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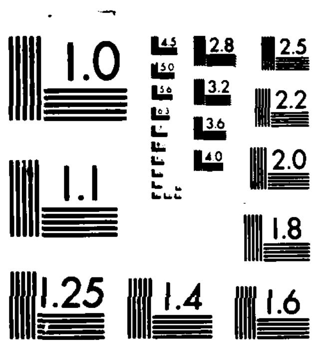

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Seismic Hazard Study for Utah

JAMES C. BATTIS

26 OCTOBER 1982

TERRESTRIAL SCIENCES DIVISION PROJECT 7600
AIR FORCE GEOPHYSICS LABORATORY
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AIR FORCE SYSTEMS COMMAND, USAF

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Chief Scientist

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With the use of two distinct seismic regionalizations, seismic hazard evaluations were conducted for Utah. The two regionalizations were used to depict the possible extremes in future seismic activity in the Utah area. The primary distinction in the models was the treatment of Basin and Range seismicity. In one model, the seismic activity in this province was uniformly distributed; in the other it was concentrated at the province boundaries. With these models, contour maps of peak acceleration and velocity were constructed for Utah, and annual risk curves were evaluated for specific sites within

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the state. In addition, deterministic hazard estimates were made based on known and suspected Quaternary faults in Utah.

It was concluded that for near-term hazard evaluations, the subplate margin provided the most useful hazard projection. Based on this model, 90 percent confidence-level accelerations in Utah are less than 115 cm/sec^2 for any 10-year period and less than 270 cm/sec^2 for any 50-year period. The deterministic modeling predicts that accelerations over 0.8 g are possible throughout much of western Utah and, in particular, the proposed MX basing area. However, it is likely that accelerations of this magnitude would occur on the order of less than once in several thousand years at any specific site within the state.

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1. INTRODUCTION

Several of the proposed deployment modes for the MX missile system have involved basing of the system in the alluvial basins of Nevada and western Utah. In support of the MX missile program, the Terrestrial Sciences Division of the Air Force Geophysics Laboratory has undertaken a program to evaluate the seismic hazard with these two states. In this report, results of the analysis for the Utah area are presented. Both probabilistic and deterministic approaches to the estimation of seismic hazard have been employed. The results of the study are set forth as contour plots of maximum credible and probabilistic peak ground motion estimates for hard rock sites. In addition, annual risk curves are presented for risk assessments in Utah. No attempt has been made to modify the rock site accelerations to compensate for the deep alluvial cover typical of the potential MX basing sites.

The approach taken in this study was to produce a conservative, though realistic, estimate of the seismic hazard in the area of interest. However, the long-term seismicity patterns in this region are not well-defined and subject to debate. To provide some sense of the uncertainty associated with the analysis, two distinct

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models of the regional seismicity have been used in the probabilistic evaluation. The results from both assumptions are presented and compared.

2. UTAH SEISMICITY

The earliest record of seismic activity in Utah is of a tremor felt in central Utah in 1853.[1] Since that event, earthquakes of sufficient size to be felt have occurred within the state at the rate of approximately one per year.[2] During the historical era, earthquake epicenters in Utah have been concentrated in a distinct band, running from the southwestern corner of the state to north-central Utah (Figure 1). Although the preinstrumental earthquake catalog is biased in favor of this zone by virtue of the population distribution during most of the state's history, instrumental coverage in the last two decades has re-emphasized this pattern of seismic activity. However, significant earthquakes have also occurred widely throughout the state and outside of this trend.

The largest earthquake within the state was the 1934 Hansel Valley earthquake that had a reported magnitude of M=6.6. This event was centered just north of the Great Salt Lake. At least 57 earthquakes have been recorded in Utah between 1853 and 1978, causing at least minor damage, Modified Mercalli intensity V or greater.[3] With use of the earthquake catalog for all of Utah from 1850 to 1974, evaluation of recurrence curves for Utah gives an incremental curve of

$$\log N = 1.15 - 0.76\,M \qquad (1)$$

and a cumulative curve of

$$\log N = 1.47 - 0.79\,M \qquad (2)$$

where N is the number of events per year per 1000 km^2 of magnitude, M, for the incremental curve or equal to or greater than M for the cumulative curve.[4]

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1. Cook, K. L., and Smith, R. B. (1967) Seismicity in Utah, 1850 through June 1975, Bull. Seismol. Soc. Am 57:689-718.

2. Cook, K. L. (1972) Earthquakes along the Wasatch Front, Utah - The record and the outlook, in Environmental Geology of the Wasatch Front, 1971. L. S. Hilpert, ed., Utah Geol. Assoc., Publ. 1, pI11-I129.

3. Meyers, H., and von Hake, C. A. (1976) Earthquake Data File Summary, National Geophysical and Solar-Terrestrial Data Center, Report KGRD-5.

4. United States Geological Survey (1976) A Study of Earthquake Losses in the Salt Lake City, Utah Area, U. S. Geological Surv. Open File Report 76-89.

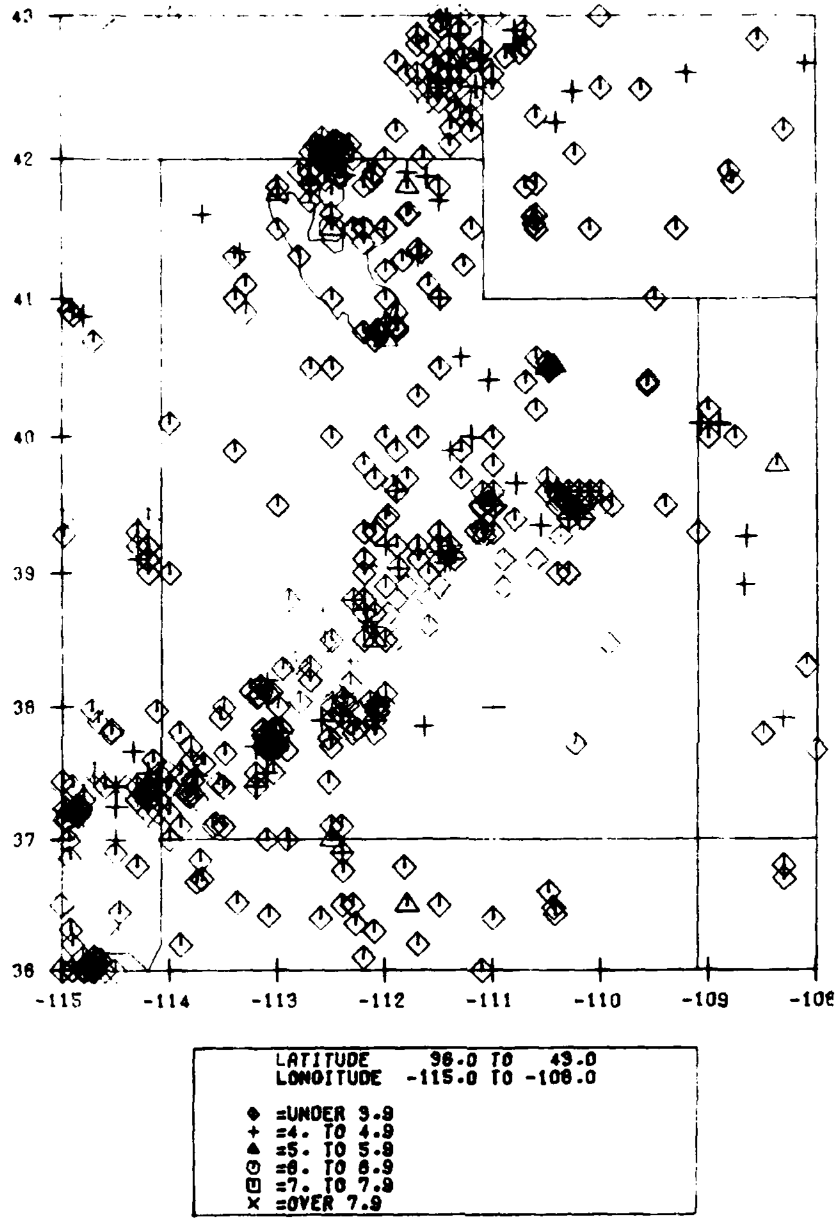

Figure 1. Earthquake Epicenters in the Utah Area From 1853 to 1978

Earthquakes in the Utah area tend to be shallow events, with the majority of epicenters having depths above 10 km.[5] However, only the 1934 Hansel Valley earthquake can be associated with surface faulting. An earthquake swarm in southwestern Utah in 1971 produced fractures in alluvium that might be related to faulting.[5] In general, the pattern and locations of earthquake epicenters in Utah tend to be diffuse and difficult to associate with specific faults.[6] Although faults are common throughout most of Utah (Figure 2), the age of most recent faulting is unknown on many of them.[1,7] In the assessment of earthquake hazard, faults having Quaternary displacements, those younger than 2 million years, are often considered potentially active.[8] Using the limited data available, Anderson and Miller have compiled a map of Quaternary faults in Utah (Figure 3). They consider this map to be preliminary; additional faults are likely to be reported with further geologic studies. The distribution of known Quaternary faulting supports the general conclusion attained from the historical earthquake record: That while most seismic activity is associated with the Wasatch, Eisinore, and Hurricane Fault zones, pote. tial exists for significant seismic activity in other areas of the state.

Historically, the 1934 Hansel Valley earthquake marks the largest event occurring in Utah. However, it is possible that larger earthquakes will occur there in the future. Detailed studies of the geologic evidence of Holocene fault displacements along the Wasatch Front suggest that individual surface faulting events have produced displacements in the range of 0.8 to 3.7 m.[9] Given the fault displacement, D, the causative event magnitude, M, can be estimated by the functional relationship derived for normal faults.[10] The Wasatch Fault zone can then be assumed to have

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5. Smith, R. B., and Sbar, M. L. (1974) Contemporary tectonics and seismicity of the Western United States with emphasis on the inter-mountain seismic belt, Geol. Soc. Am. Bull. 72:1205-1218.

6. Dosier, D. I., and Smith, R. B. (1982) Seismic moment rates in the Utah region, Bull. Seismol. Soc. Am. 72:525-551.

7. Anderson, L. W., and Miller, D. G. (1979) Quaternary faulting in Utah, in Earthquake Hazard along the Wasatch and Sierra Nevada Frontal Fault Zones, U. S. Geol. Surv., Open File Report 80-801, pp. 194-226.

8. Allen, C. R. (1975) Geologic criteria for evaluating seismicity, Geol. Soc. Am. Bull. 86:1041-1057.

9. Swan, F. H., Schwartz, D. P., and Cluff, L. S. (1979) Recurrence of surface faulting and moderate to large earthquakes on the Wasatch Fault zone at Kaysville and Hobble Creek sites, Utah, in Earthquake Hazards along the Wasatch and Sierra Nevada Frontal Fault Zones, U. S. Geol. Surv., Open File Report 80-801, pp. 227-275.

10. Slemmons, D. B. (1977) Faults and Earthquake Magnitude, U. S. Army Engin. Waterways Experiment Station, Miscellaneous Paper S-73-1.

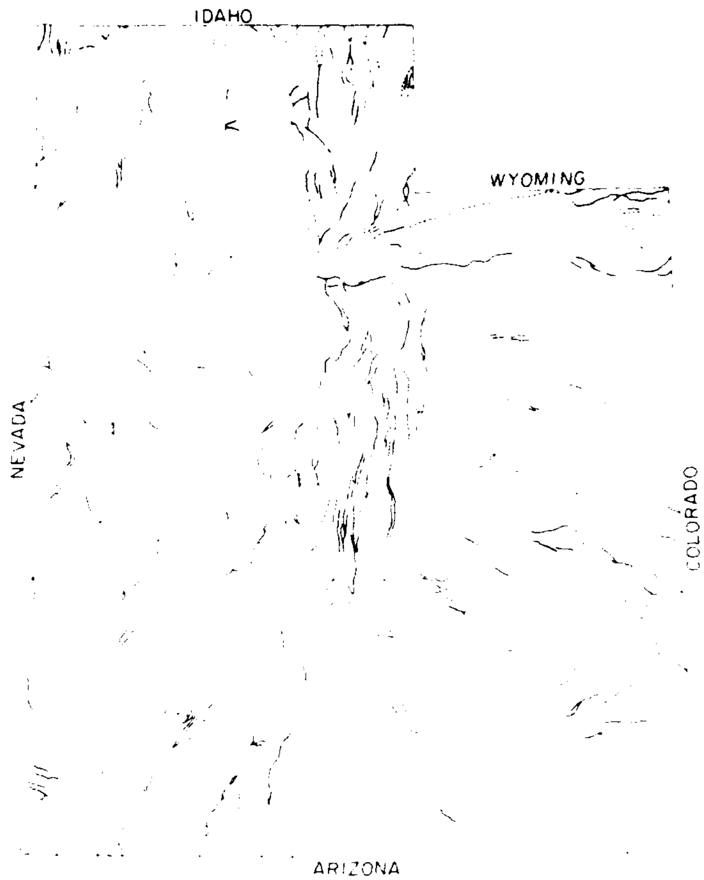

Figure 2. Known and Suspected Faults in Utah. Known faults, solid lines; suspected faults, dashed lines. [After Cook and Smith (1967)]

supported earthquakes of magnitude M=6.7 to 7.4 repeatedly during the Holocene, approximately the last 10,000 years. It must be assumed that an earthquake of about magnitude M=7.5 could occur in Utah, at least along the Wasatch Fault zone. This value is commonly taken as the maximum credible earthquake for Utah.[4]

The historical record of earthquakes implies, through Eq. (2), the recurrence of a major earthquake of magnitude M=7.0 or greater, approximately once every 52 years in Utah, or 130 years for an M=7.5 event. Based on several assumptions, as well as extrapolation, the geologic evidence suggests that earthquakes of this

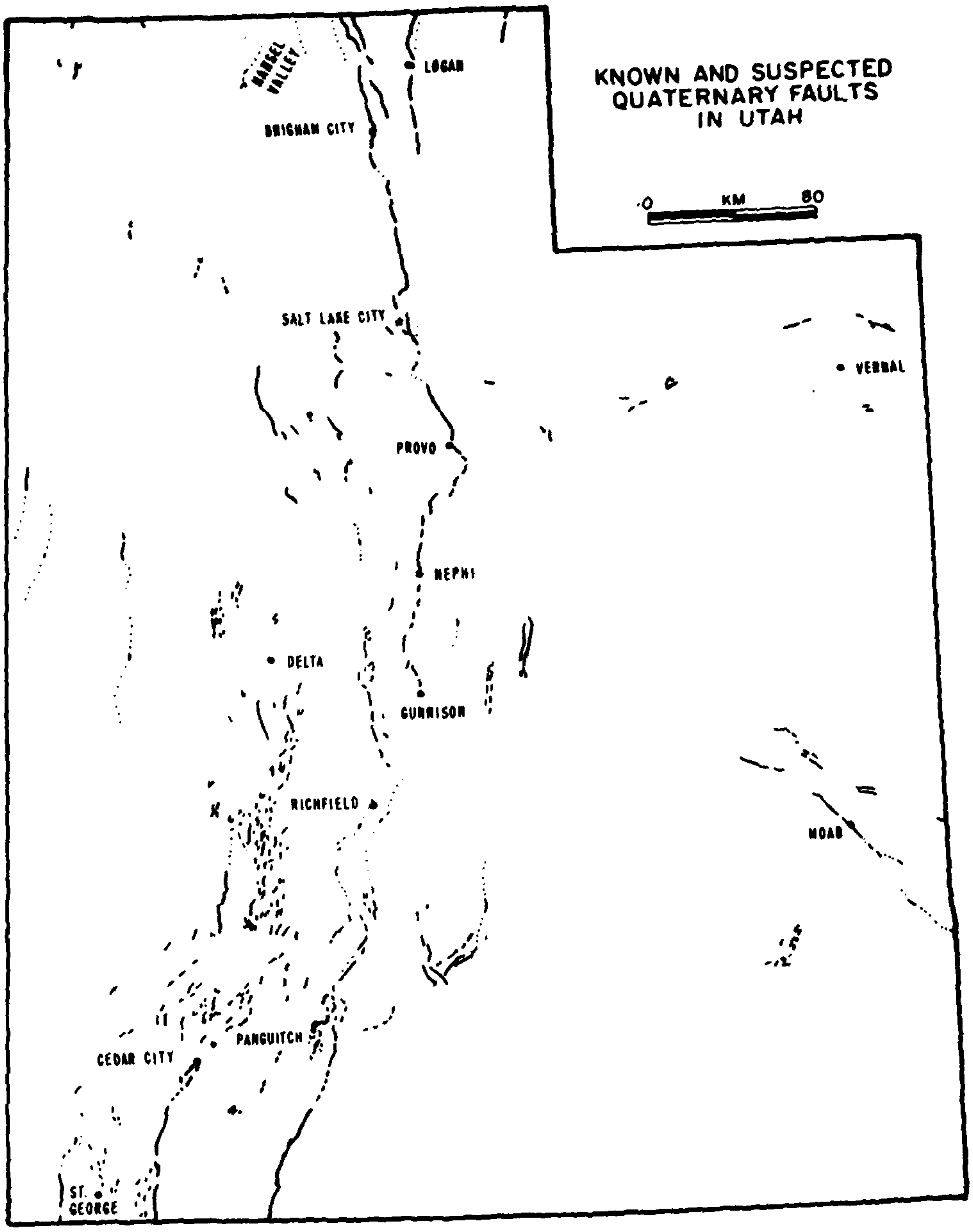

Figure 3. Known and Suspected Quaternary Faults in Utah. Known faults, solid lines; suspected faults, dashed lines. [After Anderson and Miller (1979)]

order of magnitude should have return periods between 50 and 400 years along the Wasatch Fault zone.[9] During the last 130 years, only the Hansel Valley event approached this level of magnitude. In geologic terms, the historical record is extremely short and extrapolation from these data for magnitudes which have not been recorded is probabilistic. Analysis of earthquake catalogs for China, Japan, and the Middle East, covering periods between 2,000 and 3,000 years, indicate that spatial and temporal variations in seismicity of periods equal to or longer than the Utah historical record are common.[8, 11, 12] Using various windows of the Utah catalog, Arabasz et al have shown that return periods of between 5 and 1,505 years could be estimated for a 7.5M earthquake on the Wasatch front.[13] Typically, an estimate of the order of several hundred years is assumed for the maximum credible earthquake of M = 7.5.

3. SEISMIC REGIONALIZATION

Subdivision of the Utah area into seismic source regions is required in order to analyze the seismic hazard in the state. The goal of this regionalization is to produce a set of seismic source regions whose seismicity is homogeneous and well-defined. Limitations imposed by short seismic history, the diffuse nature of the seismicity in the area of study, and questions concerning the tectonic processes of the region -- all affect the process of defining these source regions. In this section, two regionalizations are made in an attempt to compensate for the uncertainties previously stated.

The main trend of seismic activity through the state is associated with the Intermountain Seismic Belt (ISB), a trend of earthquakes ranging from northwestern Arizona north to the Montana-British Columbia border (Figure 4).[5] This zone is one of the most active seismic regions in the continental United States. It has been suggested that the ISB defines the active margins of several subplates of the North American Plate. The subplate margins are believed to correlate essentially with the physiographic province boundaries that are also shown in Figure 4. Seismicity

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11. McGuire, R. K. (1979) Adequacy of simple probability models for calculating felt shaking hazard, using the Chinese earthquake catalog. Bull. Seismol. Soc. Am. 69:877-892.

12. York, J. E., Cardwell, R., and Ni, J. (1976) Seismicity and Quaternary faulting in China, Bull. Seismol. Soc. Am. 66:1983-2002.

13. Arabasz, W. J., Smith, R. B., and Richins, W. D. (1979) Earthquake studies along the Wasatch Front, Utah: network monitoring, seismicity, and seismic hazards, in Earthquake Hazards along the Wasatch and Sierra Nevada Frontal Fault Zones, U. S. Geol. Surv., Open File Report 80-801, pp. 1-33.

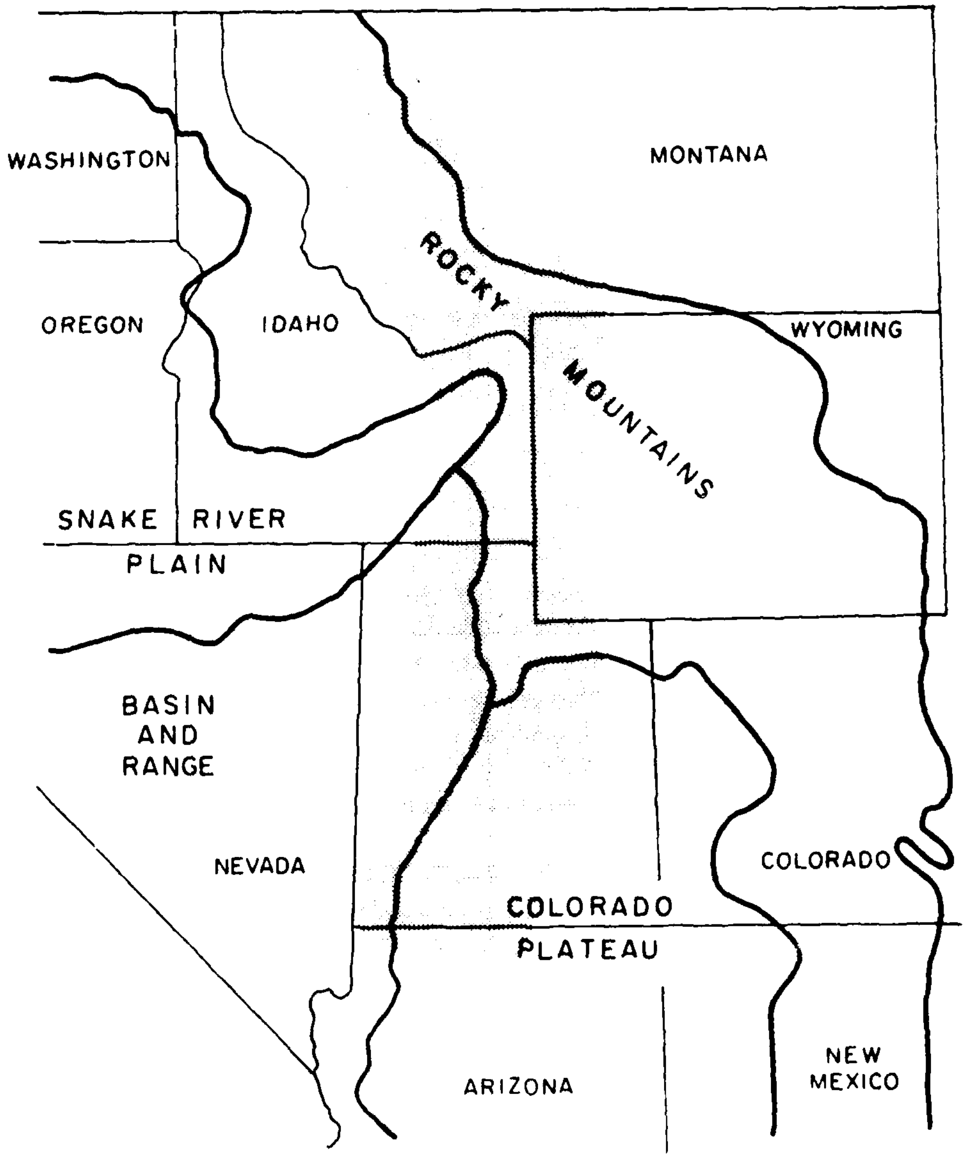

Figure 4. Intermountain Seismic Belt (stippled area) and Physiographic Provinces of the Utah Area [After Smith and Sbar (1974)]

within the ISB appears to result from forces associated with the interaction of the North American and Pacific Plates and possibly modified by a hypothesized mantle plume presently centered at Yellowstone. In the Utah area, the ISB divides the Basin and Range province on the west from the Middle Rocky Mountains and the Colorado Plateau on the east. The distinct tectonics of each of these provinces is significant in the seismic regionalization of the area.

Epeirogenic uplift has occurred in all three provinces, but it is the dominant tectonic force only in the Colorado Plateau and the Middle Rocky Mountains. In the Colorado Plateau, the uplift has been uniform throughout the province, with little crustal deformation. The rough topography of the plateau is primarily the result of fluvial erosion of undisturbed sedimentary deposits. The widespread nature of the uplift and lack of crustal deformation suggest a relatively stable zone of low-level seismicity that would be uniformly distributed; in fact, concentrations of seismic microactivity that have occurred in this region appear to be associated with human activity such as mining.[14] In the Middle Rocky Mountains, the epeirogenic uplift has been accomplished by extensive normal faulting and mountain formation. On the scale of interest in this report, the seismic activity would also be expected to be uniformly distributed, but the region would be expected to have a higher level of seismicity than the Colorado Plateau. Each of these provinces can be considered a single source region with uniform potential for seismic activity. An exception is the margin of the Colorado Plateau abutting the Basin and Range; this will be discussed later.

The major tectonic process in the Basin and Range is the lateral crustal extension which has been occurring for the last 30 million years.[15] The rifting has continued episodically to the present day, although the orientation and center of active extension has changed. During this period, typical estimates of the amount of spreading range from 50 to 300 km, with the most common estimate being about 100 km.[16] The spreading has been accomplished by extensive normal faulting, graben formation, and volcanism. Although probably related to the broad uplift of the region, the exact relationship between uplift and extension of the Basin and Range, as cause or effect, is uncertain.[15]

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14. Smith, R. B., Winkler, P. L., Anderson, J. G., and Scholz (1974) Source mechanisms of micro-earthquakes associated with underground mines in eastern Utah, Bull. Seismol. Soc. Am. 64:1295-1317.

15. Eaton, G. P. (1979) A plate tectonic model for late Cenozoic spreading in the Western United States, in Rio Grande Rift: Tectonics and Magmatism, R. E. Riecker, ed., Am. Geophys. Union, Washington, D.C., pp. 7-32.

16. Thompson, G. A., and Bruce, D. B. (1974) Regional geophysics of the Basin and Range province, in Annual Review of Earth and Planetary Sciences, F. A. Donath, ed., Annual Reviews, Inc., Palo Alto, California, pp. 213-238.

A question with significant implications for seismic regionalization is the distribution of active extension in the Basin and Range. During historic times, most significant earthquakes in the province have occurred in very limited zones that tend to be at the margins of the province. Late Quaternary faulting in the region is, however, very uniformly distributed as is low level seismicity.[17] At least three hypotheses have been advanced in an effort to explain this apparent discrepancy. First, the historical record is a short-term distribution of earthquakes in the province; second, the seismic activity (and presumably, extensional activity) is concentrated in very limited zones at any one time; these zones migrate throughout the Basin and Range.[18] Return periods for large earthquakes in any specific area are thought to be of the order of thousands of years. Finally, the last concept assumes that extensional, as well as seismic activity, is confined to the Basin and Range margins and, on the eastern edge, could be gradually migrating into the Middle Rocky Mountains and Colorado Plateau.[5]

Historical, as well as geologic evidence, is insufficient to determine the correct analysis of the seismicity of the Basin and Range. Each hypothesis, however, would require a different approach to the seismic regionalization of the province. The first concept would imply that the Basin and Range could be considered as a single or at least a limited number of zones having uniform seismic activity. Using the second hypothesis, one would have to delineate any area with indications of recent major earthquakes as a potential earthquake source. As the future migration of the active zones cannot be predicted, the remaining area would be assumed to have a uniform probability of earthquake occurrence. On the scale of regionalization used in this study, this would degenerate into the same conditions as the first approach. On the basis of the last thesis, seismic activity would be confined to the province margins with low-level background seismicity in the interior of the Basin and Range.

It is concluded that two models of seismic regionalization will provide an adequate range of seismic hazard estimations for the Utah area. In the first, known as the Uniform Seismicity (US) model, a major earthquake is assumed to have uniform probability of occurrence within several gross regions; in the second, the Subplate Margin Seismicity (SMS) model, the major seismic source regions are assumed to align with the historical seismicity patterns of the region. The primary distinction is in the treatment of the Basin and Range province earthquake potential.

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17. Slemmons, D. B. (1967) Pliocene and Quaternary crustal movements in the Basin and Range Province, USA, Journal Geosciences, Osaka City Univ., 10:91-103.

18. Ryall, A. (1977) Earthquake hazard in the Nevada region, Bull. Seismol. Soc. Am. 67:517-538.

3.1 Uniform Seismicity Model

For the Uniform Seismicity Model, the western United States was subdivided into the regions shown in Figure 5. This regionalization and the associated

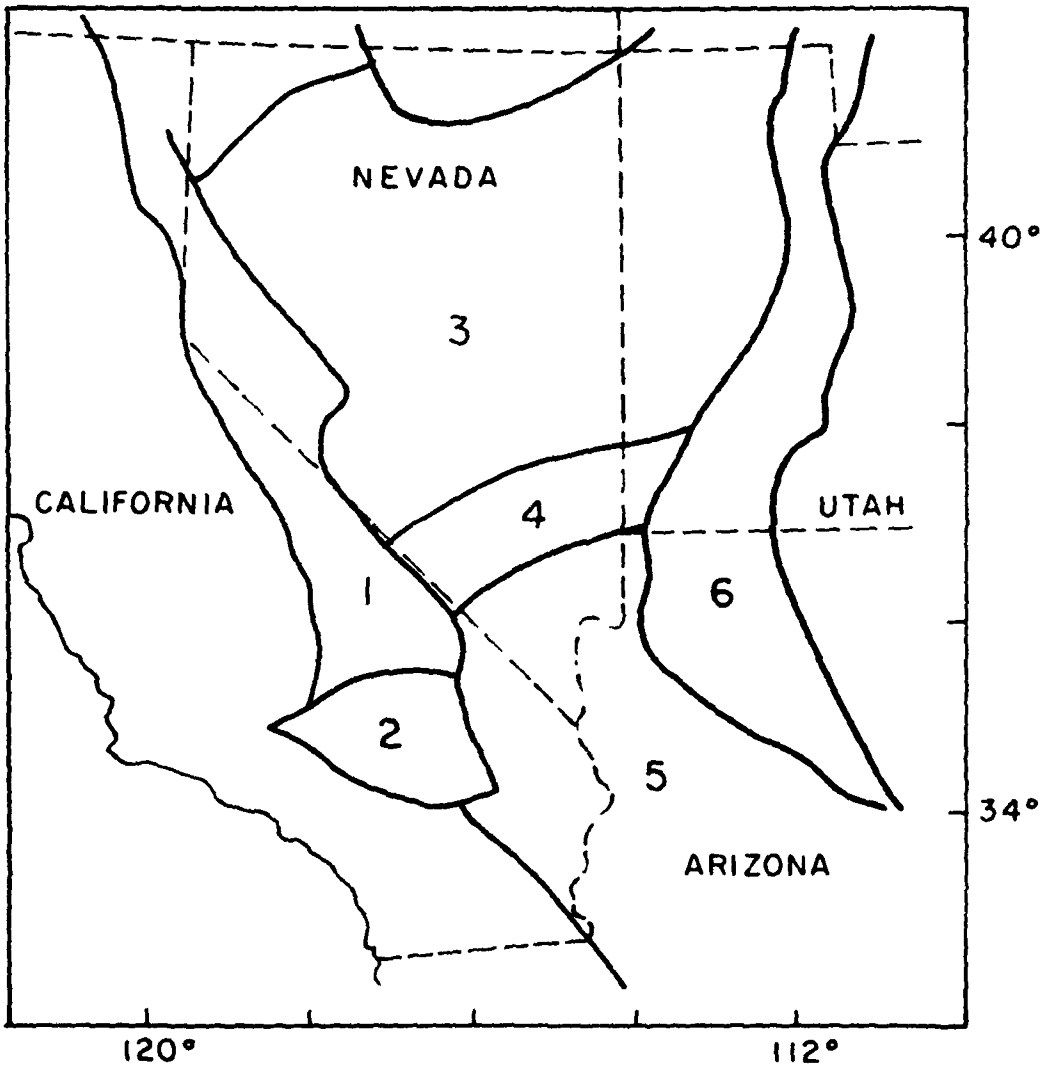

Figure 5. Uniform Seismicity Model Regionalization [(Modified From Greensfelder, et al. (1980)]

seismicity parameters are based primarily on the work of Greensfelder et al.[19] Additional analysis of seismicity was conducted for the Colorado Plateau-Rocky Mountains region to the east of the area included in that study. The regionalization is based on late Cenozoic patterns of deformation, relative Holocene strain rates, and instrumental historic seismicity. Greensfelder et al, conclude that Holocene strain rates and historic seismicity are in rough agreement with differences of less than a factor of 3. Other investigators have suggested that the differences are primarily due to the methods used for estimating strain rate rather than changes in long-term seismicity.[6]

Based on post-instrumental seismicity, 1932 to 1973, the seismicity parameters for each region were calculated (See Table 1). The values given for regions 1 through 6 are based on earthquakes west of region 6 to 108°W. The method of analysis for region 7 was similar to that used for the other regions.

Table 1. Uniform Seismicity Model Parameters

Source Region	Area (10^3 km^2)	log N* = A-b M_L		Maximum M_L	Return Period of 7.0 M_L or Greater Earthquake Years
		A	B		
1	74.6	3.18	1.0	7.75	88.5
2	25.3	2.04	0.91	7.6	845
3	253.5	2.54	0.91	7.6	11.5
4	39.2	2.60	1.0	7.2	[illegible]
5	134.7	1.70	1.0	7.5	1461
6	118.9	2.72	0.96	7.75	84
7	295.8	1.96	1.0	6.75	...

*N = number of events of magnitude M or greater per year per 1000 km^2.

19. Greensfelder, R. W., Kintzer, F. C., and Somerville, M. R. (1980) Seismotectonic regionalization of the Great Basin, and comparison of moment rates computed from Holocene strain and historic seismicity: summary, Geol. Soc. Am. Bull. 91:518-523.

In addition to recurrence curve information, maximum magnitude earthquakes are also assigned for each region and shown in Table 1. These values are based on interpretation of geologic evidence or the largest event to occur in historical times. In general, modifying this value has a significant effect only on the hazard estimation for very long return periods. Unless the maximum magnitude earthquake is grossly in error, probabilistic risk estimates in the range of interest for this report will not be modified substantially by changing this parameter.

3.2 Subplate Margin Seismicity Model

In this model, the regional seismicity is assumed to concentrate at the subplate margins, as suggested by historical seismic activity.[5] The basic regionalization of the uniform seismicity model is maintained outside of Utah. The major distinction between this model and the previous one is the lowering of the seismic potential in region 3 and the redefining of region 6 by subdivision into two new zones, with alteration of the activity levels in each new zone (Figure 6). The new

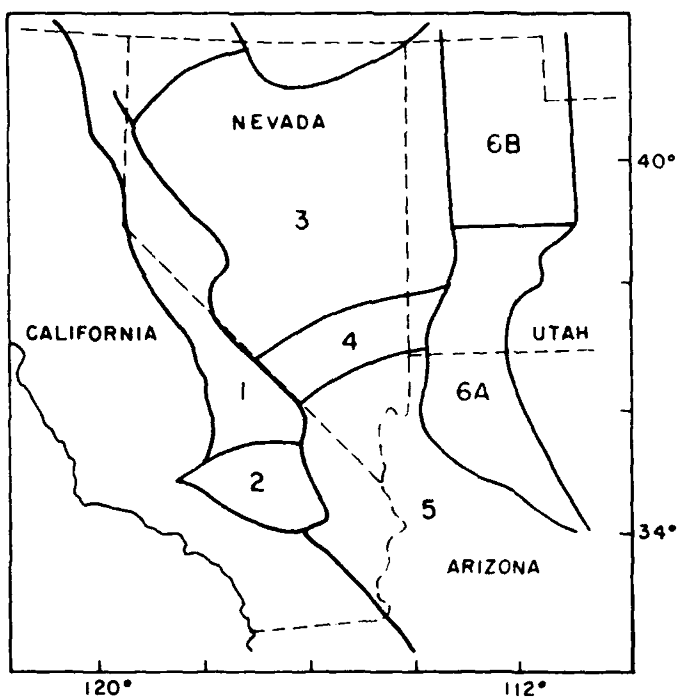

Figure 6. Subplate Margin Seismicity Model Regionalization

region 6b corresponds to the Wasatch Front Study Area defined by Arabasz et al.; it is an areal expansion of the equivalent segment of region 6 from the uniform seismicity model.[13] Adjustments in the abutting regions 3 and 7 are required by this change.

The recurrence function used for the new region 3 was derived from a previous study for an area of Nevada closely resembling the redefined region 3.[20] It is felt that the different area used in this evaluation would not introduce errors of a magnitude approaching those expected from the statistically short duration of the earthquake sample. For regions 6a and 6b, specific analysis of seismic recurrence for each was conducted using the instrumental earthquake catalog from 1932 to 1978. This included an analysis of completeness of the catalog to ensure statistical stability.[21] In addition, the modeled maximum magnitude earthquakes in regions 3 and 6a were reduced in order to provide a lower level of seismic activity in these regions as compared to region 6b as indicated by the historical record. The recurrence parameters for the subplate margin seismicity model are given in Table 2.

Table 2. Subplate Margin Seismicity Model Parameters

Source Region	Area (10^3 km^2)	log N* = A-b M_L		Maximum M_L	Return Period of 7.0 M_L or Greater Earthquake (Years)
		A	b		
1	74.6	3.18	1.0	7.75	88.5
2	25.3	2.04	0.91	7.6	845
3	217.7	1.87	0.91	7.0	146
4	39.2	2.60	1.0	7.2	739
5	134.7	1.70	1.0	7.0	1481
6a	65.6	1.50	0.81	7.0	225.5
6b	129.9	0.19	0.54	7.75	32
7	282.4	1.96	1.0	6.75	...

20. Battis, J. C., and Hill, K. T. (1977) Analysis of Seismicity and Tectonics of the Central and Western United States, Texas Instruments, Inc., Interim Scientific Report ALEX (02)-ISR-77-01, Dallas, Texas.

21. Stepp, J. C. (1972) Analysis of completeness of the earthquake sample in the Puget Sound area and its effect on statistical estimates of earthquake hazard, in Proceedings of the International Conference on Microzonation for Safer Construction Research and Application, Univ. of Washington, Seattle, Washington, pp. 897-909.

4. PROBABILISTIC HAZARD ESTIMATION

The probabilistic hazard estimation process is based on a method proposed by Cornell and implemented in a FORTRAN computer program by McGuire.[22,23] Using this program, we found that the temporal and spatial distribution of seismic activity is combined into a single statement of the probability of reaching or exceeding a given ground motion level at any site of interest. In addition to the statistical models of seismicity, given in the preceding section, knowledge of ground motion attenuation in the region of interest is required. In the following paragraphs, the statistical method, ground motion attenuation, and results of the analysis for Utah are discussed.

4.1 Risk Estimation Method

In the procedure used for this study, earthquake occurrence within each subdivision is considered a Poisson process. This implies that the occurrence, in space and time within any subregion, is independent of any preceding event. There is strong evidence that this is not true and that future earthquake occurrence is connected to past seismic activity in the region.[18,24] However, the use of the Poissonian assumption is conservative; it does not introduce additional restrictions which at best could only be based on extremely limited data samples.

Using the Poisson process, we note for each source region the probability that the ground motion will reach or exceed a specified level, a_g, defined as the integral of the product of three parameters: the independent probability density functions for occurrence of an earthquake of magnitude S, f_S; the density function that it will occur at distance R, f_R; and the conditional probability that given an event of magnitude s and at distance r, the ground motion will reach or exceed a_g. This can be stated as:

$$P[A_g \geq a_g] = \int\int P[A_g \geq a_g | s \text{ and } r] f_S(s) f_R(r) ds dr \qquad (3)$$

where $P[A_g \geq a_g | s \text{ and } r]$ is the conditional probability.[23]

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22. Cornell, C. A. (1968) Engineering seismic risk analysis, Bull. Seismol. Soc. Am. 58:1503-1606.

23. McGuire, R. K. (1976) FORTRAN Computer Program for Seismic Risk Analysis, U. S. Geol. Survey, Open File Report, 76-67.

24. Sykes, L. R. (1971) Aftershock zones of great earthquakes, seismicity gaps, and earthquake prediction for Alaska and the Aleutians, J. Geophys. Res. 76:8081-8041.

The function $f_S(s)$ is derived from the source region recurrence curve while $f_R(r)$ incorporates the spatial relationship between the total source region and the site of interest. The conditional probability is derived from a ground motion attenuation function discussed in the next section. Evaluation of the integral yields the probability that one event from the given source region will reach or exceed a_g. By multiplying this value by the expected number of events in the region for one year and summing over all source regions with some predetermined distance, we obtain the total expected number of events per year, or annual risk, R_A.

The risk can be stated in alternate forms; for example, return period, P_R, or lifetime risks, R_N. The return period is given by the inverse of R_A and corresponds to the average interval of time between the site of interest experiencing the specified acceleration or greater. The lifetime risk, R_N, is the probability of exceeding the specified acceleration in any N year period. For a Poisson process, this value is given by:

$$R_N = 1 - (1-R_A)^N. \quad (4)$$

As an example, a 475-year return period ground motion, $R_A \doteq 0.0021$, is equivalent to $R_{50} = 0.1$. This is equivalent to stating that in any 50-year period the level of ground motion having a 475-year return period will not be exceeded at the 90 percent confidence level.

4.2 Ground Motion Attenuation

The conditional probability density function discussed in the preceding section is derived from ground motion attenuation functions. Various empirical studies have been conducted to derive these functions (see Ref. 23). Typically these equations have the form

$$g = a_1 e^{a_2 M}(R + a_3)^{-a_4} \quad (4)$$

where g is the predicted motion level, M is earthquake magnitude and R the event-to-site distance. At best, these equations are of limited accuracy due to lack of radiation pattern or local travel path and site geology corrections, and the standard deviations associated with them are typically large. Most equations are based on data largely from southern California and presumed not typical of all regions of the world.[25]

25. Battis, J. C. (1981) Regional modification of acceleration attenuation functions, Bull. Seismol. Soc. Am. 71:1309-1321.

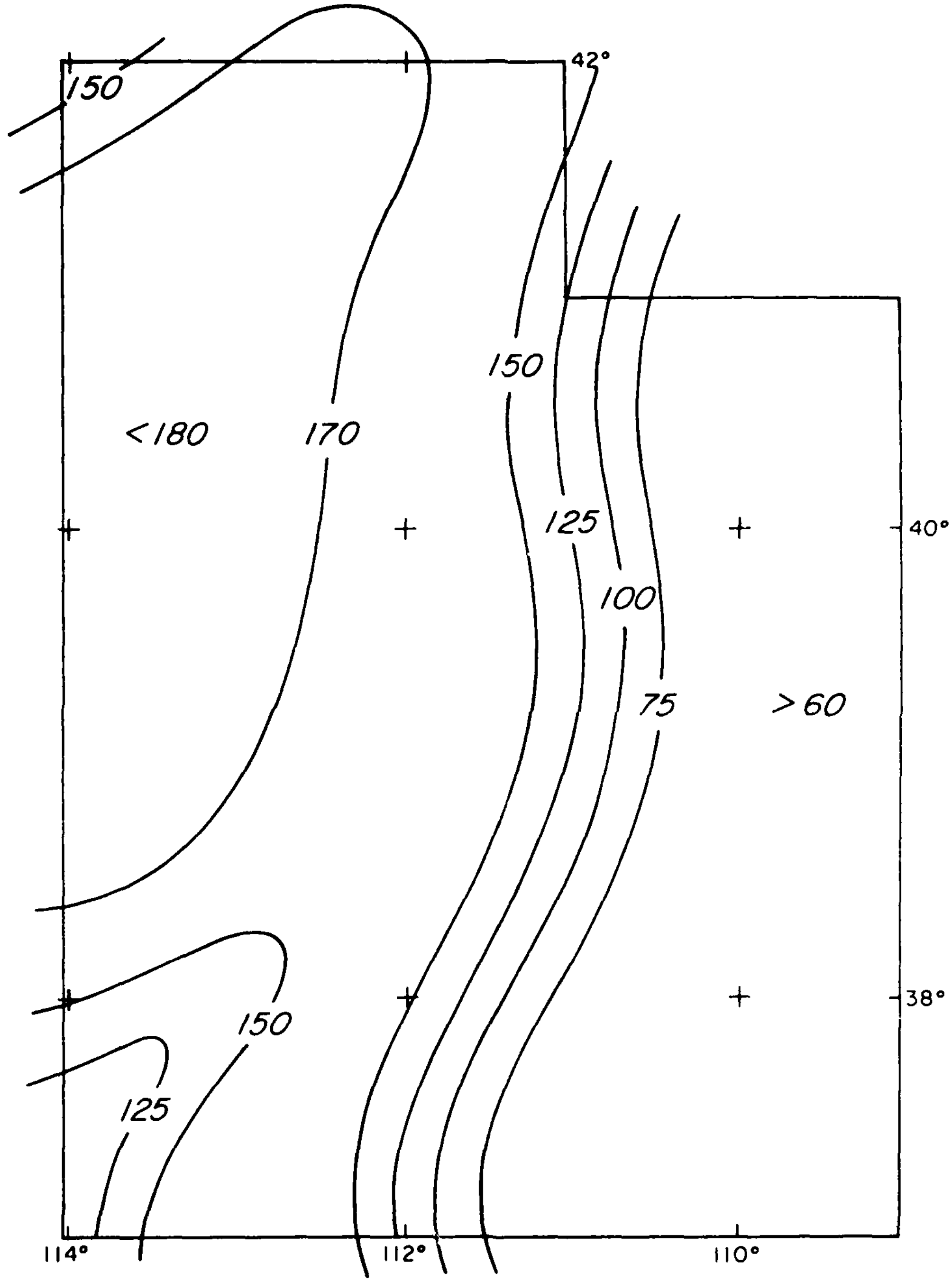

Figure 7. Uniform Seismicity Model Peak Acceleration Contours for a 10-Year Lifetime at the 90 Percent Confidence Level

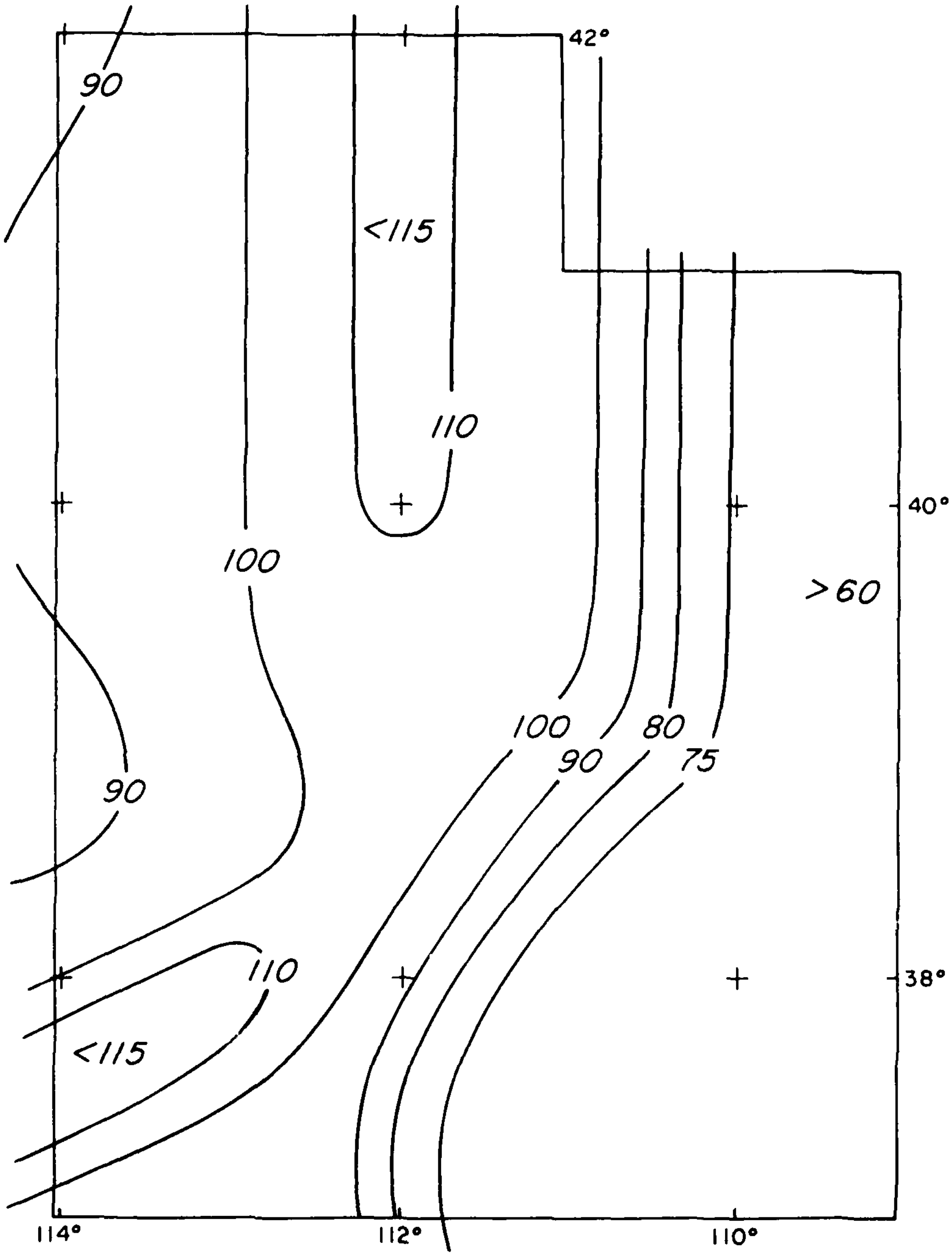

Figure 8. Subplate Margin Seismicity Model Peak Acceleration Contours for a 10-Year Lifetime at the 90 Percent Confidence Level

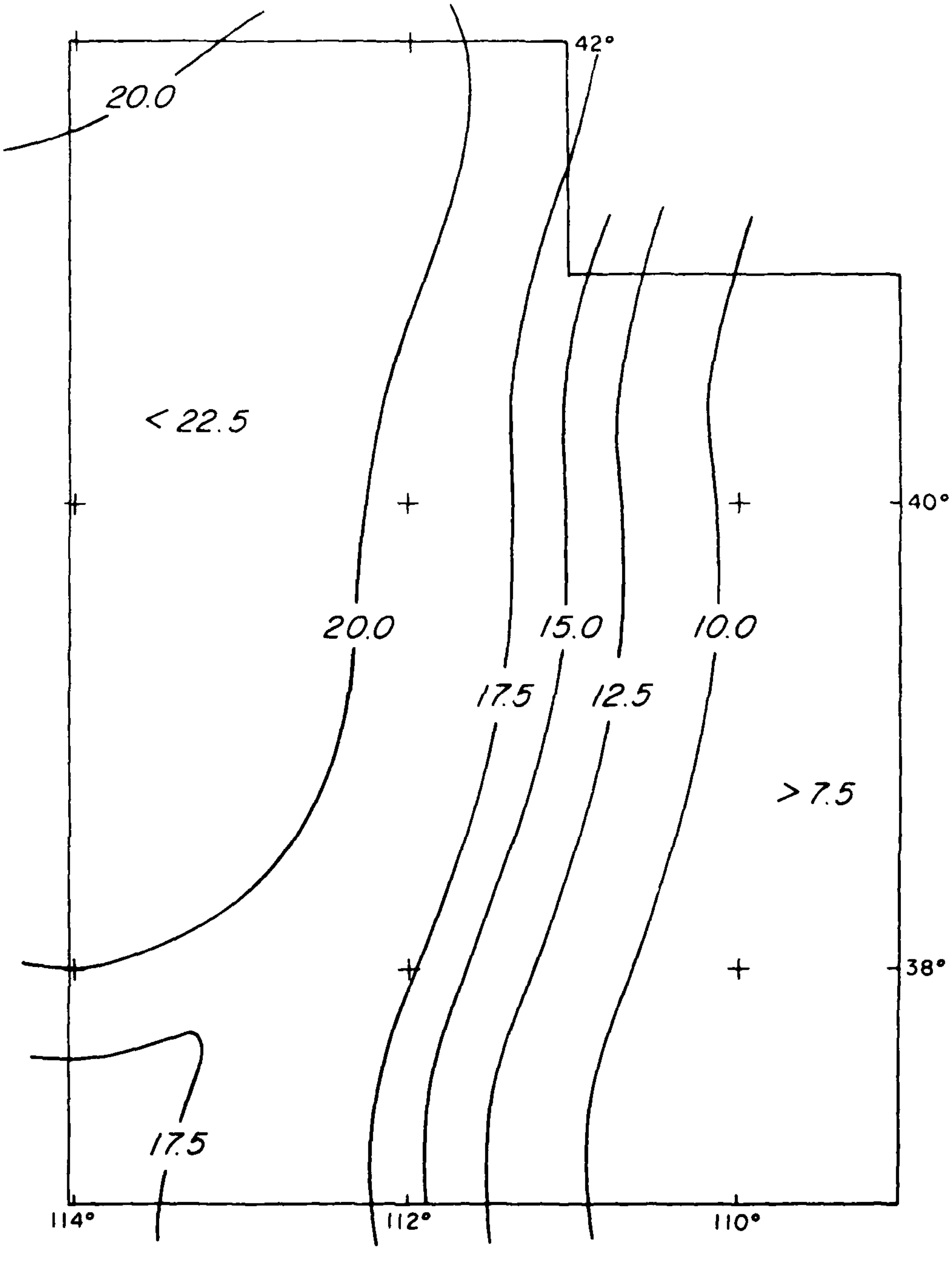

Figure 9. Uniform Seismicity Model Peak Velocity Contours for a 10-Year Lifetime at the 90 Percent Confidence Level

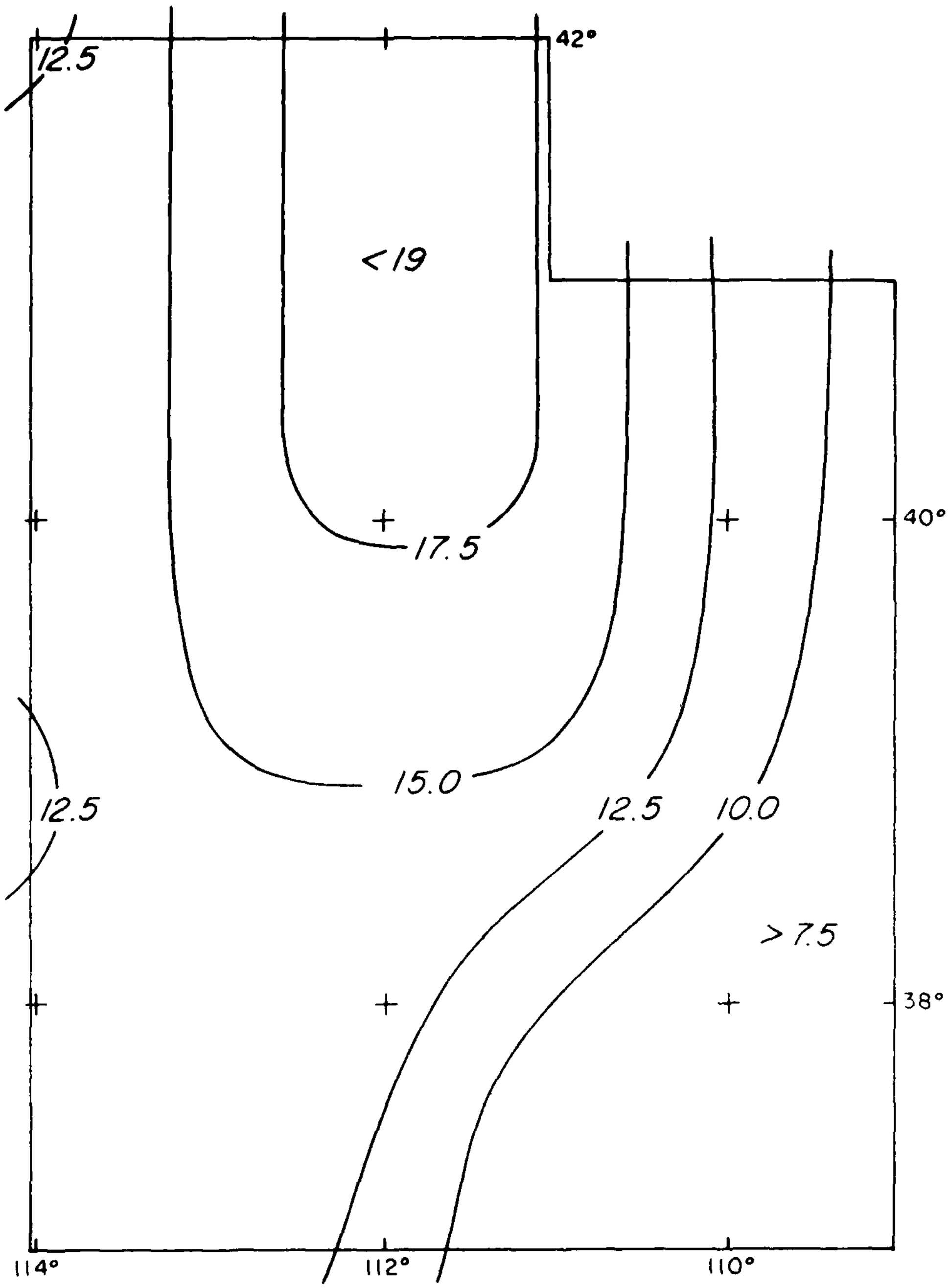

Figure 10. Subplate Margin Seismicity Model Peak Velocity Contours for a 10-Year Lifetime at the 90 Percent Confidence Level

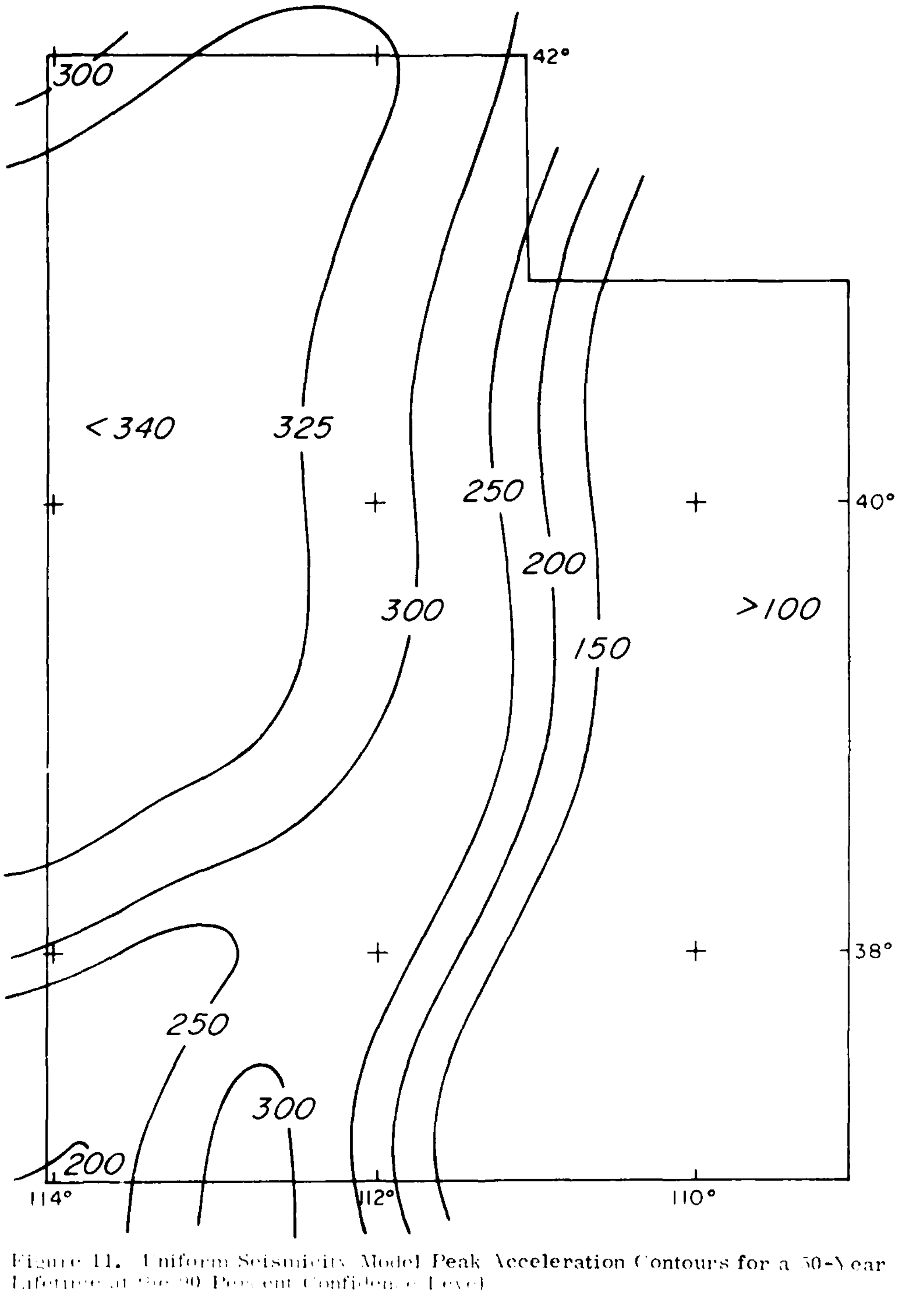

Figure 11. Uniform Seismicity Model Peak Acceleration Contours for a 50-Year Lifetime at the 90 Percent Confidence Level

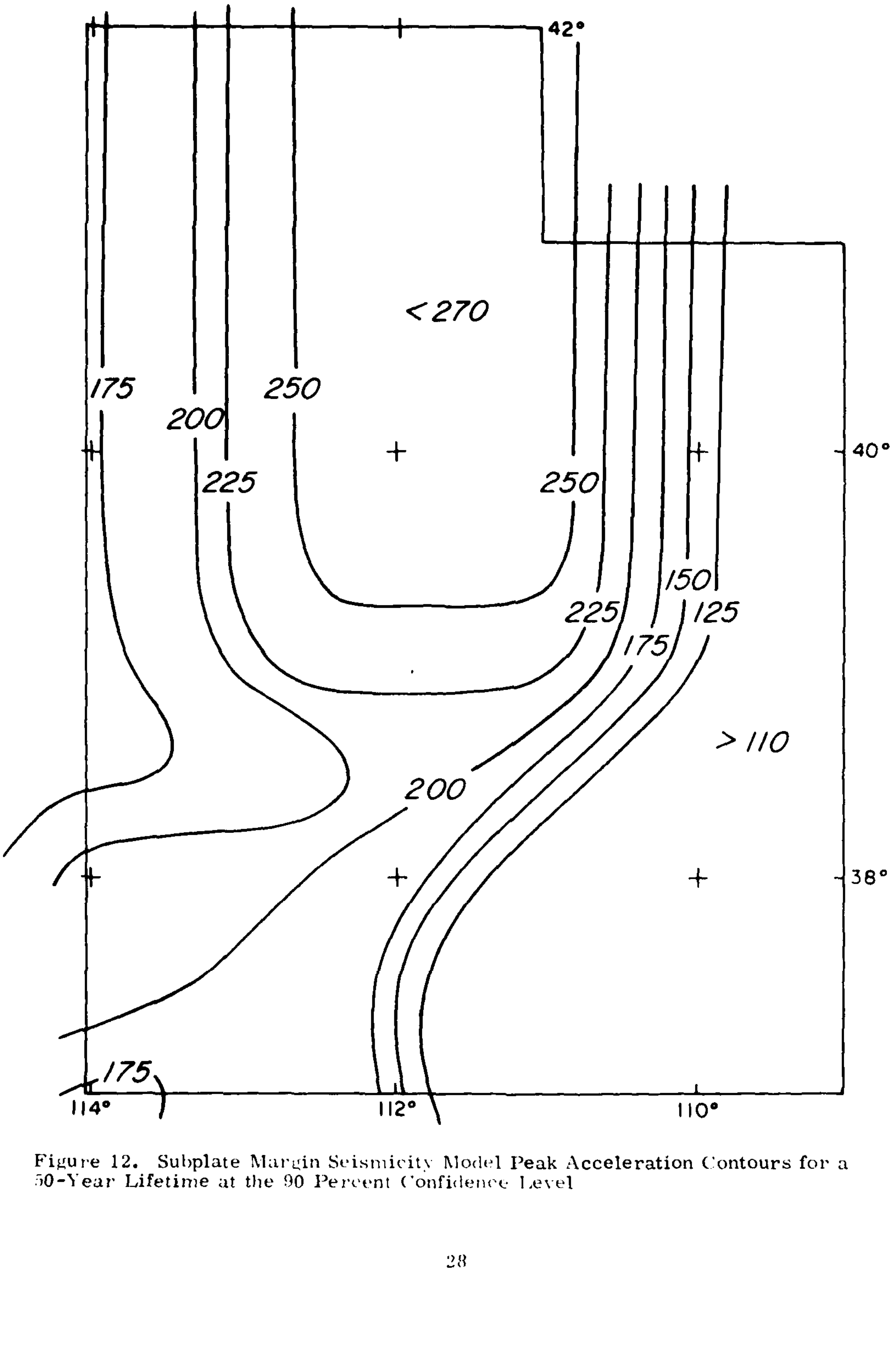

Figure 12. Subplate Margin Seismicity Model Peak Acceleration Contours for a 50-Year Lifetime at the 90 Percent Confidence Level

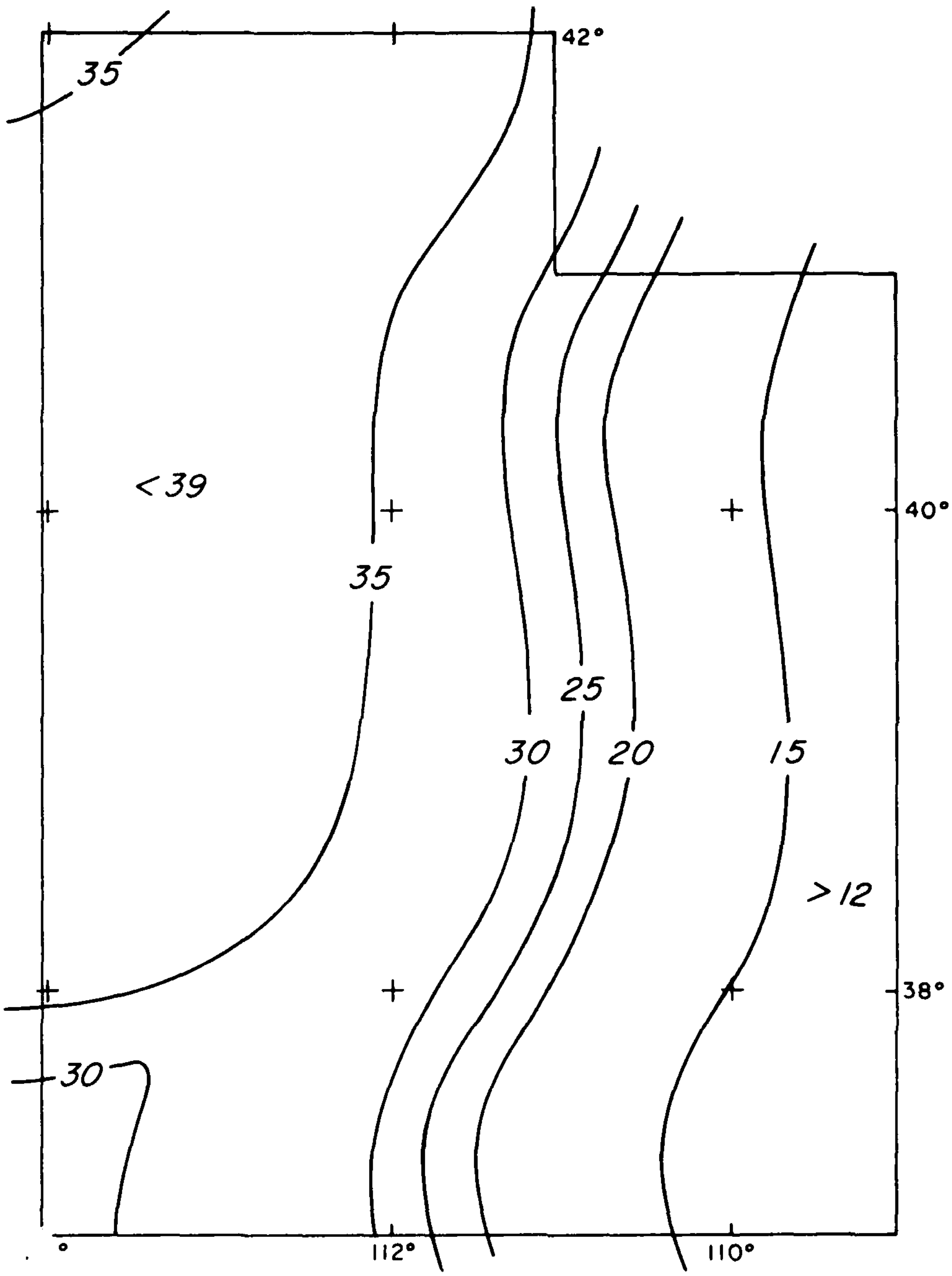

Figure 13. Uniform Seismicity Model Peak Velocity Contours for a 50-Year Lifetime at the 90 Percent Confidence Level

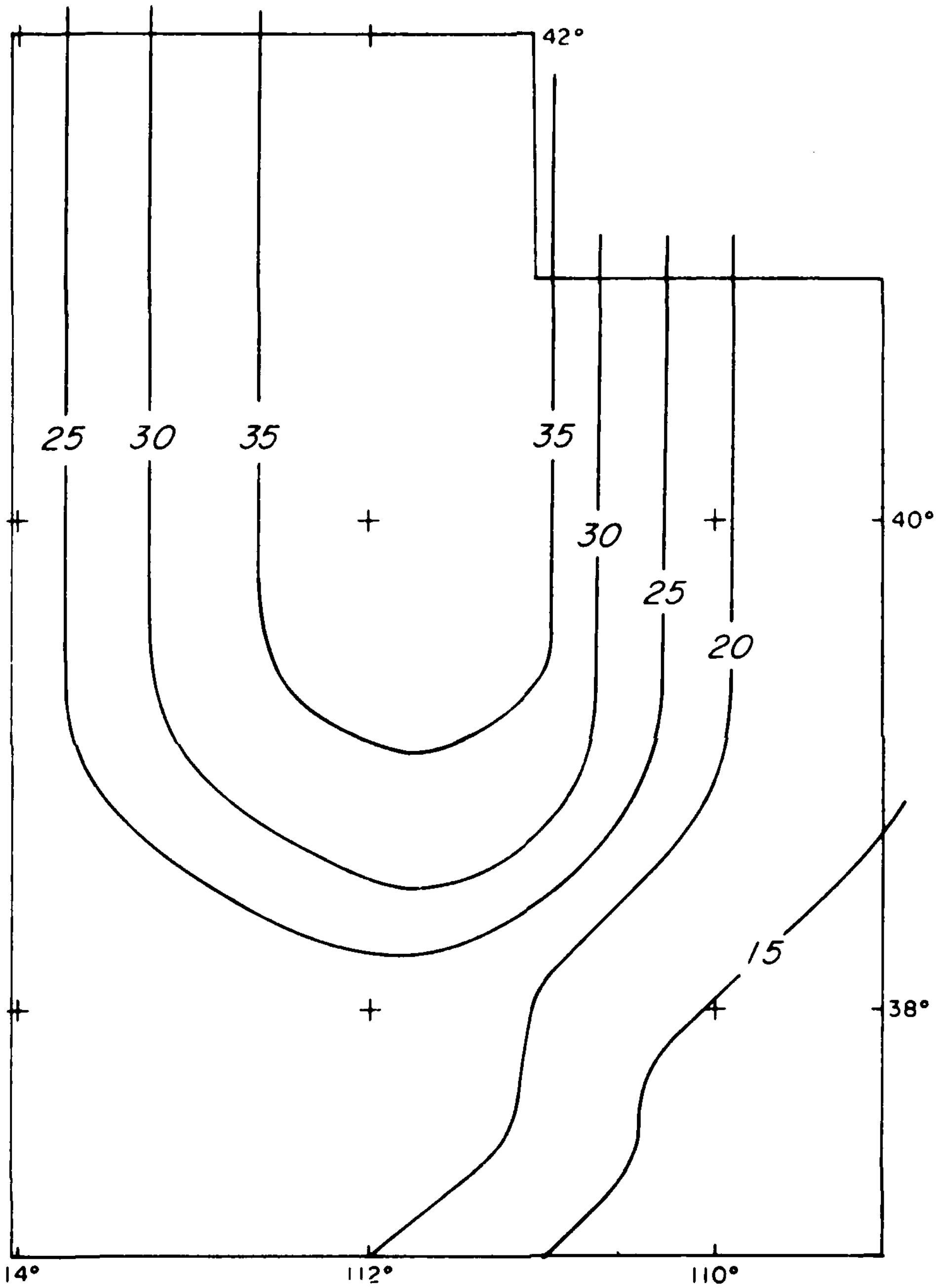

Figure 14. Subplate Margin Seismicity Model Peak Velocity Contours for a 50-Year Lifetime at the 90 Percent Confidence Level

Strong ground motion attenuation in the Utah area is not well determined.[13] Lacking adequate data upon which to base an attenuation function, we used curves derived for the California area. The function parameters for the peak acceleration, velocity, and displacement attenuation functions are given in Table 3. The

Table 3. Peak Ground Motion Attenuation Function Parameters

$$g = a_1 e^{a_2 M} (R+a_3)^{-a_4}$$

Ground Motion	a_1	a_2	a_3	a_4	δ	Source Reference No.
Acceleration (cm/sec^2)	160.20	0.908	25.0	2.076	0.707	24
Velocity (cm/sec)	5.64	0.921	25.0	1.20	0.629	25
Displacement (cm)	0.393	0.99	25.0	0.88	0.76	25

acceleration curve was derived by Battis, and the remaining two functions were evaluated by McGuire.[24,25] These equations give peak ground motion values for rock and stiff soil sites.

4.3 Statistical Hazard Results

For each of the two models described in Section 3, peak ground acceleration and velocity contour maps were evaluated for Utah using two different lifetime periods, 10 year and 50 year, and the calculations were carried out at the 90 percent confidence level of nonexceedence ($R_N = 0.1$). For the 10-year lifetime, the ground motion levels correspond to the 95-year return period motions; for the 50-year lifetime, to 475-year return period motions. These contour maps are shown in Figures 7 through 14.

Two facts concerning these maps should be pointed out. First, the ground motion levels are for stiff soil and rock sites; they have not been modified in any way for local geologic conditions. Particularly in the alluvial basins of western Utah, surface ground motions could be expected to be significantly different from reported values. Second, the general contour trends are determined by the areal extent of each source region. Any change in the source region definitions would be expected to alter the ground motion predicted at any particular location. The limitations of available geologic data and the diffuse nature of seismicity in this region allow only gross outlines of source regions to be made. This, in turn, limits application of these maps to anything more than a regional overview.

Variations in the seismic hazard predicted by the two seismicity models are apparent in Figures 7 through 14. This is especially true in western Utah and along the Wasatch Front area and expected from the different manner in which each model distributes the seismic activity in this area. As would be expected from the seismicity models, the seismic hazard based on the uniform model predicts higher levels of ground motion overall and specifically in the Basin and Range Province region of western Utah.

In addition to these contour maps, annual ground motion risk curves were evaluated for four sites that approximately correspond to Cedar City (38°N, 113°W), Wendover (41°N, 114°W), Salt Lake City-Ogden (41°N, 112°W) and Manti-La Sal National Forest (38°N, 110°W). The seismic risk evaluated at these locations show the range of hazard in the state and demonstrates the effects of the model variations. The annual risk curves for these locations are shown in Figures 15 through 22. The ground motion levels for specific annual risks for each site are given in Tables 4 through 7. For purposes of comparison, the annual seismic risk curves for Vandenberg Air Force Base, California are shown in Figure 23.[27] Vandenberg Air Force Base is located in a region of California that has a moderately high seismic hazard level.

4.4 Composite Design Response Spectra

The spectral characteristics of ground motion are typically represented in the form of response spectra. These spectra represent the maximum response of a simple, viscous-damped harmonic oscillator over a range of natural periods. For specific levels of damping, methods have been developed to estimate upper limit response spectra given the predicted ground motions levels at some site.[28] These

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26. McGuire, R. K. (1974) Seismic Structural Response Risk Analysis Incorporating Peak Response Regressions on Earthquake Magnitude and Distance, M.I.T. Dept. of Civil Eng., Research Report R74-51.

27. Battis, J. C. (1979) Seismic Hazards Estimation Study for Vandenberg AFB, USAF Geophysics Laboratory, AFGL-TR-79-0277, ADA082458.

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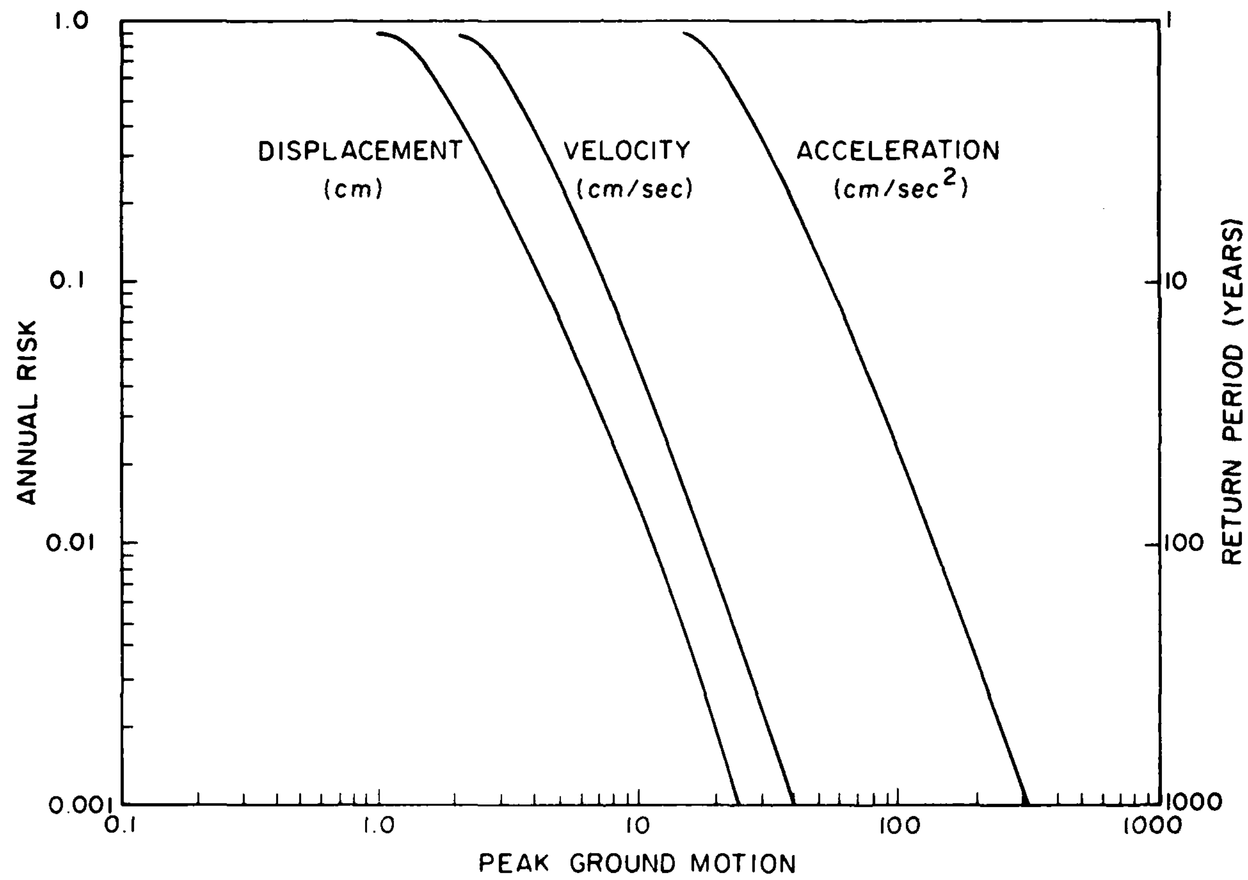

Figure 15. Annual Seismic Risk Curves for the Cedar City Area Using Uniform Seismicity Model

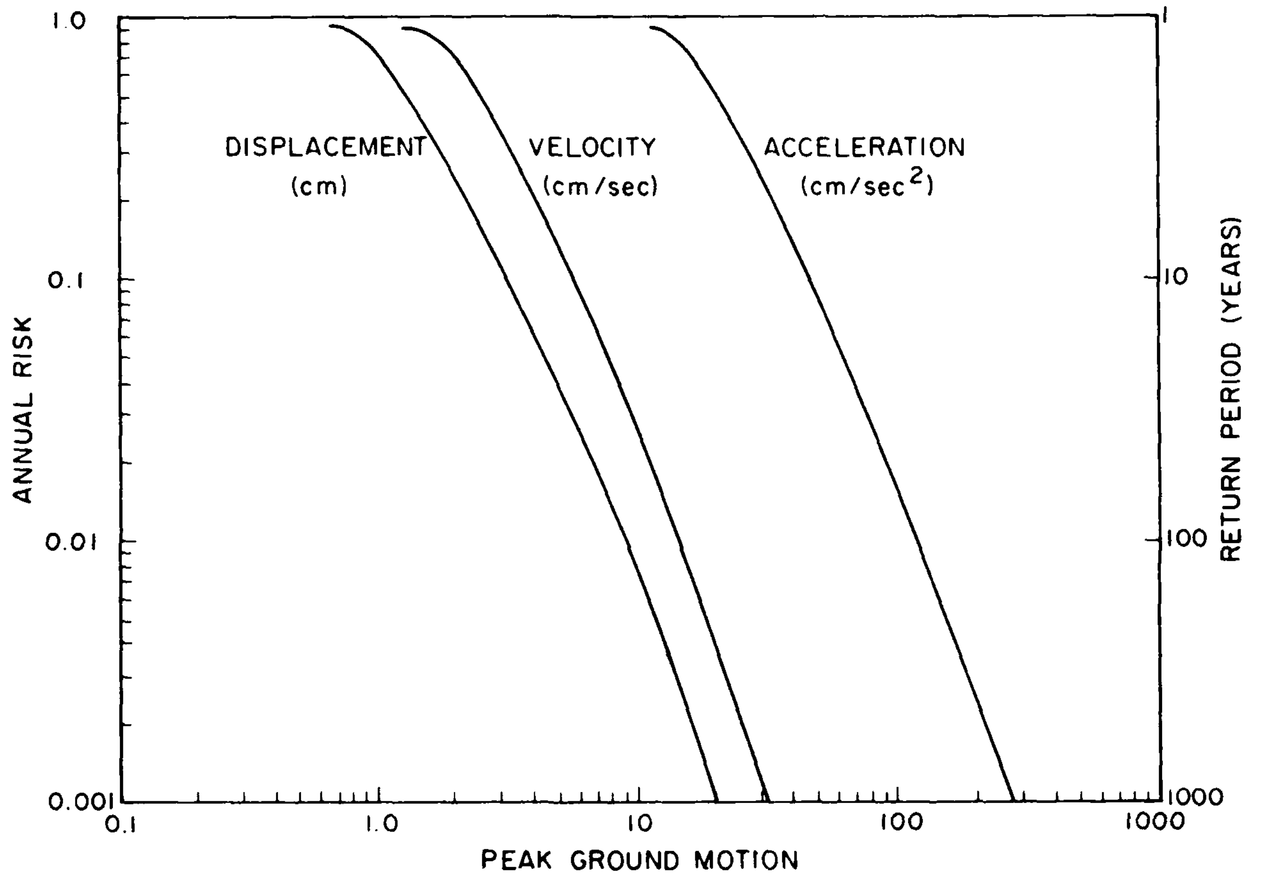

Figure 16. Annual Seismic Risk Curves for the Cedar City Area Using Subplate Margin Seismicity Model

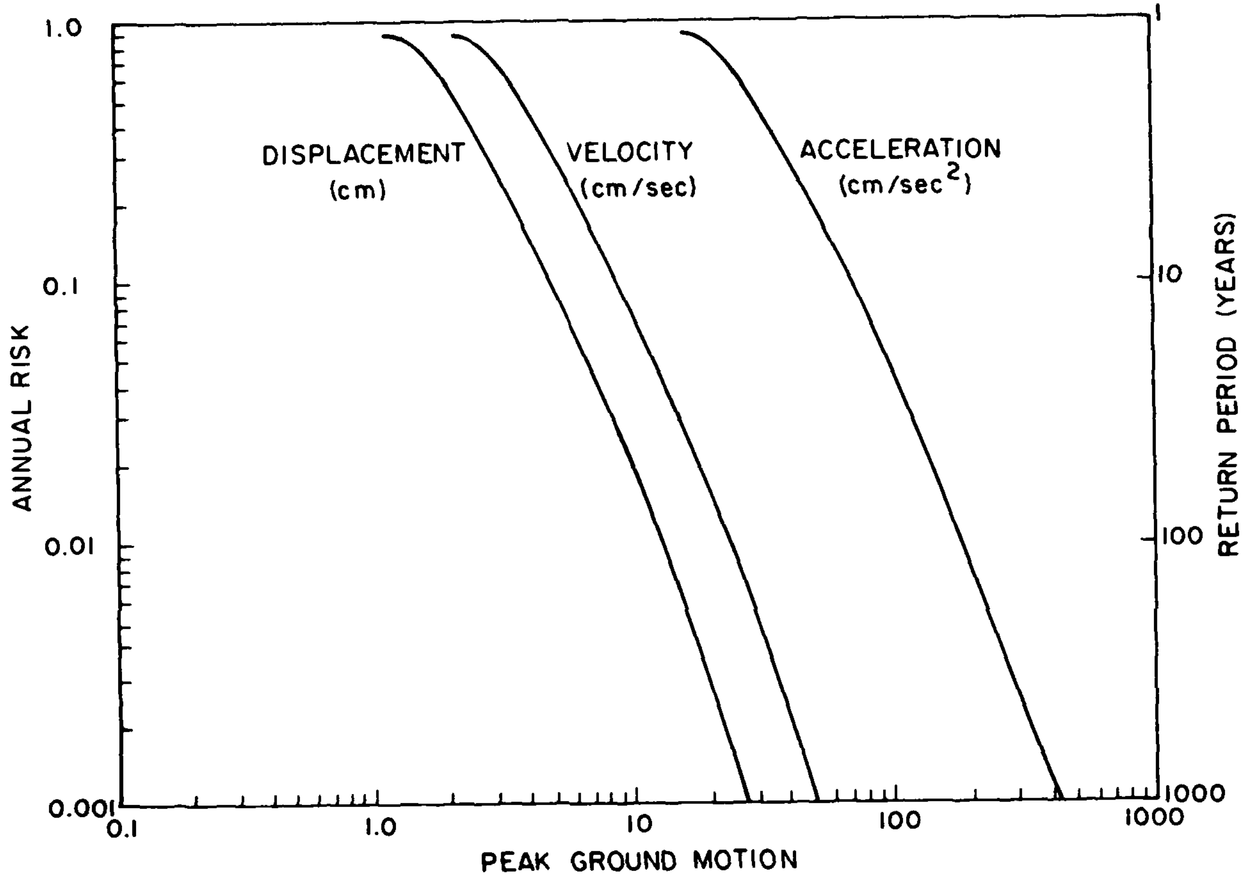

Figure 17. Annual Seismic Risk Curves for the *Wendover* Area Using Uniform Seismicity Model

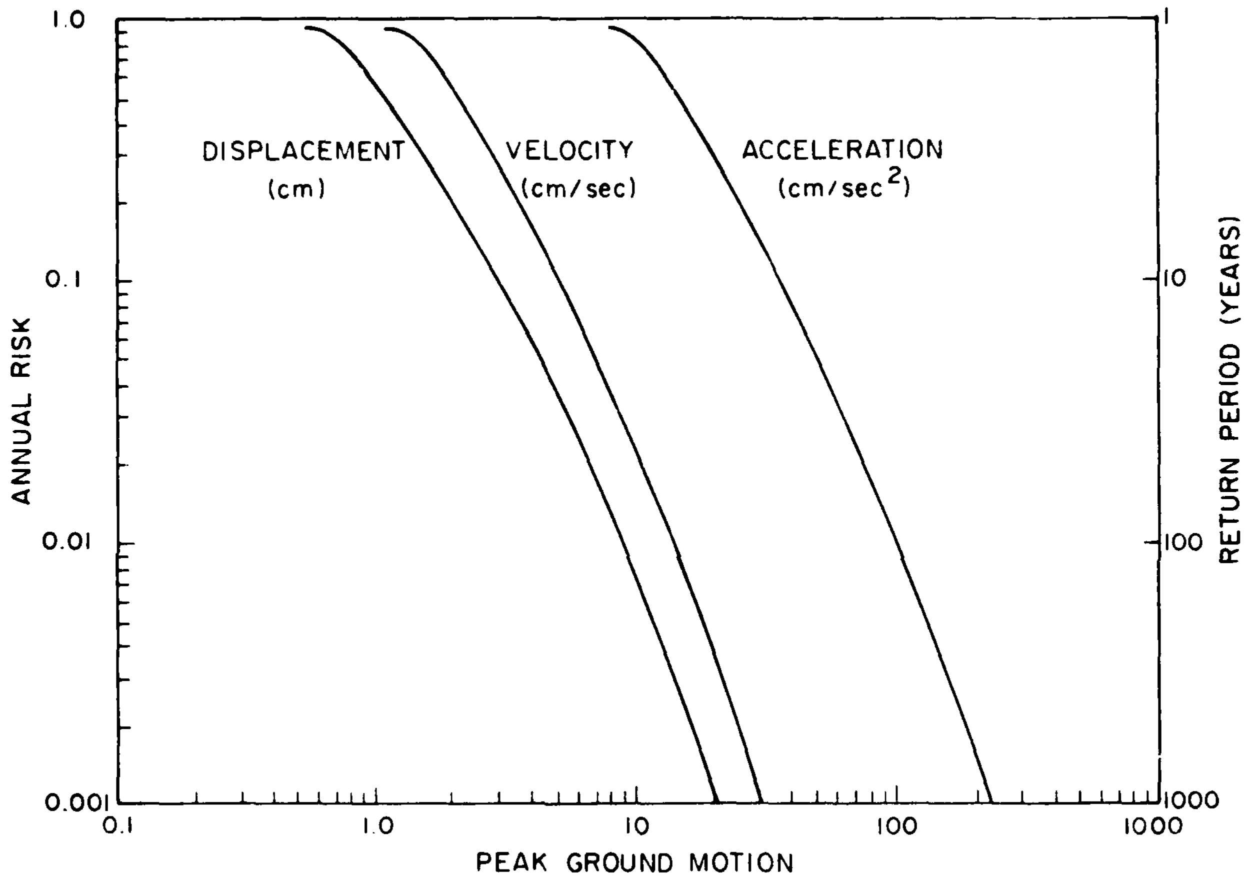

Figure 18. Annual Seismic Risk Curves for the Wendover Area Using Subplate Seismicity Model

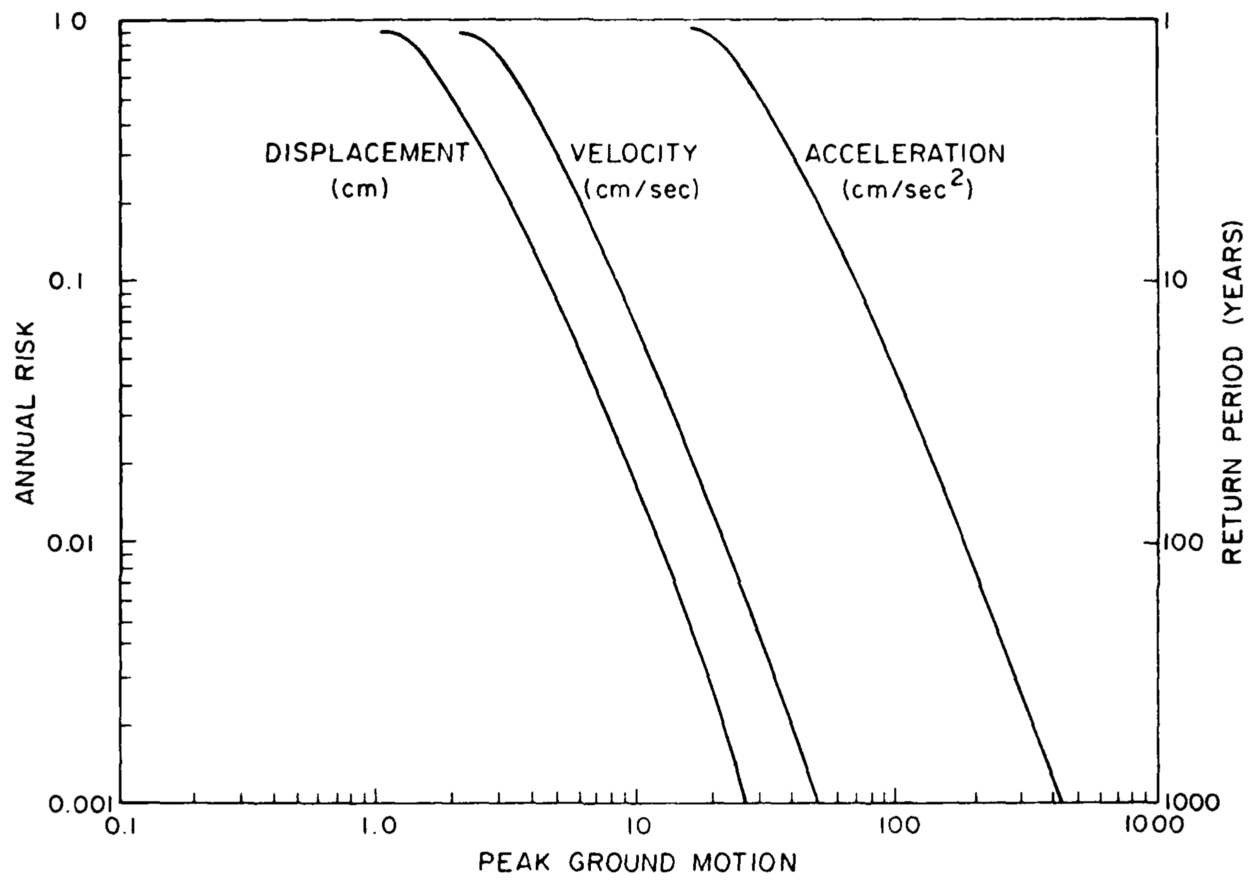

Figure 19. Annual Seismic Risk Curves for the Salt Lake City - Ogden Area Using Uniform Seismicity Model

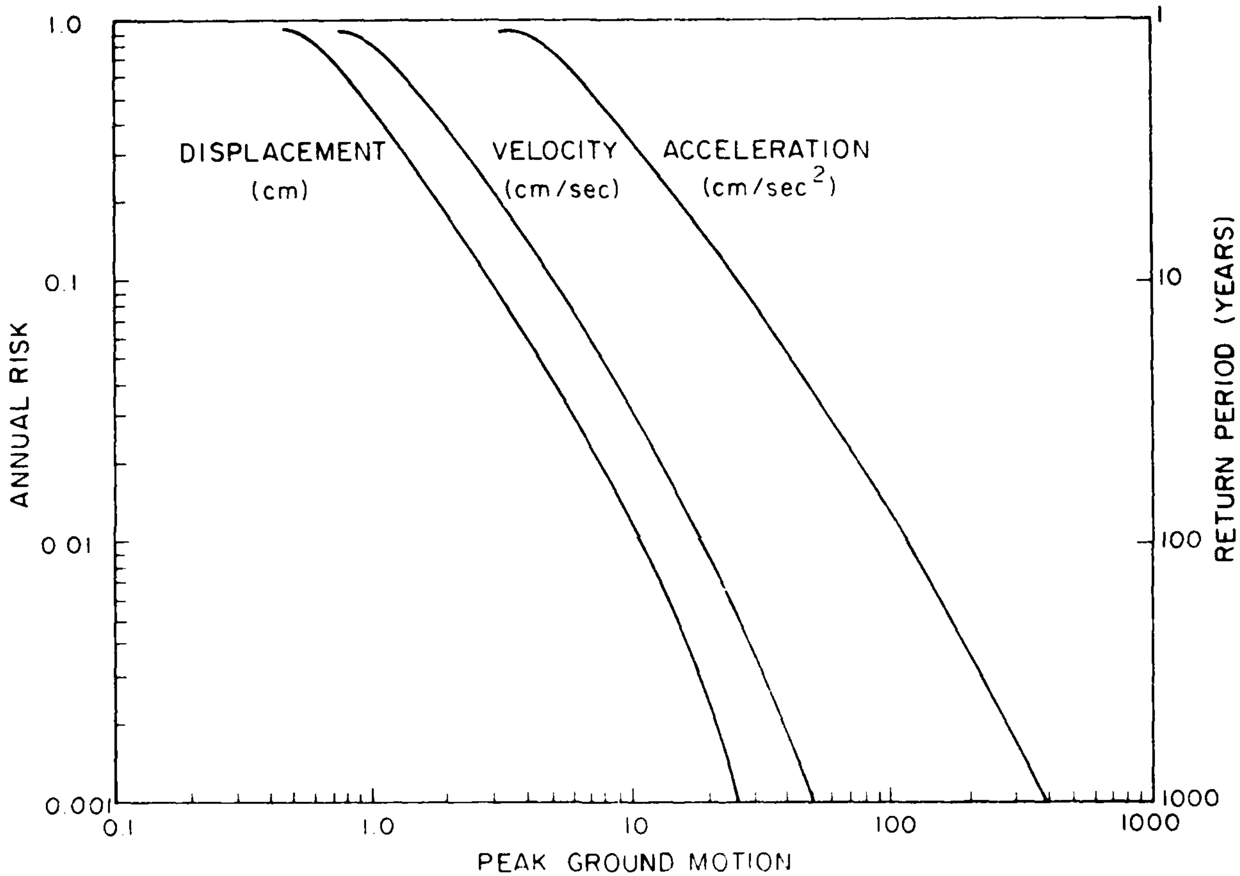

Figure 20. Annual Seismic Risk Curves for the Salt Lake City – Ogden Area Using Subplate Margin Seismicity Model

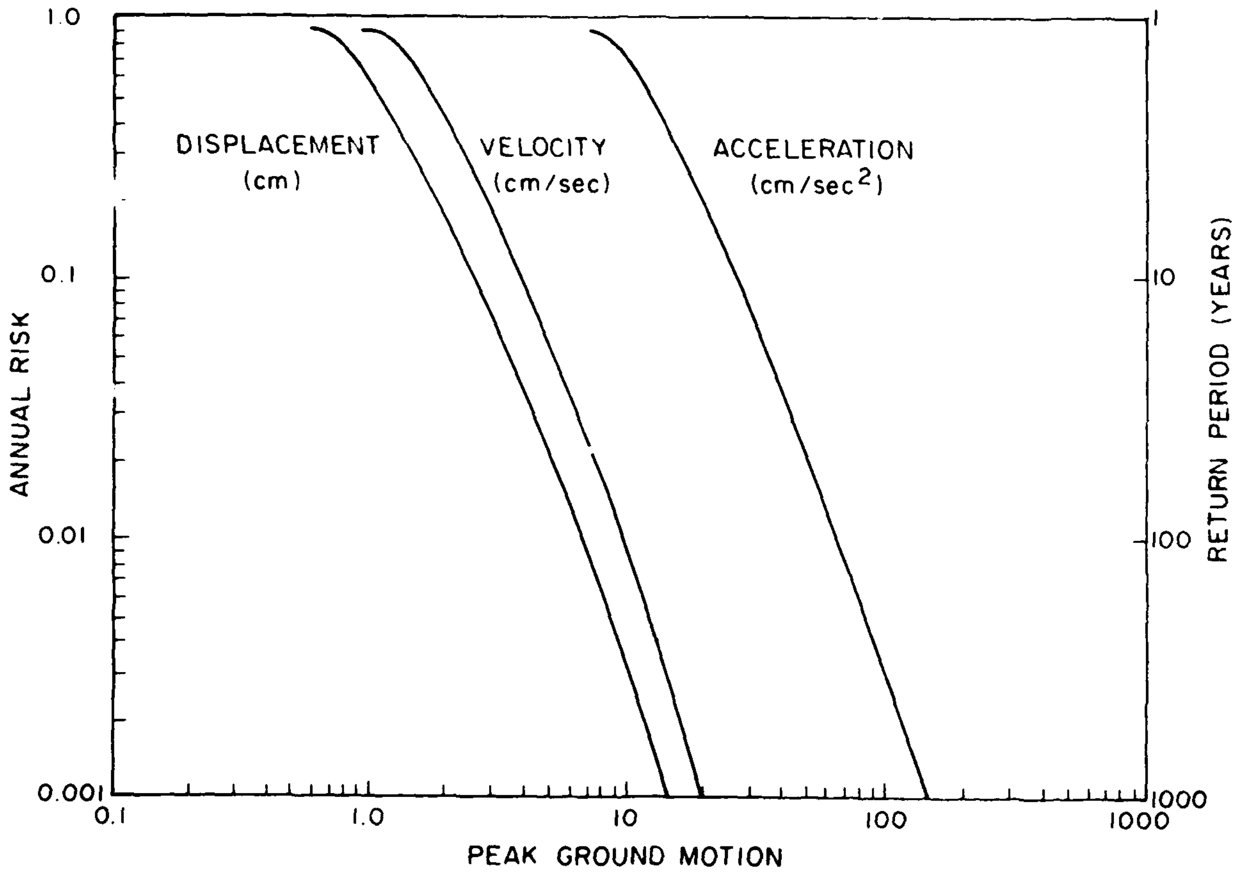

Figure 21. Annual Seismic Risk Curves for the Manti-La Sal National Forest Area Using Uniform Seismicity Model

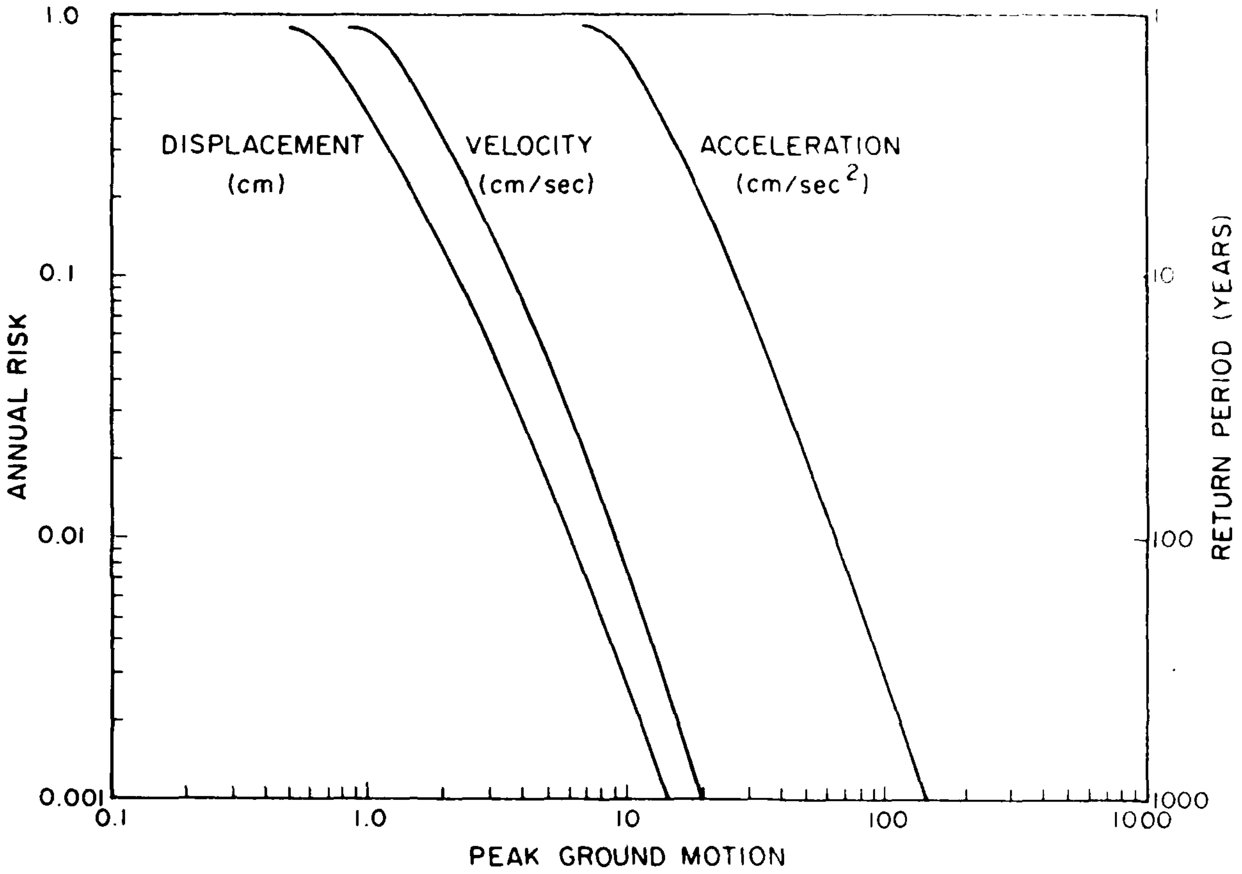

Figure 22. Annual Seismic Risk Curves for the Manti-La Sal National Forest Area, Utah: Subplate Margin Seismicity Model

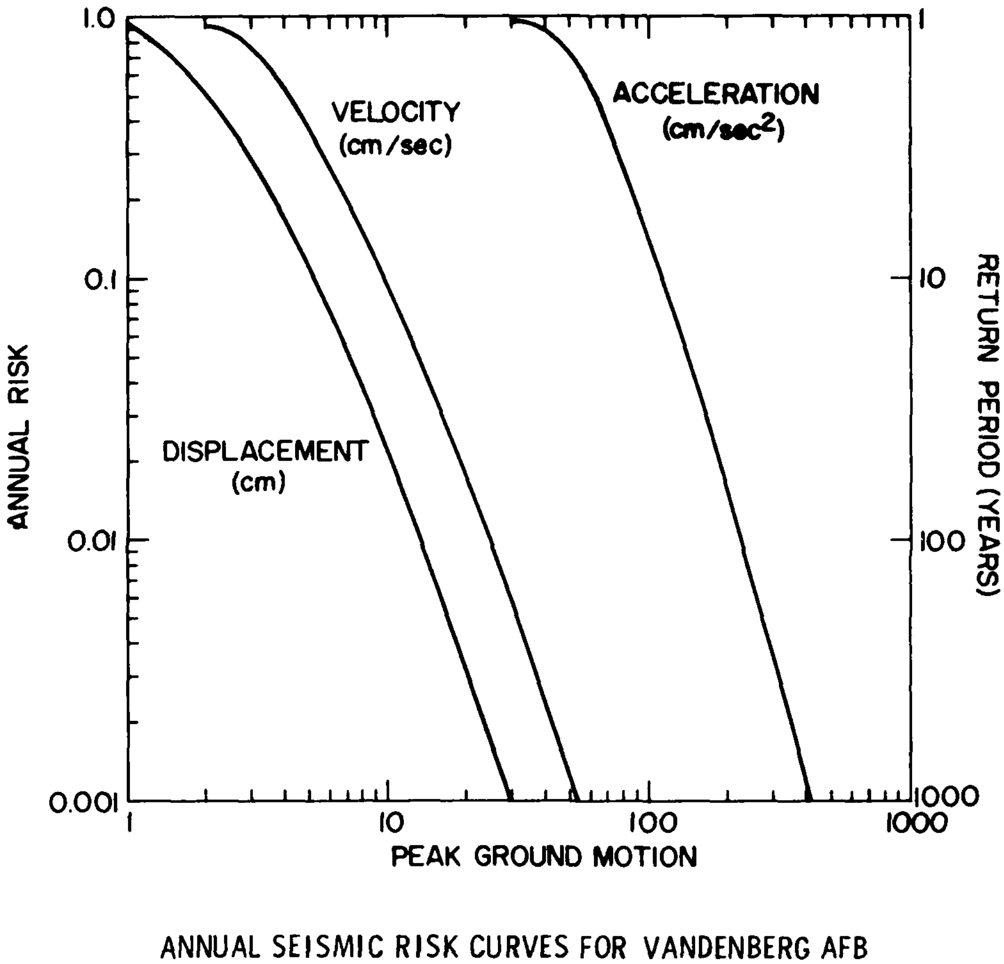

Figure 23. Annual Seismic Risk Curves for Pt Arguello (Vandenberg AFB), California

Table 4. Peak Ground Motion Annual Risk Levels for the Cedar City Area

Annual Risk	Return Period (Years)	Acceleration (cm/sec^2)		Velocity (cm/sec)		Displacement (cm)	
		US Model	SMS Model	US Model	SMS Model	US Model	SMS Model
0.5	2	2.27	20.6	3.3	2.4	1.9	1.3
0.2	5	39.7	33.4	[illegible]	4.1	3.1	[illegible]
0.1	10	54.1	[illegible]	7.4	[illegible]	[illegible]	[illegible]
0.05	20	72.0	[illegible]	[illegible]	7.4	[illegible]	[illegible]
0.02	50	104.3	[illegible]	14.2	10.8	[illegible]	[illegible]
0.01	100	136.7	[illegible]	18.4	14.1	[illegible]	[illegible]
0.005	200	178.4	[illegible]	[illegible]	[illegible]	14.4	[illegible]
0.002	500	[illegible]	211.7	[illegible]	[illegible]	[illegible]	[illegible]
0.001	1000	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]

Table 5. Peak Ground Motion Annual Risk Levels for the Wendover Area

Annual Risk	Return Period (Years)	Acceleration (cm/sec^2)		Velocity (cm/sec)		Displacement (cm)	
		US Model	SMS Model	US Model	SMS Model	US Model	SMS Model
[illegible]	[illegible]	[illegible]	14.8	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	5	47.7	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
0.1	10	65.5	34.1	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	20	80.4	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	50	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	100	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
0.005	200	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	500	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	1000	[illegible]	231.1	[illegible]	[illegible]	[illegible]	[illegible]

Table 6. Peak Ground Motion Annual Risk Levels for Salt Lake City - Ogden Area

Annual Risk	Return Period (Years)	Acceleration (cm/sec^2)		Velocity (cm/sec)		Displacement (cm)	
		US Model	SMS Model	US Model	SMS Model	US Model	SMS Model
0.5	2	29.1	71.	3.7	1.5	1.9	[illegible]
0.2	5	47.0	15.5	5.9	3.1	3.2	1.8
0.1	10	64.8	25.7	8.1	4.9	4.4	2.9
0.05	20	87.3	41.2	[illegible]	7.0	6.1	4.4
0.02	50	128.5	75.8	15.8	13.0	[illegible]	7.5
0.01	100	171.7	112.9	20.8	18.0	11.8	[illegible]
0.005	200	226.3	167.5	27.0	25.9	[illegible]	[illegible]
0.002	500	324.9	271.9	37.5	38.6	19.9	[illegible]
0.001	1000	423.6	382.0	47.6	50.7	[illegible]	[illegible]

Table 7. Peak Ground Motion Annual Risk Levels for the Manti-La Sal National Forest Area

Annual Risk	Return Period (Years)	Acceleration (cm/sec^2)		Velocity (cm/sec)		Displacement (cm)	
		US Model	SMS Model	US Model	SMS Model	US Model	SMS Model
0.5	2	[illegible]	[illegible]	1.8	[illegible]	[illegible]	[illegible]
0.2	5	14.2	19.2	[illegible]	[illegible]	[illegible]	[illegible]
0.1	10	25.7	25.7	[illegible]	[illegible]	[illegible]	[illegible]
0.05	20	33.8	33.8	[illegible]	4.8	[illegible]	[illegible]
0.02	50	48.8	48.8	6.4	[illegible]	[illegible]	[illegible]
0.01	100	[illegible]	[illegible]	9.7	9.4	[illegible]	[illegible]
0.005	200	[illegible]	180.4	11.4	[illegible]	[illegible]	[illegible]
0.002	500	[illegible]	114.1	15.3	[illegible]	[illegible]	[illegible]
0.001	1000	[illegible]	146.5	18.9	[illegible]	[illegible]	14.

are known as design response spectra. Newmark et al have developed one set of commonly used amplification factors given in Table 8.[29] These values are used to

Table 8. Horizontal Design Response Spectra Amplification Factors

Critical Damping %	Acceleration			Displacement (cm)
	33 Hz	9 Hz	2.5 Hz	0.26 Hz
0.5	1.0	4.96	5.95	3.20
[illegible]	1.0	3.54	4.25	2.50
[illegible]	1.0	[illegible]	3.13	2.05
[illegible]	1.0	2.27	2.72	1.88
10.0	1.0	1.90	2.28	1.70

modify the ground acceleration and displacement levels in order to obtain response spectral levels at specific frequencies. The levels of critical damping correspond to different foundation soil conditions, with the lowest critical damping values being for hard rock, and the highest damping values for soft soil. These spectra represent the mean plus one standard deviation spectral values for any specified ground motion.

Composite response spectra have been calculated for the 100-year return period ground motions at each of the four sites specified in Section 4.3. These spectra are given in Figures 24 to 27. These curves correspond closely to the 10-year lifetime, 90 percent confidence level response spectra. It should be noted that the curves do not necessarily represent the predicted spectra for any one earthquake. The peak ground motions at the 100-year return period could be generated by different earthquakes occurring at different times and locations. Thus, it is more accurate to view this representation as estimated upper level values for any one event over limited frequency windows.

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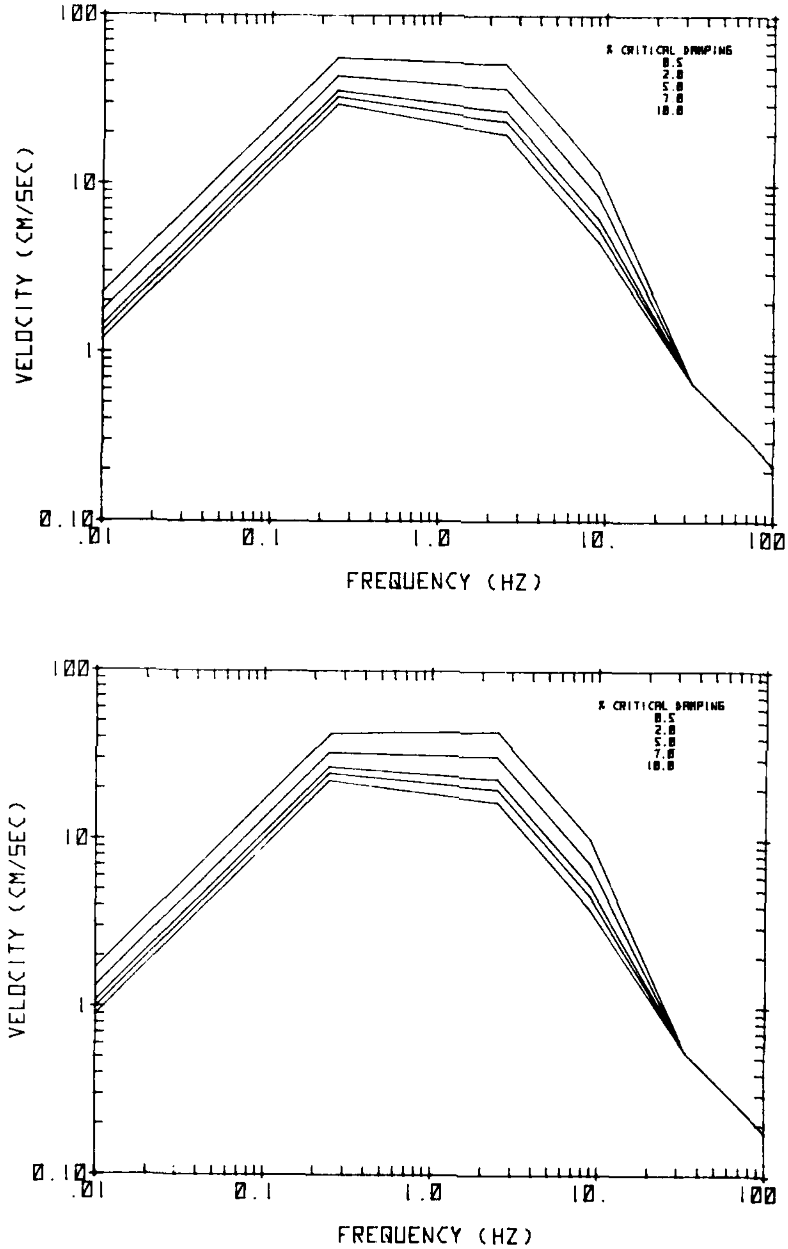

Figure 24. 100-Year Return Period Composite Response Spectra for the Cedar City Area: (a) Uniform Seismicity Model; (b) Subplate Margin Seismicity Model

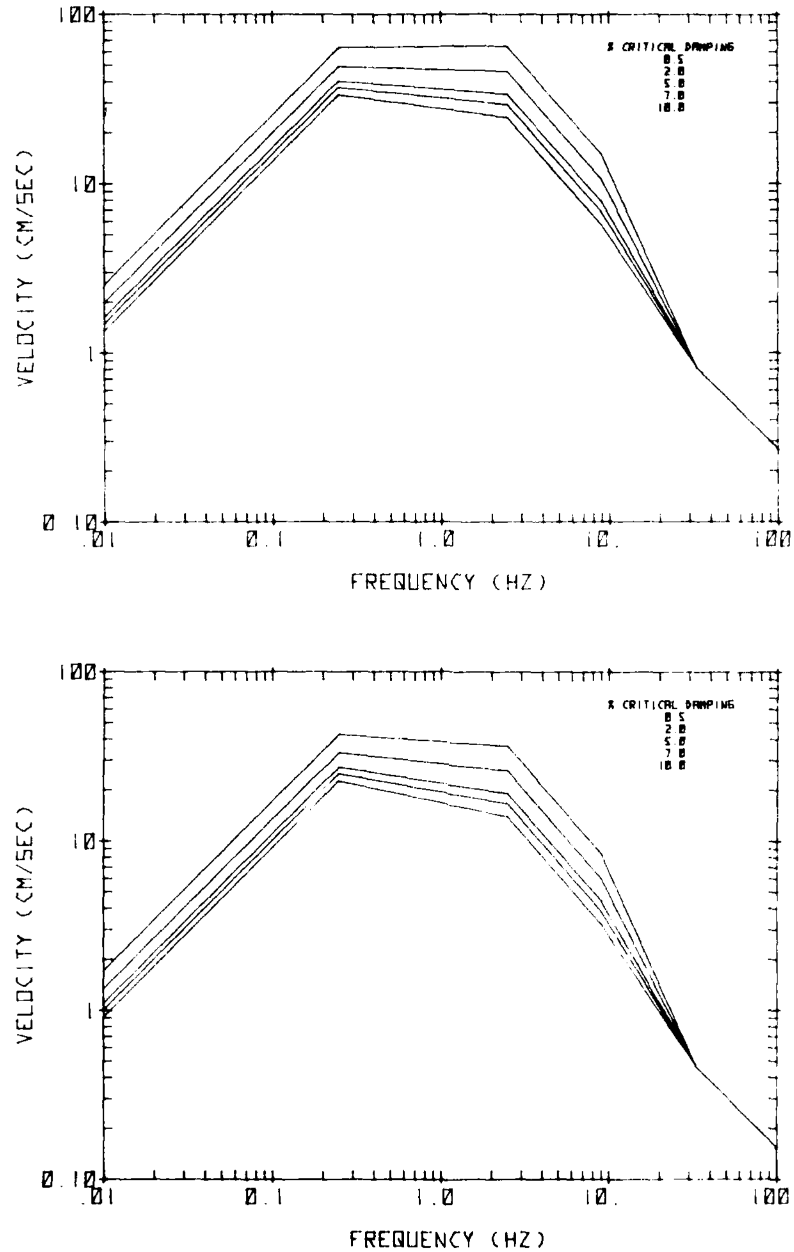

Figure 25. 100-Year Return Period Composite Response Spectra for the Wendover Area: (a) Uniform Seismicity Model; (b) Subplate Margin Seismicity Model

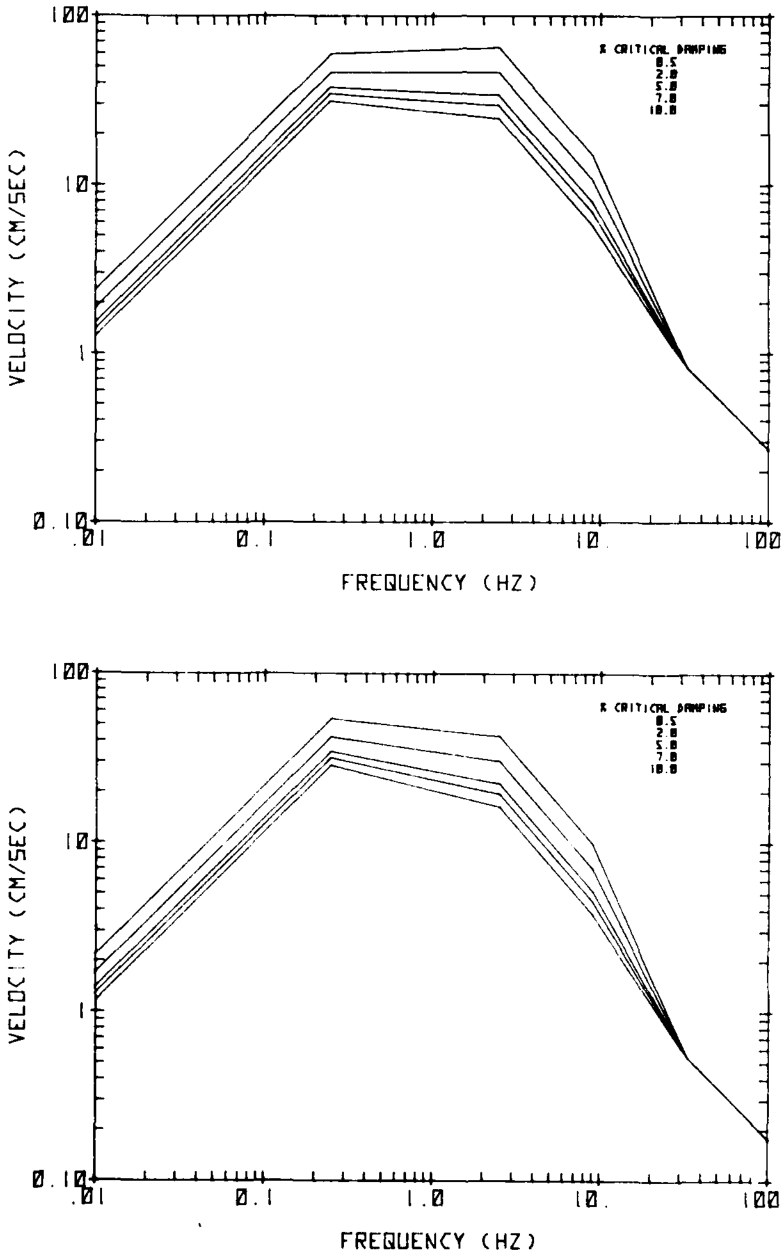

Figure 26. 100-Year Return Period Composite Response Spectra for the Salt Lake City - Ogden Area: (a) Uniform Seismicity Model; (b) Subplate Margin Seismicity Model

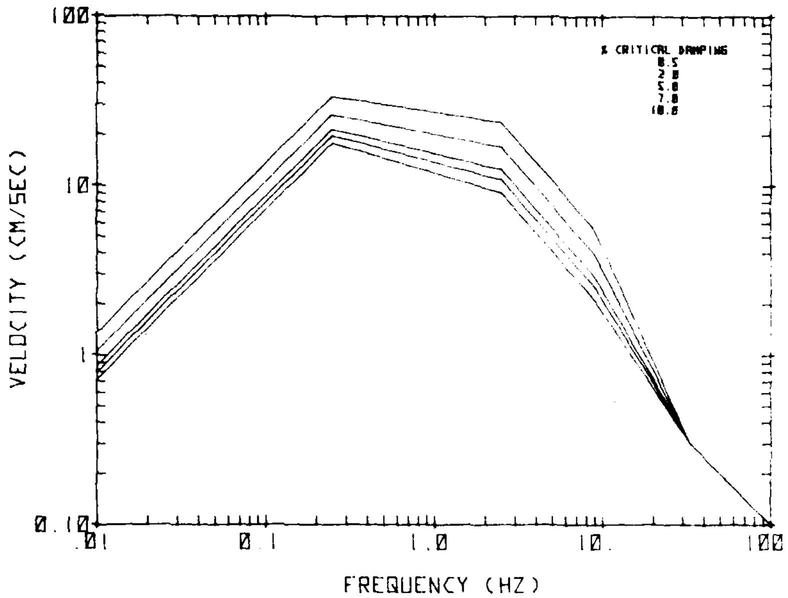

Figure 27. 100-Year Return Period Composite Response Spectra for the Manti-La Sal National Forest Area (both models produce the same spectra)

5. MAXIMUM CREDIBLE GROUND MOTION

With use of the map of known and suspected Quaternary faults in Utah (Figure 3), maximum credible ground motions were estimated for the Utah region. As many fault segments on this map could be incompletely plotted, each fault segment was assumed to be able to support the maximum credible earthquake for the source region in which it is located. The maximum credible earthquakes are based on the subplate margin seismicity model (Table 2). Ground motion distribution is based on the 90 percent confidence level motions predicted by the attenuation functions given in Table 3. The resulting contour plots are shown in Figures 28 through 30. Based on the available fault data, which in many areas is incomplete, these contour maps show the largest ground motions expected at a hard rock site in Utah without regard to the likelihood of occurrence in any time period.

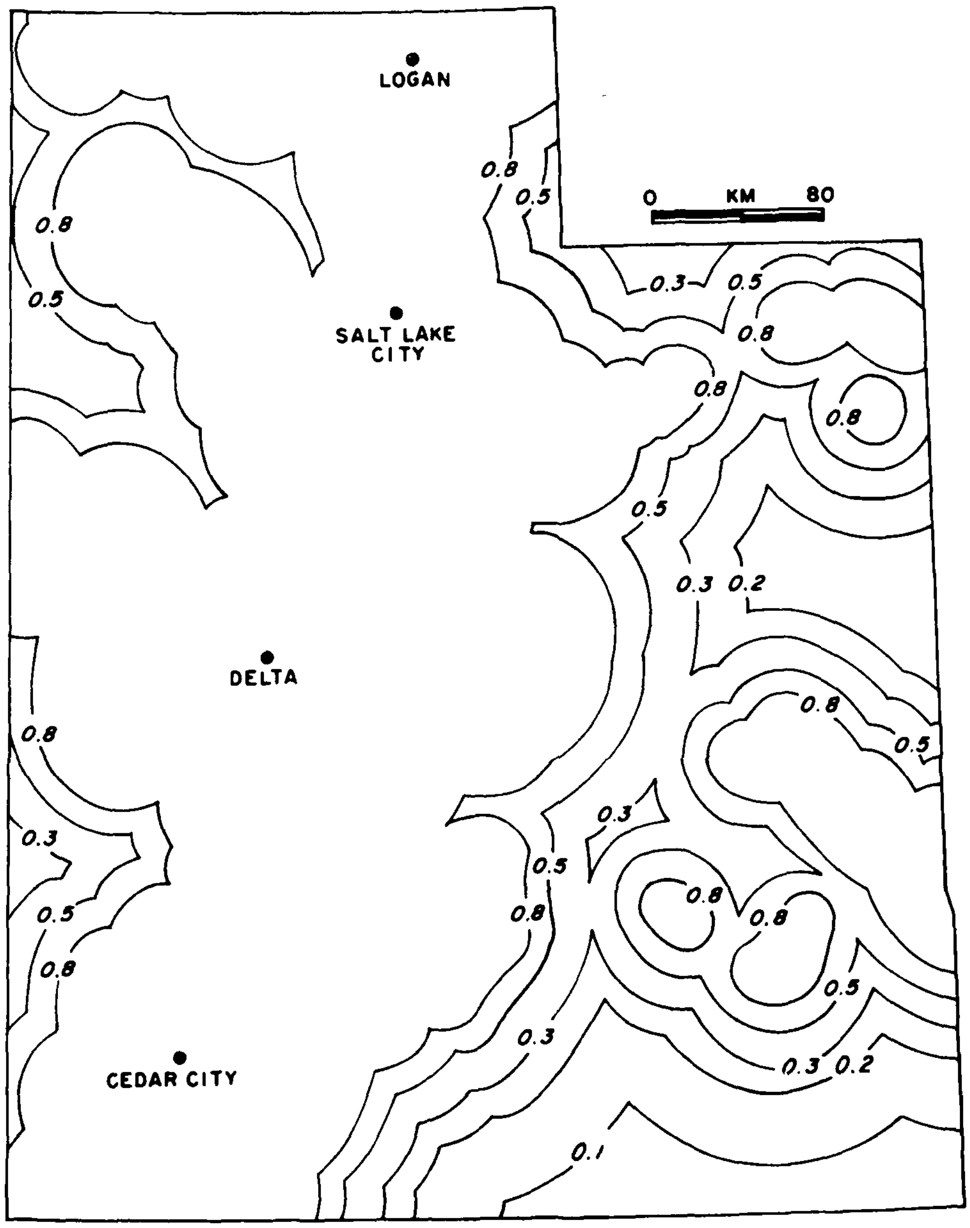

Figure 28. Deterministic Peak Acceleration Contours for Utah in Fractions of g. (contours above 0.8 g are not plotted)

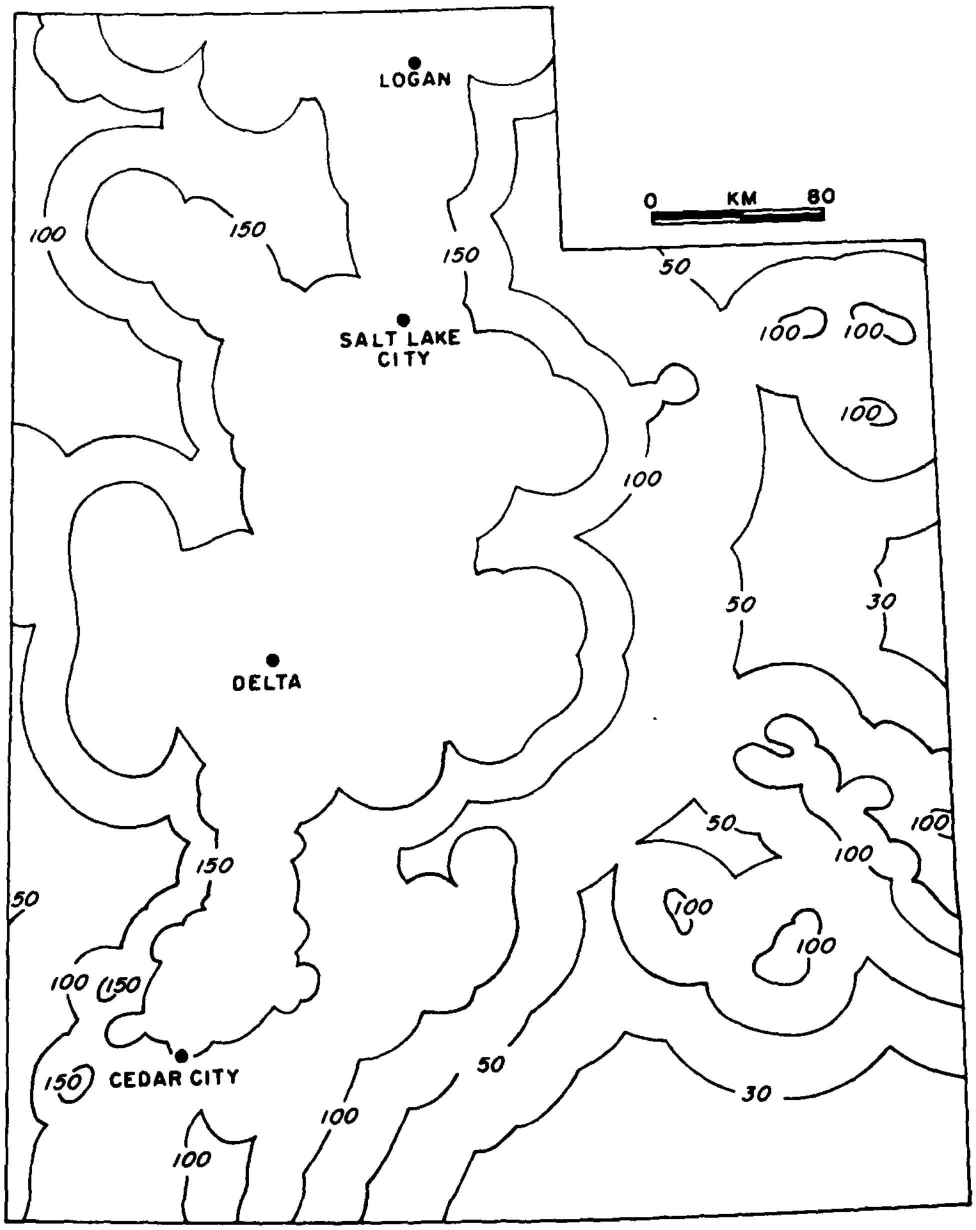

Figure 29. Deterministic Peak Velocity Contours for Utah in cm/sec

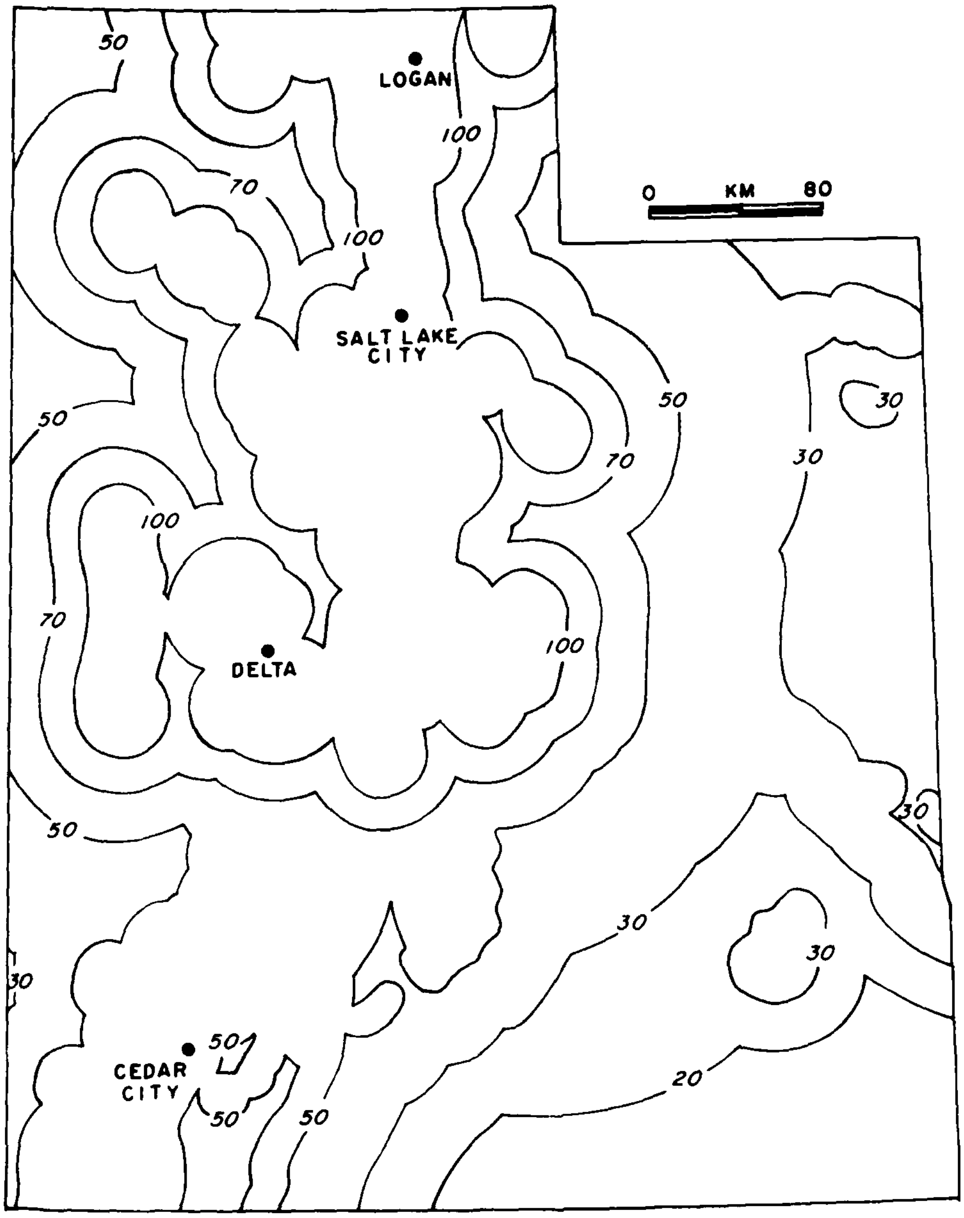

Figure 30. Deterministic Peak Displacement Contours for Utah in cm

6. DISCUSSION OF RESULTS

The level of uncertainty in the evaluation of seismic hazard for any region is high, and particularly true for this study. The source of this uncertainty includes: the definition of the seismicity characteristics throughout the region; the seismic attenuation properties of the crust; and the relation between the accelerations generated by an earthquake and the size of the event. The effect of this uncertainty can be seen by comparison of the annual risk levels given in Tables 4 through 7. Variations greater than 400 percent can be found where the only modification being considered is the distribution of seismicity.

In the present study, the definition of the seismic regionalization and the seismic characteristics of each region, such as maximum magnitude and recurrence rates, are believed to be the major source of error. As one example, the b-value of the recurrence curves is often found to have significant variations when derived using distinct time windows of earthquake history within a specified region. This is a real effect which derives from the statistical nonstationarity of the earthquake process.

Because the length of the historical record is short when compared to the duration time-scale of geologic processes, choice of the proper seismicity model is a difficult task. To some degree, the analysis done for this report attempts to handle those questions by using two models representing approximations of the extremes. The subplate margin seismicity model is considered the better model if one projects historical seismic activity into the future. However, if the historical seismicity does not represent the long-term trend, as suggested by Ryall, then the uniform seismicity could be more accurate.

For predicting seismic hazard over the near-term, up to several hundred years, the author holds that the subplate margin model provides a better picture of future earthquake activity. The primary reason for this conclusion is that as the geologic processes occur over long time periods, changes in the processes will also occur over relatively long periods.

7. CONCLUSIONS

With the use of two distinct seismic regionalizations, seismic hazard evaluations were conducted for Utah, depicting the possible extremes in future seismic activity in the Utah area. The primary distinction in the models was the treatment of Basin and Range seismicity. In one model, the seismic activity in this province was uniformly distributed, whereas in the second, it was concentrated at the province boundaries. On the basis of these models, contour maps of peak acceleration and velocity were constructed for Utah and annual risk curves evaluated for specific sites within the state. In addition, deterministic hazard estimates were made based on known and suspected Quaternary faults in Utah.

It has been concluded that for near-term hazard evaluations, the subplate margin model provided the most useful hazard projection. Based on this model, 90 percent confidence level accelerations in Utah are less than 115 cm/sec^2 for any 50-year period. The deterministic modeling predicts that accelerations over 0.8 g are possible throughout much of western Utah and, in particular, the proposed MX basing area. However, it is likely that accelerations of this magnitude would occur on the order of less than once in several thousand years at any specific site within the state.

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