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Status of seismic hazard assessment around the globe: North and South America

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Abstract
The status of seismic hazard assessment and the development of the GSHAP in the American continents are discussed. We review the methodologies used for hazard assessment in North, South and Central Americas and in the Caribbeans, the development of uniform methods and seismicity data bases and the current status in national seismic hazard programs in the Americas.

1. Introduction

Seismic hazard and risk assessment in the Americas is conducted at national, regional, and local scales using both probabilistic and deterministic methods. Probabilistic hazard assessments are performed on all scales, while deterministic assessments are performed for local (site) characterization.

Most of the current probabilistic seismic hazard assessment programs in the Americas stem from one of several papers that introduce quantitative methods for the evaluation of seismic hazard and risk assessment (Lomnitz, 1964; Cornell, 1968; Esteva, 1970). Although developed independently, these methods have common major elements and will be described as one method.

Probabilistic seismic hazard assessment estimates the probabilities for exceeding specified levels of a chosen ground motion parameter for specified exposure times. Hazard assessment programs in the Americas commonly specify a 10% probability of exceedance (90% probability of non-exceedance) of various ground motion parameters, including maximum intensity (Modified Mercalli (MMI), Rossi-Forel, etc.), maximum ground acceleration and maximum ground velocity. Exposure times of interest, primarily for engineers, are 10, 50, and 250 years. Since uncertainties in the parameters and in the modeling techniques may be explicitly incorporated into the analysis, probabilistic seismic hazard analysis is applicable in areas where only rudimentary geological, geophysical, and geotechnical data are available. The results of probabilistic seismic hazard analyses improve as the quality of the data and methods improve.

Deterministic, or scenario, seismic hazard assessment estimates catastrophe potential from the largest possible earthquake believed likely to occur within a specified region. Catastrophe potential may be specified as the distribution of seismic intensities or economic loss or injuries and loss of life. Because deterministic seismic hazard assessments are based on a specific earthquake (or series of earthquakes) in a specific region, they are applicable only in areas where the seismicity of the region, as well as the geologic, geophysical, and geotechnical data, are well quantified. Deterministic assessments sometimes are coupled with an evaluation of the probability of occurrence of the largest possible earthquake for use in engineering, economic, and/or planning decisions. Deterministic seismic hazard or risk assessments provide relatively detailed estimates of ground response or loss, but the probability of the occurrence of the largest earthquake determines the degree to which these estimates should motivate mitigation, preparedness, and response efforts. Thus probability estimates may play a major part in «deterministic» analyses.

2. Method

Seismic hazard assessment programs in the Americas involve national and regional scale probabilistic methods. While various programs differ in detail, they all involve four major steps: 1) delineation of seismic sources and source zones; 2) determination of magnitude recurrence relations for each zone; 3) estimation of attenuation relationships for the ground motion parameter of interest; 4) summation of the probabilities (exceedances) from all source zones contributing to a given site (Cornell, 1968). Figure 1 depicts these steps schemat-

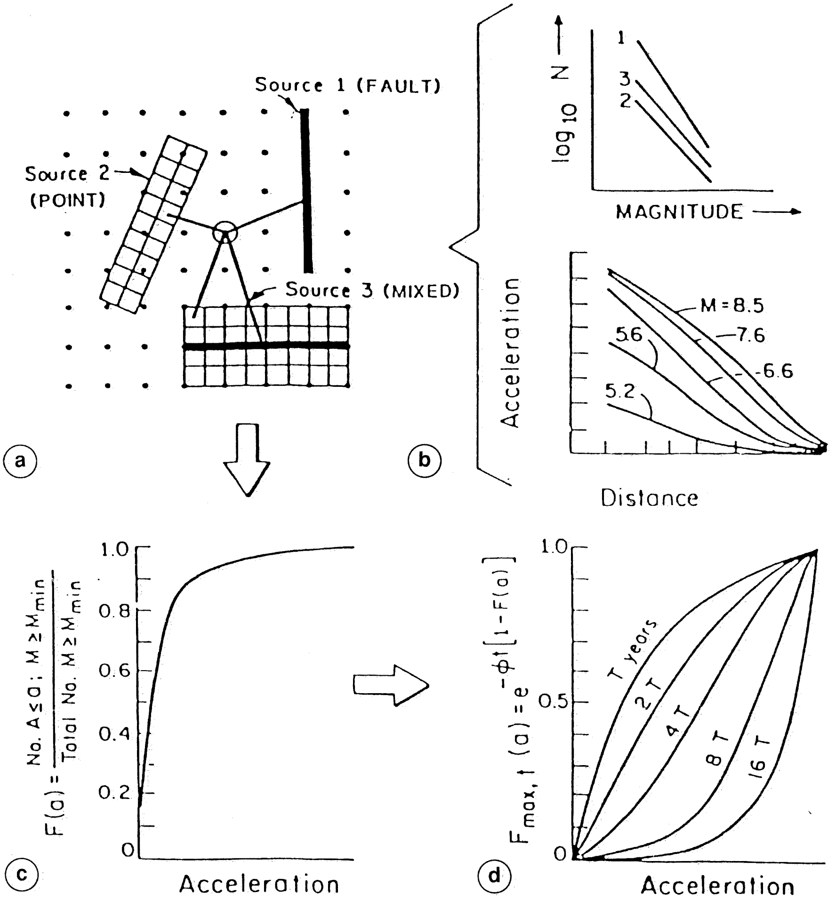


Fig. 1. The major steps of probabilistic hazard calculation. a) Source areas and types are specified within a grid of points representing the area in which the hazard is to be computed. b) Magnitude recurrence and typical attenuation relationships are determined for the region(s). c) Cumulative conditional probability distributions are calculated. d) The extreme probability ($F_{max,t}(a)$) is calculated for various accelerations and exposure times. Figure is taken from Algermissen and others (1982).

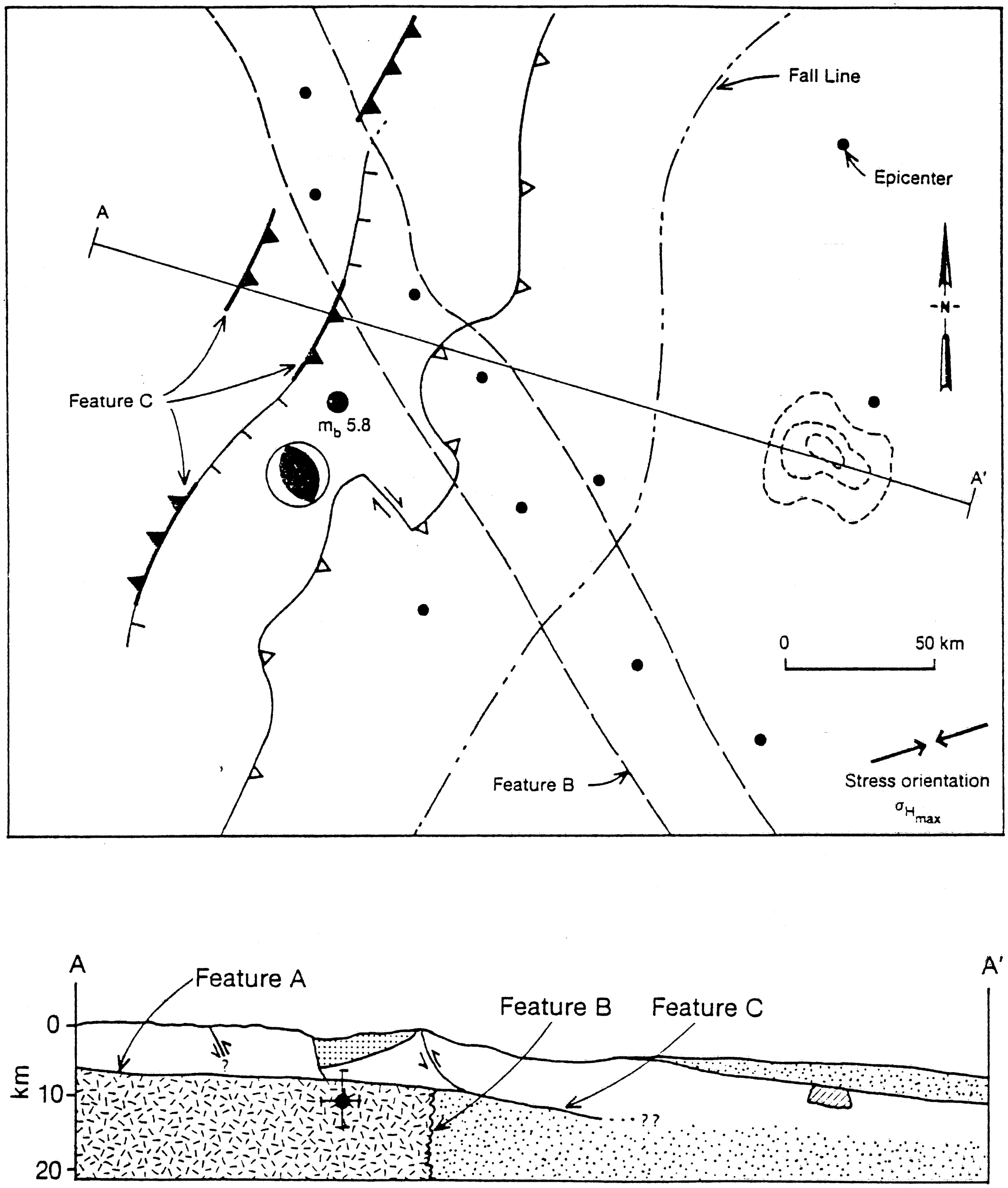


Fig. 2. Hypothetical map and cross section of known earthquakes and potentially seismogenic structures. The focal mechanism of the largest known earthquake is shown, as is the direction of the maximum stress in the region. Figure is taken from Risk Engineering, Inc., and others (1987).

ically for maximum acceleration and velocity maps.

The principle data for probabilistic seismic hazard assessments are seismicity data. Instrumental, historical, and paleoseismicity data are analyzed to both delineate source zones and determine magnitude recurrence relations.

Establishing earthquake catalog completeness is the most common problem cited by hazard researchers throughout the Americas. Previous and existing cooperative programs managed by CEPREDENAC, the U.S. Geological Survey (USGS), the Canadian Geological Survey (CGS), Centro Regional de Sismología para América del Sur (CERESIS) and Instituto de Geofísica-UNAM have begun to produce historical and instrumental seismicity data bases at various levels of completeness in time, space, and magnitude. These catalogs need to be evaluated to establish consistency of earthquake size determined throughout all GSHAP countries. Consensus needs to be established with respect to inclusion or exclusion of foreshocks and aftershocks.

The development of uniform seismicity data bases in GSHAP countries will be a major accomplishment.

Uniform regional seismicity data bases are a key component in establishing source zones in hazard calculations. Seismicity, geologic, and geophysical data needed to assess seismogenesis are combined to delineate seismic source zones. Since the actual delineations of seismic source zones ultimately are qualitative interpretations, all of these data bases need to be uniform for all regions.

An illustrative example of source and/or source zone delineations is that employed by

MATRIX OF PHYSICAL CHARACTERISTICS

ASSOCIATION WITH SEISMICITY	MODERATE TO LARGE EARTHQUAKES		SMALL EARTHQUAKES ONLY		NO SEISMICITY	
GEOMETRY RELATIVE TO STRESS/SENSE OF SLIP DEEP CRUSTAL ASSOCIATION	Favorable	Unfavorable	Favorable	Unfavorable	Favorable	Unfavorable
YES	0.80	0.40	0.30	0.10	0.060	0.012
NO	0.64	0.20	0.15	0.05	0.024	0.004

Fig. 3. An example of a «characteristic matrix» used to systematically assess potentially seismogenic structures in order to assign a probability to them. Figure taken from Risk Engineering, Inc., and others (1987).

the Seismicity Owners Group (SOG) seismic hazard methodology development program under the auspices of the Electric Power Research Institute, Inc. (EPRI). The SOG methodology was designed to define seismic sources and their associated seismicity parameters, consistent with earth science practice, that were fully tractable and amenable to scientific peer review. First, known earthquakes and potentially seismogenic structures are identified, as is the contemporary tectonic stress regime (fig. 2). Each structure is then systematically assessed to assign a subjective probability of seismic activity (fig. 3). The entire suite of possibilities is then put into a probabilistic context to translate tectonic structures into seismic sources (fig. 4).

Once sources and source zones are identified and source parameter values are established, some ground motion parameters of interest are specified. Seismic hazard curves are computed for each source characterization. Each curve has a probability associated with it. These curves are summed to produce the values of the desired level (mean, median, various fractiles) of probability of exceedance vs. ground motion parameter for graphic representation (fig. 5). Another form of presentation of the results of seismic hazard calculations are the familiar national or regional ground motion hazard maps (fig. 6).

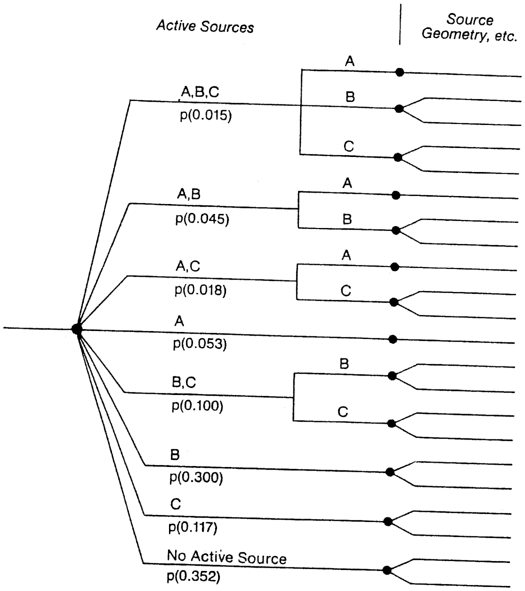


Fig. 4. Schematic of the suite of possibilities from fig. 2 and their translation to seismic sources and their associated uncertainties. Figure is taken from Risk Engineering, Inc., and others (1987).

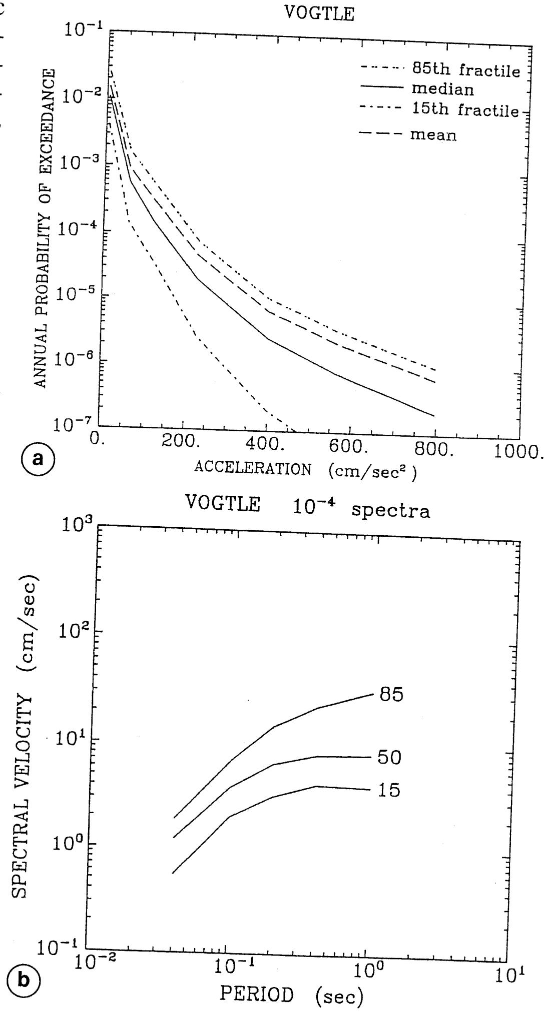


Fig. 5. An example of curves of a) annual probability of exceedance of acceleration for a suite of desired central measures and fractiles and b) spectral velocities. Figures are taken from Risk Engineering, Inc., and others (1987).

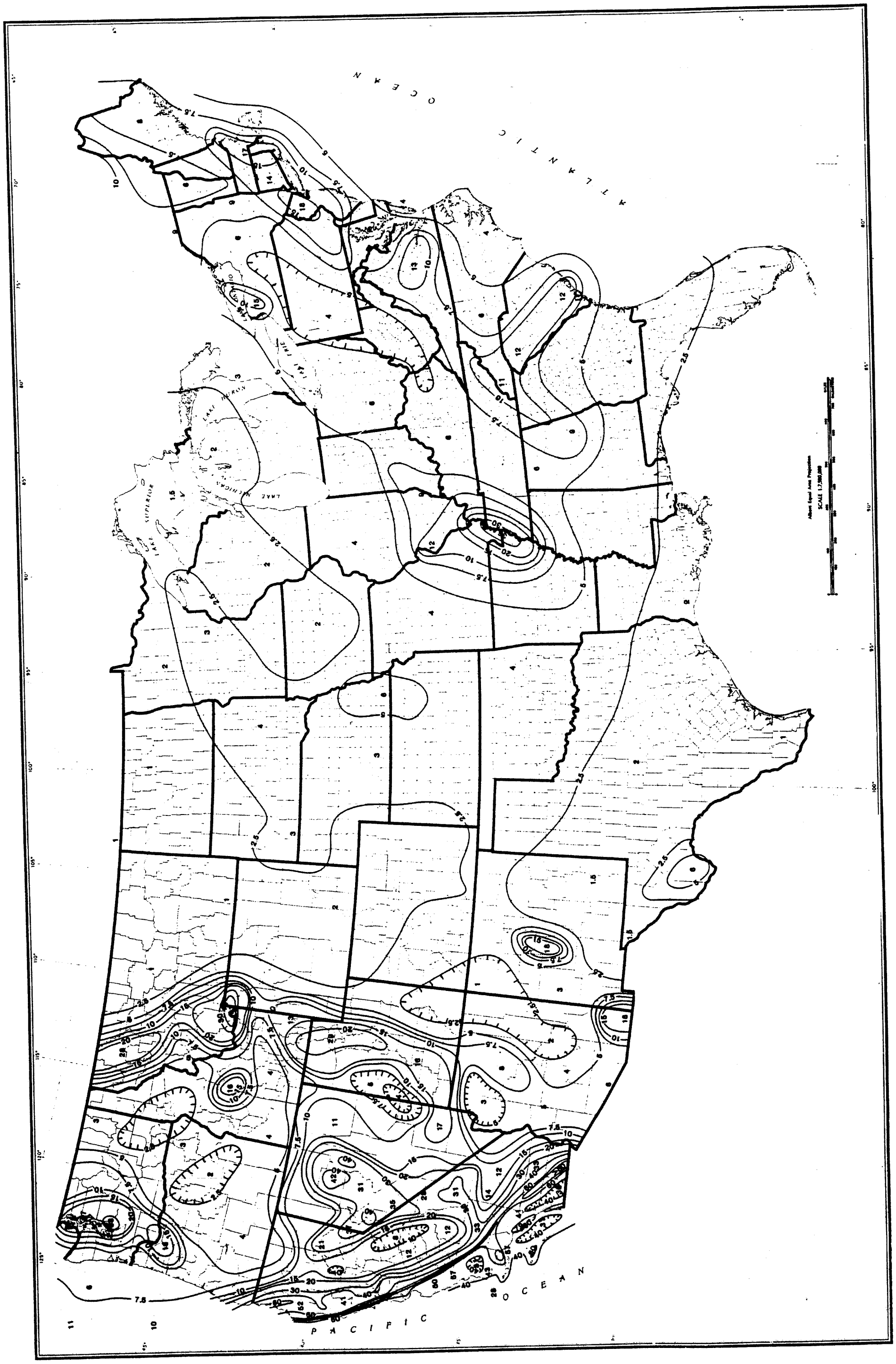


Fig. 6. Peak horizontal acceleration map (in percent g) with a 10% probability of exceedance in 50 years for the United States. Figure is taken from Algermissen *et al.* (1990).

3. National programs in the Americas

The high level of seismicity along the plate boundaries that coincide with the west coasts of North, Central, and South America has resulted in a high level of awareness and programs to accurately assess the seismic hazards throughout the Americas (fig. 7). National efforts are ongoing or proposed in a majority of countries (table I) and many also have local seismic hazard assessment programs, primarily in urban areas or near power facilities. All of the national seismic hazard assessment programs in the Americas involve the basic meth-

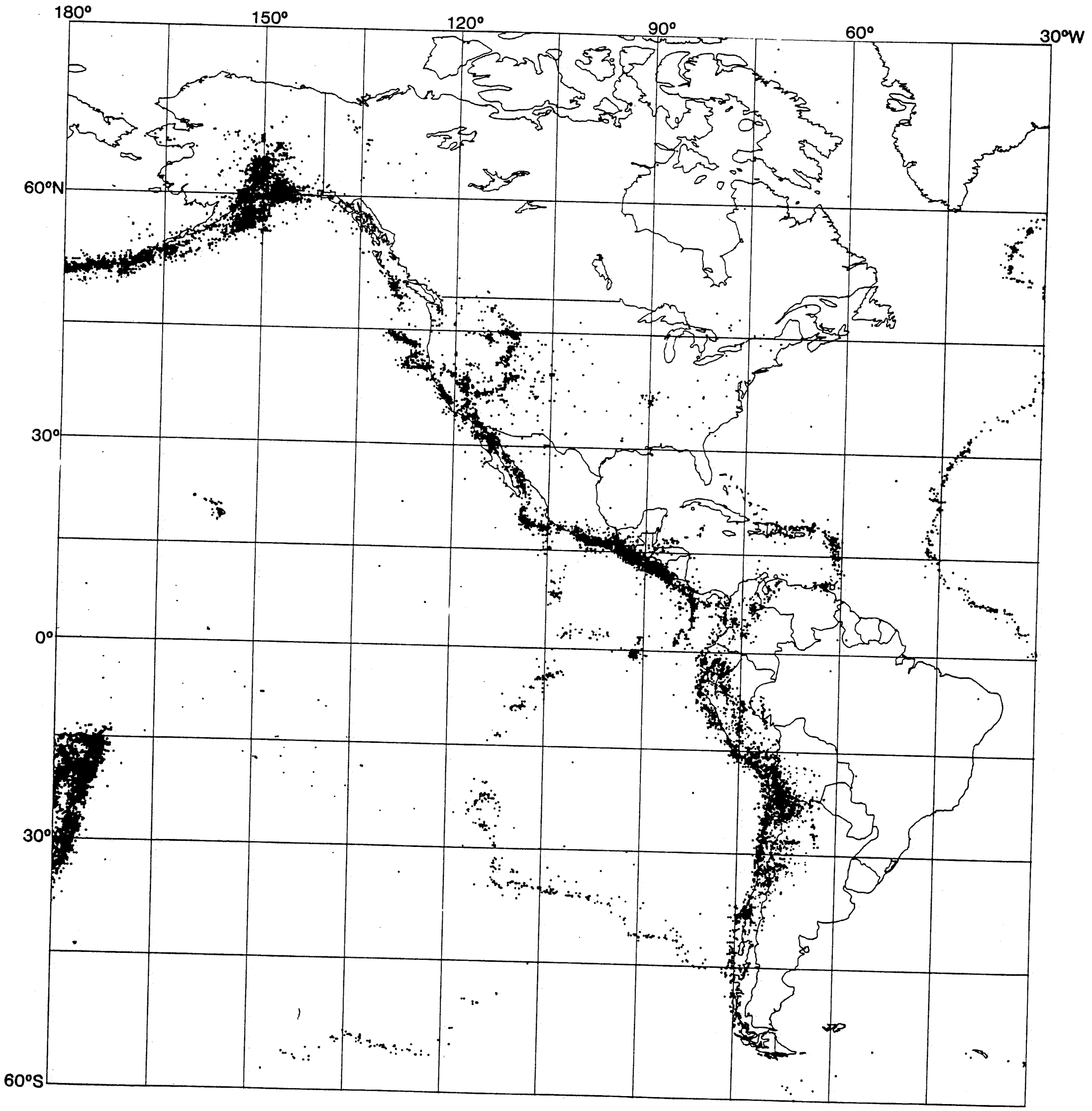


Fig. 7. Seismicity map of the Americas. Note the concentration of seismicity along the western boundaries of the Americas. Figure is modified from Tarr (1974).

Table I. Current seismic hazard assessment programs in the Americas.

Country	National and/or regional probabilistic	Local deterministic or probabilistic
Argentina	√	√
Bolivia	√	
Brazil	Proposed	√
Canada	√	√
Chile	√	√
Colombia	√	√
Costa Rica	√*	
El Salvador	√*	
Guatemala	√*	
Honduras	√*	
Mexico	√	√
Nicaragua	√*	
Panama	√*	
Peru	Proposed	√
USA	√	√

* Part of the overall Centro de Coordination para la Prevencion de Disastres Naturales en America Central (CEPREDENAC) seismology program.

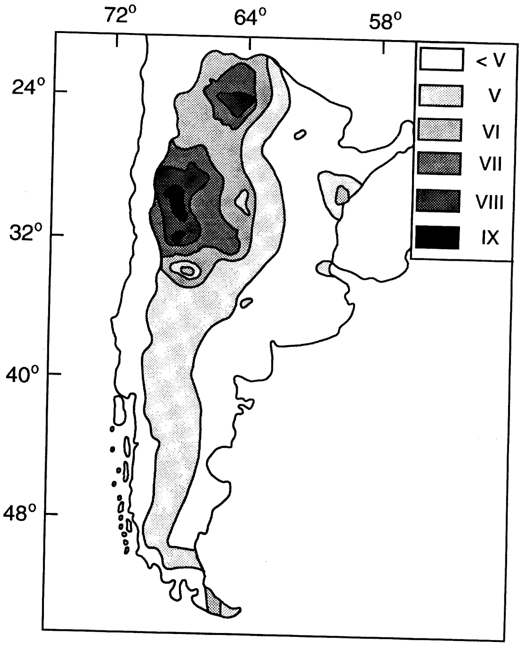
od outlined in the previous section; they differ primarily in the ground motion parameter mapped.

Argentina. The historical catalog of seismicity for Argentina begins in 1692. Seismicity has been recorded instrumentally since 1920. The most complete catalog of seismicity in Argentina was prepared under the SISRA project, a cooperative project between CERESIS and the USGS (SISRA, 1985). National hazard maps for Argentina depict the maximum intensity from all historical earthquake data (fig. 8) and peak horizontal acceleration for 50 and 100 years (fig. 9). Argentina also has performed detailed local seismic hazard assessments to determine the mean time of seismic intensity occurrence at large dam sites and the probable level of damage to large buildings in urban areas.

Bolivia. The historical catalog of seismicity for Bolivia begins in 1650. Instrumental recording began in Bolivia in 1913. Seismic hazard mapping in Bolivia is based on intensity mapping. Intensities are converted to accelerations through an empirical relation presented by Richter (1958). These values are then converted to an annual distribution of intensity from which a probability of exceeding 0.05 g in 50 years is mapped (fig. 10). Using instrumental and historical seismicity data, Bolivian seismologists also calculate an annual distribution of earthquakes and map the probabilities of future earthquakes of moderate-to-large magnitudes for different periods of time (fig. 11).

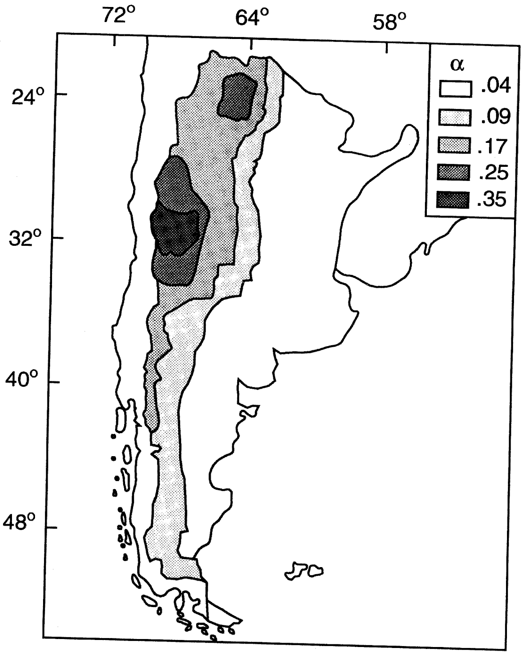
Brazil. Brazil occupies most of intraplate South America and thus has a relatively low level of seismicity (fig. 7). The historical catalog of seismicity for Brazil begins in 1560, with the instrumental collection of earthquake data beginning during the 1970's. Seismic hazard and risk studies in Brazil thus far have been local, to evaluate sites for dams, nuclear power plants, etc. There are currently 50 seismic stations recording data in Brazil, primarily in the most populous and seismically active eastern half of the country. University research institutes and private companies have recently begun to cooperate on a systematic seismic hazard and risk assessment of Brazil.

Canada. The historical catalog for Canada begins in 1568. The instrumental recording of earthquakes in Canada began in the early 20th



Maximum Seismic Intensities

Fig. 8. Isoseismals for each historic and instrumentally recorded earthquake of MMI ≥ 7 were plotted and superposed to produce the maximum seismic intensities map of Argentina. Figure is modified from SISRA, (1985).



Seismic Zones for Argentine Building Code

Fig. 9. Instrumental data from 1920 to 1976 was used to produce the most probable instrumental acceleration map (50 years) for Argentina. Figure is modified from Inpres-Cirsoc (1983).

century, but the major expansion of the Canadian national network took place in 1961. Prior to this time parts of Canada, particularly Northern Canada, were poorly monitored (Basham *et al.*, 1985). The Canadian seismic hazard and risk mapping program follows the classic Cornell (1968) approach, using computer programs coded by McGuire (1976). The seismicity map of Canada (fig. 12) serves as the basis for the delineation of source zones (fig. 13). Ground motion attenuation relationships developed for Canada (Hasegawa *et al.*, 1981) were incorporated into the programs to produce national maps of peak horizontal velocity (fig. 14) and acceleration (fig. 15) with a 10% probability of exceedance in a 50-year window (Basham *et al.*, 1985).

Central America. One of the major projects of CEPREDENAC involves Costa Rica, El Salvador, Guatemala, Honduras, Nicaragua, and Panama in a cooperative project to assess seismic hazard and risk in Central America. This CEPREDENAC project has two main goals: 1) the strengthening of existing seismic networks and 2) the evaluation of seismic hazards and risk (CEPREDENAC, 1991). As a first step toward a uniform data base, teleseismic data from earthquakes that occurred in Central America between 1904 and 1988 were collected and published by CEPREDENAC. The regional upgrade of the seismic networks and the unification of the existing local seismic network data are underway, coordinated through the Universidad Nacional de Costa Rica.

Chile. Probabilistic hazard studies in Chile have been underway since the 1960's, begin-

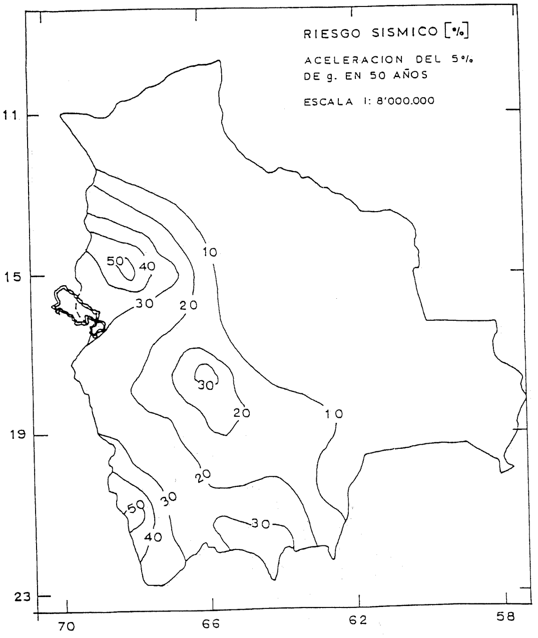


Fig. 10. Map of the probability of exceeding an acceleration of 0.05g (5%) in 50 years. Western and South-Central Bolivia have the highest seismic hazard. Figure is taken from Vega (1980).

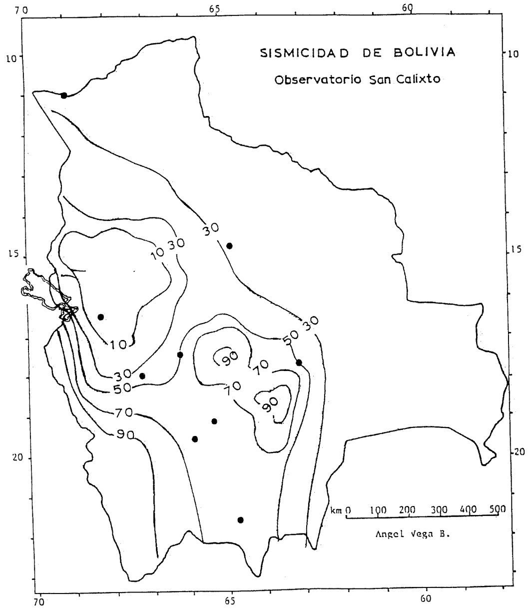


Fig. 11. Map of the probability of occurrence of a magnitude 5.5 or larger earthquake in 30 years. Figure is taken from Cabré and Vega (1989).

ning with the efforts of Lomnitz (1964, 1969, 1970, 1974). The historical catalog begins in 1535. Instrumental recording began in the 1930's. Chile has well-developed national, regional, and local hazard assessment efforts. The most recent mapping effort is a cooperative project between the University of Chile and USGS, under the auspices of the World-wide Earthquake Risk Management Program (WWERM) funded by the U.S. Office of Foreign Disaster Assistance.

Earthquake sources in Chile exist throughout the subduction zone (depths ≈ 180 km) to the shallow crust. The subduction zone is a complicated zone of faulting in which the main subduction plane changes dip (fig. 16). Thus, the seismic zones for Chile reflect the complicated source geometries (fig. 17). These zones were used in a modified Cornell (1968) hazard assessment computer code, developed by Algermissen and others (1992), to map ground acceleration with a 90% probability of non-exceedance in 50 years (fig. 18).

This cooperative program also includes an ongoing effort to produce maps of intensity values (MMI) with a 10% chance of exceedance in 50 years for the most densely populated region of Chile (between about 31.5° S to 35° S).

Colombia. The historical earthquake catalog for Colombia begins in 1566.

The first seismograph station was installed in 1922, but national monitoring really did not begin until the late 1950's. The seismotectonic structure of Colombia is complex since the Nazca, South America, and Caribbean plates converge within Colombian territory. However, in general the tectonic fabric of Colombia (major faults, mountain ranges) trends north-south. Based on the seismicity catalogs and geologic mapping, seismic zones have been delineated and ground motion maps have been produced, following the general Cornell (1968) approach but with major changes introduced by Der Kuireghian and Ang (1975). Zones of high, intermediate, and low seismic risk have

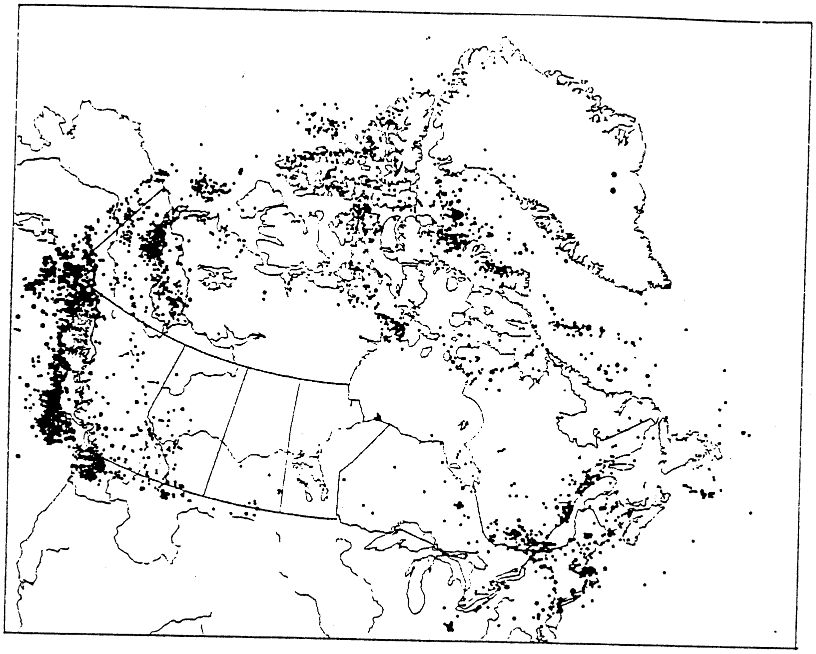


Fig. 12. Seismicity map of Canada. Figure is adapted from Anglin *et al.* (1990).

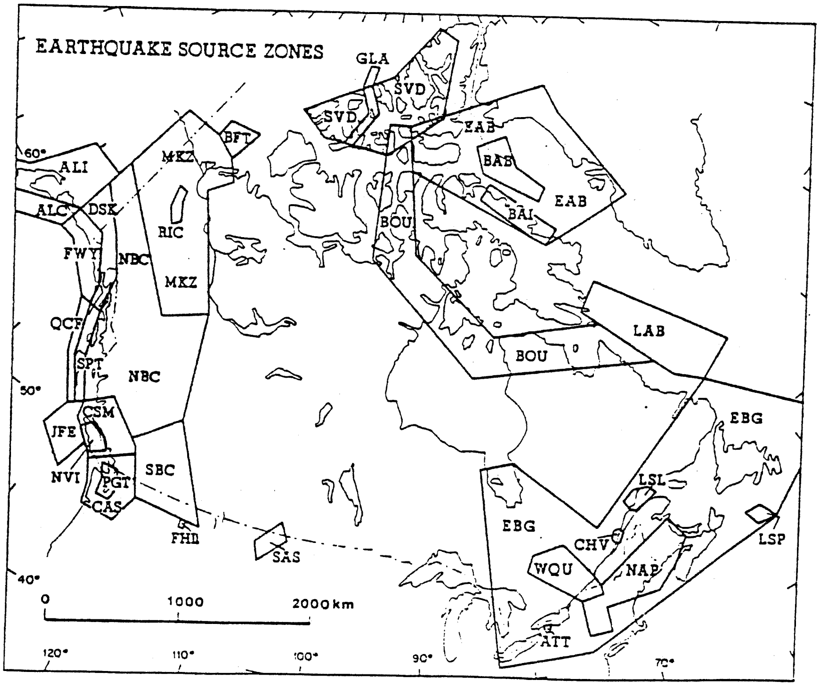


Fig. 13. Seismic source zones used to estimate seismic ground motion in Canada. Figure is taken from Basham *et al.* (1985).

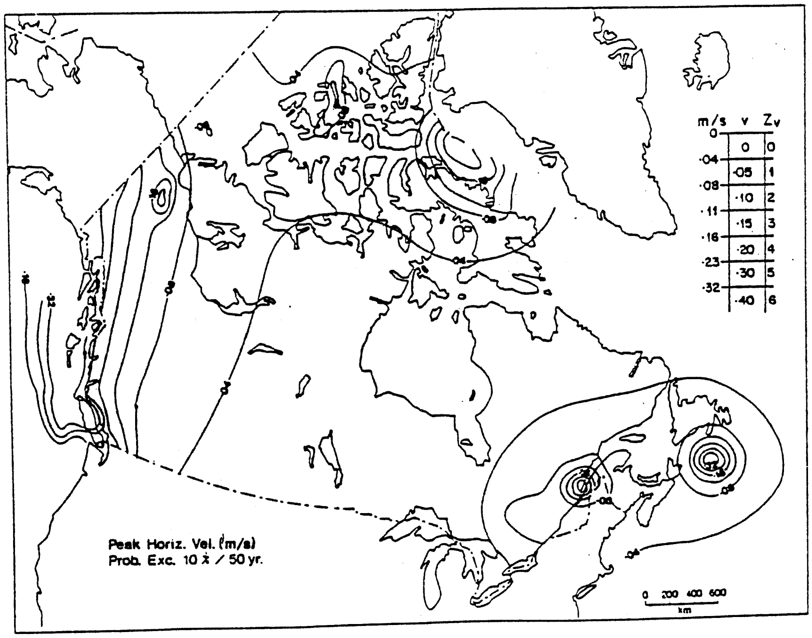


Fig. 14. Peak horizontal velocity (m/s) map with a 10% probability of exceedance in 50 years for Canada. Figure is taken from Basham *et al.* (1985).

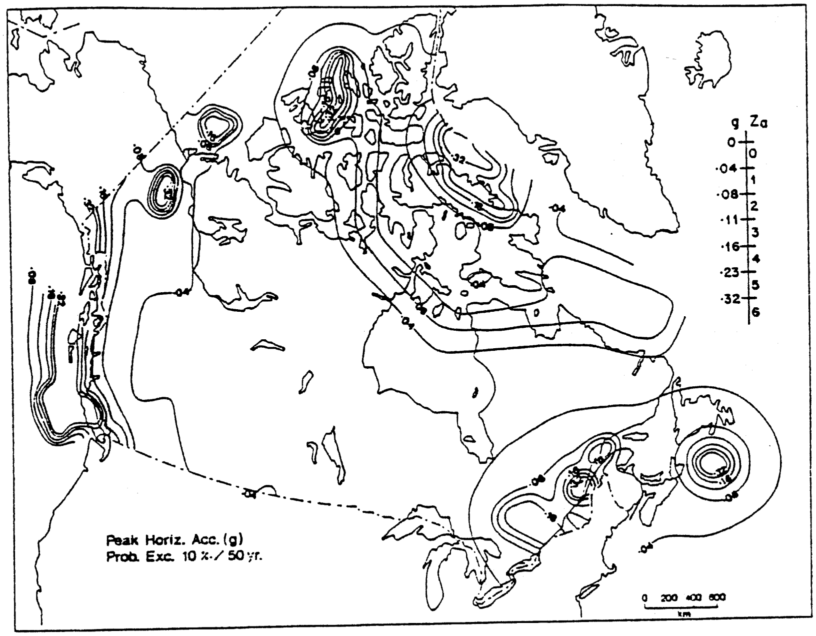


Fig. 15. Peak horizontal acceleration (g) map with a 10% probability of exceedance in 50 years for Canada. Figure is taken from Basham *et al.* (1985).

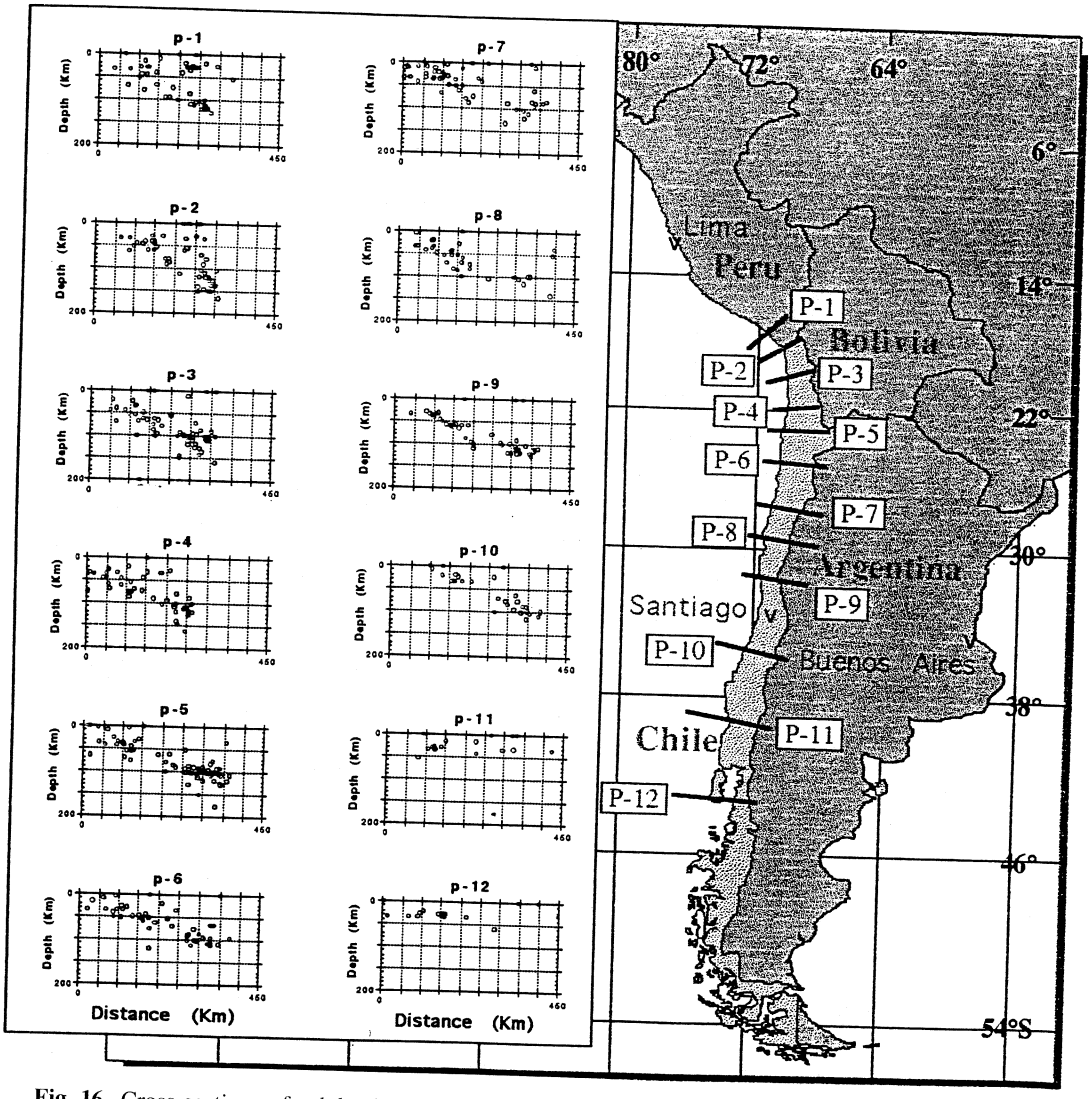


Fig. 16. Cross-sections of subduction zone earthquakes along Chile, illustrating variations in dip of the subduction zone interface. Figure is taken from Algermissen *et al.* (1992).

been mapped in Colombia (fig. 19), as have effective peak acceleration (fig. 20) and effective peak velocity (fig. 21) for a mean return period of 50 years.

Mexico. The historical catalog of earthquakes in Mexico begins in the late 14th Century. The instrumental catalog begins in the 1930's, but national coverage was not well developed until the 1960's. Mexico has nearly completed a compilation of historical earthquakes, drawing from Mexican and Spanish archives and a homogeneous catalog of instrumentally recorded earthquakes that includes the reestimation of suspect magnitudes. The first maps describing probabilities of expected

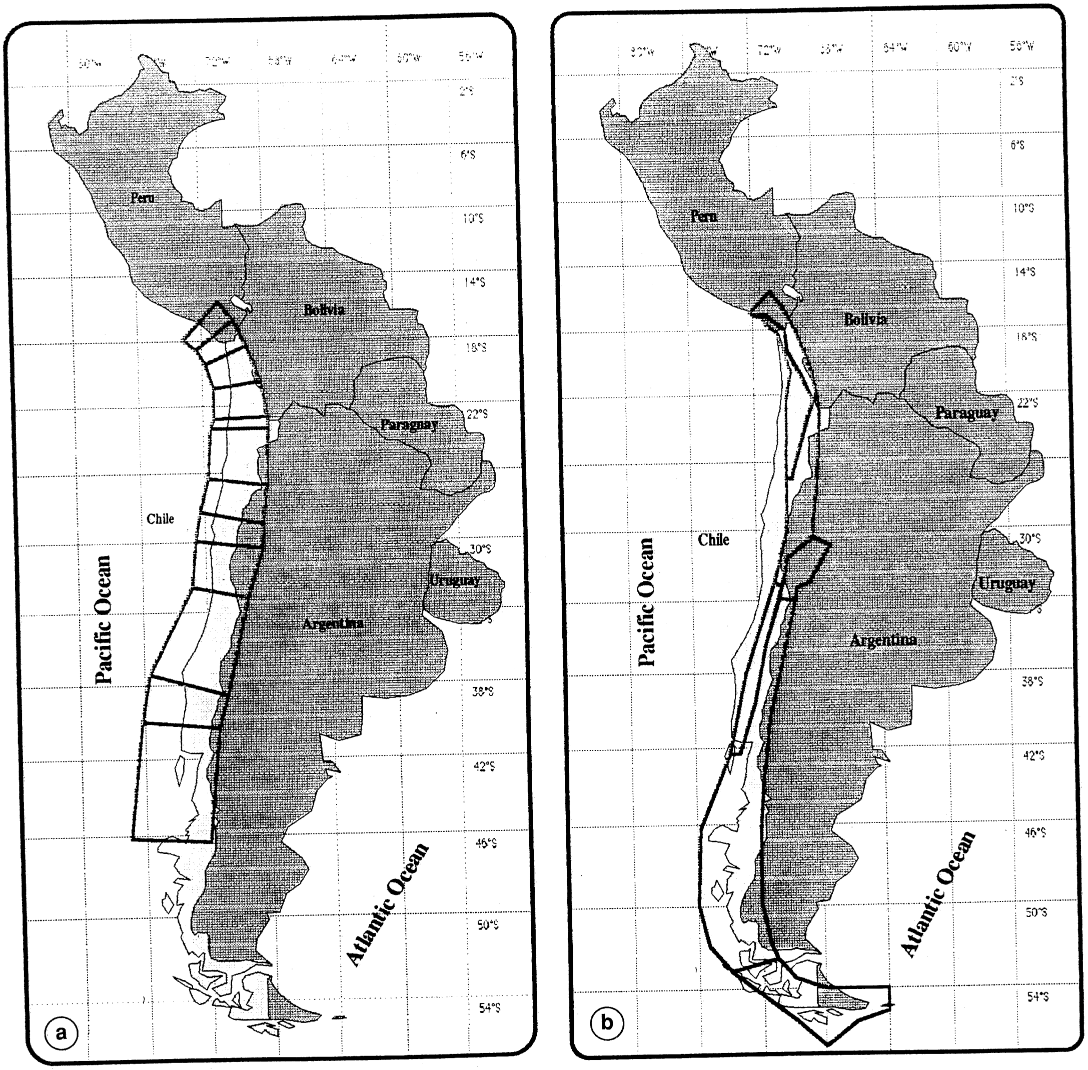


Fig. 17. a) Subduction zone earthquake sources along Chile are modelled as dipping planes. The rectangles represent segments of the Nazca-South American plate interface that dips at various angles north to south. b) Source zones for shallow earthquakes (< 30 km) in Chile. Two zones extend into Argentina representing the seismically active San Juan, Mendoza region. Figures are taken from Algermissen *et al.* (1992).

acceleration and velocity for various recurrence times were published by Esteva (1968). The most current seismic hazard and risk assessments for Mexico include frequency-dependent attenuation values and site effects.

The Instituto de Geofísica-UNAM is installing a new National Seismic Network consisting of about 40 broad-band stations linked via satellite. The various regional networks throughout Mexico will be incorporated into the National Network. A first cut at a new seismic regionalization of Mexico has been

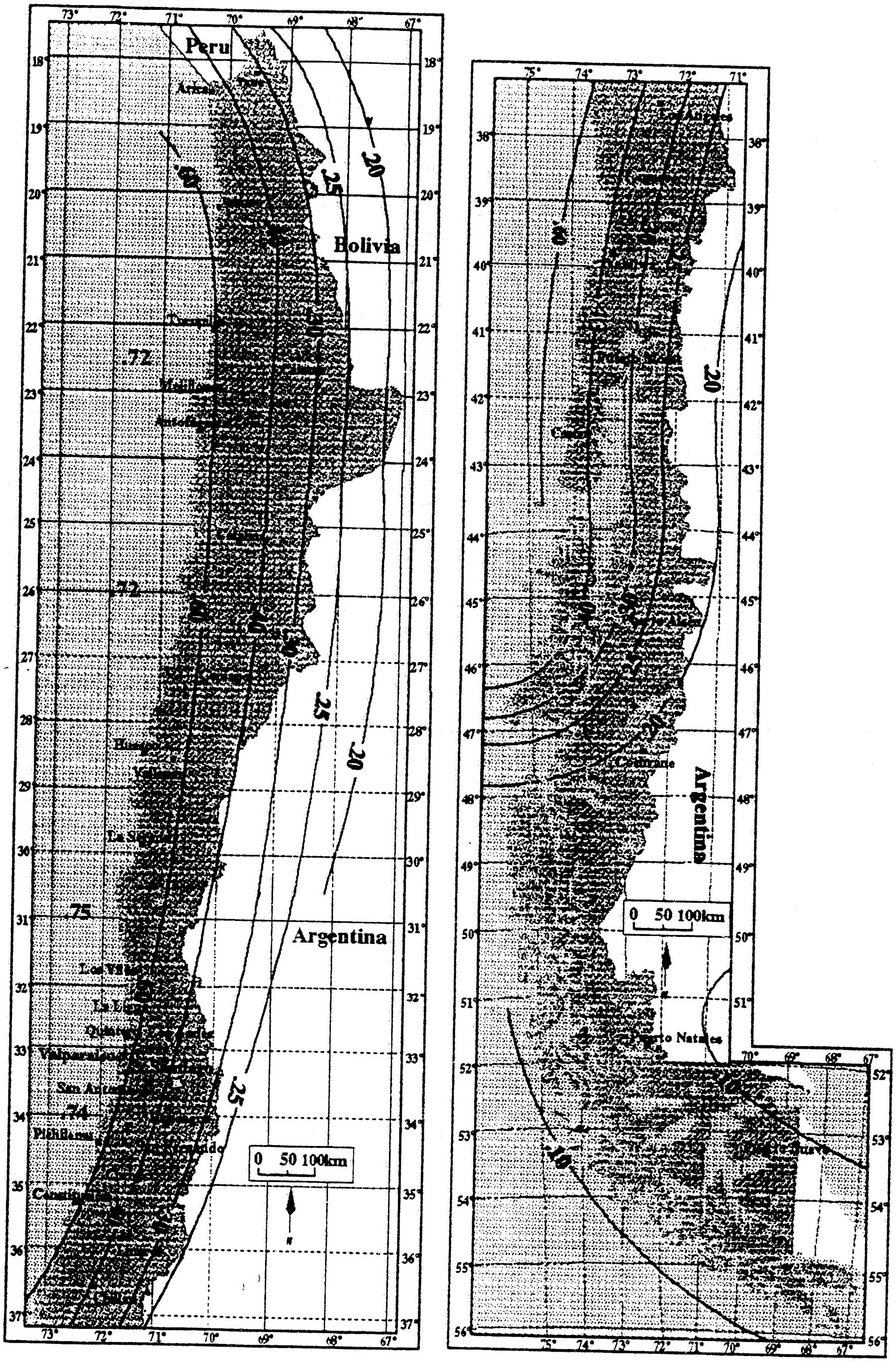


Fig. 18. Probabilistic ground motion acceleration (without variability) of Chile. These accelerations have a 10% chance of being exceeded in 50 years. Figure is taken from Algermissen *et al.* (1992).

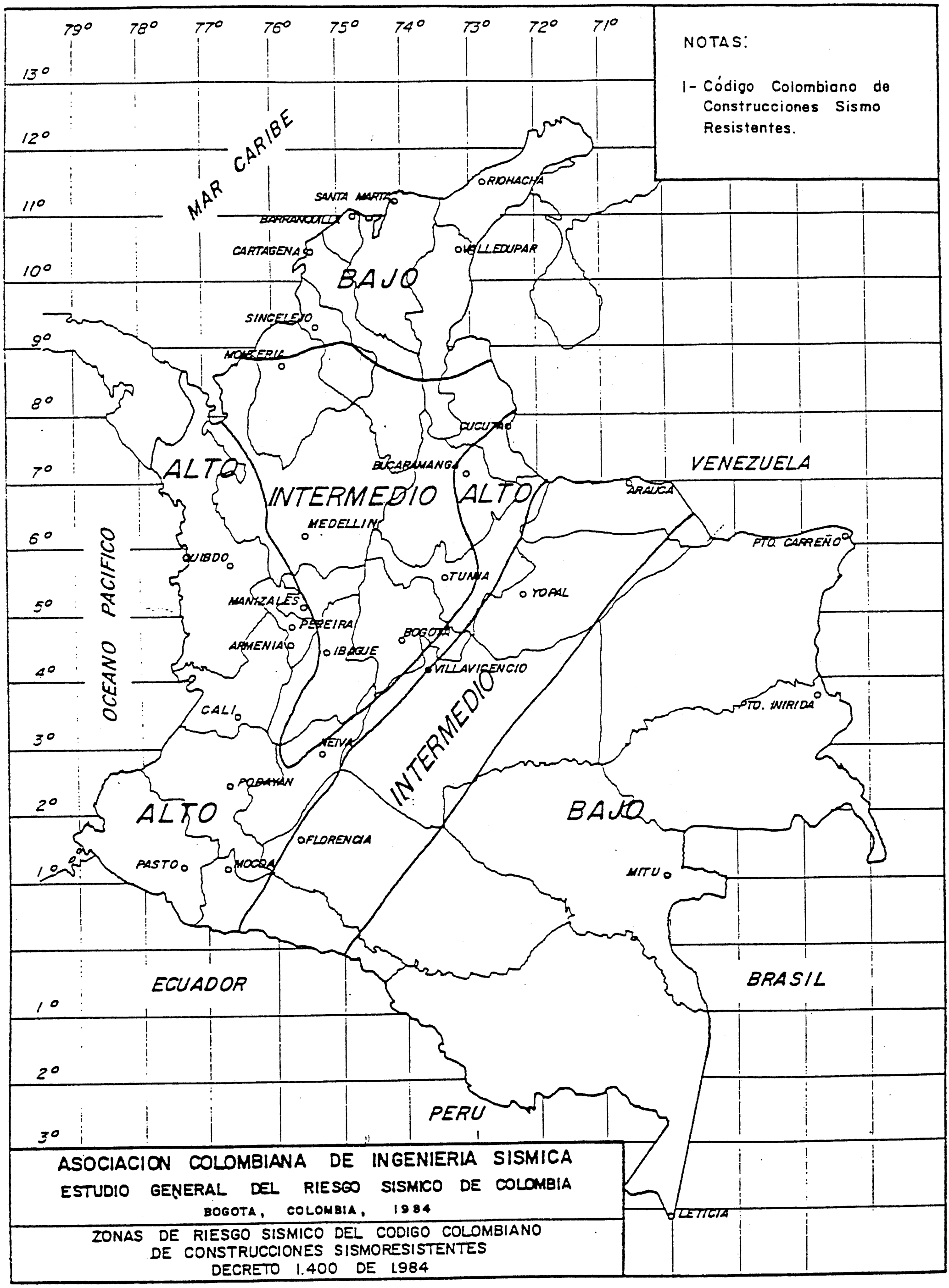


Fig. 19. Zones of high, intermediate, and low seismic risk in Colombia. Figure is taken from García *et al.* (1984).

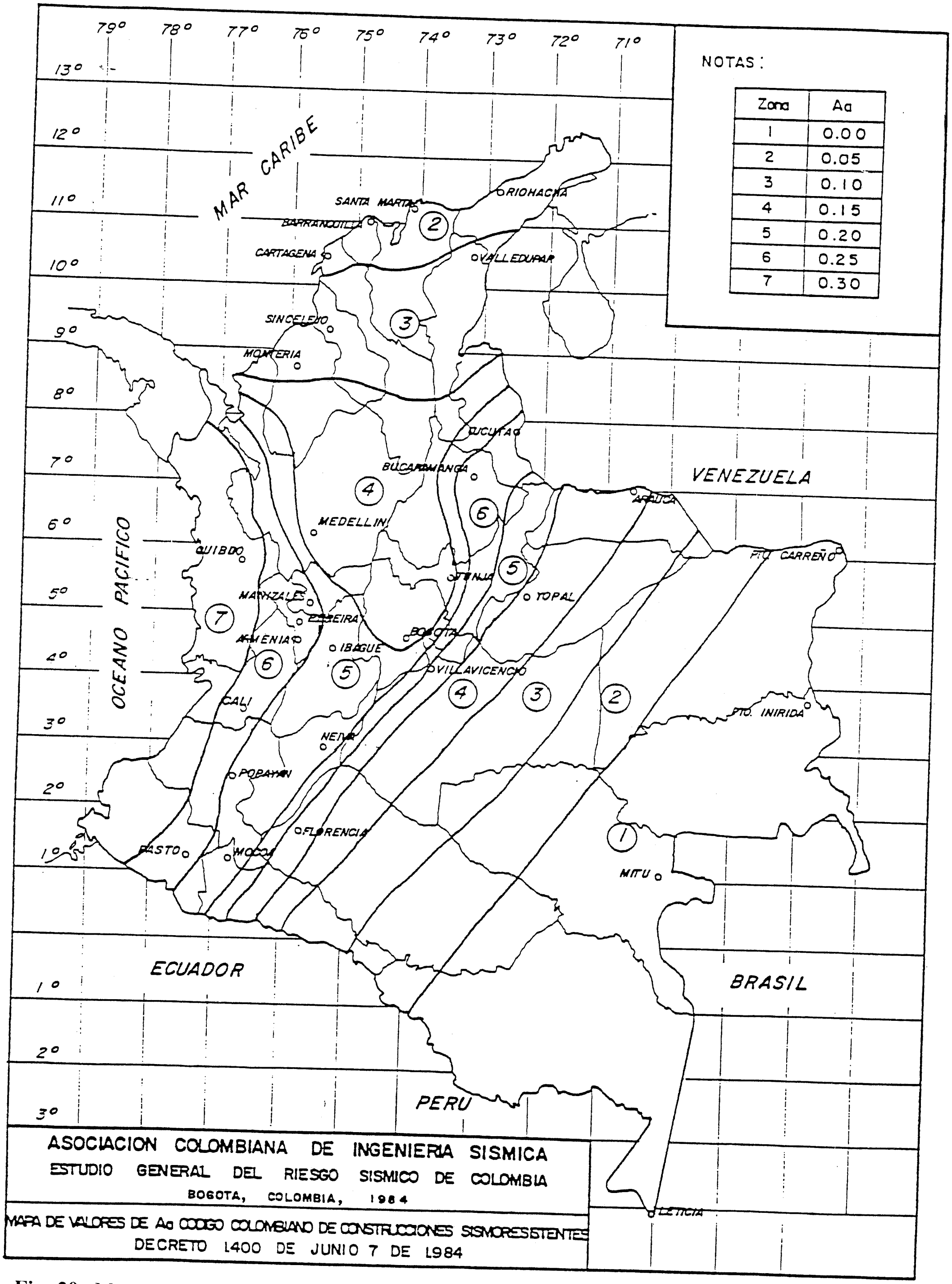


Fig. 20. Map of effective peak acceleration, A_a, for a 50 year return period for Colombia. Map is taken from García *et al.* (1984).

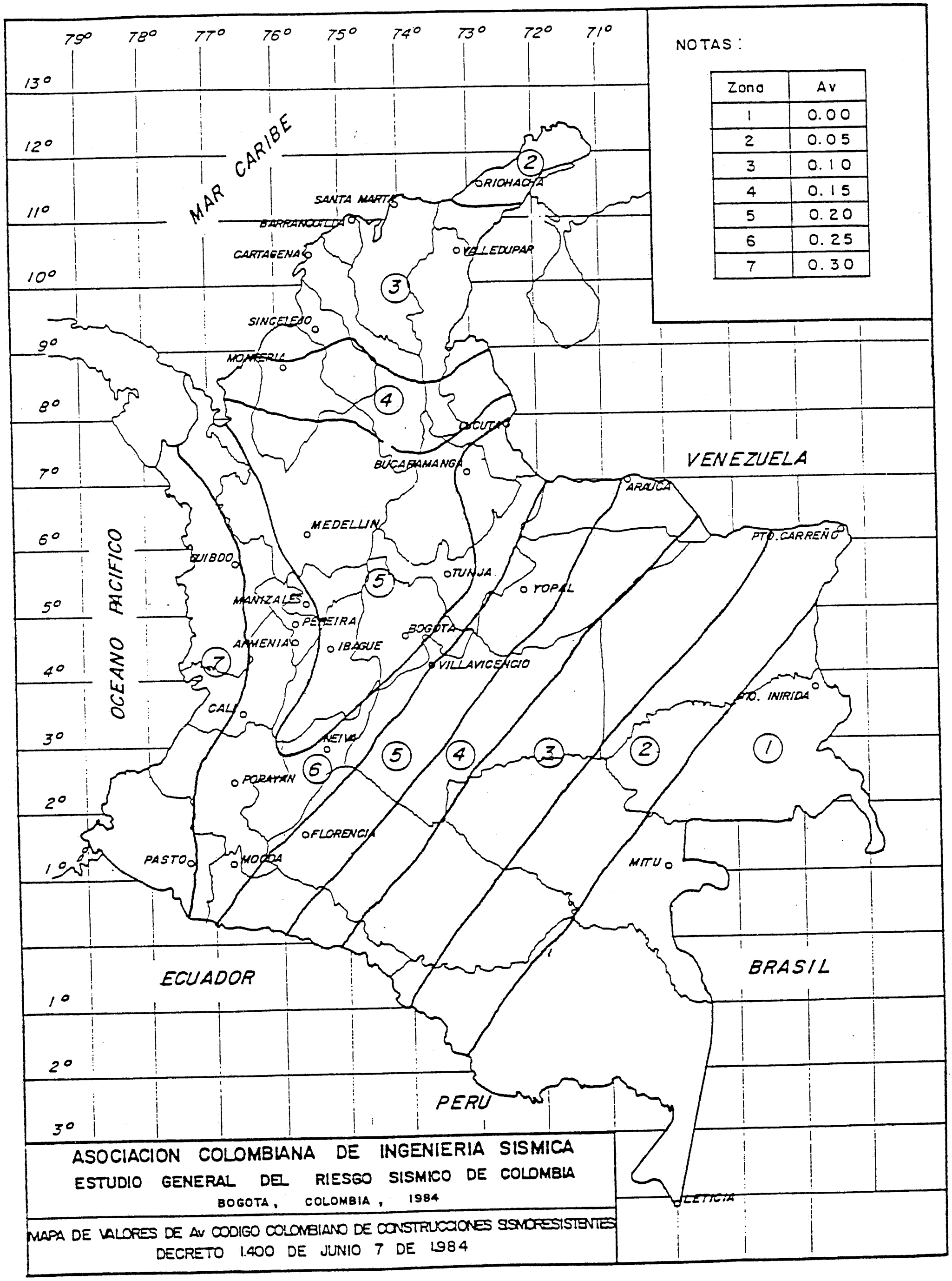


Fig. 21. Map of effective peak velocity (from acceleration), A_v, for a 50 year return period for Colombia. Map is taken from García *et al.* (1984).

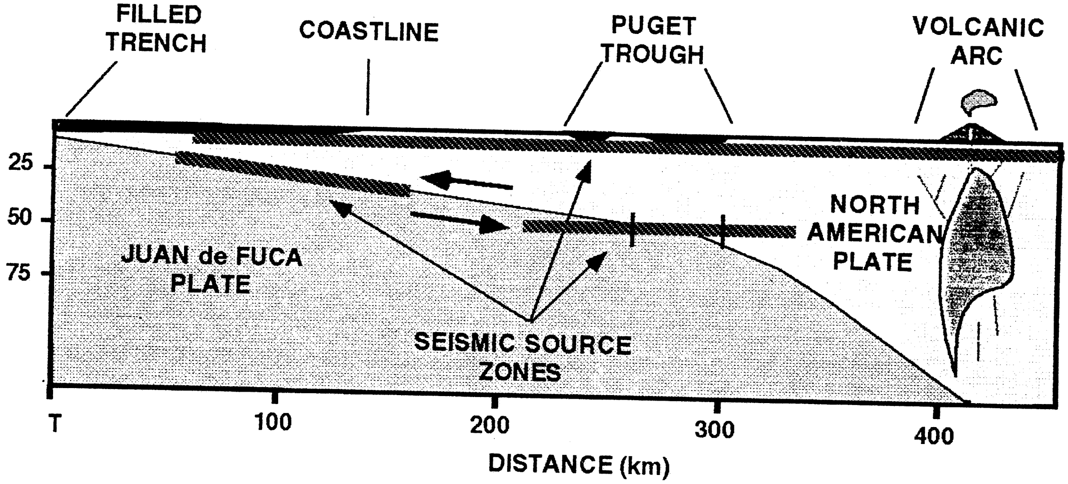


Fig. 22. Schematic of earthquake sources in the Pacific Northwest. Subduction zone earthquakes (M_s=8.5) are assumed to occur on a dipping plane rupture surface extending downdip a distance of 100 km from the trench and 200 km along strike, anywhere throughout the 1200 km long subduction zone. Intraplate earthquakes are modeled as occurring at the top of the lower plate. Shallow earthquakes are modeled as occurring in zones. Figure provided by S.T. Algermissen.

Fig. 23. Ten cities for which detailed spectra were computed at 12 periods ranging from 0.1 s to 4.0 s. Detailed spectra for Seattle or Portland (Pacific Northwest) are being prepared for future hazard maps. Figure provided by S.T. Algermissen.

completed. Plans are underway to produce seismic microzonation maps for the larger urban areas of Mexico, as well as national probabilistic landslide and liquefaction maps.

Peru. The historical catalog for Peru begins in 1471. Although some earthquakes were recorded instrumentally as early as the 1920's, systematic national recording of earthquakes began in 1955. Under the auspices of CERESIS, project SISRA produced catalogs of historical and instrumental earthquakes for all ten member nations, including Peru. Various institutions in Peru have used the SISRA data to produce their own versions of local and regional hazard maps, but no officially accepted national version currently exists. Peru has presented a proposal to the AID mission for support to produce probabilistic ground motion maps of Peru, a site response map for Lima and environs, a microzonation map of Lima, and an estimation of future losses in Lima from earthquakes.

United States. The historical catalog for the United States begins in 1534. Sparse network coverage began in 1910, and systematic national monitoring began in the late 1960's. The seismic hazard and risk assessment program in the United States is based on the Cornell (1968) method. The earliest national maps, probabilistic estimates of maximum acceleration based on seismicity, were produced by Algermissen and Perkins in 1976. Through their subsequent work and the work of many other researchers, sophisticated codes that in-

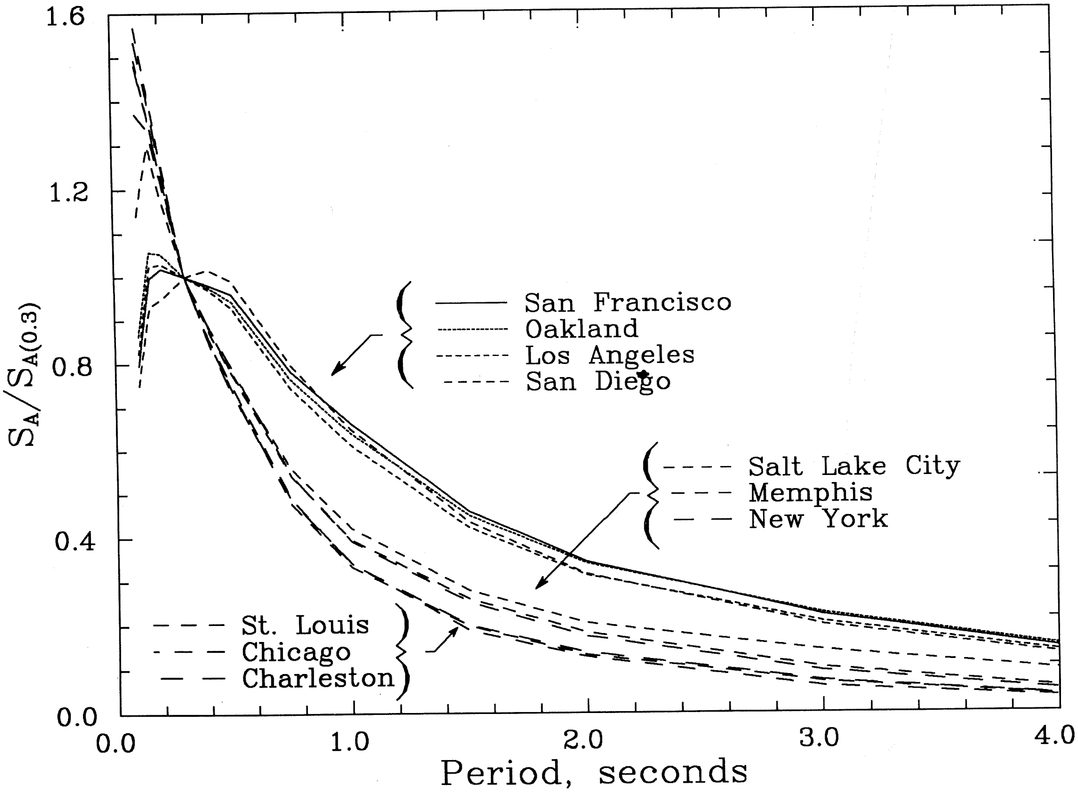


Fig. 24. Summary slide of detailed spectra for the 10 cities in fig. 23 (normalized to 0.3 s period). Figure is taken from Algermissen and Leyendecker (1992).

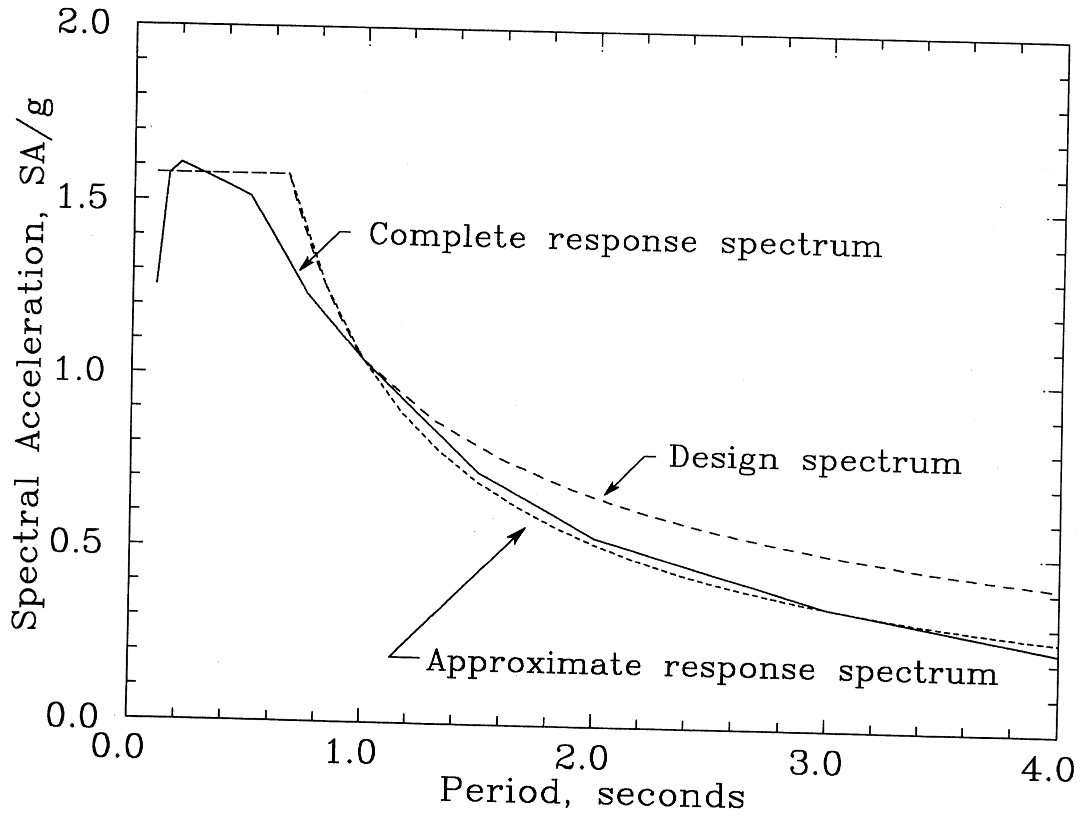


Fig. 25. Comparison of San Francisco detailed spectrum with the generalized spectral shape used to produce Western U.S. maps. The solid curve is the complete spectrum for San Francisco. The lightly dashed line is an approximation assuming a curve with a slope 1/T. The heavy dashed line is the curve with a slope $1/T^{2/3}$ used in the map calculations. Figure provided by S.T. Algermissen.

clude parameter variability, geologic, geophysical and geotechnical data as input, and a wide variety of ground motions as output have been developed (*e.g.*, Algermissen and Leyendecker, 1992; Bender and Perkins, 1987; Risk Engineering *et al.*, 1987; Dames and Moore, 1986; McGuire, 1976). The most recent national maps for the U.S. depict spectral acceleration at periods of 0.3 s and 1.0 s, 5% damping, S_2 soil, with a 10% chance of exceedance in 50 and 250 years (Algermissen and Leyendecker, 1992). The spectral ordinates computed are the response of a damped, single degree of freedom structure to ground motion of some particular period. The S_2 soil profile corresponds to cohesionless or stiff clay conditions, including sites where the soil depth exceeds 200' and the soil types overlying rock are stable deposits of sands, gravels, or stiff clays. Because the tectonic regimes and spectra vary across the U.S., these «national» maps are produced by region. For example, the Pacific Northwest, a subduction environment, is subject to very different earthquake sources that the intraplate Central and Eastern U.S. Earthquake sources in the Pacific Northwest are subduction zone earthquakes, intraplate earthquakes, and earthquakes in the shallow crust, each modelled differently (fig. 22).

The different seismotectonic regimes across the U.S. also produce different spectra (fig. 23 and 24). The spectral shapes fall into two natural groups: cities in California where the

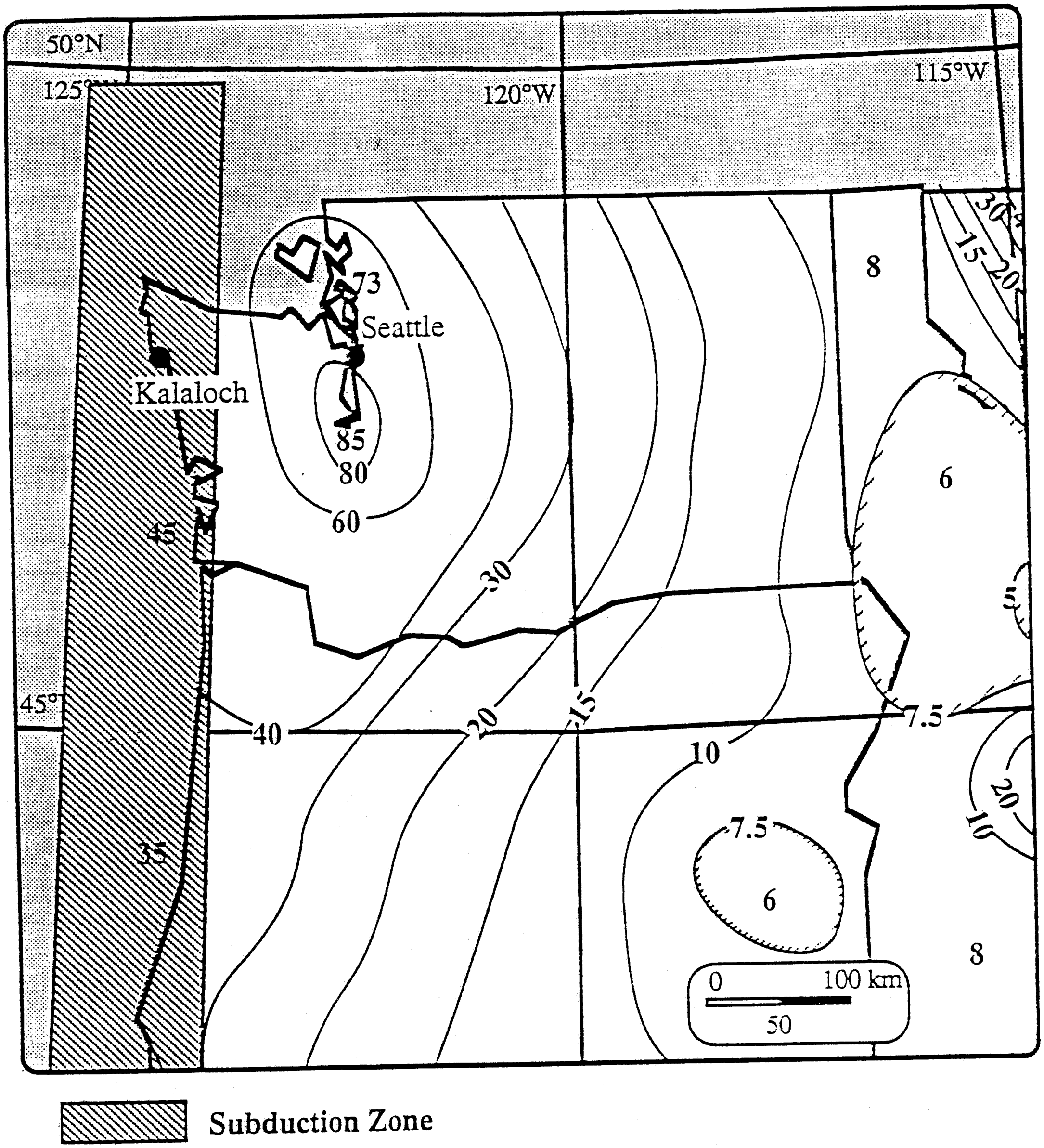


Fig. 26. Spectral response map of the Pacific Northwest showing acceleration (in % of g) for 0.3 s, 5% damping, with a 10% probability of exceedance in 50 years. Figure is taken from Algermissen and Leyendecker (1992).

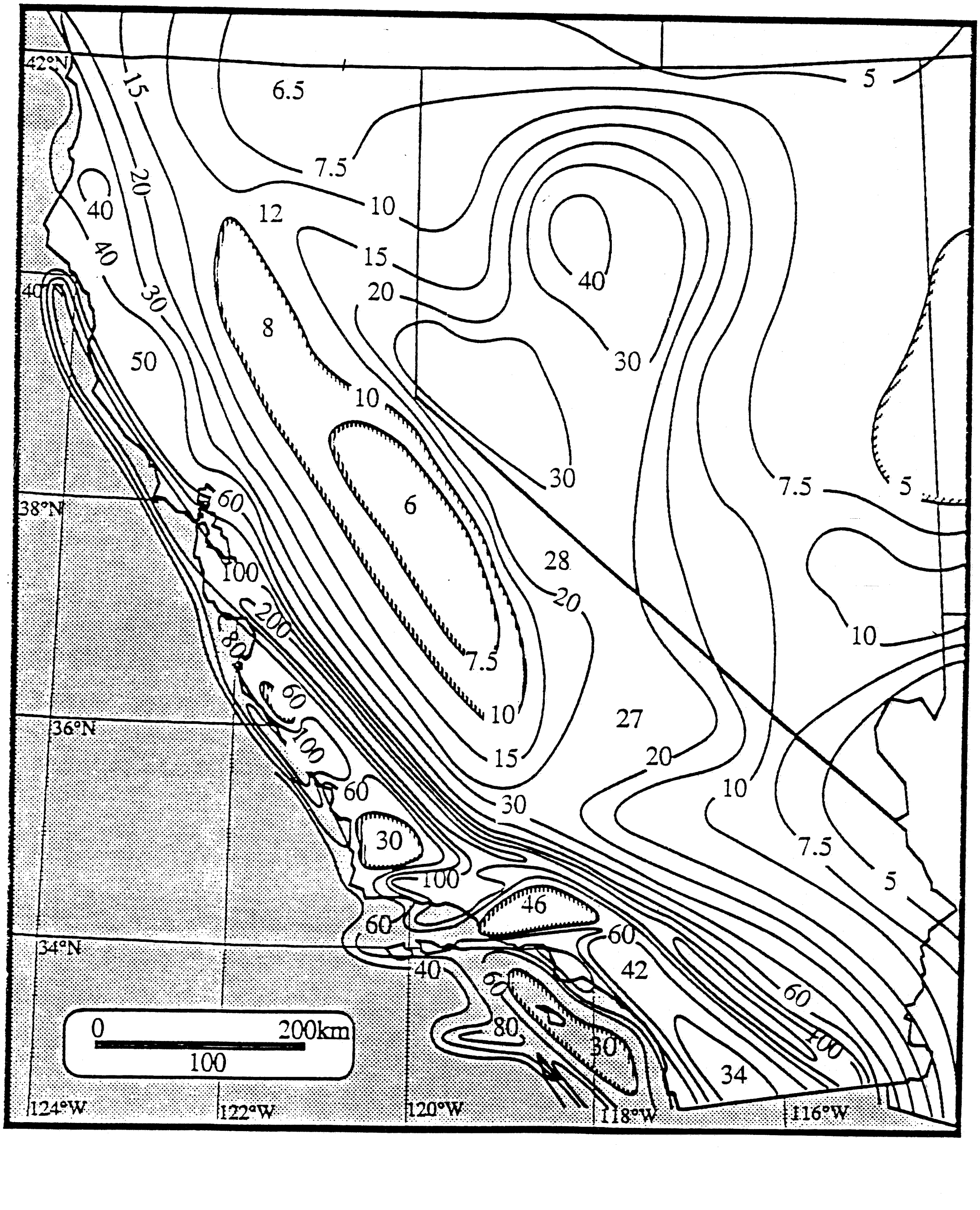


Fig. 27. Spectral response map of California showing acceleration (in % of g) for 0.3 s, 5% damping, with a 10% probability of exceedance in 50 years. Figure is taken from Algermissen and Leyendecker (1992).

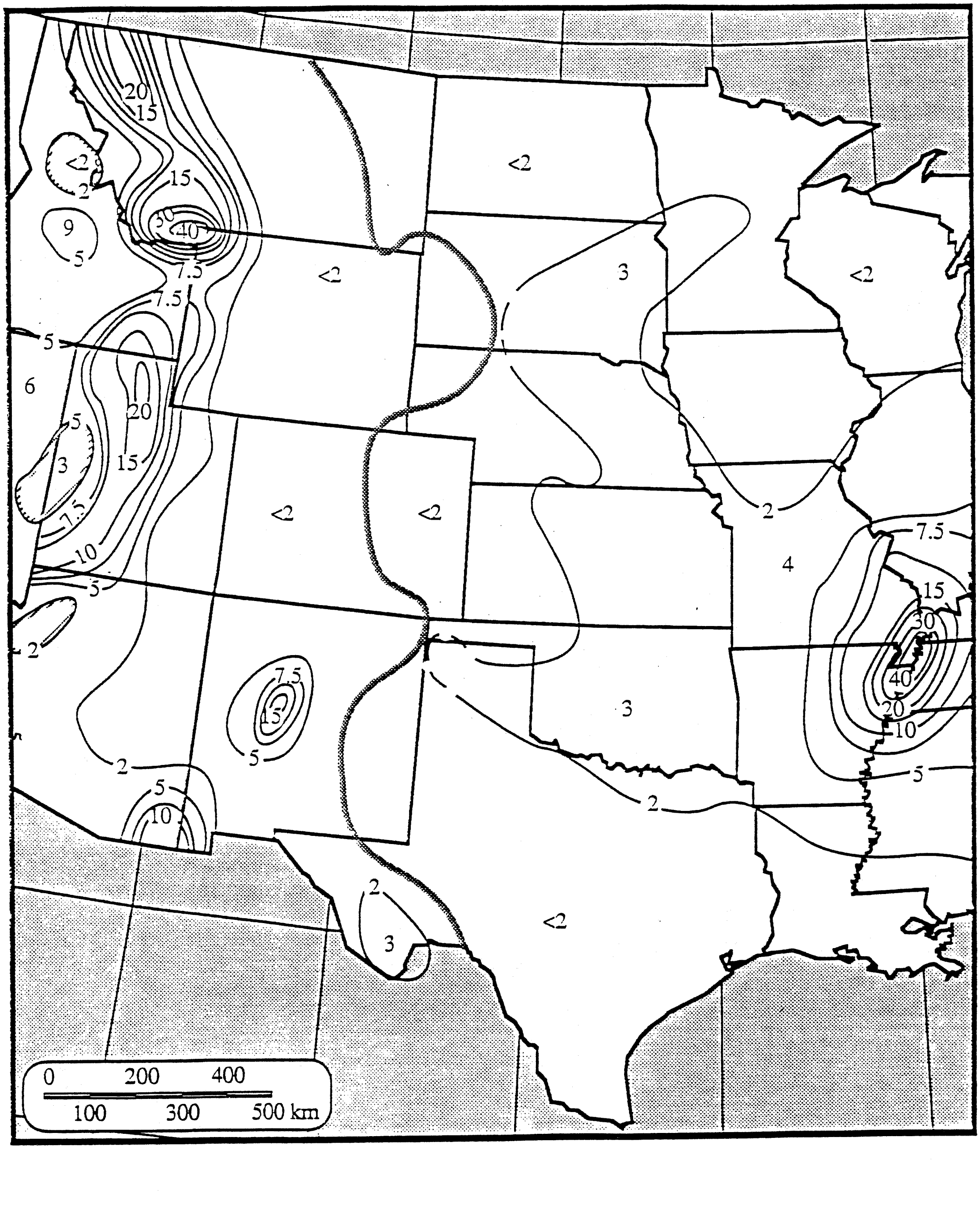


Fig. 28. Spectral response map of the western mountains and central plains of the United States showing acceleration (in % of g) for 0.3 s, 5% damping, with a 10% probability of exceedance in 50 years. Figure is taken from Algermissen and Leyendecker (1992).

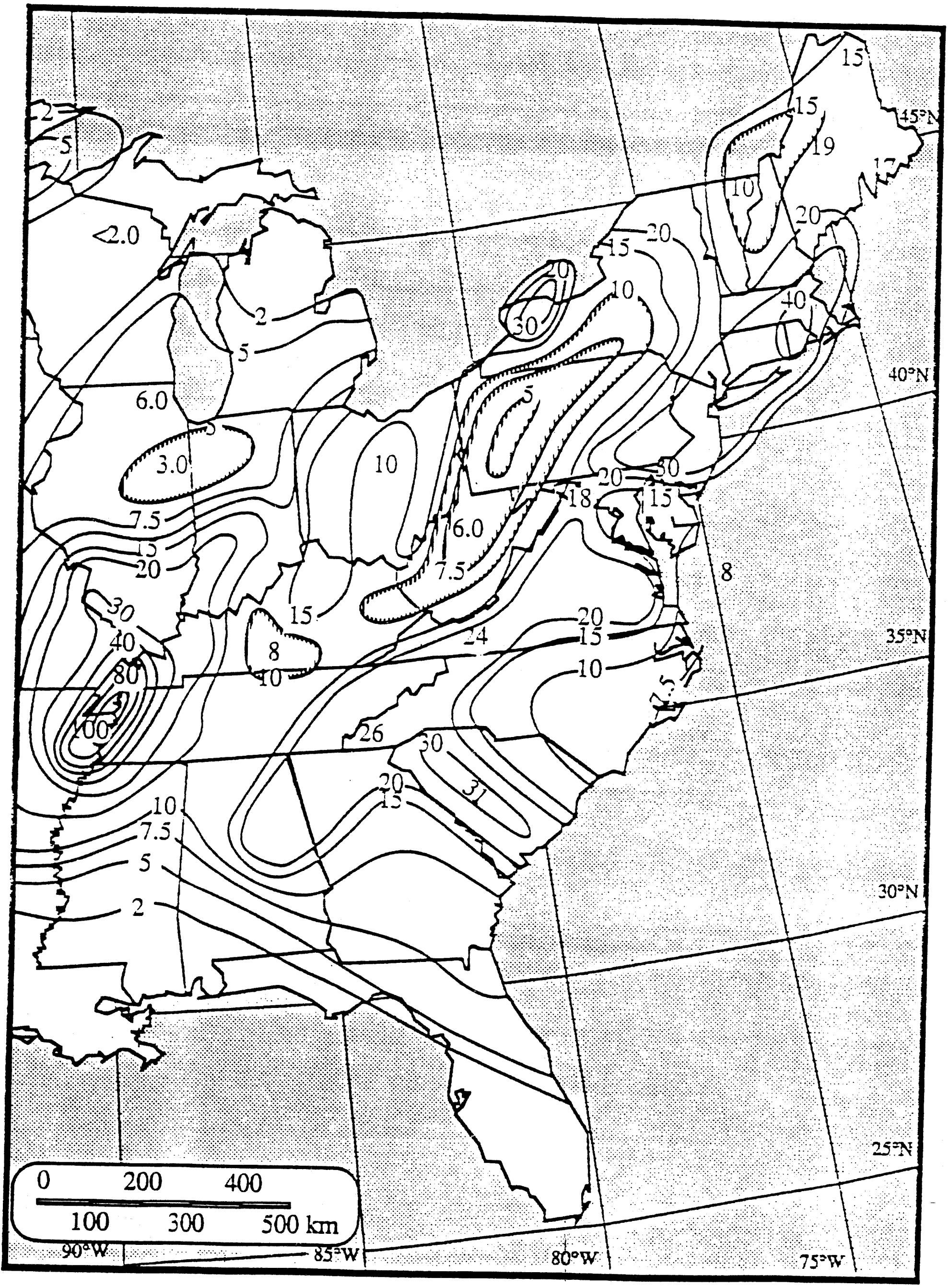


Fig. 29. Spectral response map of the Central and Eastern United States showing acceleration (in % of g) for 0.3 s, 5% damping, with a 10% probability of exceedance in 50 years. Figure is taken from Algermissen and Leyendecker (1992).

spectra «rollover» at periods of less than 0.5 s and cities in the Central and Eastern U.S., where the response is high at short periods.

This natural grouping and the impracticability of providing a separate map for each of the 12 spectral ordinates has resulted in the determination of generalized spectral shapes for use in map production (fig. 25). The short period portion of the acceleration response spectra is determined by the 0.3 s spectral ordinate and is constant. The varying, longer period portion of the spectrum is constructed by passing a curve with a slope of $1/T^{2/3}$ through the spectral response ordinate at a period of 1.0 s. As can be seen in fig. 25, this results in a conservative estimate of the complete spectral shape for the Western U.S. Note that this convention will result in underestimation of the spectral values in the short period for the Central and Eastern U.S.

Finally, all of the sources, zones, attenuation functions, response functions, etc., are combined to calculate uniform hazard spectral maps for the United States (fig. 26, 27, 28, and 29). Given the differences in the various inputs and functions discussed previously, it is simpler to produce regional maps, but these maps are smoothly concatenated to produce national maps (fig. 28).

Very detailed, site specific (local) hazard maps have been produced in urban areas and near power facilities throughout the United States. In most cases, these maps have been produced using the methods described above, but assuming specific, rather than generalized, parameter values and ground motion functions.

4. Summary

Earthquake hazard and risk mapping in the Americas is conducted at national, regional, and local scales using both probabilistic and deterministic methods. Probabilistic earthquake hazard and risk assessment estimates the probabilities of exceeding specified levels of a chosen ground motion parameter for specified exposure times. Deterministic or scenario earthquake hazard and risk assessment estimates the ground motion from a given earthquake, often the largest possible earthquake believed likely to occur within a specified region or on a specific fault. All probabilistic earthquake hazard and risk assessment involves four major steps: 1) determination of seismic sources and source zones; 2) determination of magnitude recurrence relations for each source or zone; 3) estimation of attenuation relationships for the ground motion parameter of interest and 4) summation of the probabilities (exceedances) from all source zones contributing to a given site (Cornell, 1968; Esteva, 1968). National seismic hazard assessment programs throughout the Americas involve these basic methods, differing primarily in the ground motion parameter mapped.

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