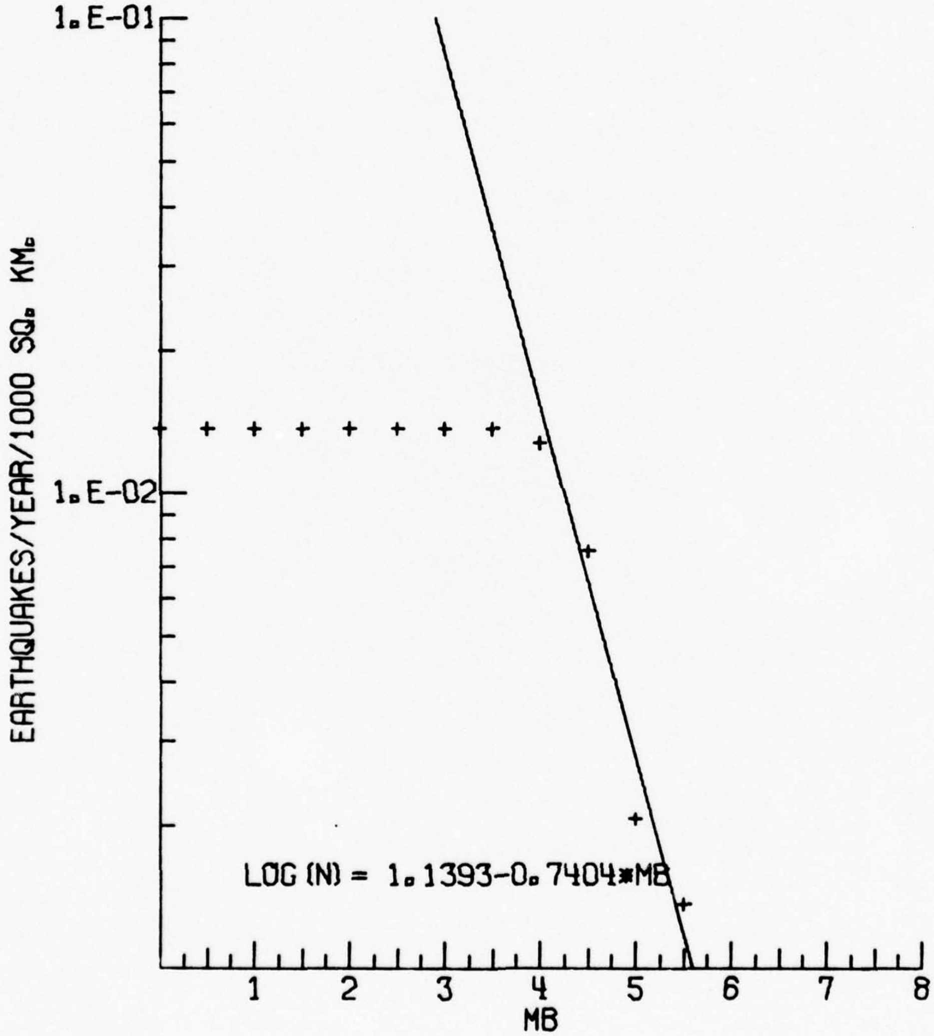

Figure III-4. Cumulative Recurrence Curve for the Colorado Source Region

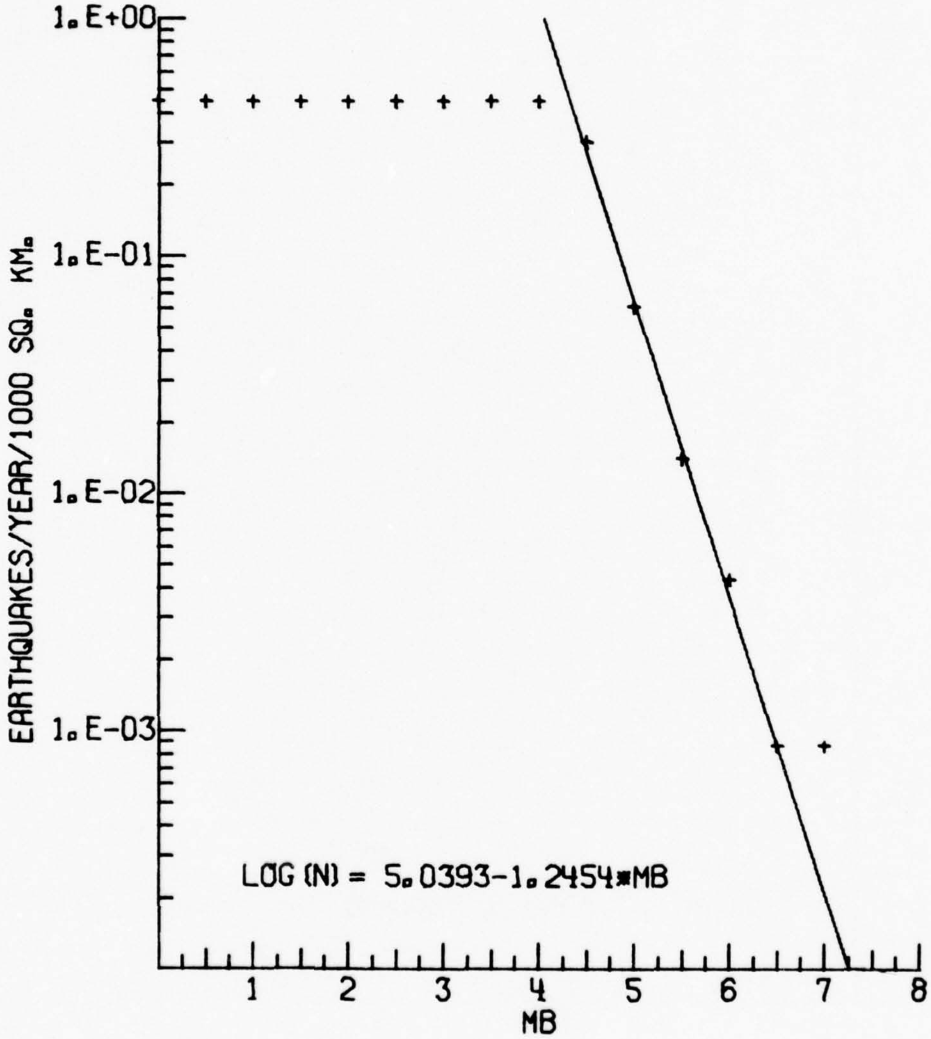

Figure III-5. Cumulative Recurrence Curve for the Garlock Fault Source Region

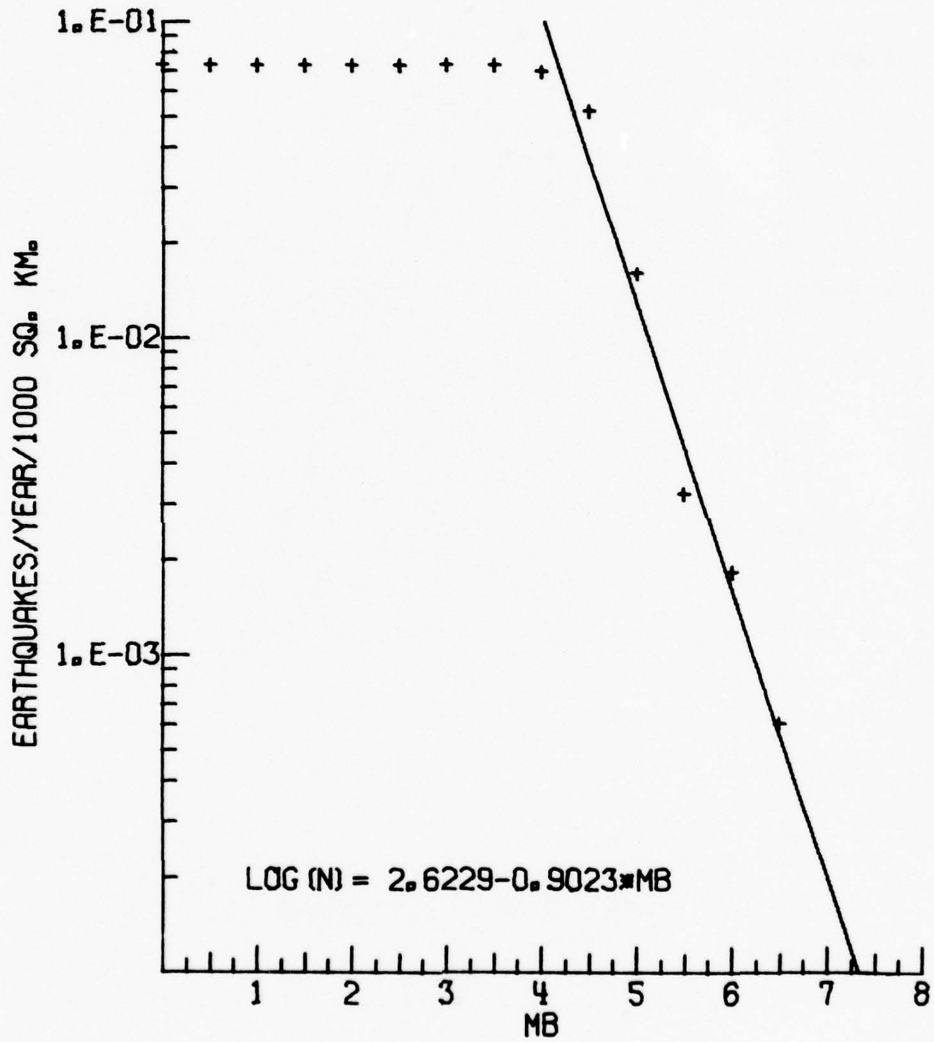

Figure III-6. Cumulative Recurrence Curve for the Gulf of California Source Region

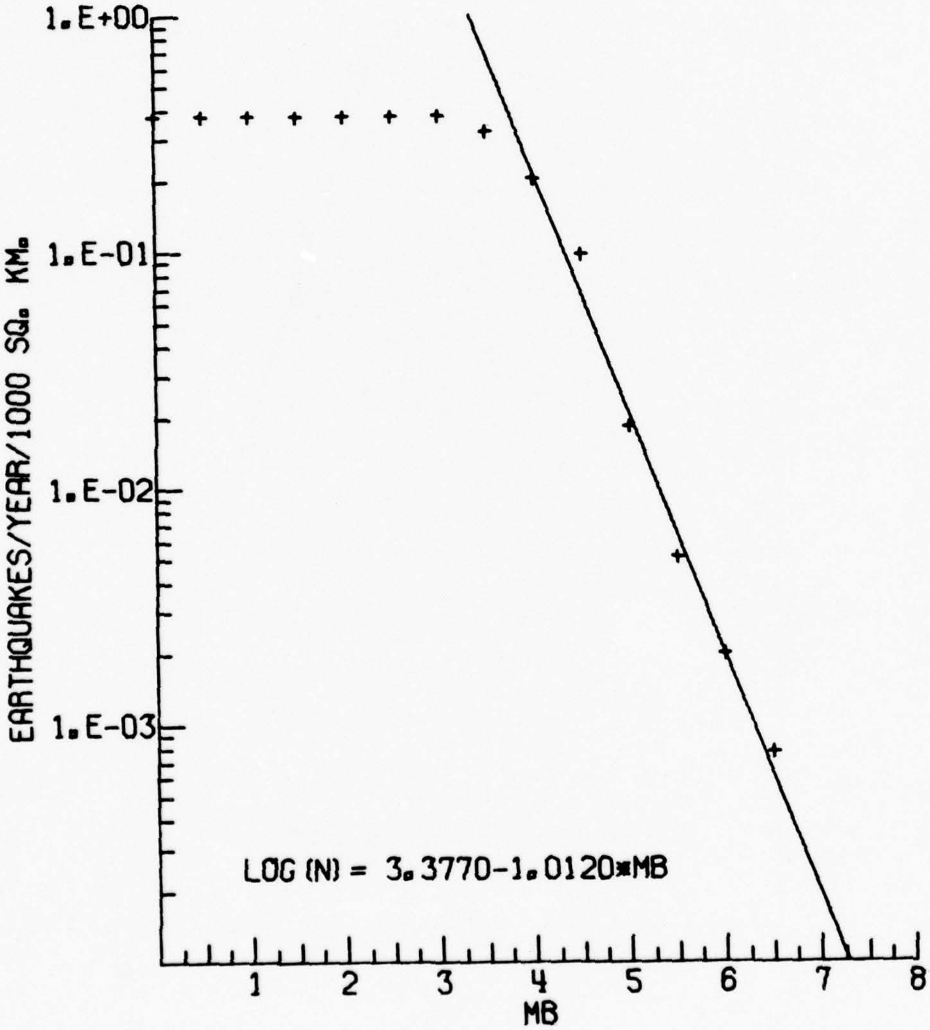

Figure III-7. Cumulative Recurrence Curve for the Nevada Fault Zone Source Region

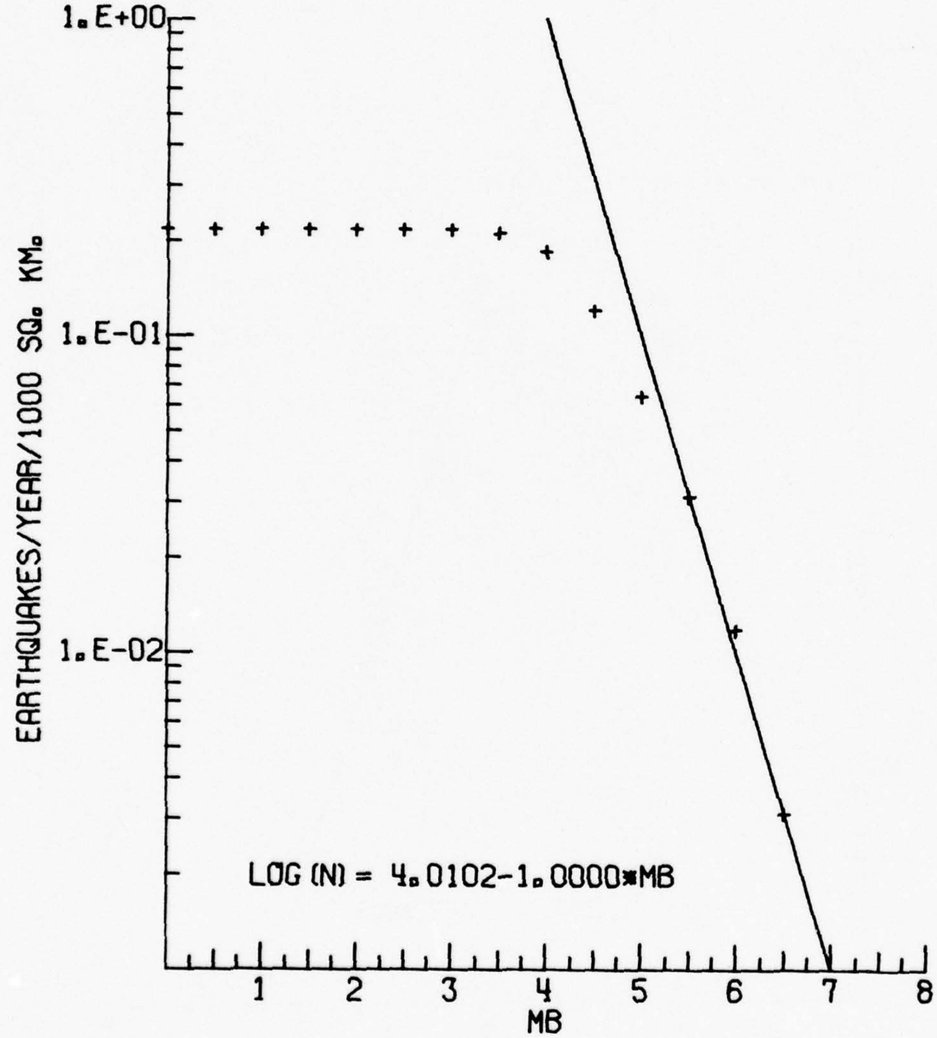

Figure III-8. Cumulative Recurrence Curve for the Nevada Test Site Source Region

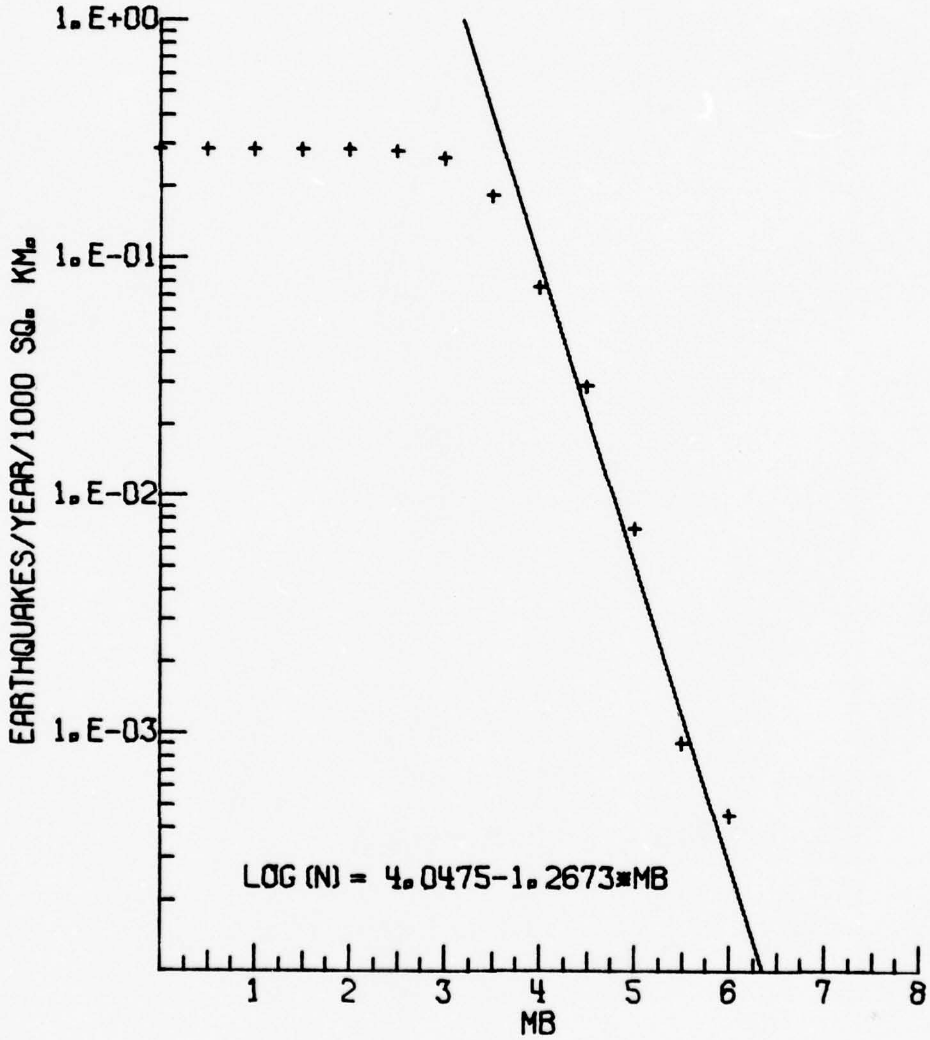

Figure III-9. Cumulative Recurrence Curve for the Northern Coastal Faults Source Region

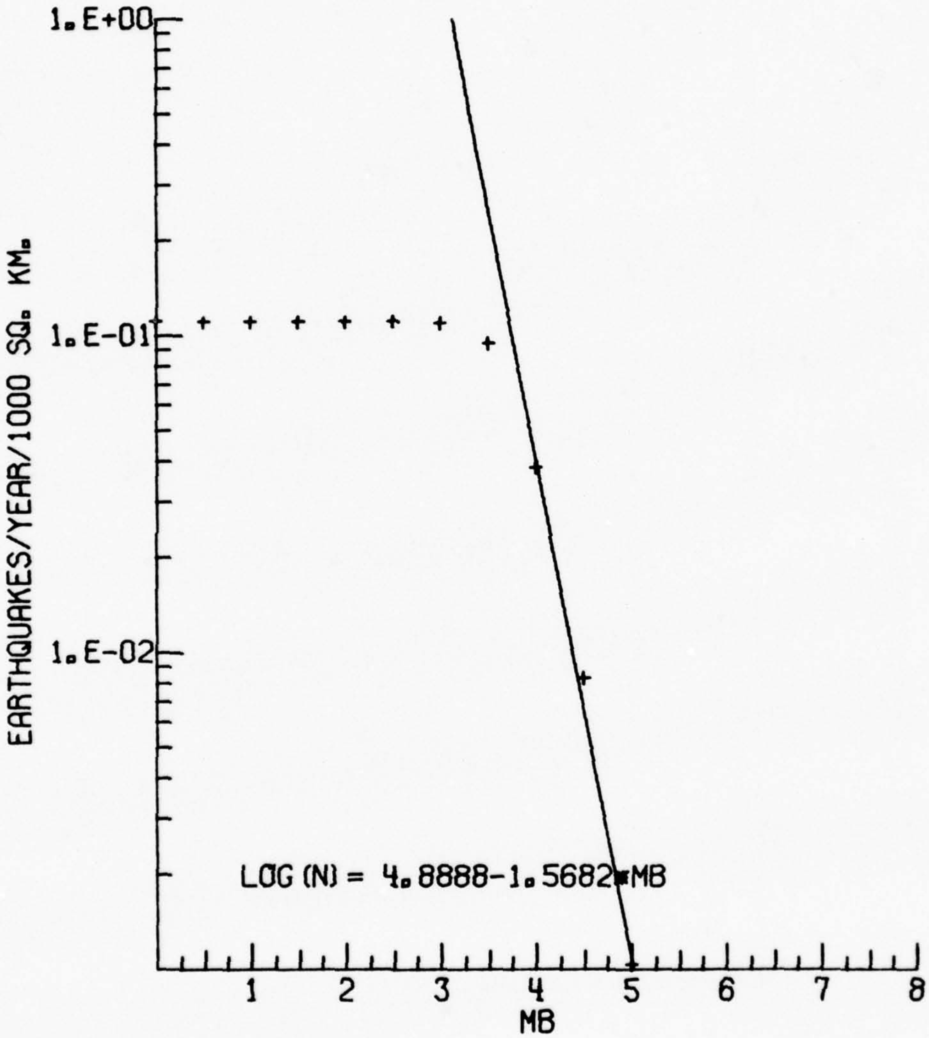

Figure III-10. Cumulative Recurrence Curve for the Northern Interior Faults Source Region

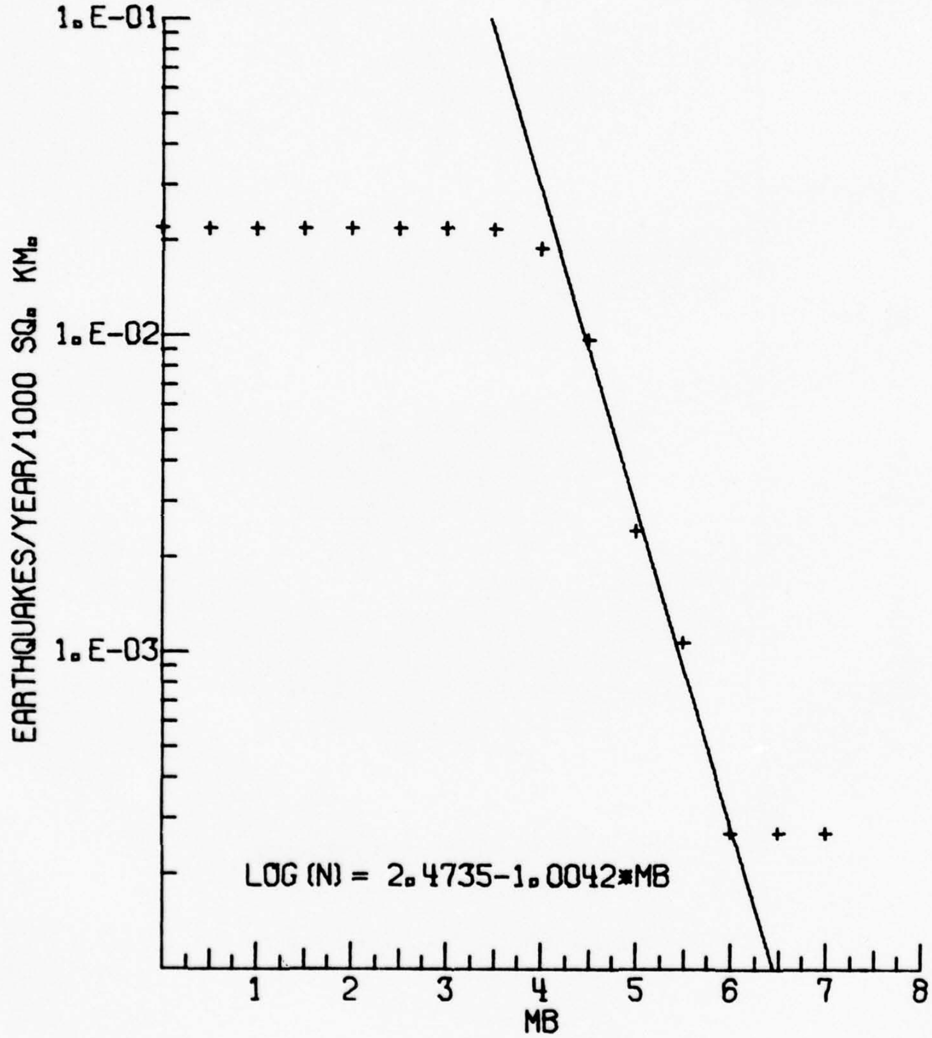

Figure III-11. Cumulative Recurrence Curve for the Northern Nevada Source Region

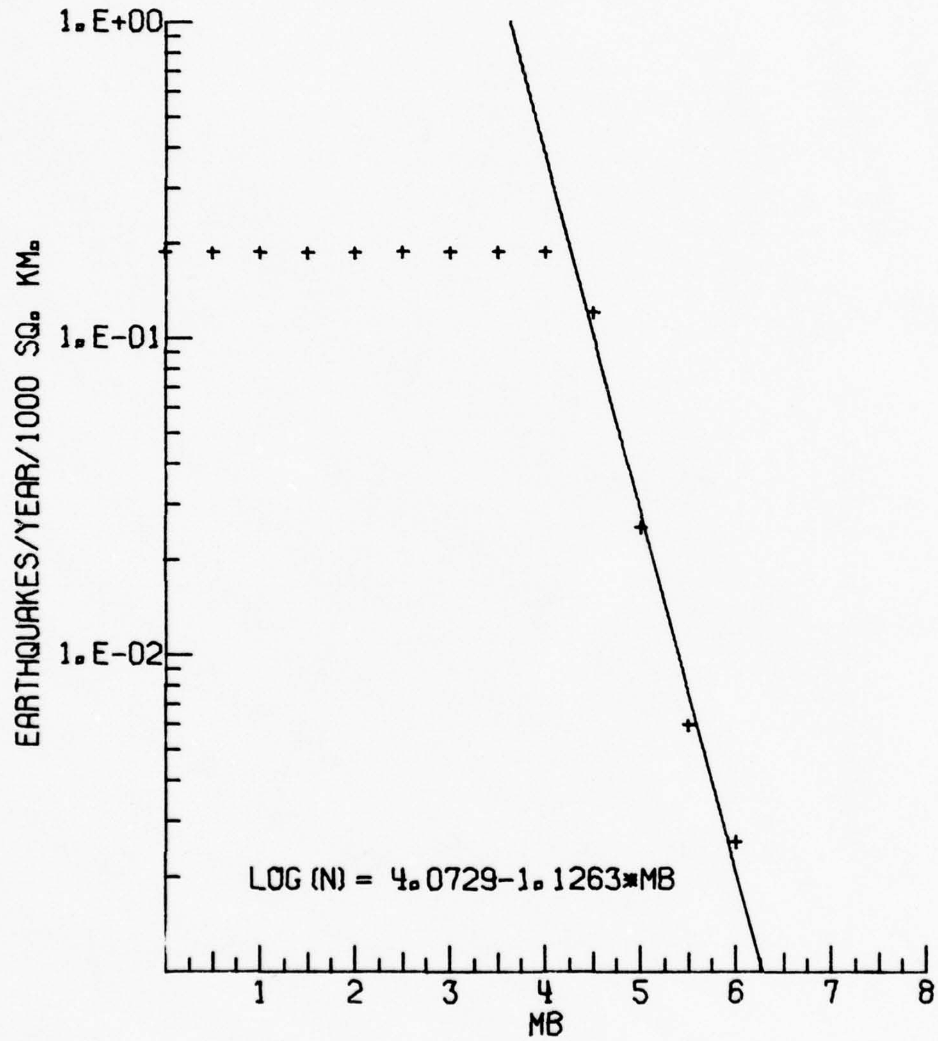

Figure III-12. Cumulative Recurrence Curve for the San Andreas Fault Source Region

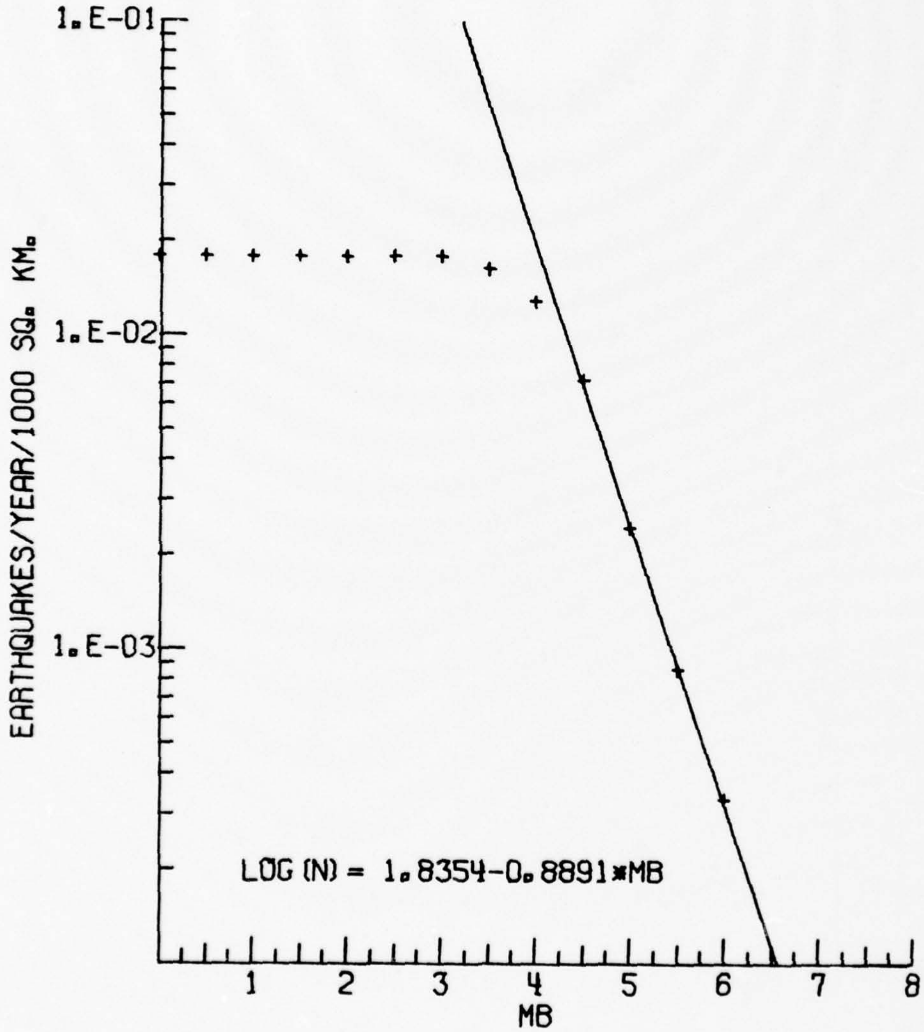

Figure III-13. Cumulative Recurrence Curve for the Utah–Arizona Source Region

TABLE III-I. SOUTHWESTERN UNITED STATES SOURCE REGION PARAMETERS

Source	A_{m_b}	b_{m_b}	Area	A_{m_L}	B_{m_L}	M_L°	M_L^{max}	$b_{m_L} \ln 10$	N/Yr at M_L°
Coastal Ranges	5.6036	1.3861	2.44×10^4	5.226	1.0382	3.9	6.1	2.3905	15.0048
Coastal Faults	4.3706	1.2131	9.61×10^3	3.8053	0.9086	3.9	6.5	2.0922	2.8364
Northern Baja Peninsula	4.8467	1.1800	2.86×10^4	4.7971	0.8838	3.9	6.9	2.0351	22.5144
San Jacinto	5.0054	1.2121	1.77×10^4	4.7061	0.9079	3.9	6.5	2.0904	14.7128
Mojave	5.3474	1.3674	2.24×10^4	4.9528	1.0242	3.9	6.5	2.3583	9.1416
San Andreas	4.0729	1.1263	3.66×10^4	4.1992	0.8436	3.9	7.5	1.7425	2.2276
Northern Coastal	4.0475	1.2673	6.08×10^4	4.2143	0.9492	3.9	7.25	2.1856	0.5381
Northern Interior	4.8888	1.5682	3.38×10^4	4.4167	1.1746	3.9	7.0	2.7046	0.2041
Nevada Fault Zone	3.3770	1.0120	1.36×10^5	4.2192	0.7580	3.9	8.25	3.8975	1.7453
Garlock Fault	5.0393	1.2454	1.95×10^4	4.7402	0.9328	3.9	7.75	2.1479	6.5247
Utah–Arizona	1.8354	0.8891	1.73×10^5	2.9390	0.6659	3.9	6.1	1.5334	2.2053
Gulf of California	2.6229	0.9023	8.19×10^4	3.3848	0.6758	3.9	6.9	1.5561	0.6879
Nevada Test Site	4.0102	1.000	3.91×10^4	4.3264	0.7490	3.9	7.0	1.7246	6.5309
Northern Nevada	2.4735	1.0042	5.03×10^4	2.8937	0.7521	3.9	7.5	1.7319	0.1822
Colorado	1.1393	0.7404	4.69×10^4	1.8657	0.5546	3.9	6.1	1.2769	0.1079

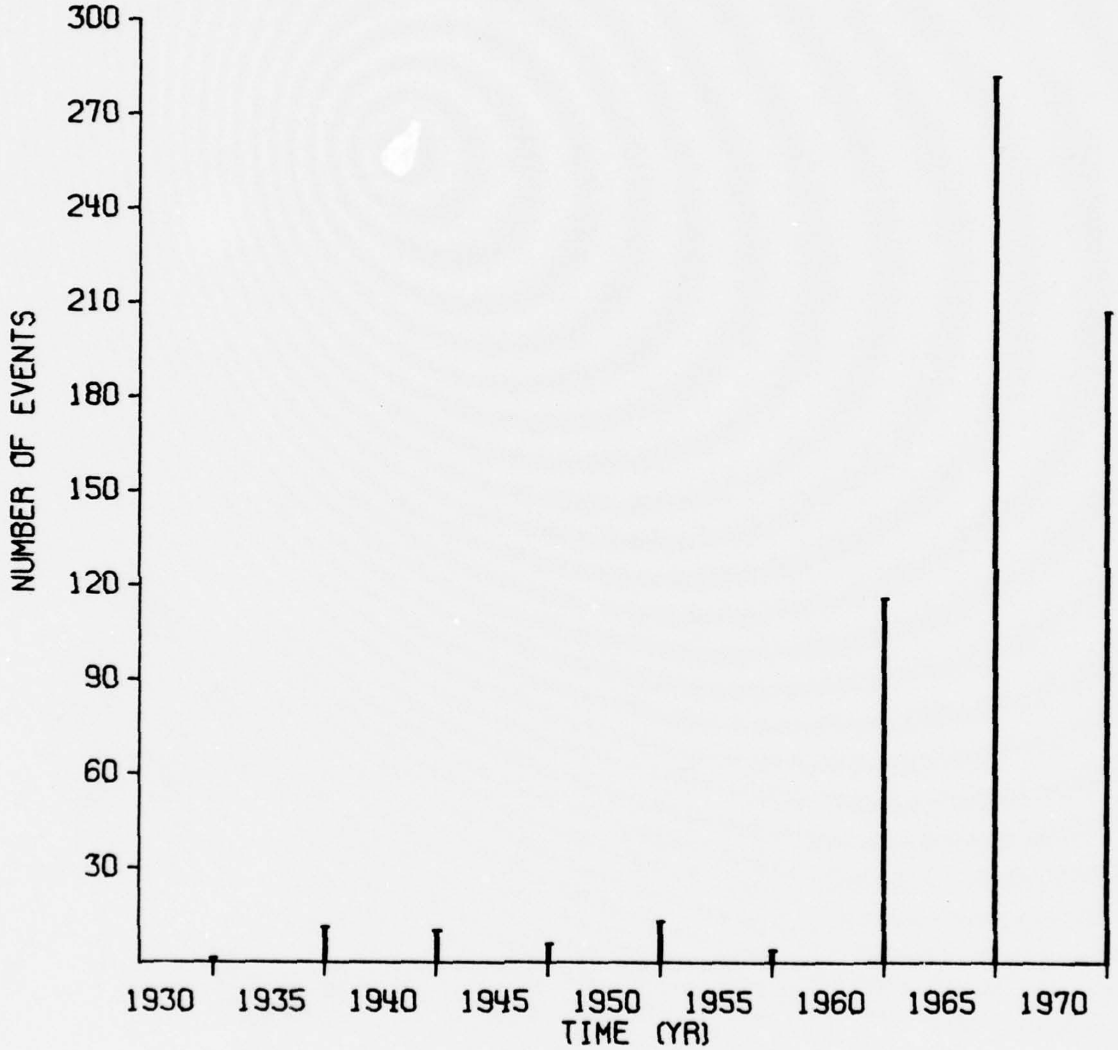

Figure III-14. Histogram of all Seismic Events Reported Within the NTS Source Region

B. SEISMIC RISK EVALUATION

In contrast to the other seismicity studies, in this case the site of interest lies inside of one of the defined source regions, specifically NTS. Obviously, the seismic risk evaluation will become extremely sensitive to the rate of seismic activity assigned to this source area. As no definitive recurrence curve could be generated for NTS, several hypotheses of the seismic activity for NTS should be used.

The first of these hypotheses was to use the recurrence function given in Table III-1 for NTS. This relation was derived using all events at NTS, including announced and unannounced nuclear explosions and any associated aftershocks. It is apparent that this curve should represent the upper limit of the possible recurrence curves which might be valid for this source area if testing were to stop. In addition, it demonstrates the effects at NTS if testing were to continue at the present level.

The second hypothesis allows only the normal regional background activity determined in the seismicity study to occur at NTS (eliminating NTS as a specific source). Finally, the third hypothesis assumes that the seismic activity rate found for the Nevada Fault Zone source area holds at NTS with appropriate correction for total source area. In the following discussions, these are known as hypotheses H1 through H3, respectively.

Using hypothesis H1, a plot of the contours of the 100-year return period peak ground accelerations at NTS was generated. However, within the NTS source area, the contours were essentially flat with some peak ground acceleration falloff, at the bounds of the source region, caused by edge effects. Thus, the contours were more closely related to the exact definition of the source region boundaries than to any physical reality. Without a much more detailed description of the local seismicity, any discussion of the spatial variation of risk was unwarranted. Given the level of analysis that could be carried out for this study, it would be best to assume that the level of risk was uniform over all of NTS.

In Figures III-15 through III-17, the peak ground acceleration, velocity, and displacement curves for NTS, based on each of the three hypotheses, are shown. The ground motion values associated with specified annual risks are also listed in Tables III-2 through III-4.

In general, the curves associated with hypothesis H1 are overly conservative but are almost assuredly an absolute upper limit of all reasonable risk curves. It seems reasonable to hold that hypothesis H3 produces the most realistic curves based on the fact that NTS, even without nuclear testing, is a more active source region than the background levels could represent. However, using hypothesis H2, a lower limit on the seismic risk at NTS can be evaluated.

A seismic hazard assessment for NTS has also been conducted by Rogers, et al. (1977) with methods that were significantly different than those used in this study. However, the results of their analysis are in agreement with those found in this study. In addition, Algermissen and Perkins (1972) have also analyzed the seismic risk for areas of Arizona reasonably close to NTS and have found compatible results. Thus, the risk curves presented here constitute very reasonable estimates of the seismic hazard at NTS.

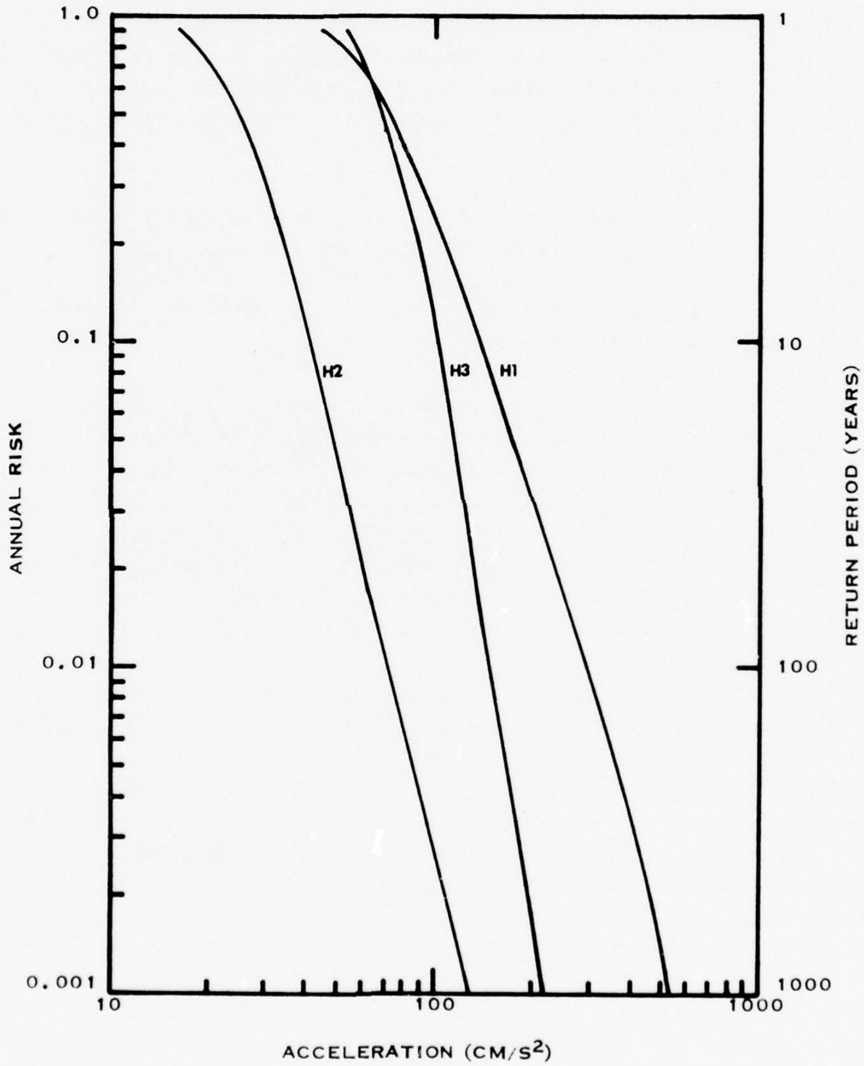

Figure III-15. Peak Ground Acceleration Risk Curves for NTS, Based on Hypotheses H1, H2, and H3

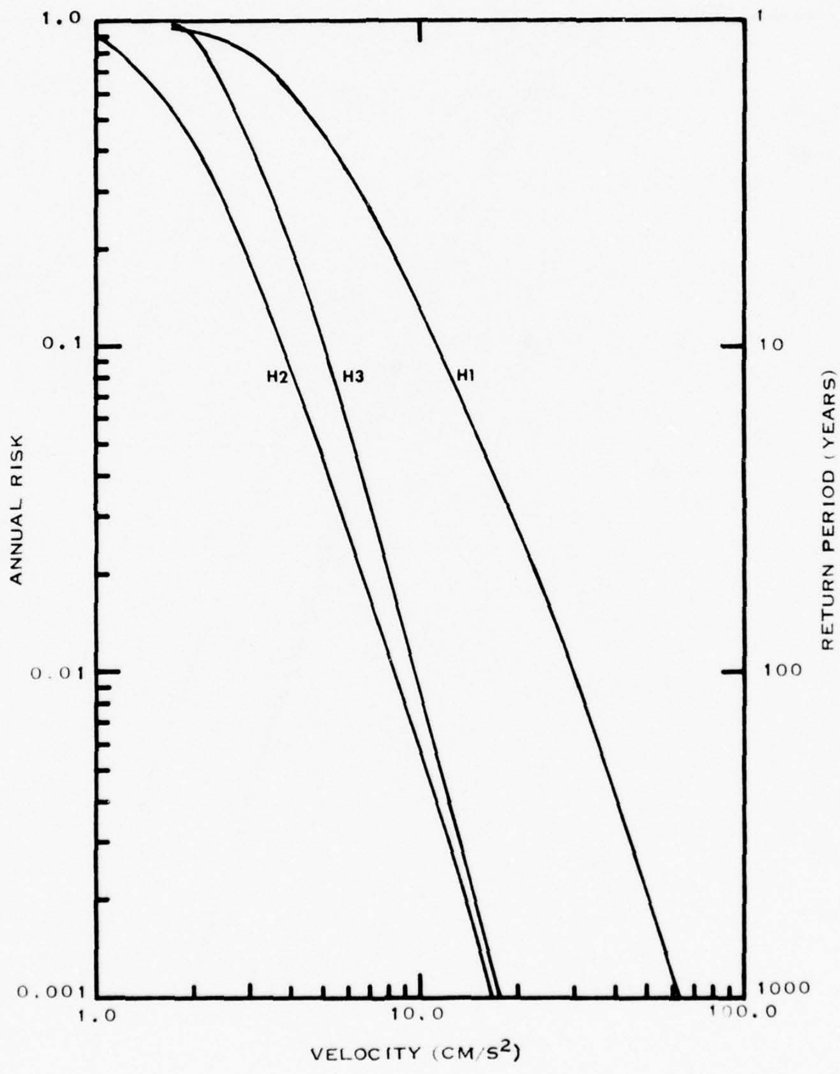

Figure III-16. Peak Ground Velocity Risk Curves for NTS, Based on Hypotheses H1, H2, and H3

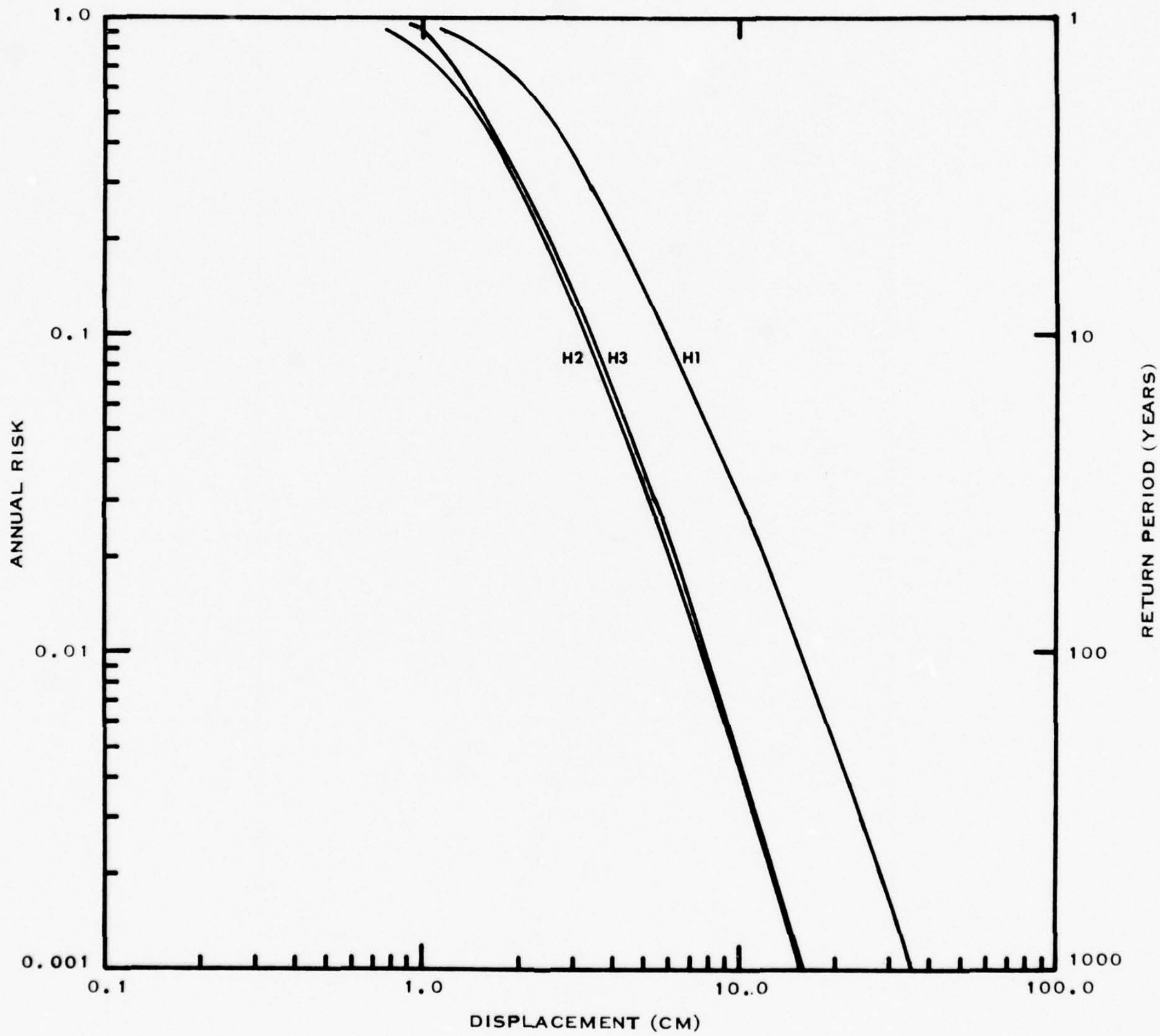

Figure III-17. Peak Ground Displacement Risk Curves for NTS, Based on Hypotheses H1, H2, and H3

TABLE III-2. PEAK GROUND ACCELERATION RISK LEVELS FOR NEVADA TEST SITE

Risk/Year	Return Period (Years)	Hypothesis H1	H2	H3
1.0	1	25.4	15.0	49.0
0.5	2	71.5	25.6	72.6
0.2	5	107.8	33.0	88.2
0.1	10	139.7	39.6	100.9
0.05	20	177.6	47.3	113.7
0.02	50	238.7	59.8	132.9
0.01	100	294.4	71.5	149.2
0.005	200	359.0	85.2	167.5
0.002	500	459.8	107.3	195.1
0.001	1000	547.6	127.4	218.9

TABLE III-3. GROUND VELOCITY RISK LEVELS FOR NEVADA TEST SITE

Risk/Year	Return Period (Years)	Hypothesis H1	H2	H3
1.0	1	1.0	0.5	1.0
0.5	2	4.7	1.9	2.7
0.2	5	8.4	2.9	4.1
0.1	10	11.8	3.9	5.0
0.05	20	16.2	4.9	6.2
0.02	50	23.5	6.8	8.0
0.01	100	30.6	8.6	9.7
0.005	200	38.9	10.6	11.7
0.002	500	52.1	13.9	15.0
0.001	1000	64.0	16.9	17.9

TABLE III-4. PEAK GROUND DISPLACEMENT RISK LEVELS AT NEVADA TEST SITE

Risk/Year	Return Period (Years)	H1	Hypothesis H2	H3
1.0	1	0.5	0.5	0.5
0.5	2	2.4	1.4	1.6
0.2	5	4.3	2.4	2.5
0.1	10	6.0	3.2	3.4
0.05	20	8.4	4.3	4.4
0.02	50	12.3	6.0	6.0
0.01	100	16.0	7.6	7.7
0.005	200	20.4	9.6	9.6
0.002	500	27.6	12.7	12.7
0.001	1000	34.1	15.5	15.6

C. COMPOSITE RESPONSE SPECTRA

As in the previous studies, composite response spectra for 10-, 100-, and 1,000-year return periods for each of the hypotheses were constructed and are shown in Figures III-18 through III-26. The statements made above concerning the risk curves evaluated, using each of the different hypotheses, also holds true for these response spectra. For example, the response spectra found using hypothesis H3 are more reasonable. Once again, only 0.5 percent and 10 percent of critical damping spectra are shown, as these represent the upper and lower limits, respectively, of the reasonable variations caused by local soil conditions.

D. FAULTS AT NTS

In Figure III-27, the major potentially active faults near NTS are shown (Rogers, et al., 1977; Howard, et al., 1978). In addition to these, numerous smaller faults have been identified in the area (Stewart and Carlson, 1974). While these minor faults should not be eliminated as potential sources of at least locally high-amplitude peak ground motions, on an overall regional basis, the longer faults could generate the most severe motions. For most faults, though even more so for the smaller faults, it is difficult to estimate the state of activity or inactivity of a fault. Table III-5 is a list of these faults and estimates of the maximum creditable earthquake which can be associated with them. The magnitudes of the maximum creditable earthquakes were evaluated using Equation (II-7) and estimates of the maximum rupture lengths determined for each of the faults.

TABLE III-5. POTENTIALLY ACTIVE FAULTS NEAR NEVADA TEST SITE
(Modified From Rogers, et al. 1979)

Fault Name	Fault Length (Miles)	Probable Rupture Length	Maximum Creditable Earthquake
Mine Mountain	18	18	6.8
Cane Spring*	15	15	6.6
Rock Valley*	22	22	6.9
Mercury Valley	2.5	2.5	5.6
Yucca*	16	16	6.7
Bare Mountain	5	5	6.0
Funeral Mountains	24	24	6.9
Death Valley*	84	42	7.3
Furnace Creek*	145	75	7.6
Las Vegas	84	42	7.3
Kawich Valley	28	28	7.0

*Holocene rupture or historic seismic activity.

Using the maximum creditable earthquakes given in Table III-5, a contour map of the maximum creditable peak ground accelerations was generated. This plot was generated assuming that the maximum creditable earthquake assigned to each fault has a uniform probability of occurring at any point along the fault. The evaluation of the contours of peak ground acceleration were made using the attenuation curve parameters given in Table II-2. This contour map is displayed in Figure III-28.

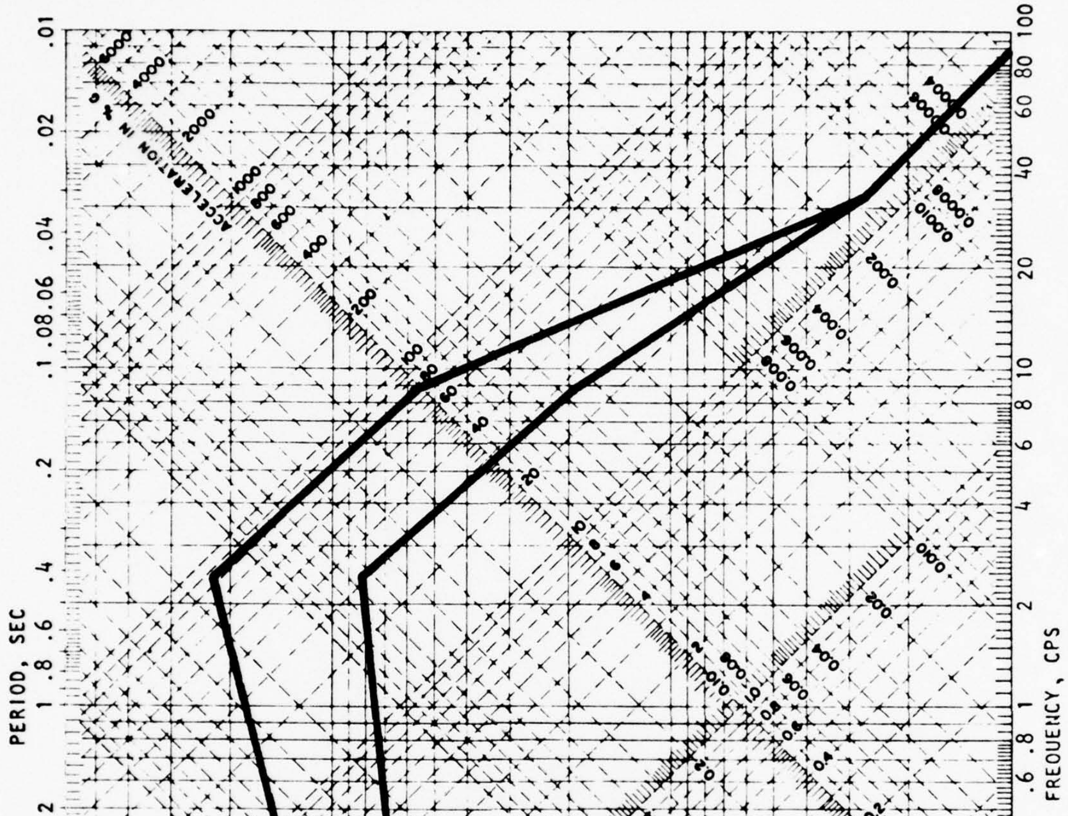

Figure III-18. Composite Response Spectra for NTS for 10-Year Return Period Ground Motions, Assuming Hypothesis H1 [0.5 Percent (Upper) and 10 Percent (Lower) of Critical Damping Curves Shown]

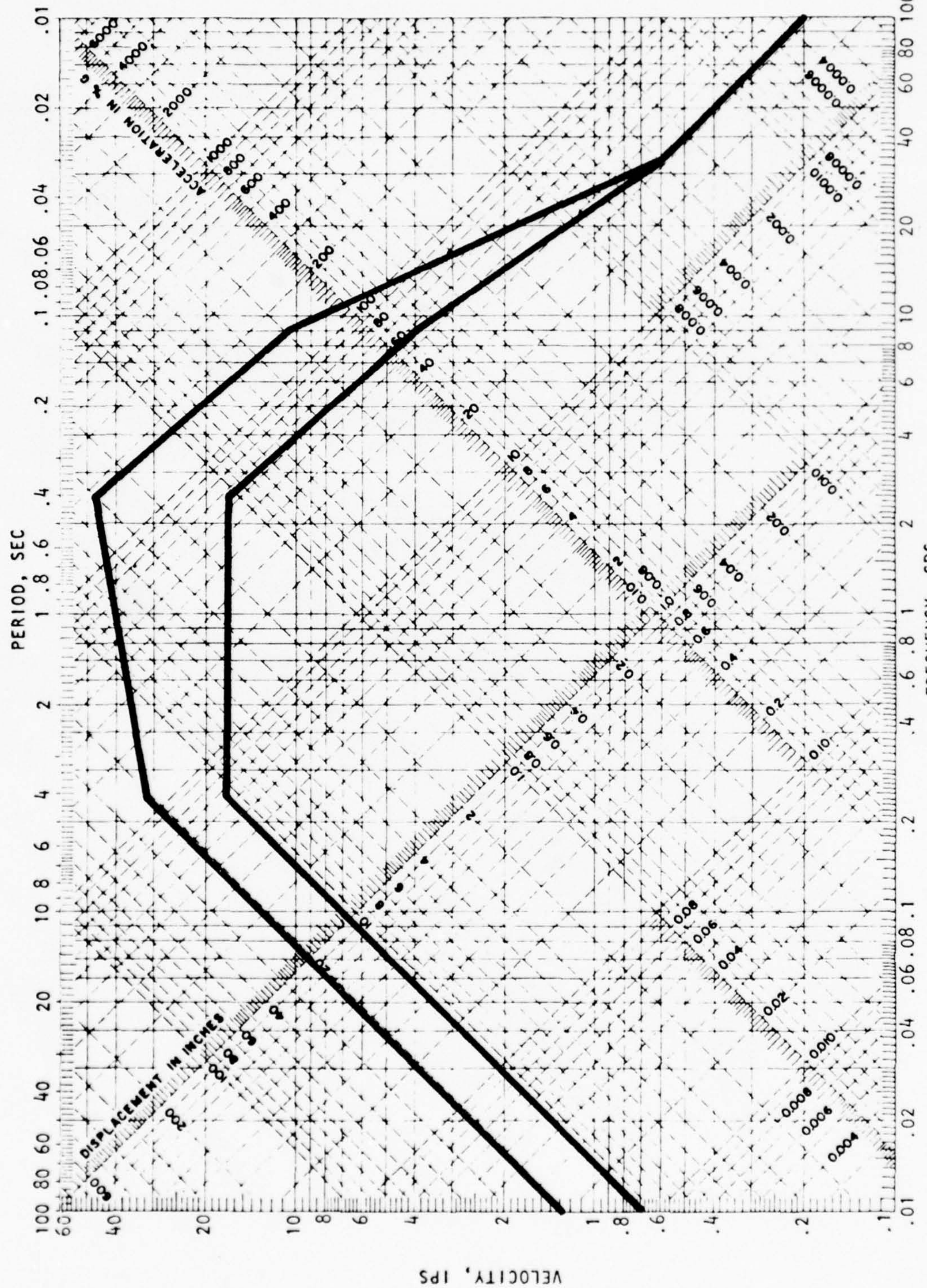

Figure III-19. Composite Response Spectra for NTS for 100-Year Return Period Ground Motions, Assuming Hypothesis H1 [0.5 Percent (Upper) and 10 Percent (Lower) of Critical Damping Curves Shown]

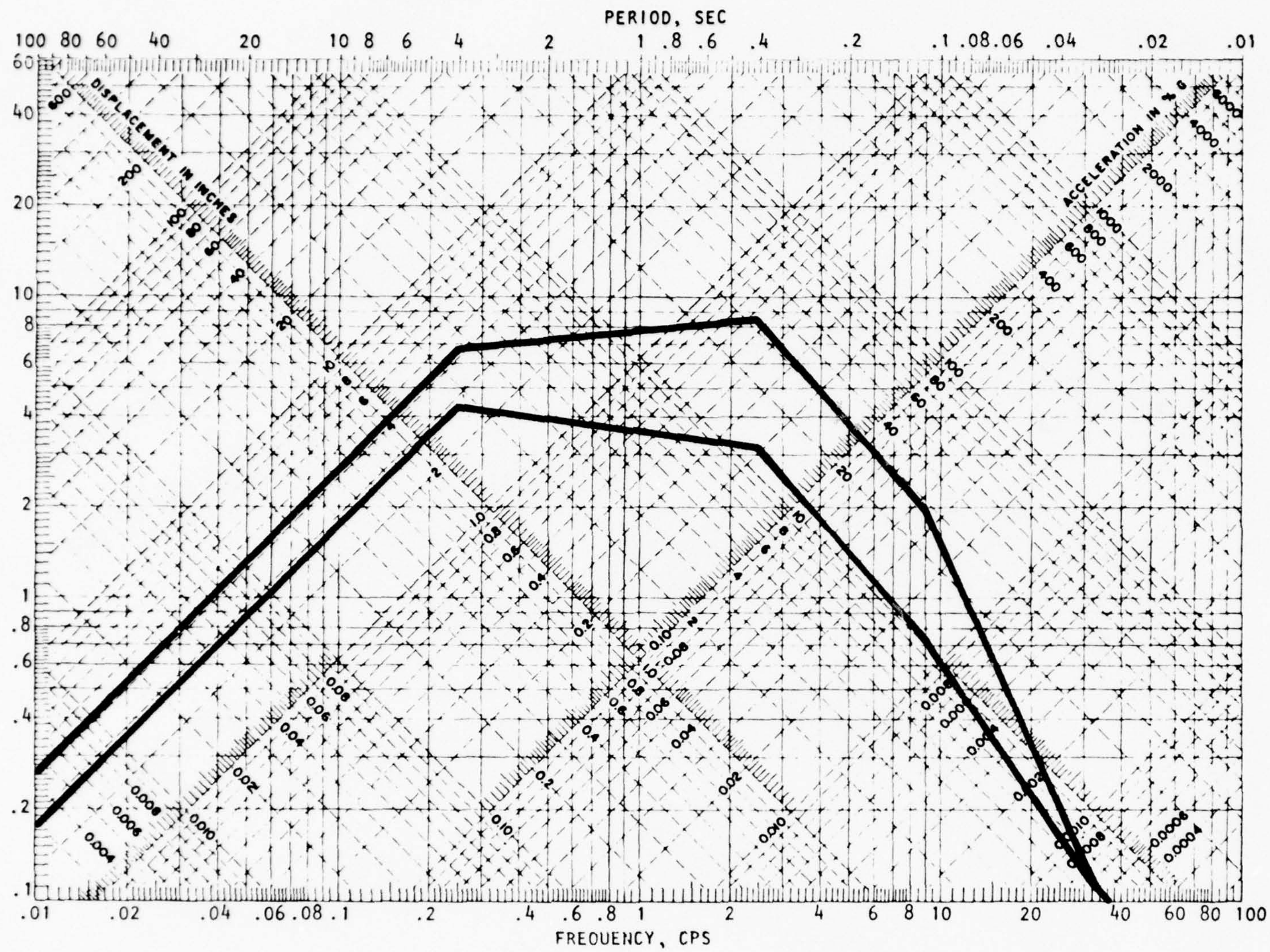

Figure III-20. Composite Response Spectra for NTS for 1000-Year Return Period Ground Motions, Assuming Hypothesis H1 Plotted at 0.1× True Responses [0.5 Percent (Upper) and 10 Percent (Lower) of Critical Damping Curves Shown]

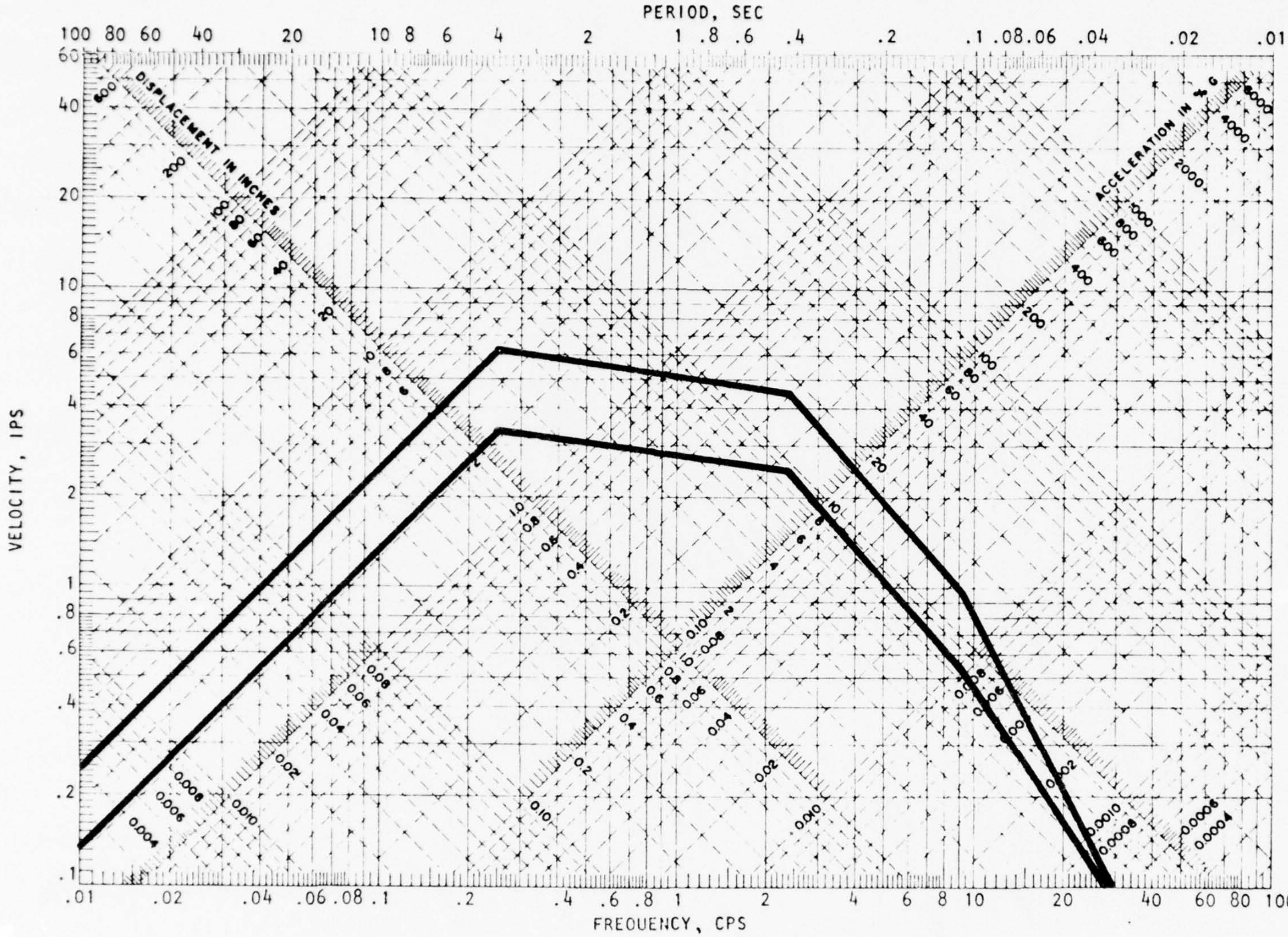

Figure III-21. Composite Response Spectra for NTS for 10-Year Return Period Ground Motions, Assuming Hypothesis H2 [0.5 Percent (Upper) and 10 Percent (Lower) of Critical Damping Curves Shown]

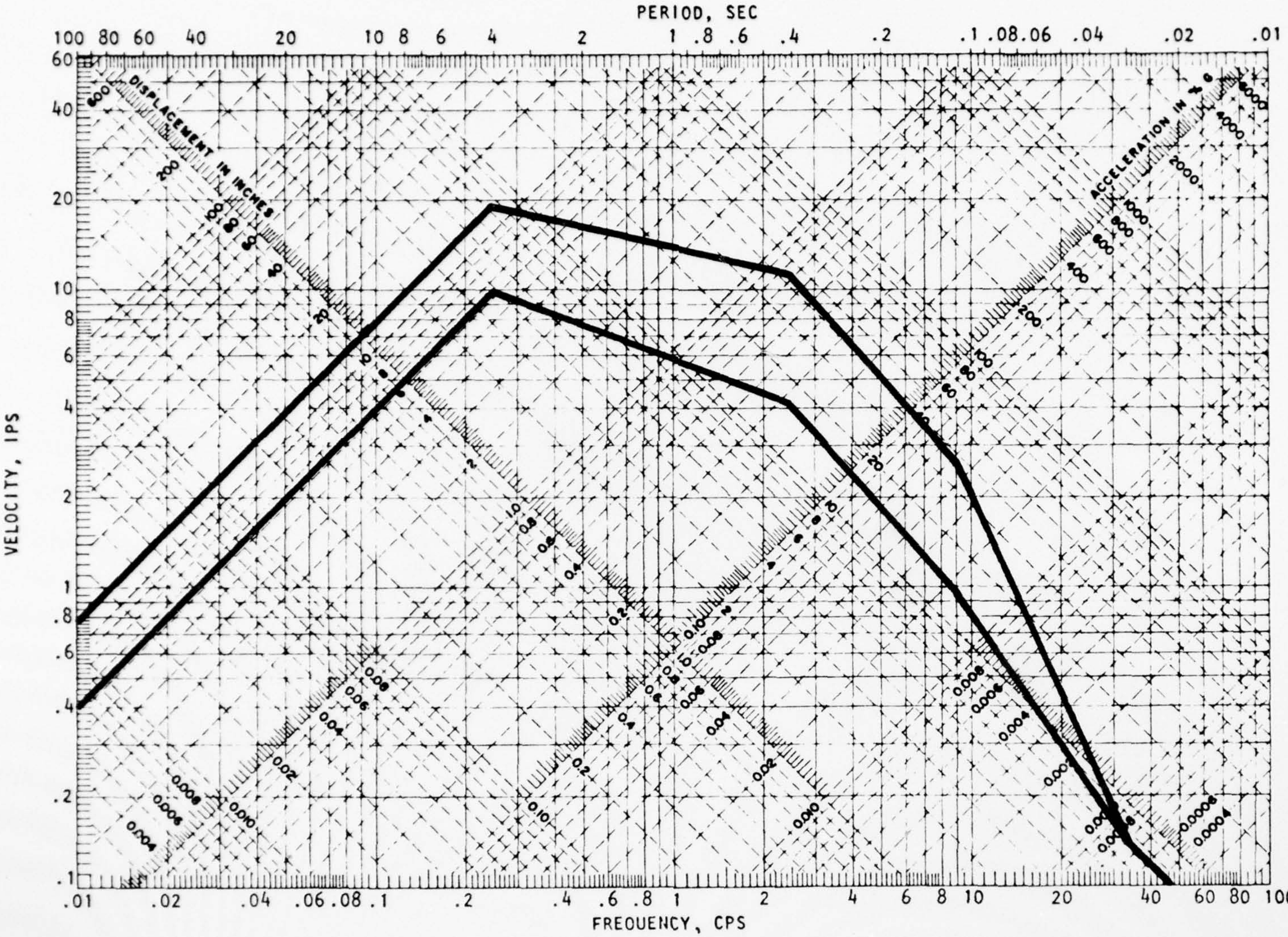

Figure III-22. Composite Response Spectra for NTS for 100-Year Return Period Ground Motions, Assuming Hypothesis H2 [0.5 Percent (Upper) and 10 Percent (Lower) of Critical Damping Curves Shown]

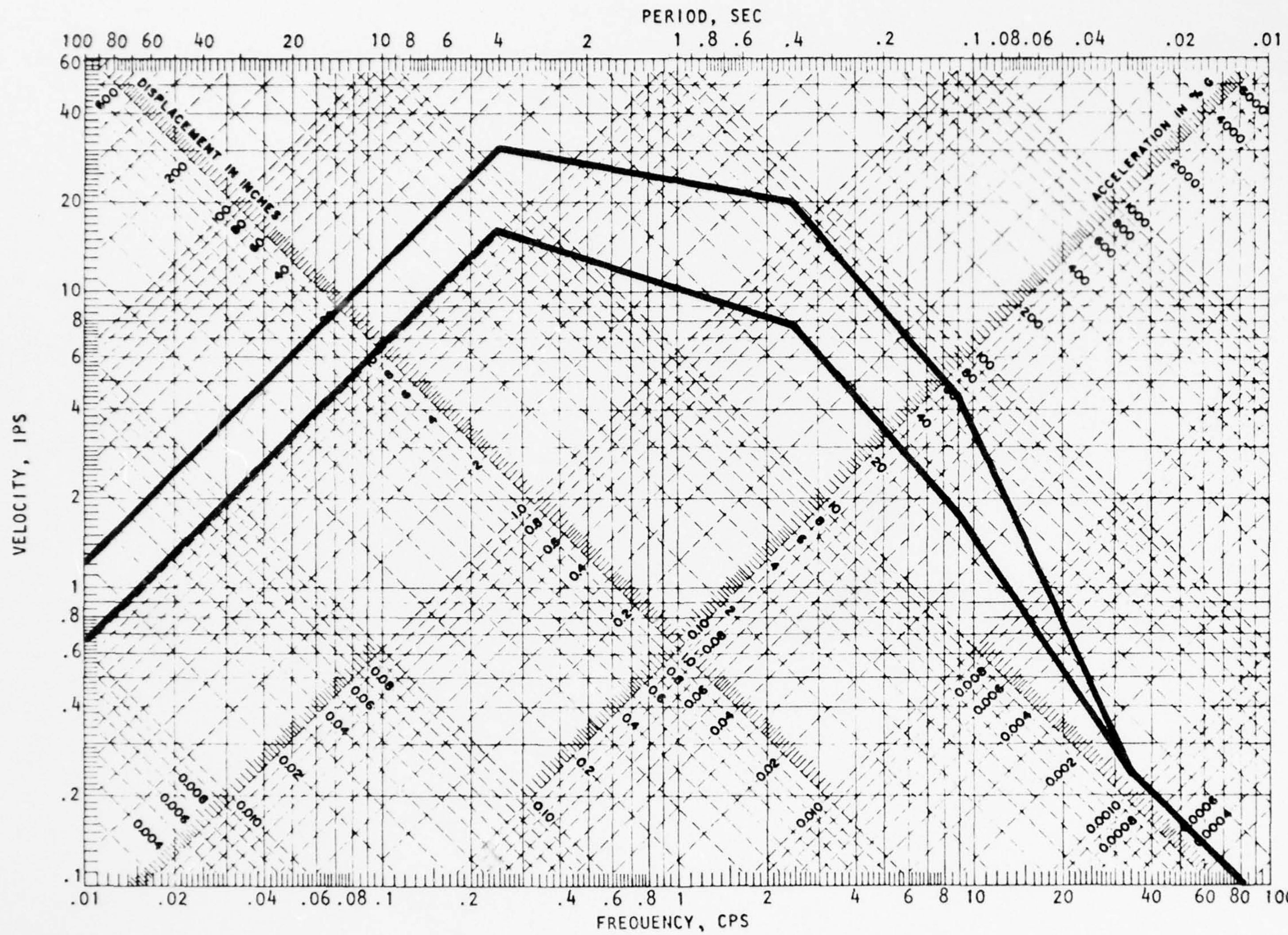

Figure III-23. Composite Response Spectra for NTS for 1000-Year Return Period Ground Motions, Assuming Hypothesis H2 [0.5 Percent (Upper) and 10 Percent (Lower) of Critical Damping Curves Shown]

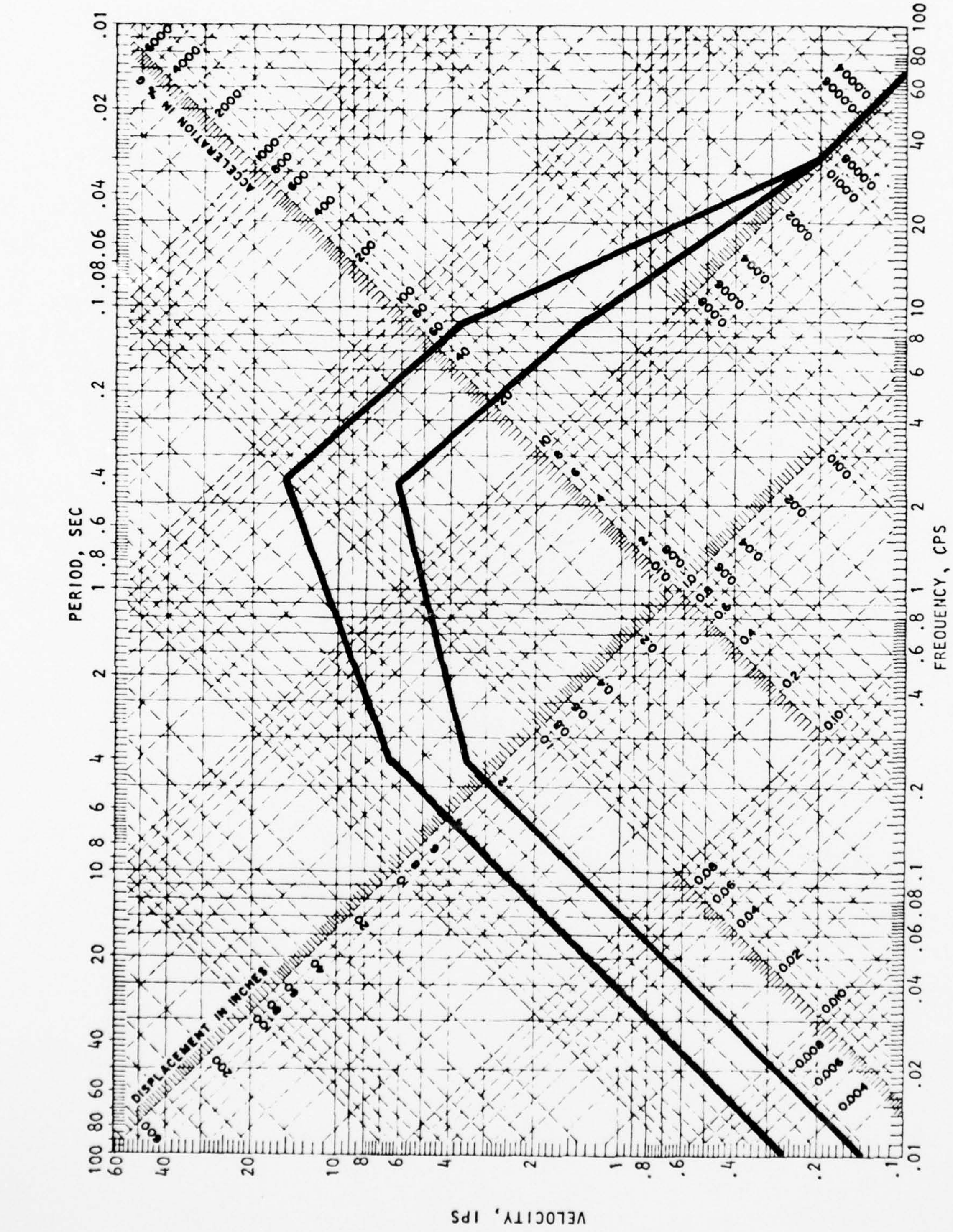

Figure III-24. Composite Response Spectra for NTS for 10-Year Return Period Ground Motions, Assuming Hypothesis H3 [0.5 Percent (Upper) and 10 Percent (Lower) of Critical Damping Curves Shown]

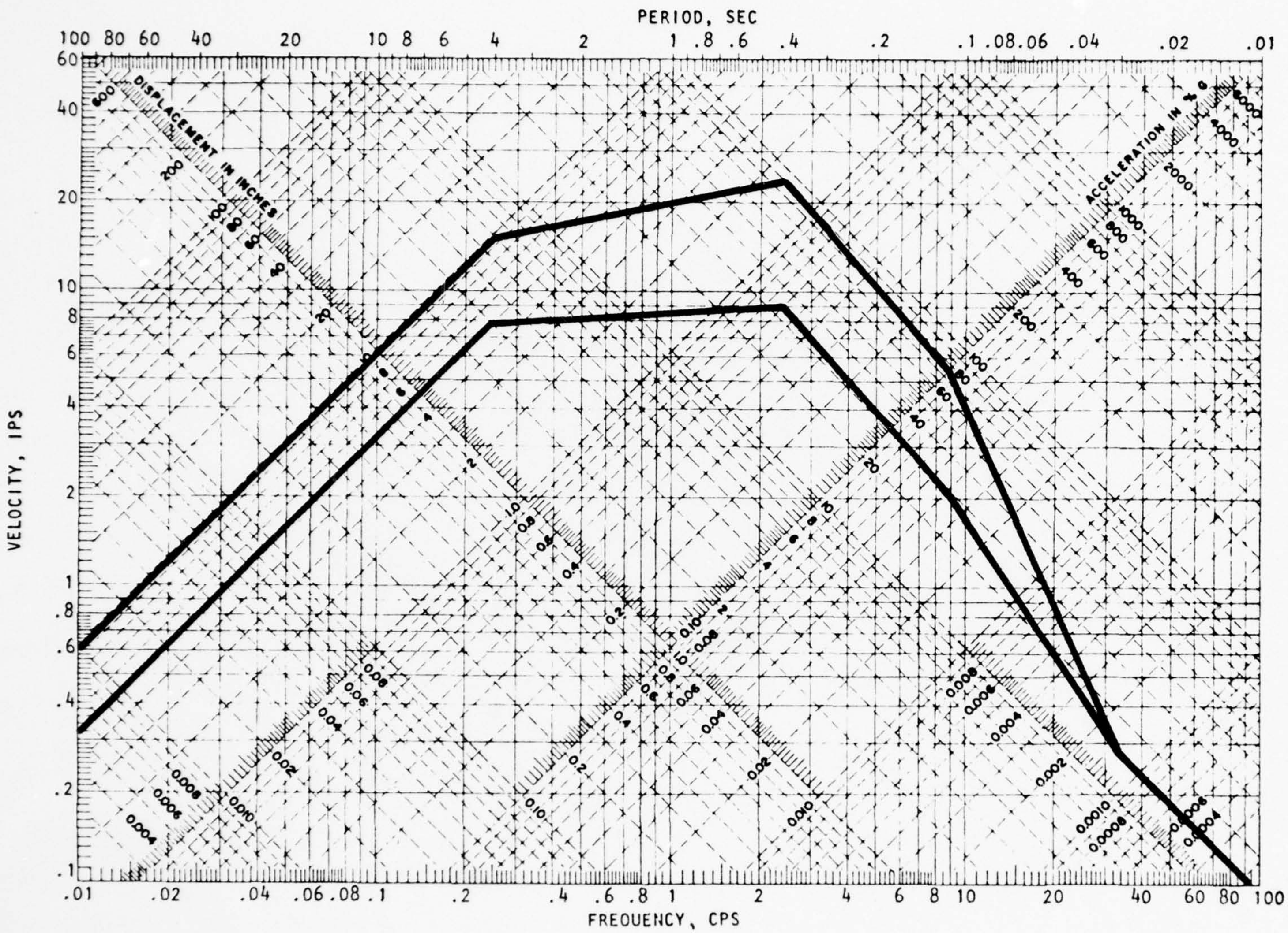

Figure III-25. Composite Response Spectra for NTS for 100-Year Return Period Ground Motions, Assuming Hypothesis H3 [0.5 Percent (Upper) and 10 Percent (Lower) of Critical Damping Curves Shown]

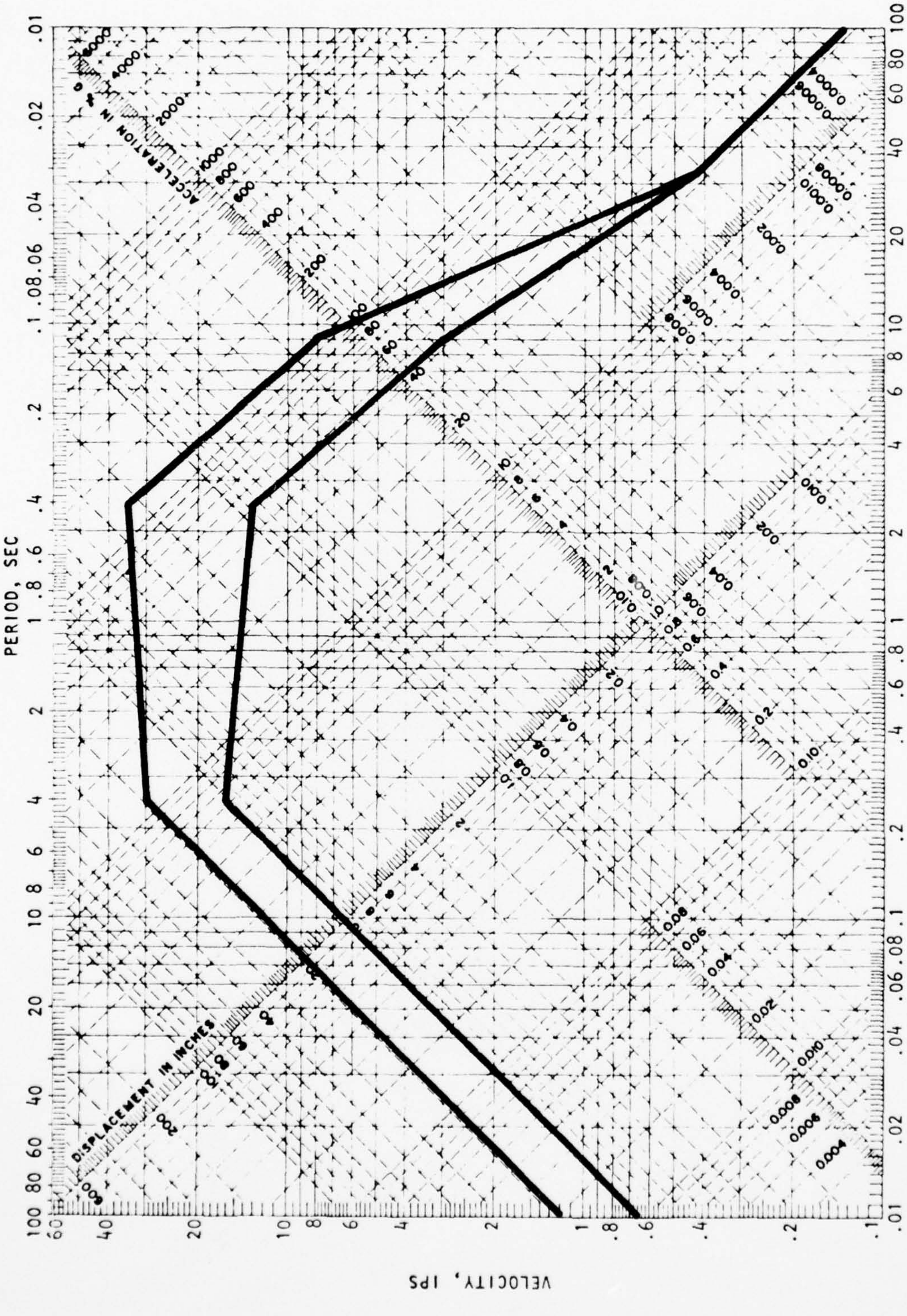

Figure III-26. Composite Response Spectra for NTS for 1000-Year Return Period Ground Motions, Assuming Hypothesis H3 [0.5 Percent (Upper) and 10 Percent (Lower) of Critical Damping Curves Shown]

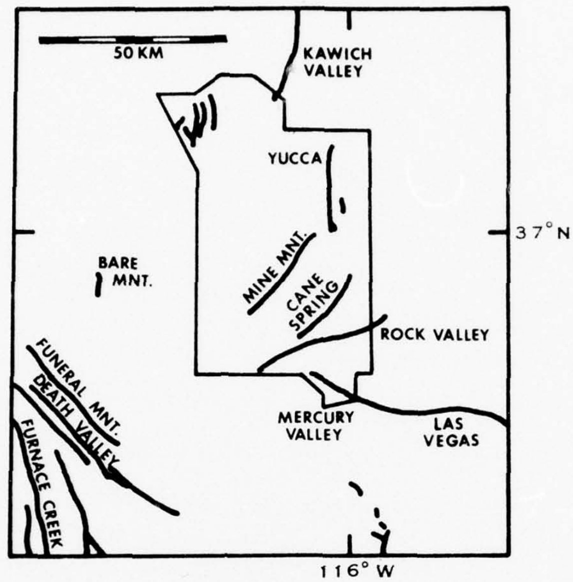

Figure III-27. Major Faults Near NTS

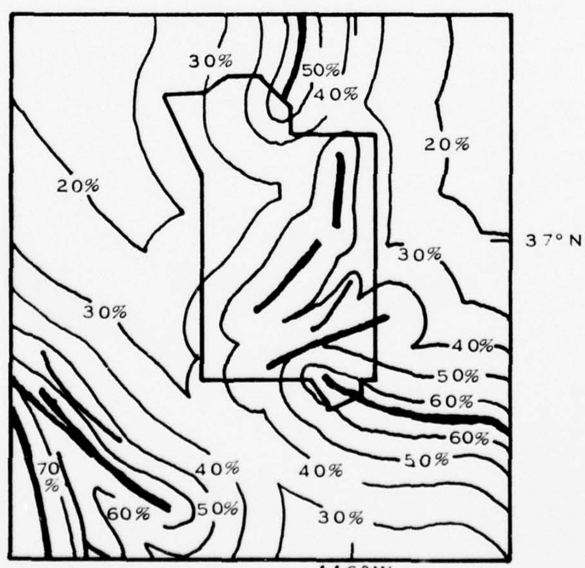

Figure III-28. Contours of Maximum Creditable Peak Ground Accelerations at NTS (Contours in Percent *g*)

SECTION IV

GROUND MOTION ATTENUATION

One of the tasks under the Geophysical Studies for the Missile Basing Program was the analysis of ground motion data with the intent of developing some form of widely applicable ground motion attenuation equation. After reviewing this problem, several severe difficulties became apparent. Basically, ground motion attenuation was found to be highly variable with region and most of the available peak ground motion data is from a limited tectonic setting. It became apparent that to achieve the desired result would require a level of statistical analysis well beyond the intended scope of this program. In the following section, this problem is discussed briefly.

The chief problem in justifying the use of a uniform ground motion attenuation equation is the apparent diversity of the rate of attenuation throughout the world. One example of this situation can be shown by comparing the intensity isoseismal contours for the Mississippi Valley earthquake of 1811 and the 1906 San Francisco earthquake. The magnitudes of these events are thought to be comparable (Nuttli, 1973a) and have been shown to be 7.4 and 7.5 m_b, with the largest being the 1906 event. However, the area enclosed within the intensity VII isoseismal contour for the Mississippi Valley earthquake was approximately 600,000 km^2 as compared to 30,000 km^2 for the San Francisco earthquake (Nuttli, 1973a). Similarly, areas of 2,500,000 km^2 and 150,000 km^2 were found to be enclosed within the intensity V isoseismal contour for each event, respectively. As the levels of ground motion defining the isoseismal contours must be assumed to be regionally independent, the additional enclosed area reported for the 1811 event must have been caused by lower attenuation in the central and eastern United States, as compared to California. By taking the square root of the ratio of the associated areas $(A_{1811}/A_{1906})^{1/2}$, which is the ratio of the effective radii of the isoseismal contours if they were circular, for both isoseismal contours, it is shown that the ground motions of the Mississippi Valley event propagated four times as far before being attenuated as much as the ground motions in California.

It is apparent from this example that the attenuation of seismic ground motion can vary significantly from region to region. It is also known that the eastern United States is not unique in having a characteristically low attenuation rate. Similar examinations of isoseismal contours for earthquakes on the Indian subcontinent reveal the same high Q structure for this area (Richter, 1958).

The question can then be raised as to the desirability of generating a standard attenuation curve for worldwide application. With the regional variations in rate of attenuation of ground motion, it is apparent that such a uniform equation would be forced to either overestimate or underestimate the actual peak ground motions for some areas of the world. In turn, the use of this equation in the seismic risk analysis process would result in overestimation or underestimation of risk. Considering the example given above, the degree of overestimation or underestimation of risk would be almost certain to be well beyond a desirable level.

The next solution would be the evaluation of several attenuation curves, each of which would be used for some restricted regions. But, at this point, the second major problem is encountered. Most strong motion measurements have been recorded in only one tectonic region, specifically in the western United States (Hudson, 1972). Basically, there is insufficient ground motion data to generate the desired equations for areas outside of the western United States without the analysis of both seismic wave attenuation and earthquake intensity distributions in the region of interest, as done by Nuttli (1973a, 1973b).

The development of either a single uniform attenuation equation or a set of equations was not feasible within the scope of this project. Many attenuation equations have already been generated and are listed by McGuire (1976). A new analysis of the available data would not contribute anything significant. The comparability of the attenuation functions given by McGuire was studied by Battis (1978).

SECTION V
PROGRAM REVIEW AND CONCLUSIONS

Over the past 3 years, studies have been conducted that have had, as a final goal, the evaluation and estimation of seismic risk at five Air Force facilities in the western United States. As part of the process of risk estimation, it has been necessary to develop a significant computer software package to examine regional seismicity characteristics and to integrate the results of these studies into a risk estimate for the site of interest. In this section, a brief review is made of both the software created for this project and the results of the seismic risk evaluations made for each of the five sites. Finally, a summary of the other topics examined during this project is presented.

A. COMPUTER SOFTWARE DEVELOPMENT

As a preliminary step in each of the seismic risk evaluations, it would be necessary to conduct a regional seismicity study to establish spatial and temporal trends in seismic activity in some area about the sites of interest. These studies involve the examination of the historic earthquake record for the given region using various forms of analysis. To expedite these studies, it was decided at the initial stages of this program to design and implement an interactive computer processing system for seismicity analysis. The advantages of this system were seen as the control of the processing flow, given the analyst at execution time and the ability of the analyst to make execution time decisions, such as defining ranges for curve fitting, which could not easily be programmed.

This interactive system was designed for use on the PDP-15 computer at the Seismic Data Analysis Center (SDAC). The software was setup to access a regional earthquake data file resident on a large-capacity disk, to perform various editing procedures on this file and to generate visual displays and statistical evaluations of the data files. Among the analysis routines available to the system user are displays of nominal strain release with respect to space or time, histograms of the event files, the evaluation of cumulative and incremental recurrence relationships and examination of the data file for completeness, or consistency of the mean rate of occurrence of seismic activity (Battis and Hill, 1977; Hill and Battis, 1978). Editing of the data file with respect to earthquake location, magnitude, depth, and time of occurrence provides the ability to examine the spatial and time characteristics of the seismicity patterns.

The standard earthquake data catalogue used to generate the regional data disk files was the National Oceanic and Atmospheric Administration Earthquake Data File (Meyer and von Hake, 1976). To use these data, software was developed for accessing and editing the earthquake data file tape, to generate the regional disk files mentioned above, and to allow the merging of additional data into the data set. In addition, software to generate epicenter and nominal strain release maps from the regional data files was created (Battis and Hill, 1977).

Finally, the evaluation of seismic risk required the assimilation of the various results of the seismicity studies into a single statistical estimate of risk. The method initially proposed by Cornell (1968) for this purpose was adopted. This technique had already been implemented by McGuire (1976) and the FORTRAN program required only minor modification to be usable on the SDAC IBM 360/44 computer facility.

B. SEISMIC RISK EVALUATIONS

During the geophysical studies for the Missile Basing Program, seismic risk evaluations were conducted for five Air Force facilities in the western United States. Specifically, these sites include the Cheyenne, Wyoming area, the site of a Minuteman missile wing, Edwards Air Force Base, California, White Sands Proving Ground, New Mexico, Luke Air Force Base, Arizona and the Nevada Test Site (NTS). For the first two sites, the question of the level of seismic risk at the sites derived from the observation of specific geophysical phenomena observed at or near the facilities. For the other three installations, the reason for the risk studies was the possible use of each site as an MX missile system installation. The difference in motivation of the evaluations resulted in somewhat different forms of analysis for the various sites.

In March of 1975, the Pocatello Valley, Idaho, earthquake, magnitude 6.1 m_b, caused severe disturbances to instrumentation located at Minuteman Missile Facilities near Cheyenne, Wyoming, over 600 km from the epicenter of the event. In June of the same year, however, an event thought to be of similar magnitude occurred at Yellowstone National Park, Montana, and no disturbances were reported at the Minuteman Facilities near Cheyenne, even though the epicentral distance was equivalent to the earlier event. The Cheyenne studies attempted to determine the cause of the different effects from these events and to estimate the likelihood of a recurrence of the disturbances.

Each of the two earthquakes and several fore-shocks and aftershocks were analyzed using far-field surface-wave amplitude spectral fitting (Battis and Hill, 1977) to evaluate the source mechanism and depth of each event. Based on these studies and published information on the source regions of each event, neither of the earthquakes was found to be atypical of their respective source area. However, two significant differences were found between the events. First, all indications were that the magnitude of the Yellowstone earthquake had originally been overestimated and was later reduced to 5.6 m_b. This change alone might explain the observed difference in effect between the events. In addition, it was found that the maximum Rayleigh-wave radiation from the Pocatello Valley earthquake was directed at Cheyenne while the Yellowstone event had a Rayleigh wave node in the direction of Cheyenne. In both cases, Love wave nodes were directed at Cheyenne. This might suggest that the disturbances were related to Rayleigh-wave radiation from the Pocatello Valley event. This fact, along with the results of the analysis of the predicted ground motions of all reported earthquakes within 450 km of Cheyenne (Battis, 1978), suggests that the disturbances observed at the Minuteman Facilties near Cheyenne were probably related to the specific source mechanism and location of the Pocatello Valley earthquake.

A regional seismicity study of much of the central United States and the northern Rocky Mountain states was also conducted (Battis and Hill, 1977). The results of this study were used to estimate seismic risk at Cheyenne, Wyoming (Battis, 1978). In Figure V-1, a best estimate of the peak ground acceleration risk for Cheyenne is shown. Because of inadequate coverage of the earthquake history within 500 km of Cheyenne, this curve is very tenuous. In addition, analysis of the seismic risk at Cheyenne solely from the Pocatello Valley earthquake source region suggests a recurrence of the observed disturbances approximately once every 15 years (Battis, 1978).

The evaluation of seismic risk at Edwards Air Force Base, California, was initiated after the reports of the observation of a geologically rapid regional uplift, throughout much of southern

California, centered at Palmdale, California (Battis and Hill, 1977; Battis, 1978). Subsequent to the report of the uplift, it was suggested premonitory velocity variations had been observed within the area of uplift (Whitcomb, 1976), implying the potential for significant and imminent seismic activity in the region. Since these initial reports, changes in the amount of uplift and the areal extent of the uplift have been reported. The possibility that the uplift is a seismic precursor is continuing to be investigated. However, re-analysis of the data used by Whitcomb and additional studies of other possible precursors have significantly reduced the scientific basis for predicting an imminent seismic hazard in the uplifted zone. Now, neither the cause nor the tectonic implications of the uplift are understood. It is still most reasonable to approach the situation with conservatism and to assume that some seismic hazard is associated with the uplift phenomena.

Under this condition, the evaluation of the seismic risk at Edwards Air Force Base is not a problem of establishing ground motion return periods, for it is assumed that significant seismic activity could occur at any time in the near future. Then, only the estimation of the worst possible earthquake that could occur near the base and the evaluation of maximum ground motion, which might be experienced at the facility, are of interest. To carry out this analysis, the major faults or fault systems near Edwards Air Force Base were identified and maximum creditable earthquakes for each of the faults were estimated on the basis of total fault lengths and plausible rupture lengths (Battis, 1978). Using this information and empirical ground motion attenuation equations, contours of peak accelerations, velocities, and displacements near Edwards Air Force Base were plotted. The maximum creditable ground motions predicted for Edwards Air Force Base were 0.5 percent *g*, 80 cm/sec, and 35 cm, respectively. In general, these motions result from activity either on the Garlock or San Andreas Faults near the installation. Based on the seismicity study for this region (Battis and Hill, 1977), a return period of approximately 4,000 years was found for these ground motions.

For the last three sites (White Sands Proving Ground, Luke Air Force Base, and NTS) seismic risk calculations were made without the complications of any unusual geophysical occurrences known near the sites. In each case, a regional seismicity study was conducted for a region within 800 km of the site of interest. Seismic source regions were identified and levels of activity were assigned to each of these regions. Based on these evaluations, seismic risk curves for each site were constructed. These results were reported in Battis (1978) and also in previous sections of this report. The estimated upper-limit risk curves for each site are shown in Figure V-1.

Finally, at each site potentially active faults were identified and maximum creditable earthquakes were evaluated for each. One such fault is the Algodones Fault, which could cause severe damage in southwestern Arizona and at Luke Air Force Base, should occur along it. From the fault length of the Algodones Fault, it is possible to estimate a maximum creditable earthquake of 7.3 M_L magnitude for this fault. In addition, it can be shown that other faults associated with the Algondones Fault are now active. From other evidence, it can be inferred that the likelihood of an event of this size on this fault is low, but real.

C. EARTHQUAKE PREDICTION

During this program, earthquake prediction technology was examined (Battis and Hill, 1977). Prediction technology is unreliable at the present time, even though several apparently

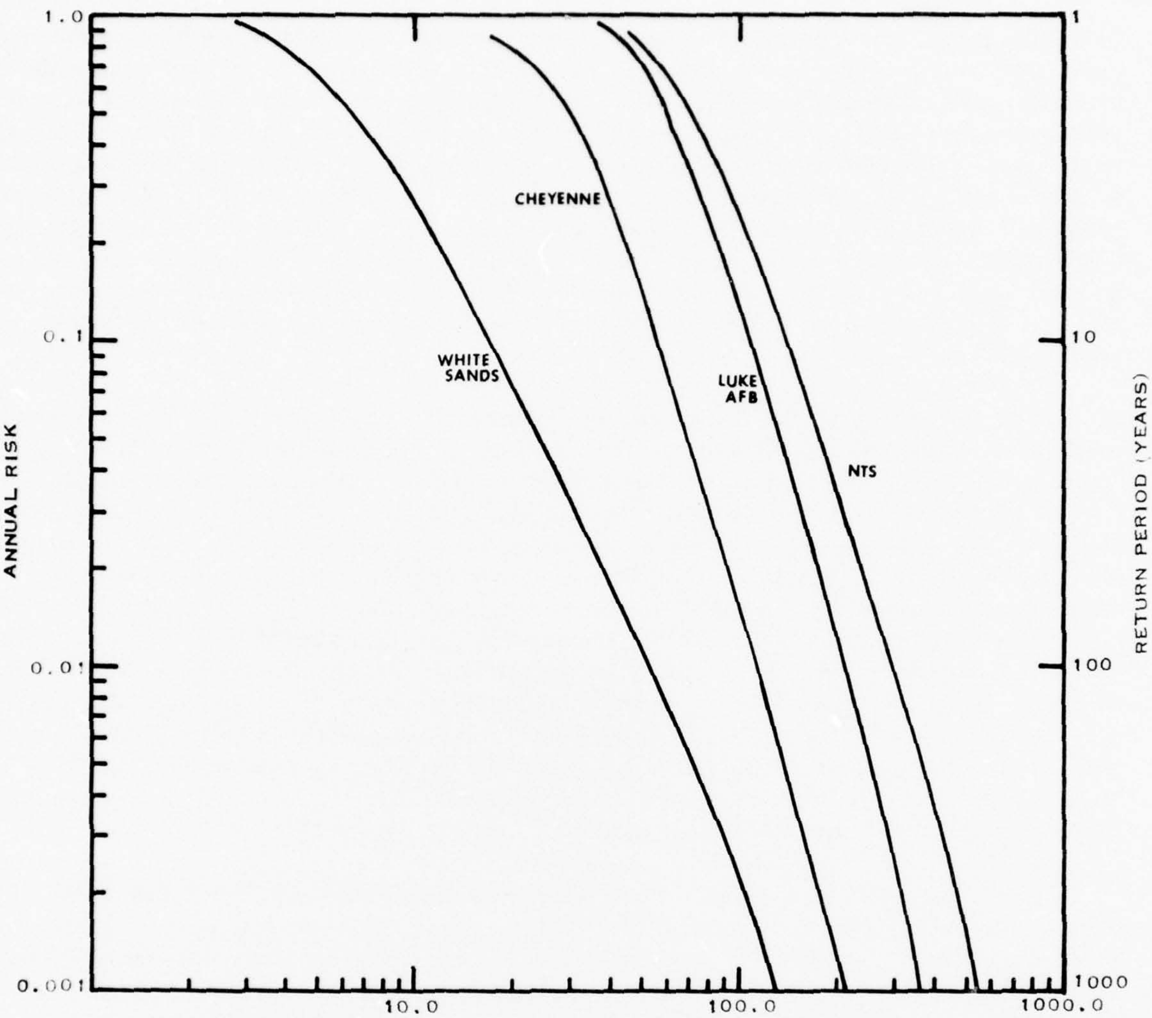

Figure V-1. Maximum Annual Risk Curves for Ground Acceleration at Four Air Force Bases in the Western United States

successful predictions were noted. The majority of work on this subject is being conducted in southern California, and it is likely that earthquake prediction will become routine in this area before anywhere else in the United States. It is also not clear that work done in this region is directly applicable to other regions because of both tectonic and source mechanism differences. Finally, the implications of present earthquake prediction studies suggest the need for intense instrumentation within the region of interest; a condition true only in a limited number of areas throughout the world.

D. GROUND MOTION PREDICTION

In an earlier section, the problems associated with ground motion prediction were reviewed. These include a lack of worldwide data and the importance of propagation effects in evaluating ground motion at a distance. Earlier efforts could not be improved upon in this program. Therefore, some discussion of the work of previous investigators was made.

SECTION VI
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APPENDIX A

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