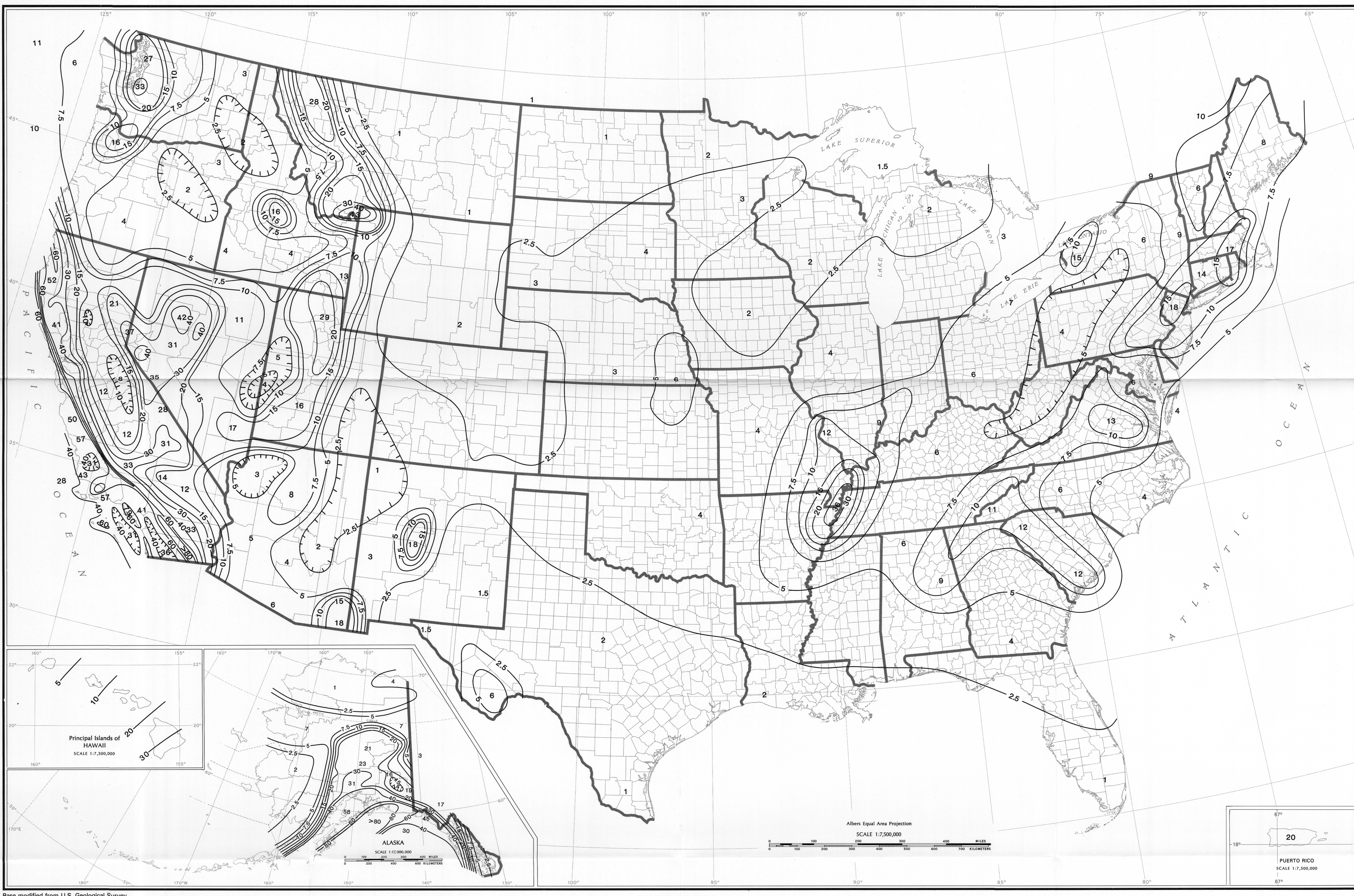
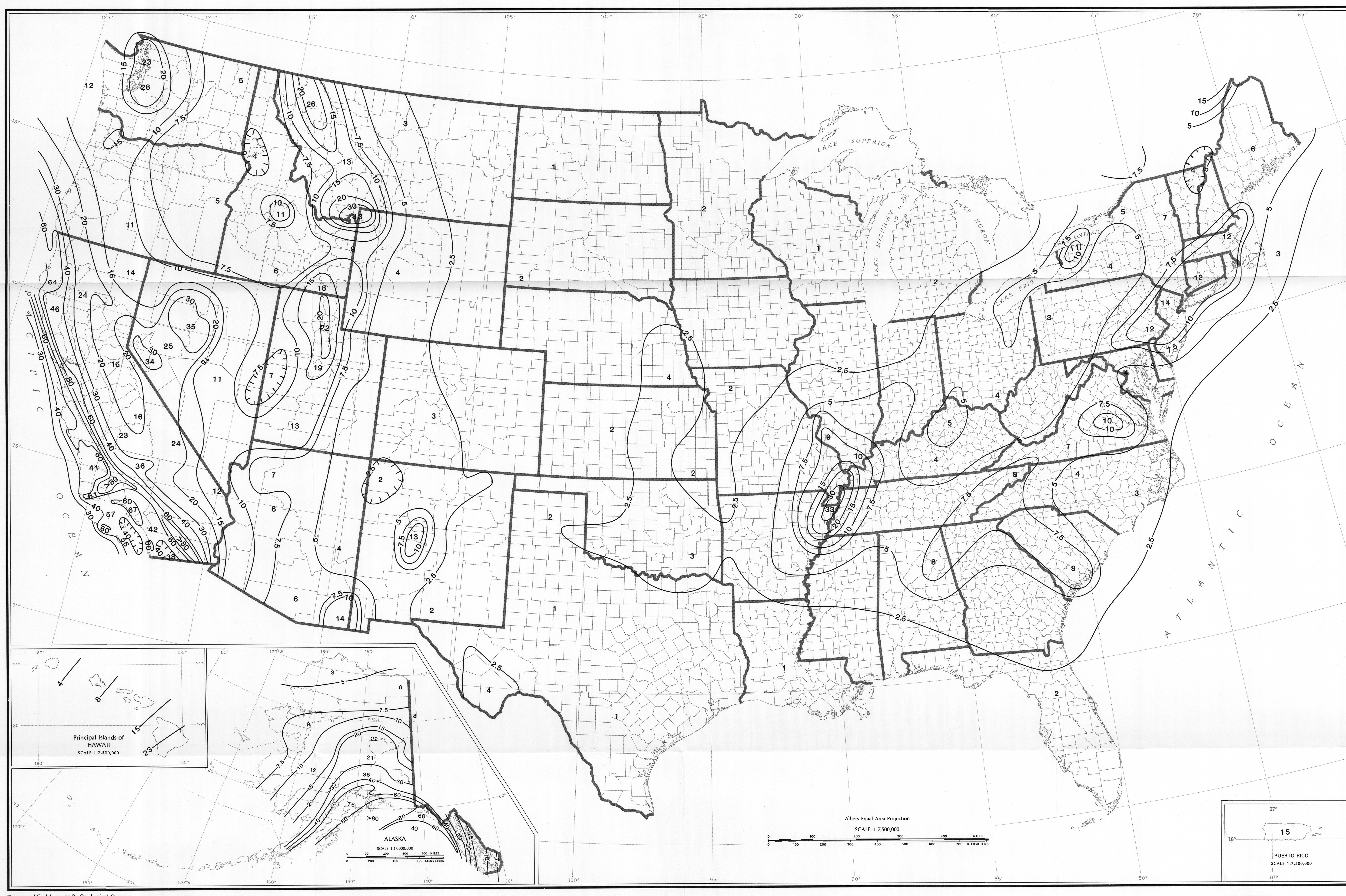


Base modified from U.S. Geological Survey National Atlas, 1970

MAP A.–HORIZONTAL ACCELERATION (90 PERCENT PROBABILITY OF NOT BEING EXCEEDED IN 50 YEARS)

EXPLANATION

—— 40 —— Contour--Horizontal acceleration expressed as percent of gravity. Some areas show acceleration values without contours. Hachures indicate closed area of lower acceleration. Data for Hawaii and Puerto Rico from Federal Emergency Management Agency (1985)



Base modified from U.S. Geological Survey National Atlas, 1970

MAP B.–HORIZONTAL VELOCITY (90 PERCENT PROBABILITY OF NOT BEING EXCEEDED IN 50 YEARS)

EXPLANATION

—— 5 —— Contour--Horizontal velocity expressed as centimeters per second. Some areas show velocity values without contours. Hachures indicate closed area of lower velocity. Data for Hawaii and Puerto Rico from Federal Emergency Management Agency (1985)

PROBABILISTIC EARTHQUAKE ACCELERATION AND VELOCITY MAPS FOR THE UNITED STATES AND PUERTO RICO

By

S. T. Algermissen, D. M. Perkins, P. C. Thenhaus, S. L. Hanson, and B. L. Bender

1990

INTRODUCTION

The ground-motion maps presented here (maps A-D) show the expected seismic-induced or earthquake-caused maximum horizontal acceleration and velocity in rock in the contiguous United States, Alaska, Hawaii, and Puerto Rico. There is a 90 percent probability that the maximum horizontal acceleration and velocity shown on the maps will not be exceeded in the time periods of 50 and 250 years (average return period for the expected ground motions of 474 and 2,372 years). Rock is taken here to mean material having a shear-wave velocity of between 0.75 and 0.90 kilometers per second. (Algermissen and Perkins, 1976). Mapped values shown here for the contiguous United States are modified from those of Algermissen and others (1982) by accounting for statistical uncertainty in the ground-motion attenuation relations and in the magnitude-fault rupture length relation, as described in the following discussion. Algermissen and others (1982) provide details and background information concerning the development of the ground-motion hazard maps that are only generally described herein.

HAZARD MODEL

The calculation of the ground motions is based on the assumptions that earthquakes are exponentially distributed with regard to magnitude and interoccurrence time and uniformly distributed in space with regard to source zones and source faults. The exponential magnitude distribution is an assumption based on empirical observation. The assumption of an exponential interoccurrence time is that of a uniform distribution in time (the Poisson process) and is consistent with historical earthquake occurrence insofar as it affects the probabilistic hazard calculation. Large earthquakes closely approximate a Poisson process, but 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. The usefulness of the Poisson process in the engineering analysis of earthquake ground motion has been known for a long time (see, for example, Lomnitz, 1974; a recent treatment of the problem justifying the use of the Poisson process even where large earthquakes may be quasi-periodic is given by Cornell and Winterstein, 1988). In general, use of the Poisson process provides appropriately conservative values of ground motion for engineering purposes if sites of interest are affected by more than two sources of earthquakes.

Spatially, in the model used here, seismicity is grouped into discrete areas termed seismic source zones or seismic source faults. The ideal characteristics of a seismic source zone or fault is that it have seismicity and should represent a reasonable seismotectonic or seismogenic structure or zone. 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 for which a relationship between this deformation and historic earthquake activity can be reasonably inferred. If a seismotectonic or seismogenic structure or zone cannot be identified, the seismic source zone is based on historical seismicity. In source zones, earthquakes are modeled as either point ruptures or linear ruptures of finite length. Earthquakes modeled as linear ruptures of finite length are approximations or generalizations of real (known) faults or of hypothetical (inferred) faults. Strikes of inferred faults are modeled parallel to regional structural trends.

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

Once the sources have been delineated and the distribution of earthquakes likely to occur in each source zone or along a fault is decided upon, the effect at each site due to the occurrence of earthquakes in each source zone or for each fault can be computed using suitable ground-motion attenuation curves.

From the cumulative distribution of ground motion, F(a), at each site, the expected number of times a particular amplitude of ground motion is likely to occur in a given period of years at the site is calculated, and, consequently, the maximum amplitude of ground motion in a given number of years corresponding to any level of probability may be obtained. 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 used to generate F(a).

TREATMENTS OF UNCERTAINTY

The probabilistic model, seismic source zones, and data used in the computation of the present maps are, with some exceptions noted below, from Algermissen and others (1982). The principal change from the Algermissen and others (1982) maps is that uncertainty in attenuation and fault rupture length have been included in the calculation. We briefly recapitulate the assumptions used here.

The fault rupture length relationship used for the maps is that of Mark (1977). The acceleration attenuation for the western United States is from Schnabel and Seed (1973), modified for the eastern United States by Algermissen and others (1982). The velocity attenuation used in the preparation of the maps was developed by Perkins and others (unpublished data, 1989) using a data set and methods of analysis similar to that of Schnabel and Seed (1973). The estimates of uncertainty for fault rupture length and attenuation are taken from McGuire and Shedlock (1981). McGuire and Shedlock (1981) give a standard deviation for Mark's (1977) fault rupture relationship of $\log_{10}$ (rupture length) = 0.52 for a given magnitude and a standard deviation for the Schnabel and Seed (1973) attenuation relationship of $\ln_e$ (acceleration) = 0.62. The same standard deviation, $\ln_e$ (velocity) = 0.62, was assumed for the velocity attenuation curves developed by Perkins and others (unpublished data, 1989) because they were developed in a manner similar to the Schnabel and Seed (1973) acceleration curves and show comparable variability. For computational purposes, the probability of a value greater than 6σ was set to zero.

MODIFICATIONS IN SOURCE MODELS AND MINIMUM MAGNITUDE

The changes from the Algermissen and others (1982) source model involve the removal of modeled faults (linear ruptures) in seismic source zones 104, 107, and 115 (see Algermissen and others, 1982) in the eastern United States and an increase in the modeled minimum magnitude earthquake from 4.0 to 4.6 M_L. Source zone 104 encompasses the Ramapo fault zone; zone 107, the eastern Massachusetts thrust province; and zone 115, the Clarendon-Linden lineament. Earthquakes from these sources, as well as other earthquakes in the eastern United States, were modeled as point sources in preparing the present maps because of continuing uncertainty in relating seismicity to the Ramapo fault (compare Aggarwal and Sykes, 1978, with Ratcliffe, 1981, 1982) and an apparent growing consensus that the rupture lengths for earthquakes in the eastern United States are relatively short (Electric Power Research Institute, 1987). Eastern U.S. sources in general, therefore, are adequately modeled by point sources at the scale of the national maps. Finite ruptures were retained in the New Madrid, Missouri, area (zone 87), where very large earthquakes may occur.

Minimum magnitudes of interest to ground-motion hazard models become particularly important in regions of low-to-moderate earthquake activity when attenuation variability is modeled (Bender and Campbell, 1989). There are relatively few large earthquakes in the eastern United States; small and moderate earthquakes therefore dominate the ground-motion hazard. Attenuation variability allows these small earthquakes to produce some high peak ground motions. Because the maps represent a fixed nonexceedance probability (10 percent in the given exposure times), these high amplitudes from small earthquakes dominate the ground-motion estimates even though these amplitudes are of short duration and generally do not cause significant damage to engineered structures. For that reason, we have raised the minimum magnitude of earthquakes of concern from 4.0 (Algermissen and others, 1982) to 4.6 herein. Considerably more research is needed before this issue can be resolved entirely satisfactorily. One statistical approach that might merit use in future hazard mapping efforts uses a tapered distribution of low-magnitude earthquakes wherein some, but not all, small earthquakes generate high-amplitude ground motions of engineering significance (Bender and Campbell, 1989). Nonetheless, the parameters of such a distribution remain to be defined by empirical earthquake damage data.

Although raising the minimum magnitude has lowered the probabilistic ground motion at some places in the eastern United States, the principal effect of incorporating attenuation uncertainty in the calculations has been to raise the map values. The higher the ground-motion values on the maps of Algermissen and others (1982), the greater is the increase in those values when attenuation uncertainty is taken into account. For the most active faults in California, the increase in ground motion may be as much as a factor of two on the 250-yr exposure time map. Along the San Andreas fault system, including the San Jacinto and Elsinore faults and the southern extension of the Newport-Inglewood faults, levels of acceleration exceed 80 percent of the acceleration of gravity, and velocities exceed 80 centimeters per second. These areas are delineated by contours marked >80 (either percent of gravity or centimeters per second) and are principally on the 250 year exposure time maps. For long exposure times, the ground-motion maps are influenced greatly by the parameter variabilities assumed for attenuation and velocity, resulting in peak values of acceleration and velocity that are very large along highly active faults. Special studies are required in these areas of high expected ground motion to more accurately constrain sources of uncertainty in estimating near-field ground motions to be considered in seismic design.

AREAS OUTSIDE THE CONTIGUOUS UNITED STATES

Using the data and the probabilistic model of Thenhaus and others (1982), the ground-motion maps for Alaska were recomputed to include fault rupture length and attenuation variability. The same standard deviations for fault rupture length and attenuation as used for the contiguous United States were used in the recomputation of the Alaska ground-motion maps.

The ground-motion maps for Hawaii and Puerto Rico are provided here for completeness and are taken directly from the "NEHRP Recommended Provisions for the Development of Seismic Regulations for New Buildings, Part 2, Commentary" (Federal Emergency Management Agency, 1985). The only modification of the maps is the conversion of the velocity contours from inches per second to centimeters per second to conform with units used on the other maps. The ground-motion values shown for Hawaii and Puerto Rico do not represent the results of a particular probabilistic ground-motion calculation but are weighted averages of the ground-motion estimates available at the time of the Applied Technology Council (1978) study. However, the mapped values are reasonable and in general agreement with our preliminary studies of probabilistic ground motion in these areas.

REFERENCES

Aggarwal, Y.P., and Sykes, L.R., 1978, Earthquakes, faults, and nuclear power plants in southern New York and northern New Jersey: Science, v. 200, p. 425-429.

Algermissen, S.T., and Perkins, D.M., 1976, A probabilistic estimate of maximum acceleration in rock in the contiguous United States: U.S. Geological Survey Open-File Report 76-416, 44 p., 2 pls.

Algermissen, S.T., Perkins, D.M., Thenhaus, P.C., Hanson, S.L., and Bender, B.L., 1982, Probabilistic estimates of maximum acceleration and velocity in rock in the contiguous United States: U.S. Geological Survey Open-File Report 82-1033.

Applied Technology Council, 1978, Tentative provisions for the development of seismic regulations for buildings, ATC 3-06: National Science Foundation Publication 78-8, 505 p.

Bender, Bernice, and Campbell, K.W., 1989, A short note on the selection of minimum magnitude for use in seismic hazard analysis: Seismological Society of America Bulletin, v. 79, p. 199-204.

Cornell, C.A., and Winterstein, S.R., 1988, Temporal and magnitude dependence in earthquake recurrence models: Bulletin of the Seismological Society of America, v. 78, p. 1522-1537.

Electric Power Research Institute (EPRI), 1987, Seismic hazard methodology for the central and eastern United States, Vol. II: Responses to NRC Questions, p. 2-12.

Federal Emergency Management Agency, 1985, NEHRP (National Earthquake Hazards Reduction Program) recommended provisions for the development of seismic regulations for new buildings, 1985 Edition, part 2, Commentary: Earthquake Hazards Reduction Series 18, Building Seismic Safety Council, 200 p.

Lomnitz, Cinna, 1974, Global tectonics and earthquake risk: Developments in Geotectonics 5, Elsevier Scientific Publishing Co., 320 p.

Mark, R.K., 1977, Application of linear statistical models of earthquake magnitude versus fault length in estimating maximum expectable earthquakes: Geology, v. 5, p. 464-466.

McGuire, R.K., and Shedlock, K.M., 1981, Statistical uncertainties in seismic hazard evaluations in the United States: Bulletin of Seismological Society of America, v. 71, no. 4, p. 1287-1308.

Ratcliffe, N.M., 1981, Reassessment of the Ramapo fault system as control for current seismicity in the Ramapo seismic zone and the New York recess: Geological Society of America Abstracts with Programs, v. 13, no. 3, p. 171.

_____1982, Results of core drilling of the Ramapo fault and Sky Meadow Road, Rockland County, New York, and assessment of evidence for reactivation to produce current seismicity: U.S. Geological Survey Miscellaneous Investigations Series Map I-1401, 1 sheet.

Schnabel, P., and Seed, H.B., 1973, Acceleration in rocks for earthquakes in the western United States: Bulletin of Seismological Society of America, v. 63, p. 501-516.

Thenhaus, P.C., Ziony, J.I., Diment, W.H., Hopper, M.G., Perkins, D.M., Hanson, S.L., and Algermissen, S.T., 1982, Probabilistic estimates of maximum seismic horizontal ground acceleration on rock in Alaska and the adjacent continental shelf: Earthquake Spectra, v. 1, no. 2, p. 286-306.

Manuscript approved for publication, January 9, 1990
INTERIOR—GEOLOGICAL SURVEY, RESTON, VIRGINIA—REPRINTED 1991

For sale by U.S. Geological Survey Map Distribution, Box 25286, Federal Center, Denver, CO 80225