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SEISMIC ENERGY RELEASE AND HAZARD ESTIMATION IN THE BASIN AND RANGE PROVINCE

by

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INTRODUCTION

The study of the distribution of seismic energy release and the probabilistic estimation of ground motion presented in this report has been prepared in support of the program being conducted in the Geological Survey to identify favorable radioactive waste disposal areas in the Basin and Range Province. The results of this report depend, in part, on the review of seismicity and compilation of a catalog of the larger shocks in the Basin and Range Province already completed (Askew and Algermissen, 1982). The Basin and Range Province is taken here as the area defined by Fenneman (1946) and shown in Figure 1.

EPICENTER MAPS

Two epicenter maps have been prepared for this report. Plate 1 shows the larger earthquakes, $M_S \geq 5.0$, in the Basin and Range Province. These earthquakes are listed in the catalog prepared for the Basin and Range Province (Askew and Algermissen, 1982). Earthquakes with $M_S \geq 7.0$ have been identified by year of occurrence in Plate 1. Activity along the Wasatch and related faults in Utah and the major zone of seismicity in west central Nevada are easily identified. Plate 2 includes all lower magnitude events that have been located. These events are particularly useful in identifying seismic trends and areas of low level activity that may not be obvious in Plate 1. Earthquake activity shown for the Nevada Test Site may consist, in part, of explosions that could not be separated from the seismicity of the area (Askew and Algermissen, 1982).

STRAIN ENERGY RELEASE

Plates 1 and 2 provide two representations of earthquake epicenters in the Basin and Range Province. Other representations of seismicity have also been found useful for identifying areas that have been active historically and for identifying patterns of seismicity that may be correlated with geologic structures. The strain release in earthquakes mapped in plate 3 is used here as an alternative to epicenter maps as a representation of seismicity. Here, we have used the sum of the square roots of the energies of individual earthquakes, which is roughly proportional to the strain release in earthquakes. The area over which strain release is summed is $.25^{\circ}$ of latitude by $.33^{\circ}$ of longitude (at 37° latitude). This area is approximately 823 km^2 over the area of our map. Using $\log E = 11.8 + 1.5 M_s$ (Gutenberg and Richter, 1956b) and taking the strain release as the square root of E, we have mapped the equivalent number of magnitude $M_s = 4.0$ events (N_4) per 823 km^2, where N_4 is computed using (Allen and others, 1965)

$$N_4 = 10^{0.75\,(M_s - 4.0)}$$

N_4 is obtained by dividing the strain release resulting from all of the earthquakes in each 823 km^2 block by the strain release in a $M_s = 4$ earthquake.

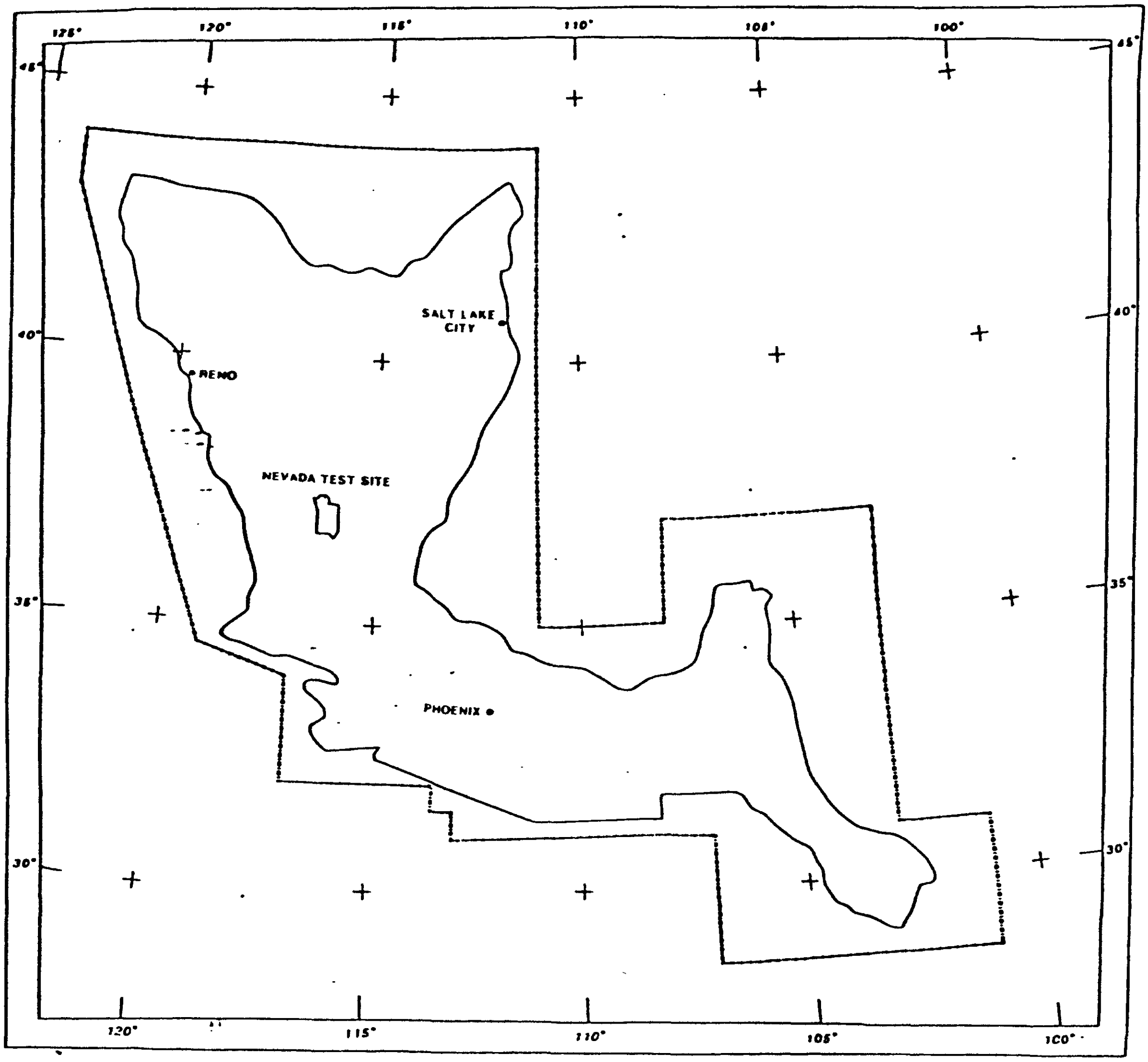

Figure 1--Solid line shows boundary of Basin and Range Province as defined by Fenneman (1946). Dotted line shows boundary of area included in catalog.

For a variety of reasons, this type of representation of energy release is only approximate, but it is quite useful in outlining areas of high strain release and for identifying seismic trends in the Basin and Range.

PROBABILISTIC GROUND MOTION MODEL

Introduction

The probabilistic ground motion used for the estimation of ground motion in the Basin and Range has been described by Algermissen and Perkins (1976) and Algermissen and others (1982) and will only be outlined here.

The concept of hazard mapping used here is to assume that earthquakes are exponentially distributed with regard to magnitude and randomly distributed with regard to time. The exponential magnitude distribution is an assumption based on empirical observation. The distribution of earthquakes in time is assumed to be Poissonian, that is, a random process in time. The assumption of a Poisson process for earthquakes in time is consistent with historical earthquake occurrence insofar as it affects the probabilistic hazard calculation. Large shocks closely approximate a Poisson process, while small shocks may depart significantly from a Poisson process. The ground motions associated with small earthquakes are of only marginal interest in engineering applications and consequently the Poisson assumption serves as a useful and simple model (Cornell, 1968). Spatially, the seismicity is modeled by grouping it into discrete areas termed seismic source zones. The most general requirements for a seismic source zone is as follows: (1) it should have seismicity, and (2) it should represent a reasonable seismotectonic or seismogenic structure or zone. If a seismogenic structure or zone cannot be identified, the seismic source zone is based on historical seismicity. A seismotectonic structure or zone is taken here to mean a specific geologic feature or group of features that are known to be associated with the occurrence of earthquakes. A seismogenic structure or zone is defined as a geologic feature or group of features throughout which a style of deformation and tectonic setting are similar and a relationship between this deformation and historic earthquake activity can be inferred.

The Probabilistic Model

Development of probabilistic ground motion maps using the concepts outlined above involves three principal steps: (1) delineation of seismic source areas; (2) analysis of the magnitude distribution of historical earthquakes in each seismic source area; and (3) calculation and mapping of the extreme cumulative probability $F_{max,t}$ (a) of ground motion, a, for some time, t. These steps are shown schematically in figure 2.

Once the source zones have been delineated and the distribution of earthquakes likely to occur in each small division of the source or along a fault is decided upon, the effect at each site due to the occurrence of earthquakes in each small division of the source or for each fault can be computed using suitable ground motion attenuation curves such as those shown in Figure 2B. In practice, the distribution of ground motion is computed for a number of sites located on an appropriate grid pattern (Fig. 2A).

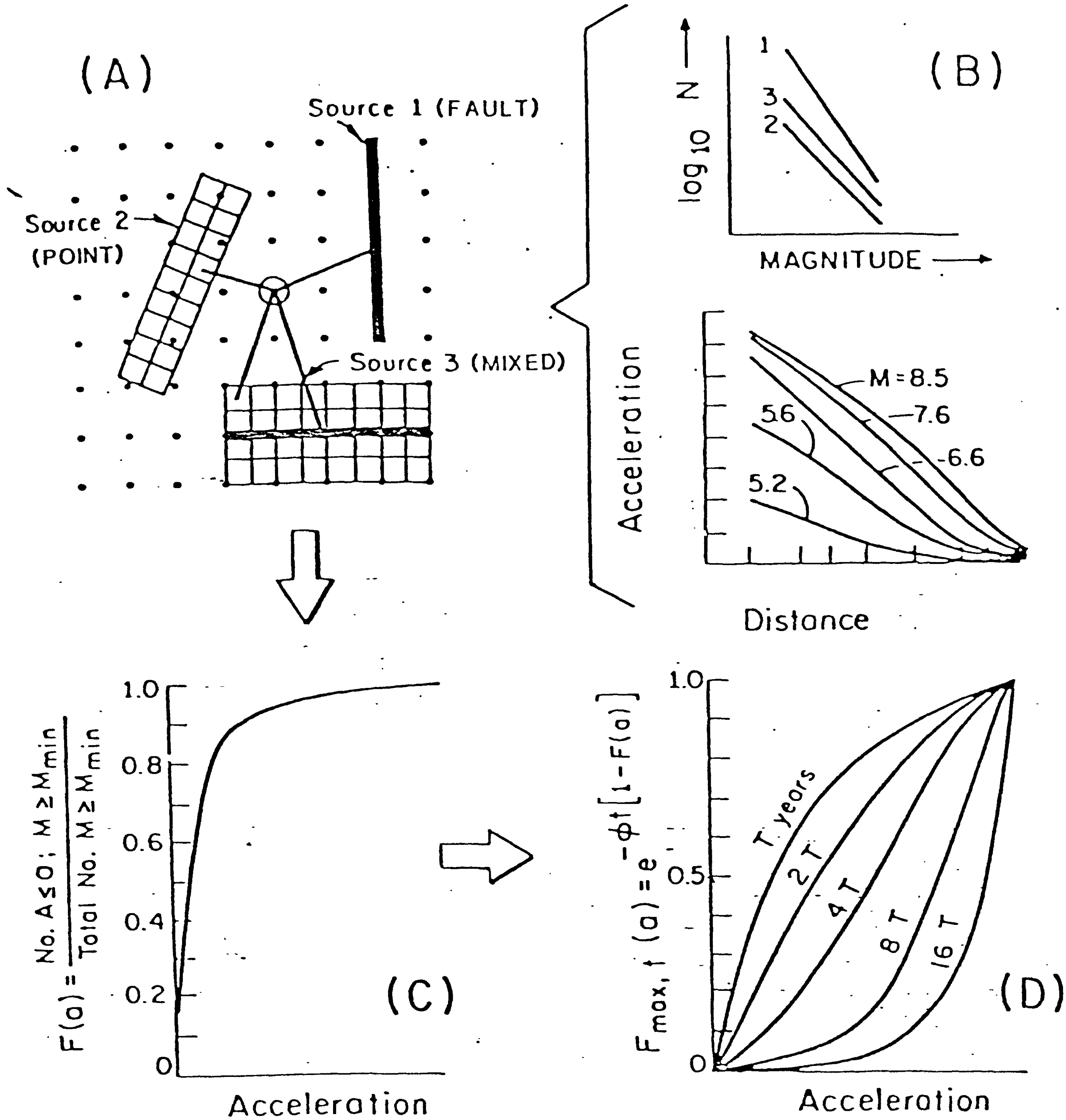

Figure 2--Elements of the probabilistic hazard calculations.

(A) Typical source areas and grid of points at which the hazard is to be completed.

(B) Statistical analysis of seismicity data and typical attenuation curves.

(C) Cumulative conditional probability distribution of acceleration.

(D) The extreme probability $F_{max,t}$ (a) for various accelerations and exposure times (T).

From the distribution of ground motion, F(a), at each site (part C of Fig. 2), it is possible to determine directly the expected number of times a particular amplitude of ground motion is likely to occur in a given period of years at a given site, and, thereby, the maximum amplitude of ground motion in a given number of years corresponding to any level of probability. The probability, $F_{max,t}$ (a), of not exceeding some amplitude, a, during a particular exposure time, t, is given by:

$$F_{max,t}(a) = e^{-\phi t[1-F(a)]}$$

where ϕ is the mean rate of occurrence of earthquakes in some seismic source zone.

In the computer program, a table of accelerations (or velocities) and the cumulative distribution function (CDF) of the accelerations (or velocities) is constructed for each point of interest. For example, if a is acceleration and F(a) is the CDF of the acceleration at some point, then, for a particular exposure time t = T, $F_{max,t}$ (a) is calculated, and the value of a for a given extreme probability is found by interpolation. For the maps presented here, $F_{max,t}$ (a) is 0.90, that is, a 90 percent chance that the ground motion will not be exceeded.

The development of a probabilistic model for earthquake hazard analysis requires data and assumptions concerning parameters such as the earthquake rupture length, the magnitude distribution and the sequence of occurrence in time of the earthquakes, the geometry of the seismic source zones and the attenuation of seismic waves. A more complete discussion of the probabilistic model used is given by Algermissen and others, 1982.

Seismic Source Zones

The seismic source zones used in modeling the Basin and Range Province are shown in Plate 4. Geological information relevant to determining source zone boundaries in this region was discussed at a series of regional seismic-source zone meetings convened by the U.S. Geological Survey during 1979 and 1980. These meetings were structured as informal workshops consisting of small groups of regional experts gathered together for the purposes of (1) presenting and discussing current research related to earthquake hazards within various regions of the United States, (2) speculating on the nature of the earthquake generating process on a regional scale, (3) voicing concerns and recommendations for various seismic source zones, and (4) suggesting treatment of these zones in application to probabilistic earthquake hazards maps.

Three of the meetings dealt with parts of the Basin and Range province as separate regions: The Great Basin, Northern Rocky Mountains and Southern Rocky Mountains. For areas within the Basin and Range province, the committees' definition of seismic source zones was based primarily on the age of latest fault displacement. Because the hazard estimation in this report is based on the historical record of earthquakes, we have modified some zone boundaries drawn at the meetings (and based only on geological criteria) to account for the geographical distribution of seismicity seen historically. For example, zones outlined at the seismic source zone meetings and defined only on geologic criteria may divide tight clusters of seismicity. This is the case in the Reno-Carson City-Lake Tahoe area of western Nevada. Boundaries of four zones drawn at the seismic source zone meetings, based on fault information, join in this area (see Thenhaus and Wentworth, 1982) and segment the northern part of a regional seismicity trend that follows the Sierra Nevada-Great Basin boundary zone. Distributing this seismicity into the zones defined at the meeting would have resulted in zones of relatively low seismicity that extend into northeastern California, western Nevada and the central Sierra Nevadas. This would have resulted in a lower rate of earthquake occurrence in the immediate Reno-Carson City-Lake Tahoe area. We have chosen to preserve the influence of the Sierra Nevada-Great Basin boundary on seismicity in this area. For this reason we have modified the source zones defined at the meeting and extended zone I029 along the Sierra Nevada-Great Basin Boundary Zone north to include the Reno-Carson City-Lake Tahoe area. The following is a brief discussion of the geologic basis for the source zones taken from Algermissen and others (1982).

The Nevada Seismic Zone (zone I031) has been distinguished from a more regional zone generally characterized by Holocene fault displacements (zone I034) (Wallace, 1977a,b; 1978a,b,c). Similarly, the Southern Nevada Seismic Zone (zone I017) has been separated from a broad area of the southern Great Basin characterized by late Quaternary fault displacement (zones I017, I018 and I019). Zones I032 and I033 within the Nevada seismic zone are based on the aftershock zones of large surface rupturing historic earthquakes.

Zones I037, I038, I039, and I040 encompass and include the Wasatch fault zone at the eastern margin of the Great Basin. The zones are based on studies of ages of latest surface displacements along faults in this area as summarized by Bucknam and others (1980). The zones have been generalized somewhat from Bucknam and others (1980) to reflect the regional geographic distribution of historical seismicity. Except for zone I039, which is characterized by late Quaternary faulting, zones conterminous to, and including, the Wasatch fault (zone I040) are characterized by faults having Holocene age displacements.

The eastern Snake River Plain (zone I054) is basically aseismic; however, the western part of the Plain (included in zone I058) has had historic seismicity.

Zone I058 includes an area of normal faulting north of the Snake River Plain and on the western edge of the Idaho Batholith. Southeast of the Snake River Plain, the Intermountain Seismic Belt crosses the Overthrust Belt of southeastern Idaho and southwestern Wyoming (zone I052). Long normal faults with probable Holocene movements (Thenhaus and Wentworth, 1982) are superimposed on the older Laramide age thrusts in the Overthrust Belt. An earthquake focal mechanism in the Caribou Range of southeastern Idaho indicates normal faulting generally on strike with mapped normal faults in this area (Sbar and others, 1972).

In the southern Rocky Mountain region, an area of Holocene fault displacement bounds the Albuquerque Basin on the south on La Jencia fault (Machette, 1978) (zone I007). Areas of possible Holocene age displacements are located in the southern Rio Grande Rift (zone I002) and extreme southeastern Arizona (zone I004) just north of the 1887 Sonora earthquake area (zone I004). Sanford and others (1979; 1981) consider the Rio Grande Rift (zones I007 and I003) to be the most seismically active area in New Mexico in historic times with the majority of seismic activity occurring in the Albuquerque Basin (zone I007). They also note the apparent association of seismicity with the Jemez Lineament (zone I008).

The structural continuity of the southwest margin of the Colorado Plateau is broken by northeast-trending, Precambrian faults which not only have controlled the northeastern migration of volcanic activity in the San Francisco volcanic field, but also apparently influence the regional distribution of seismicity (zone I014) (Shoemaker and others, 1978).

Magnitude Distribution of Earthquakes in each Seismic Source Zone

After the seismic source zones were delineated and the catalog was corrected for incompleteness (see Algermissen and others, 1982), relationships of the form

$$\log N = a - bM \qquad (1)$$

were determined by a maximum likelihood fit to the seismicity in each source zone. N is the number of earthquakes in a given magnitude range per unit of time and a and b are constants to be determined. If the seismicity of individual source zones in a region is low, the b value (slope) in the above equation was determined by considering the seismicity in an ensemble of source zones. For example, the Wasatch fault (zone I040) has geological evidence of recurrent Holocene displacements (Swan and others, 1980) but historically no earthquakes greater than magnitude $M_s = 5$ have occurred on the fault (Arabasz and others, 1980) (see plate 1). Seismicity from zones conterminous to the Wasatch fault (that enclose the entire Intermountain seismic belt through western Utah) has been combined with earthquakes in the Wasatch fault zone itself. A b-value was then calculated for this ensemble of zones. The b-value applies to each zone used in the combination. The a-value (equation 1) for each source is determined by fitting a line with slope b through the seismicity for each zone. Zones having the same b-values in table 1 indicate the regions over which b-values were calculated. Geographically these regions correspond to 1) the Sierra Nevada-Great Basin boundary zone and Mohave Desert areas of the western Great Basin region, 2) the Intermountain seismic belt of the eastern Great Basin region, 3) the central Basin and Range Province (both northern and southern) and, 4) the Colorado Plateau and its margins. Because some of these regions extend well beyond the area of interest of this report, neither all of the zones, nor all of the seismicity upon which constants a and b (equation 1) are based are shown here.

For each seismic source zone the maximum magnitude was determined from a consideration of (1) the largest historical earthquake that had occurred (in zones with high rates of activities); (2) the tectonic setting of any particular zone and (3) weighted evaluation of (1) and (2).

The magnitudes used in this paper have been obtained in two ways: (1) from the earthquake catalog containing instrumentally determined magnitudes, and (2) by computing the magnitude obtained from the maximum intensity I_o (Askew and Algermissen, 1982). Since instrumental magnitudes are not available for a number of important earthquakes, many magnitudes in the catalog are based on maximum intensity. Table 1 lists pertinent information concerning the magnitude distribution of earthquakes assumed for each seismic source zone. In the Nevada Seismic Zone, the maximum magnitude was reduced to $M_s = 6.4$ in zones in which large historical earthquakes had occurred (zones I022, I032 and I033 in Plate 4). The assumption is that in the Nevada seismic zone large earthquakes are not likely to recur in the same zones where they have already occurred historically, at least in the time period of interest of the hazard maps (up to exposure times of 50 years). This assumption is consistent with current thinking concerning the temporal and spatial distribution of large shocks in western Nevada (Wallace, 1977a, 1978c; Ryall, 1977; Ryall and others, 1966; Van Wormer and Ryall, 1980; Ryall and Van Wormer, 1980). Historical earthquakes with magnitudes greater than 6.4 in zones I022, I032 and I033 were distributed into the surrounding zone. For example, the earthquakes with magnitudes greater than 6.4 in zones I032 and I033 were distributed into zone I031. The larger shocks in zone I022 were distributed into I020.

Modeling of Earthquakes

Earthquakes were modeled as point sources if the fault rupture lengths were considered to be unimportant with regard to the scale of the mapping. For large earthquakes ($M_s \sim 6.0$) the earthquakes were modelled as faults using the relationship $\log (L) = 1.915 + 0.389 M_s$ where L is the average fault rupture length in meters and M_s is the magnitude (Mark, 1977).

Attenuation

The attenuation curves used for acceleration were those developed by Schnabel and Seed (1973). For velocity, attenuation curves developed by D. M. Perkins, S. T. Harding and S. C. Harmsen (Perkins, 1980) for the western United States were used. See Algermissen and others (1982) for further discussion.

Ground Motion Parameters Mapped

Six probabilistic maps are included in this report. They are acceleration in rock and velocity in rock mapped for exposure times of 10, 50 and 250 years. The mapped ground motion values are estimated to have a 10 percent chance of exceedance in the period of time considered (10, 50 or 250 years, depending on the map).

DISCUSSION

In general, the distribution of ground motion throughout the Basin and Range Province (plates 5-10) can be divided into the four geographic regions previously mentioned. Ground motion values for all exposure times considered are highest at the eastern and western margins of the Great Basin in Utah and Nevada. This is consistent with the observed geographical distribution of historical seismicity. It is also consistent with a longer-term indicator of the distribution of potentially damaging earthquakes which is the geographic distribution of Holocene age fault scarps. Holocene age fault scarps (particularly those showing recurrent Holocene movement) occur primarily near the eastern and western margins of the Great Basin while the central portion is generally characterized by late Quaternary faulting (Thenhaus and Wentworth, 1982).

In the southern Basin and Range Province of Arizona, ground motion values are only slightly higher in southwestern Arizona than along the Colorado Plateau margin. This difference is due primarily to constants a and b in equation 1. As no Holocene faulting occurs in this region (Thenhaus and Wentworth, 1982) little can be said about geological correspondences to the distribution of short-term ground motion hazard. An area of relatively higher hazard in the southern Basin and Range Province (but still no higher than the central Great Basin to the north) corresponds to the northeast-trending Precambrian faults associated with volcanic trends of the San Francisco volcanic field (zone I014) (Shoemaker and others, 1978).

The highest ground motion values in the southern Basin and Range province are those of zone I004. Ground motion values there are comparable to values in portions of the Intermountain Seismic Belt and the Sierra Nevada-Great Basin boundary zone to the north. Zone I004 is taken from the seismic source zone meetings (discussed previously) and is based on the suspected occurrence of Holocene faulting in the vicinity of the 1887 Sonora earthquake. The zone boundaries are poorly defined. More recent reconnaissance mapping in this area indicates no Holocene faulting in extreme southeastern Arizona (D. G. Herd, oral communication, 1981). In extreme southwestern New Mexico, one short fault scarp in zone I004 does have Holocene displacement (M. N. Machette, oral communication, 1981). If Holocene faulting were to be used as a strict guide to source zone boundaries, however, zone I004 would be narrowed considerably. Surface rupture associated with the 1887 Sonora earthquake occurred on a fault that has evidence of a local surface rupturing event around 10,000 to 15,000 years B.P. A similar event is believed to have occurred at approximately 100,000 years B.P. (D. G. Herd, oral communication, 1981, 1982). The boundaries of zone I004 distribute seismicity in the 1887 earthquake locale over a somewhat broader area than where it occurs historically. If the earthquake were to be placed in a more regional zone, say extending through all of central or southwestern Arizona, the result would be a substantial lowering in the ground motion values near the epicentral region, while ground motion values throughout central or southeastern Arizona would not increase appreciably. This is not a prudent choice for short-term hazard estimation and would be inconsistent with the treatment of similar source areas for large historical earthquakes elsewhere in the United States (for example, see the discussion of the 1886 Charleston, South Carolina earthquake in Algermissen and others, 1982). Furthermore, fault scarp studies in the 1887 earthquake epicentral region (D. G. Herd, oral communications, 1981, 1982; Herd and McMasters, 1982) documents recurrent displacements since late Quaternary time. Such a history of recurrent fault movement is presently unknown elsewhere in the southern Basin and Range province of Arizona (Thenhaus and Wentworth, 1982) and argues for a unique geologic setting for the 1887 earthquake.

Consequences of modelling long return period ground motions (on the order of 10,000 years, or, ground motions having an annual probability of exceedance of 1/10,000) remains an unresolved problem. Such long term hazard estimates must necessarily account for the long term average recurrence of surface faulting events as they are preserved in the geologic record as fault scarps. Earthquake recurrence estimates obtained from fault scarp studies and from analysis of the historic seismicity compare favorably in the Great Basin area when relatively large source zones are considered, however, such estimates diverge sharply for individual faults, or small source zones (Bucknam and Algermissen, 1982). These conclusions indicate uncertainty as to the seismotectonic cycles operating on individual faults in the northern Basin and Range province. Such cyclic activity would need to be defined in some manner to confidently model time-dependent hazard in this region.

Table 1.--Seismic parameters for source zones

Zone No.*	No. of Modified Mercalli Maximum Intensity V's per year	b_I	Maximum Magnitude M**
c014	0.91990	-0.66	7.9
c015	1.49200	-0.45	7.9
c016	0.22560	-0.51	7.9
c017	0.02760	-0.48	7.3
c018	1.09200	-0.49	7.3
c024	2.97000	-0.43	8.5
I001	0.22700	-0.73	7.3
I002	0.03600	-0.73	7.3
I003	0.08800	-0.73	6.1
I004	0.22700	-0.54	7.3
I005	0.09100	-0.73	7.3
I006	0.13500	-0.73	7.3
I007	0.41900	-0.73	7.3
I008	0.21100	-0.73	6.1
I009	0.19400	-0.54	6.1
I010	0.20800	-0.54	7.3
I011	0.55100	-0.64	7.3
I012	0.34900	-0.64	7.3
I013	0.05500	-0.64	7.3
I014	0.49000	-0.73	7.3
I015	0.01800	-0.73	6.7
I017	0.69300	-0.59	7.3
I018	0.26100	-0.54	7.3
I019	0.11717	-0.54	7.3
I020	1.84900	-0.64	7.3
I022	0.19600	-0.64	6.1
I023	0.15350	-0.54	7.3
I029	1.31900	-0.64	7.3
I030	0.58800	-0.64	7.3
I031	1.82685	-0.54	7.3
I032	0.48114	-0.54	6.1
I033	0.08557	-0.54	6.1
I034	0.62380	-0.54	7.3
I035	0.20070	-0.54	7.3
I036	0.01800	-0.58	6.1
I037	0.05100	-0.58	7.3
I038	0.80600	-0.58	7.3
I039	0.12000	-0.58	7.3
I040	0.29100	-0.58	7.3
I052	0.19000	-0.58	7.3
I054	0.01800	-0.58	6.1
I058	0.19800	-0.58	7.3
I077	0.03469	-0.46	6.1

*The zones are shown in Plate IV.
**See text for definition of M. The magnitudes listed here represent the center of an interval range used in the actual computation.

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