U. S. DEPARTMENT OF THE INTERIOR
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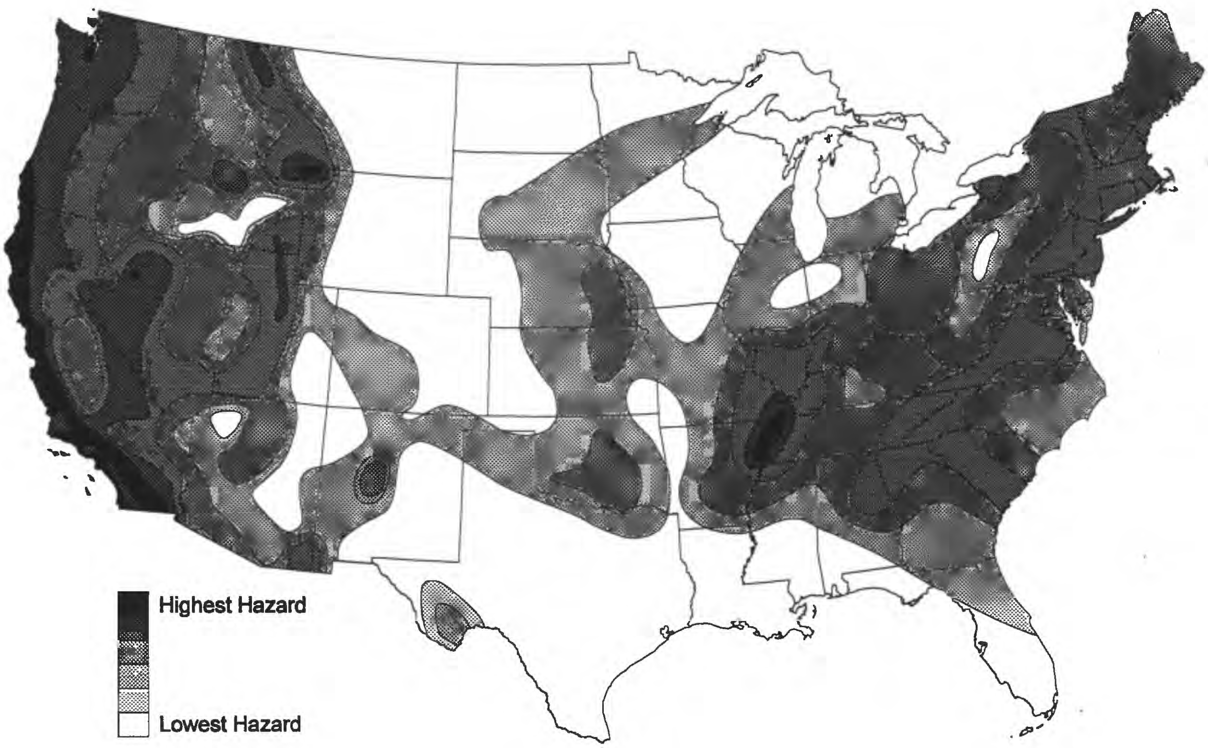
USGS SPECTRAL RESPONSE MAPS AND THEIR RELATIONSHIP WITH SEISMIC DESIGN FORCES IN BUILDING CODES



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This report is preliminary and has not been reviewed for conformity with U.S. Geological Survey editorial standards and stratigraphic nomenclature. Any use of trade, product or firm names is for descriptive purposes only and does not imply endorsement by the U.S. Government.

COVER: The zone type map is based on the 0.3 sec spectral response acceleration with a 10 percent chance of being exceeded in 50 year. Contours are based on Figure B1 in this report. Each zonal increase in darkness indicates a factor two increase in earthquake demand. The lightest shade indicates a demand < 5% g. The next shade is for demand > 10% g. Subsequent shades are for > 20% g, > 40% g, and > 80% g respectively.

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E. V. Leyendecker[1], D. M. Perkins[2],
S. T. Algermissen[3], P. C. Thenhaus[4], and S. L. Hanson[5]

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[1] Research Civil Engineer, U.S. Geological Survey, MS 966, Box 25046, DFC, Denver, C0, 80225
[2] Geophysicist, U.S. Geological Survey, MS 966, Box 25046, DFC, Denver, C0, 80225
[3] Associate and Senior Consultant, EQE International, 2942 Evergreen Parkway, Suite 302, Evergreen, CO, 80439 (with the U. S. Geological Survey during the time of the spectral response map preparation)
[4] Principal Geologist, EQE International, 2942 Evergreen Parkway, Suite 302, Evergreen, CO, 80439 (with the U. S. Geological Survey during the time of the spectral response map preparation)
[5] Computer Scientist, U.S. Geological Survey, MS 966, Box 25046, DFC, Denver, CO, 80225

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USGS SPECTRAL RESPONSE MAPS AND THEIR RELATIONSHIP WITH SEISMIC DESIGN FORCES IN BUILDING CODES

by

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Abstract

Seismic design forces in current United States building codes are effectively based on hazard maps that were included in the report *Tentative Provisions for the Development of Seismic Regulations for Buildings*, prepared by the Applied Technology Council (ATC). The ATC maps were derived from the 1976 U. S. Geological Survey (USGS) probabilistic acceleration map of the U. S., with some significant differences, including truncation of peak accelerations in the western U. S. and creation of "velocity-based" maps. In spite of the differences, the ATC maps are often referred to as USGS maps. Because the relationship between USGS maps and maps actually used in building codes is complex and often confusing to those not familiar with the code revision process, this report points out how USGS maps relate to maps in current building codes. It is shown that, although maps used in current editions of building codes have their origin in USGS maps, they are actually quite different and have not been updated in spite of the availability of later USGS maps developed since the mid-1970's.

Beginning in 1976 the USGS maps have taken the form of probabilistic maps of peak acceleration. New maps in 1982, 1988, and 1990 added maps of peak velocity to those of peak acceleration. Now maps of spectral response ordinates at natural periods of 0.3 and 1.0 seconds for a reference site condition (soil profile S_2) are available for the United States. The spectral response maps are for a 10 percent probability of exceedance for exposure times of 50 and 250 years (return periods of 474 and 2372 years). These maps are revisions of spectral response maps first prepared in 1991. The 1994 revision gives recognition to the increased likelihood of occurrence of large earthquakes on the Cascadia subduction zone. Both the 1991 and 1994 maps are included in this report.

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1 Research Civil Engineer, U.S. Geological Survey, MS 966, Box 25046, DFC, Denver, C0, 80225
2 Geophysicist, U.S. Geological Survey, MS 966, Box 25046, DFC, Denver, CO, 80225
3 Geophysicist, U.S. Geological Survey, MS 917, 12201 Sunrise Valley Drive, Reston, VA 22092
4 Principal Geologist, EQE International, 2942 Evergreen Parkway, Suite 302, Evergreen, CO, 80439 (with the U. S. Geological Survey during the time of this map preparation)
5 Computer Scientist, U.S. Geological Survey, MS 966, Box 25046, DFC, Denver, CO, 80225

The use of uniform-hazard spectra for design would offer a procedure that equalizes the hazard of design ground motion exceedance across all building periods for all regions of the country. However, it would be too cumbersome for building code purposes to require the large number of contour maps needed to define the complete response spectrum. Accordingly, an approximate uniform-hazard response spectrum requiring fewer maps is described in this report. The short-period response of the *approximate uniform-hazard response spectrum* is defined by the 0.3-second ordinate while response at longer periods varies as a function of the 1.0-second ordinate and the period, T. Selection of these mapped spectral-response ordinates is based, in part, on studies of complete uniform-hazard spectral response shapes (spectral ordinates for periods ranging from 0.05 sec to 4.0 sec) for selected cities in different seismic environments across the U.S. Results show that the *complete uniform-hazard response spectrum* can be approximated using the two mapped spectral values.

Possible equations for determination of a *design spectrum* based on the *approximate uniform-hazard response spectrum* are presented in the report. This *design spectrum* includes the site (geotechnical) properties and structural properties. The similarity of the design equations with those already in use in existing codes means that there would be little difficulty in adopting the proposed procedures.

Introduction

Seismic design in the United States is based in large part on one of the three model building codes - *National Building Code* (Building Officials and Code Administrators International, 1993), *Standard Building Code* (Southern Building Code Congress International, 1994), and the *Uniform Building Code* (International Conference of Building Officials, 1994) - and/or the national standard *ANSI/ASCE 7 - Minimum Design Loads for Buildings and Other Structures* (American Society of Civil Engineers Standard, 1994). Each of these documents is influenced to some degree by the *NEHRP (National Earthquake Hazard Reduction Program) Recommended Provisions for the Development of Seismic Regulations for New Buildings* (Building Seismic Safety Council, 1995) and *Recommended Lateral Force Requirements and Commentary* (Structural Engineers Association of California, 1990). These latter reports are referred to herein as the *NEHRP Provisions* and the *Lateral Force Requirements* (this report is also frequently referred to as the "Blue Book") respectively.

In response to expressed needs by the building code community, the USGS has prepared maps identifying the seismic hazard in the United States. Since 1976 these maps have taken the form of probabilistic maps. These maps express the earthquake hazard as a probability of exceeding a specific measure of ground motion in a specific time period. For example, the first such map (shown in Appendix A, Figure A.1) was for the 10 percent probability of exceeding the peak accelerations shown in a 50-year time period. In fact, all of the maps of seismic zones or ground motion in the current editions of the documents listed in the preceding paragraph originated, albeit with changes based on the approval process used by the preparing organizations, from the 1976 U. S. Geological Survey (USGS) map of peak ground acceleration.

It is important to be aware that the USGS maps are scientific documents that have undergone scientific review. On the other hand maps in building codes and standards are the result of a consensus process approved by the preparing organization. A map, or any other provision, that is submitted to a code or standards organization for approval may be quite different after it has gone through the organization's consensus process. Because the relationship between maps prepared by USGS and maps actually used in building codes and related documents is complex and often confusing, a section of this report traces the various maps prepared by USGS and points out how USGS maps relate to maps in current codes and related documents.

This report traces the development of probabilistic earthquake hazard maps by the USGS and their use in building codes and related documents, culminating in a series of uniform-hazard (equal probability) spectral response ordinate maps for natural periods of 0.3 and 1.0 seconds that are included in this report. The probabilistic maps are for a 10 percent probability of exceedance for exposure times of 50 and 250 years (return periods of 474 and 2372 years). These maps were originally prepared in response to requests and guidance from organizations such as the Building Seismic Safety Council, Structural Engineers Association of California, and the National Center for Earthquake Engineering Research. Examples of how the maps might be used in developing seismic design spectra for use in building codes are also included.

Use of Maps in Building Codes

Since the spectral response maps in this report are intended for building code use, it is worthwhile to briefly review the form of equations used in building codes. Prior to the development of probabilistic earthquake hazard maps, most codes used the concept of zones (e. g. the 1985 *Uniform Building Code*), and some still do (e. g. the 1994 *Uniform Building Code*). In the 1985 UBC each zone has a seismic coefficient associated with it, the higher the hazard, the larger the coefficient. The zone coefficients were used in the following equation:

$$V = ZIKCSW \tag{1}$$

where

V = total base shear or lateral force
Z = zone coefficient
I = occupancy importance factor
K = numerical coefficient related to structural properties
C = numerical coefficient
$= \dfrac{1}{15\sqrt{T}}$ but not to exceed 0.12
T = fundamental elastic period of vibration of the building in seconds
S = numerical coefficient for site-structure resonance
W = dead load as defined by the code

The numerical coefficient C may be referred to as the lateral force coefficient. The actual formulation for this coefficient has changed with different editions of the *UBC,* as well as other codes. The coefficient C for the 1985 UBC is shown in Figure 1. It may be seen that the coefficient is defined by a constant value at short building periods and a portion varying as a function of a constant and the building period, T, in the denominator raised to an exponent. The limit of 0.12 describes the coefficient for short period structures, while the variable portion of the equation describes the coefficient for buildings with longer periods. Although an approximation, for moment-frame structures the period is approximately the number of stories divided by 10. Thus a ten-story moment-frame building has a natural period on the order of 1 second.

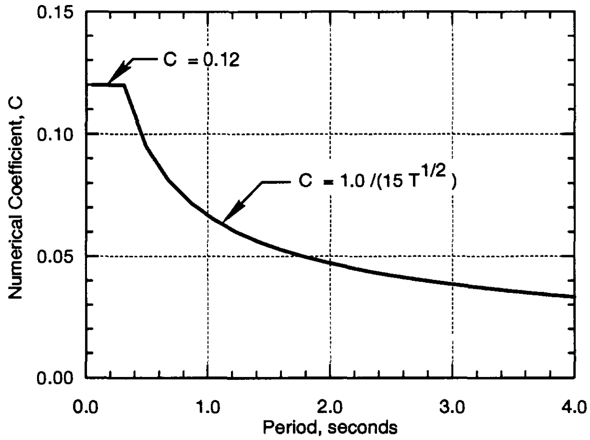


Figure 1. Variation of the lateral force coefficient with the building period in the 1985 *UBC.*

In 1985 the first edition of the *NEHRP Provisions* was published. One of the advantages of this document was that it used a more realistic measure of ground motion than earlier building codes. The form of the equation used in the *NEHRP Provisions* was

$$V = C_S W \tag{2}$$

where

V = total base shear or lateral force

C_S = seismic design coefficient

$$= \left(\frac{1.2}{T^{2/3}}\right)\left(\frac{A_v S}{R}\right) \leq \frac{2.5}{R}$$

T = fundamental period of of the building in seconds

A_v = seismic coefficient representing effective peak velocity-related acceleration

A_a = seismic coefficient representing effective peak acceleration

S = seismic coefficient for the soil profile characteristics

R = seismic response modification coefficient

W = total gravity load of the building as defined by the provisions

For ease in examining the form of the equation for C_s, all terms in the equation except T are taken as unity. The resulting equation is shown in Figure 2. Although the amplitudes in the Figures 1 and 2 are quite different, the shapes are similar. As in the case of the 1985 UBC, it may be seen that the coefficient is defined by a constant value at short building periods and a portion varying as a function of a constant and the building period, T, in the denominator raised to an exponent. The limit of 2.5 describes the coefficient for short period structures, while the variable portion of the equation describes the coefficient for buildings with longer periods. It is not appropriate to compare the numbers in the two figures since there are some other major differences (such as the K and R factors) between the 1985 UBC and the 1985 *NEHRP Provisions*. However it is clearer in the *NEHRP Provisions* that the design coefficients are closely related to building response. The *NEHRP Provisions* obtain a response spectrum by converting peak ground acceleration (A_a) to a spectral response value by multiplying by 2.5 (see the Commentary to the *Provisions*). A similar, but more complex series of calculations is done to convert the velocity to an acceleration-related coefficient and then to a spectral response value.

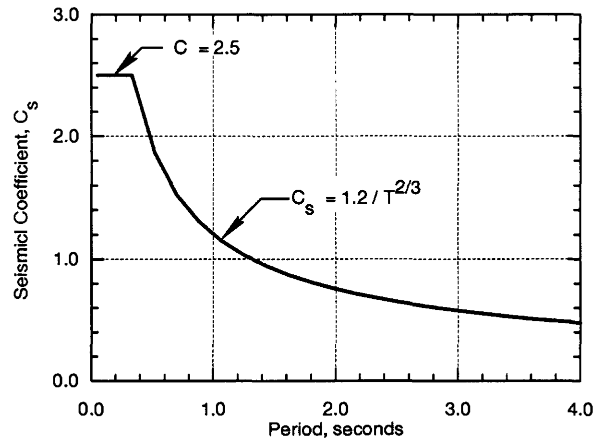


Figure 2. Variation of the lateral force coefficient with the building period in the 1985 *NEHRP Provisions*.

In 1988 the seismic provisions of the seismic design provisions of *Uniform Building Code* underwent a major revision. The form of the equation for the lateral force was changed to

$$V = \left(\frac{ZIC}{R_W} \right) W \tag{3}$$

where

V = total base shear or lateral force
Z = seismic zone factor
I = importance factor
K = numerical coefficient related to structural properties
C = numerical coefficient
$= \frac{1.25\ S}{T^{2/3}}$ but not to exceed 2.75
T = fundamental period of vibration of the building in seconds
S = site coefficient for soil characteristics
W = seismic dead load as defined by the code

Once again the numerical coefficient C in the *UBC* may be referred to as the lateral force coefficient. Although the 1985 UBC and 1988 UBC equations appear different they are actually similar except for amplitude. However, it is not appropriate to compare the numerical values of the coefficients, C, alone in the 1985 and 1988 codes since there were other fundamental changes as well. For example, the Z factors were changed. The coefficient C is shown in Figure 3 for the 1988 *UBC* (the same equation is in subsequent editions of the *UBC*). As in the case of the 1985 code, it may be seen that the coefficient is defined by a constant value at short building periods and a portion varying as a function of a constant and the building period, T, in the denominator raised to an exponent. The limit of 2.75 describes the coefficient for short period structures, while the variable portion of the equation describes the coefficient for buildings with longer periods. Comparisons of the equations in the 1985 NEHRP and the 1988 UBC shows that they are quite similar except that the short period values are slightly different (2.5 versus 2.75), and the coefficient with the building period is different (1.2 versus 1.25). These differences are primarily a result of the consensus processes required by the two organizations.

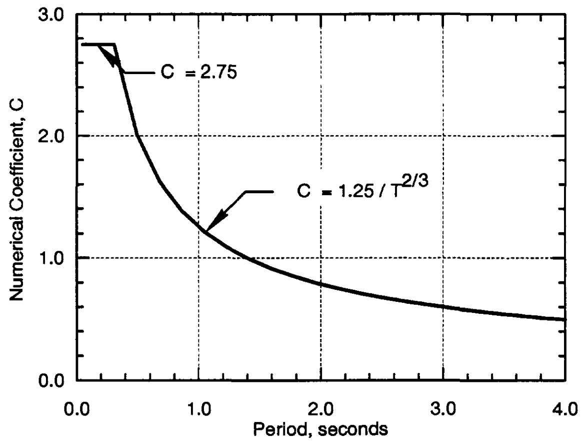


Figure 3. Variation of the lateral force coefficient with the building period in the 1988 *UBC*.

Thus the objective in the design process, regardless of the measure of ground motion, has been to obtain a *response* spectrum and modify it (by factors such as R) to obtain a *design* spectrum. Much of this process has involved both a *spectral shape* and *scaling factor* reflecting considerable judgement based on past performance of structural types to earthquakes. The use of spectral response maps, such those presented in this report, results in a *design* spectrum without so much dependence on judgement (the authors recognize that judgement can not and should not be eliminated). Intermediate steps such as that used in arriving at the 2.5 or 2.75 factors and applying them to peak values of ground motion to attempt to obtain a spectrum are bypassed.

Development and Use of Probabilistic Maps

As previously mentioned, the first U. S. national probabilistic map of peak ground acceleration was prepared by Algermissen and Perkins in 1976. This map, shown in Figure A1, is for a 50-year exposure time with a 10 percent probability of exceedance (474 year return period). During the time this map was being prepared, the Applied Technology Council (ATC), under contract with the National Science Foundation and the National Institute of Standards and Technology (then the National Bureau of Standards), was in the process of preparing a major set of new recommendations for seismic design of buildings. The final ATC report, *Tentative Provisions* *for the Development of Seismic Regulations for Buildings*, is often referred to simply as ATC 3-06 (ATC, 1978). The USGS, along with many other individuals and organizations, participated in this project and provided major input with its mapping effort. Using the map in Figure A1 as a starting point and responding to ATC committee input, the ATC prepared a map of "effective peak acceleration, A_a," (Figure A2). The A_a map differed from the USGS map with some shifting of contours and different contour intervals. However, perhaps the biggest difference between the two maps was the truncation of A_a at a maximum value of 0.4. Some of the rationale for the differences and a discussion of "effective peak acceleration" is in the commentary to the ATC report. Because of these differences, the ATC map is not a true probabilistic map, although it is frequently referred to as such.

The ATC approach to design required the use of two maps in order to develop response spectra. The acceleration map representative of short period structural response has been described. A second map of peak ground velocity representative of structural response for periods of one to two seconds was also needed. At the time of the project (in the mid 1970's) data were not available to prepare such a map with the same rigor as that used to prepare the 1976 USGS map of peak ground acceleration. Accordingly the ATC committee on ground motion used the A_a map and considerable judgement to develop an "effective peak velocity-related acceleration, A_v" map. This map is shown in Figure A3. The rationale and assumptions for this map are given in the commentary to the ATC report. Another very good explanation of the rationale is also available in ANSI A58.1 *Minimum Design Loads on Buildings and other Structures* (American National Standards Institute, 1982).

Although the contour maps shown in Figures A2 and A3 were available, the maps used in the ATC 3-06 design procedure were county-by-county maps. Each county in the U. S. was assigned a level of seismic hazard that was constant within a county. The general rule was that the highest contour in a county was the value assigned to the county. The contour maps themselves were in the commentary to the ATC 3-06 report.

It is important to recognize that the use of two maps in design and the development of the A_v map were major developments at the time of the ATC project. In fact this effort resulted in the 1985 *NEHRP Provisions* and the 1988 UBC revisions. However, it is also necessary to keep in mind that the A_v map was created from the A_a map using a simple set of rules. It was not a probabilistic map and did not have the same rigorous base in calculation as the 1976 USGS map. Accordingly, subsequent velocity-related maps developed with more rigor were bound to be different from the A_v map. The 1976 USGS and 1978 ATC mapping efforts are summarized in Appendix D, Table D1, along with the remainder of the developments in mapping in building codes and related documents that are described below.

In 1982 the American National Standards Institute (ANSI, 1982) revised its earthquake design requirements and included a zone map based on the ATC A_v map. In fact the map contours simply became zone boundaries and seismic design coefficients were assigned to the zones. For simplicity and to remain consistent with practice in model codes at the time, only one map (the more conservative of the A_a and A_v maps) was used in this national standard.

In 1982 the USGS published new peak ground acceleration maps using more detailed seismic sources incorporating more geological data. The number of maps was increased to include maps with exposure times of 10, 50, and 250 years for 10 percent probabilities of exceedance. New attenuation relations for peak ground velocity, not available for the 1976 effort, were devised in a manner analogous to that used for the acceleration attenuations, so that complementary acceleration and velocity maps could be prepared.

Also in the early 1980's the Building Seismic Safety Council (BSSC) was formed. With funding from the Federal Emergency Management Agency and technical assistance from the National Institute of Standards and Technology (then the National Bureau of Standards), the BSSC began a national effort to turn the ATC 3-06 report into a national consensus resource document available for use in improving seismic design practice across the United States. Once again, the USGS participated in the effort, along with numerous individuals and organizations. The result of the BSSC effort was the 1985 edition of the *NEHRP Provisions* (BSSC, 1986), a resource document for those preparing model codes or other design documents. The *NEHRP Provisions* was not intended to be, and is not, a model code. The report included the original ATC county-by-county maps as a measure of ground motion. However the contour versions of the A_a and A_v maps were moved from the commentary to the provisions and either set of maps was allowed in design. No substantial effort was made to include the new 1982 USGS maps, in part because the extent of the BSSC effort left insufficient time to consider the issue of new maps. Since BSSC anticipated an update on a three year cycle, time to evaluate the new USGS maps was considered available for the 1988 cycle.

In response to recommendations from the BSSC mapping committee, as part of the BSSC 1988 update, the 1982 USGS maps were recalculated to incorporate variability in attenuation and raise the minimum magnitude. A design procedure to use the revised USGS maps was also developed by a BSSC working group. In spite of this effort, the 1988 edition of the *NEHRP Provisions* (BSSC, 1989) continued to rely on the maps used in the 1985 edition of the *NEHRP Provisions*. The revised USGS maps and the tentative design procedure were included in an appendix to the provisions as an alternative design approach. The intent was that the approach in the appendix would receive trial use and evaluation so that it could be considered in the 1991 update of the *NEHRP Provisions*.

Also in 1988 the *Uniform Building Code* (UBC) included a major revision of its seismic design provisions based on recommendations of the Structural Engineers Association of California (SEAOC). The recommendations of the SEAOC have, since 1960, been the basis of the seismic design requirements in the *Uniform Building Code*. Since many of the SEAOC members participated in development of the ATC 3-06 report as well as in the on-going efforts of the BSSC, it is not surprising that the proposed design provisions to the 1988 UBC were similar to the ATC report and the 1985 *NEHRP Provisions*.

Since 1960 the SEAOC Seismology Committee had not been asked by the UBC code authorities to provide zone maps to accompany the recommended seismic design provisions. However, the code authorities would not consider the recommended design provisions for the 1988 edition without an accompanying map (E. Zacher, Brunnier Associates, oral and written communication, 1995). The SEAOC committee decided that, because of the extent of the changes to the design provisions, the mapping would retain zone boundaries rather than contours of ground motion. An effort was made by SEAOC to involve organizations across the U. S. to develop a map. As one of the organizations contacted, the USGS provided information and assistance. Structural engineering organizations and geological organizations in several states were also contacted. A series of zone maps were proposed by SEAOC with the input from organizations in Arizona, Idaho, Montana, Oregon, Utah, and Washington based on criteria indicated in the commentary (Appendix 1E2a-Z) to the SEAOC Recommended Lateral Force Requirements and Commentary (SEAOC, 1988). Different versions of a proposed map were published in *Building Standards* (ICBO, September-October, 1986; November-December, 1986; and July-August, 1987). The map in Figure A4 was one of the proposed maps (ICBO, November-December, 1986). Other versions of a zone map were also prepared at various stages of SEAOC Committee deliberations.

The map finally adopted for use in the 1988 UBC, Figure A5, was the result of action taken by ballot at the 65th Annual Education and Code Development Conference (September 20 - 25, 1987) of International Conference of Building Officials, publisher of the UBC. Note the differences between Figures A4 and A5, particularly in the zones in the western states.

In 1988 the American Society of Civil Engineers also published a revision of the 1982 ANSI standard as ANSI/ASCE 7 *Minimum Design Loads on Buildings and other Structures*. The 1988 ANSI/ASCE 7 standard reaffirmed the same zone map used in the 1982 ANSI Standard.

In 1990 the USGS published its most recent series of maps for peak ground acceleration and peak ground velocity (Algermissen and others, 1990). These maps had formerly appeared only in the 1988 *NEHRP Provisions*. Figure A6 shows one of the maps from the series, a map of peak ground acceleration for a 50 year exposure time with a 10 percent probability of exceedance (note that the contour intervals in Figure A6 differ from those in Figures A1 in order to provide maximum usefulness to organizations such as BSSC). Other maps available in the series are summarized in Table D1.

In 1990 the USGS started work on probabilistic spectral response maps as a result of requests from a number of interested groups such as the Structural Engineers Association of California (for example, Hays, 1989) and subcommittees of the BSSC. In 1991 a series of probabilistic spectral response hazard maps, suitable for building code and structural design application, was prepared for the conterminous United States (Building Seismic Safety Council, 1992; Algermissen and others, 1991; Algermissen and Leyendecker, 1992; and Leyendecker and others, 1994). The maps were originally prepared for possible use in the *1991 NEHRP Provisions* (BSSC, 1992) (hence the reference to them as the "1991 spectral ordinate maps") by the U.S. Geological Survey with significant input from the Subcommittee on Seismic Hazard Maps of the Building Seismic Safety Council and the Structural Engineers Association of California. The maps presented 5 percent damped uniform-hazard (equal probability) response spectral ordinates (for periods of 0.3 and 1.0 sec) for a reference site condition, soil profile S_2. This soil profile was defined in the *1991 NEHRP Provisions* as a "profile with deep cohesionless or stiff clay conditions where the soil depth exceeds 200 feet and the soil types overlying rock are stable deposits of sands, gravels, or stiff clays." The maps were for a 10 percent probability of exceedance for exposure times of 50 and 250 years (return periods of 474 and 2372 years). Methods for developing an approximate elastic uniform-hazard spectra from a selected number of spectral ordinates (0.3 and 1.0 sec) were described in Algermissen and others (1991), Algermissen and Leyendecker (1992), and Leyendecker and others (1994). However, the *1991 NEHRP Provisions* retained the A_a and A_v maps (both county-by-county and contour) as the basis for design. The spectral maps and procedures for using them in design were placed in an appendix. The reason for including the maps in an appendix was, once again, to encourage examination and trial use of the proposed procedures for the purpose of evaluation. Since the spectral response maps were considered superior to use of peak ground motion for design, the 1988 appendix using peak acceleration and velocity was deleted.

In 1994 the spectral ordinate maps were revised for inclusion in the *1994 NEHRP Provisions* (BSSC, 1995) (hence the reference to them as the "1994 spectral ordinate maps") to reflect increased likelihood of the hazard in the Pacific Northwest from the Cascadia subduction zone. Although the BSSC conducted an intensive study of the use of the spectral maps, consensus could not be reached on using the maps as a recommended procedure. As a consequence, the revised spectral ordinate maps were included in the commentary to the report, along with a number of other proposed maps. In contrast to the 1991 *NEHRP Provisions, no procedure for using the maps was included.* The *1994 NEHRP Provisions* (BSSC, 1995) continue to use the A_a and A_v maps (county-by-county and contour versions) but with some cautionary notes that the hazard may be underestimated in some areas.

The most recent *UBC* (ICBO, 1994) uses the zone map shown in Figure A7, a map similar to the one adopted in 1988 but with some changes to reflect a change in Arizona and to reflect concerns that the earthquake hazard was greater in the northwest than indicated in the 1988 map. The *1993 National Building Code* (BOCA, 1993) uses the A_a and A_v contour maps (county boundaries are shown as well as state boundaries) from the *1991 NEHRP Provisions* with interpolation points added to the maps. The *1994 Standard Building Code* (SBCCI, 1994) also uses the A_a and A_v contour maps from the *1991 NEHRP Provisions* (county boundaries are not shown because of the small page format in this report). The 1994 ASCE 7 standard uses two contour maps based on A_a and A_v but differing somewhat with different contours in the northwest and additional contours in the central U. S. and the northeast. The modified maps for A_a and A_v used in this standard are shown in Figures A8 and A9 respectively.

A major effort was initiated by the USGS in 1994 to review the basis of the seismic hazard maps with the plan of issuing a new set of maps in 1996. This effort includes conducting a series of regional workshops to seek the best possible seismological and geological input in developing new maps. This series of workshops has resulted in new approaches to developing the maps. Additionally, USGS is cooperating with the Applied Technology Council as a mechanism to obtaining input from those that use the maps. USGS is also cooperating with the Building Seismic Safety Council in a project (Project 97) to revise the maps in the *NEHRP Provisions* for the 1997 edition. These efforts have been described by Frankel and others (1994) and by Frankel (1995).

Selection of Spectral Response Ordinates

The use of two spectral-response ordinates to approximate a uniform hazard spectrum is based on a study of uniform-hazard spectra for selected cities in the U. S. Hazard analyses were performed for twelve cities in the U.S. : San Francisco, Oakland, Los Angeles, San Diego, Salt Lake City, Memphis, St. Louis, Chicago, New York City, Charleston, and Seattle (Figure 4). Limited analyses were done for about 30 additional cities. The cities were selected because they have different hazard levels (Algermissen and others, 1990) and, because of their locations, different attenuation functions are used in the determination of ground motion.

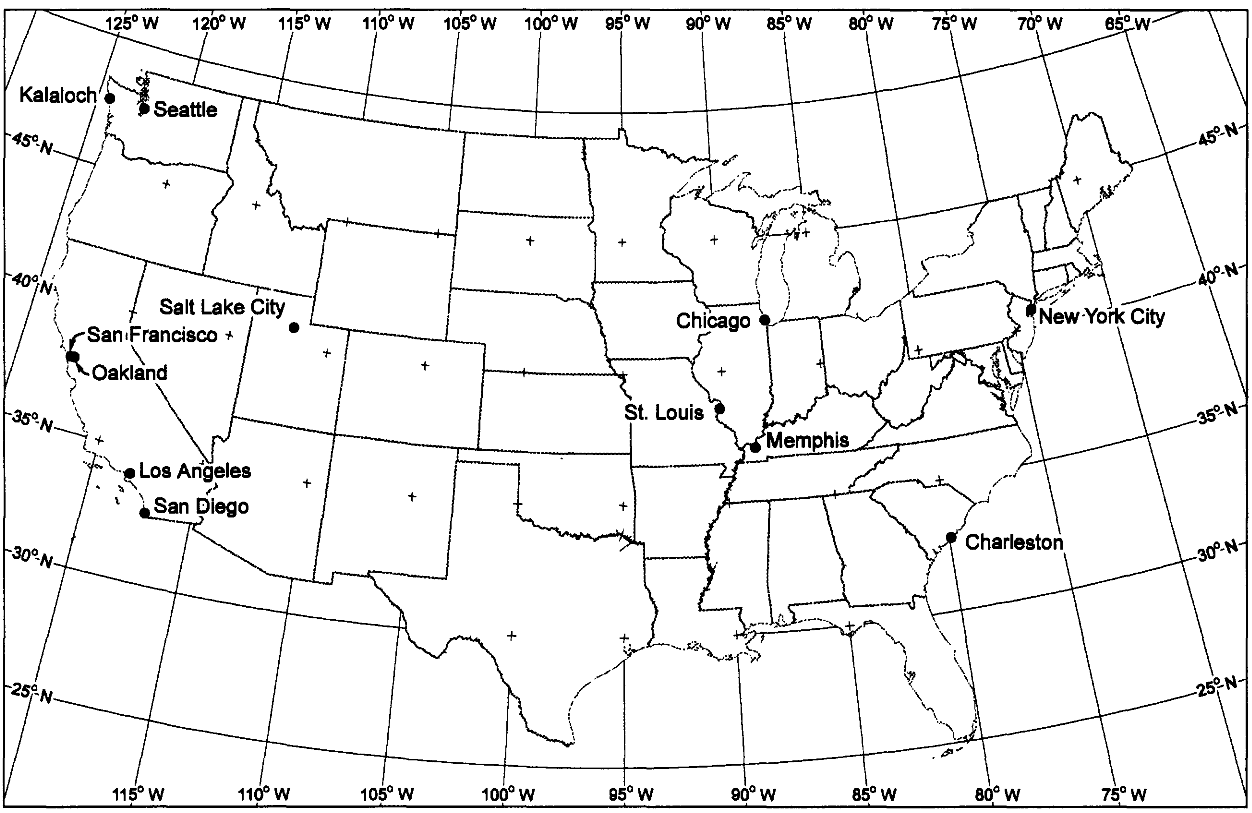


Figure 4. Location of twelve cities used to study spectral shapes.

The shapes of the spectral response curves were studied for the cities using the spectral ordinates available from the attenuation functions. Twelve ordinates were used for the western U. S. (Joyner and Boore, 1982) and thirteen ordinates were used for the eastern U. S. (Boore and Joyner, 1991). These spectra for 5 percent damping are shown in Figure 5, normalized to unity at a period of 0.3 sec by dividing each ordinate by the spectral ordinate at 0.3 second. It is clear that the spectral shapes fall into two groups, those with a high short-period response and those with a gradual rollover at short periods. The two spectral shapes are primarily influenced by the characteristics of the attenuation functions and the earthquake rates in the seismic source zones. Based on examination of the curves in Figure 5, the remaining discussion takes San Francisco as typical of cities whose spectral shape has a gradual rollover at short periods, and Memphis as typical of cities whose spectral shape has a high response at short periods. Other cities could just as readily have been selected. It is important to discuss the two characteristic spectral shapes because the shapes influence the selection of the spectral ordinates for mapping and the possible design equations that are discussed later.

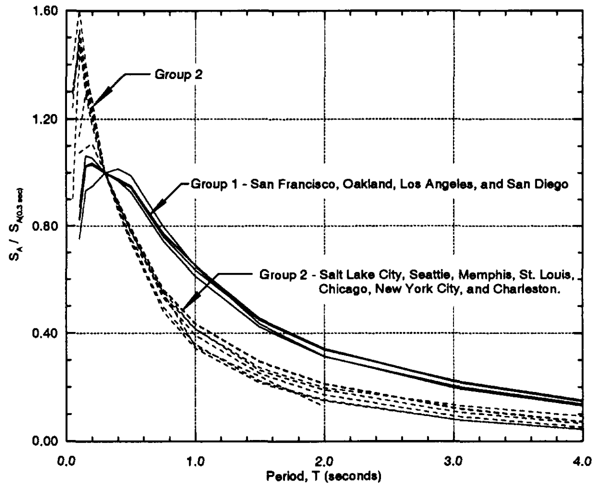
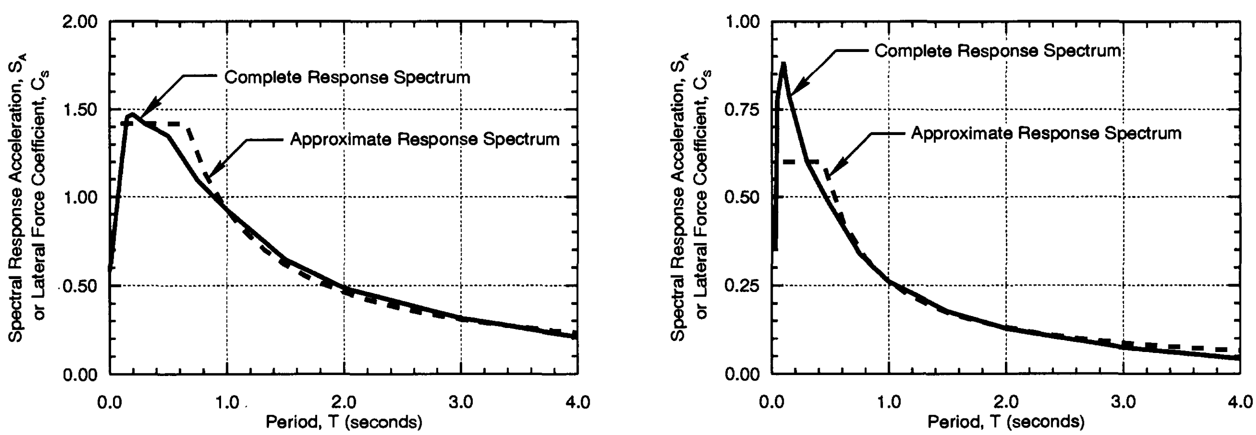


Figure 5. Normalized response spectra for 5 percent damping for an exposure time of 50 years with 10 percent probability of exceedance.

The non-normalized spectra for San Francisco are shown in Figure 6a to illustrate more clearly the short-period response in the spectral shape. Two curves are shown in the figure: (1) a *complete response spectrum* using all ordinates of the attenuation function and (2) an *approximate response spectrum.* The procedure for arriving at the latter spectrum is discussed below. In the case of Memphis, Figure 6b, the *complete response spectrum* has a sharp peak at relatively short periods as compared to that for San Francisco.



(a) San Francisco (a) Memphis

Figure 6. Comparison of complete and approximate response spectrum for two cities representative of Groups 1 and 2. S_A is in units of a fraction of gravity.

The *approximate response spectra* shown in Figure 6 were obtained using only the spectral ordinates at 0.3 and 1.0 seconds, as illustrated in Figure 7. The shape of the approximate response spectra exploit the common features of design spectra seen in Figures 2 and 3 – a flat short period region and a region dependent on the period. The short-period response is defined by the 0.3-second ordinate. Response at longer periods varies as a function of the 1.0-second ordinate and the period, T, as shown. The constant k is equal to 1 sec. An *approximate response spectrum* is developed simply because it would be too cumbersome for building code purposes to require use of the large number of contour maps needed to define the *complete response spectrum*. As was shown in Figure 6, the *approximate response spectrum* is a good representation of the *complete response spectrum* for the two spectral shapes in the region of most structural interest. However, the selection of 0.3-second was an attempt to balance the design value that would be a good index of damage potential to short stiff buildings. While there is little difference for Group 1 cities, the difference would be large if another value, such as the 0.2-second ordinate, had been selected for the Group 2 cities. This is an issue worth further discussion by users. Another period could have easily been selected and mapped.

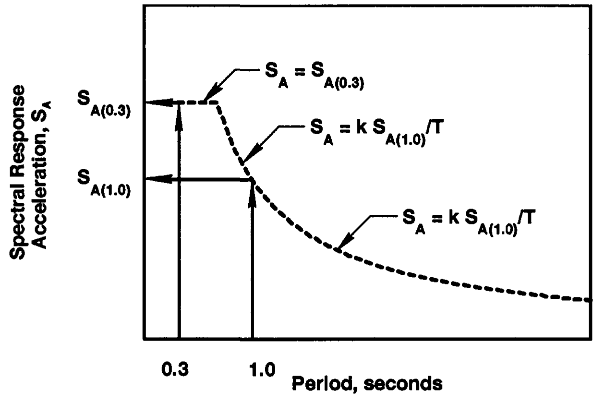


Figure 7. Determination of 5 percent damped elastic response spectrum.

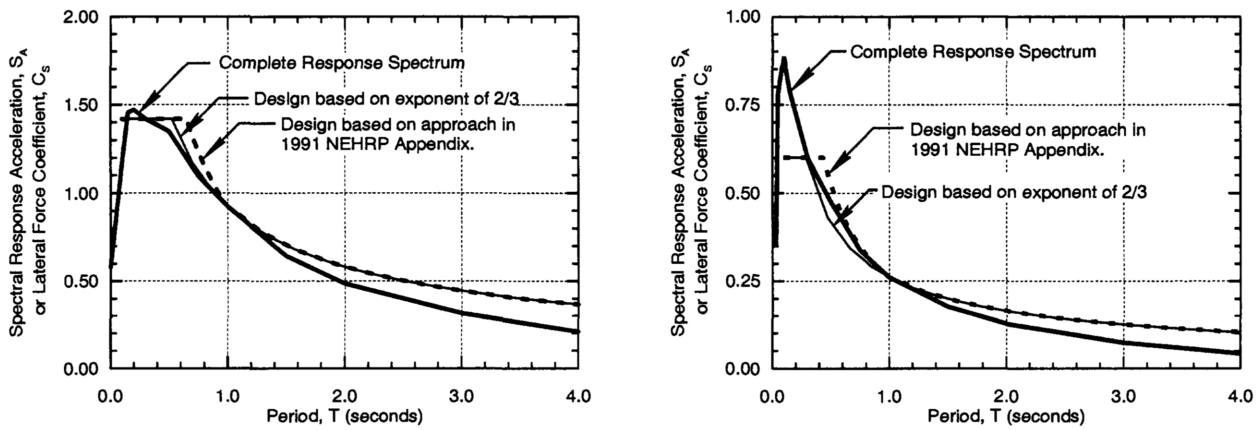
Spectral Ordinate Maps

The USGS has prepared three successors to the 1976 map of peak acceleration including adding velocity maps, as well as producing two new series of spectral response acceleration maps. The two series of spectral response acceleration maps are included with this report. The most recent series referred to as the "1994 spectral ordinate maps" are in Appendix B. The other series is referred to as the "1991 spectral ordinate maps" and is in Appendix C. Except for some differences in the northwest (described later), the basic description of the two series is the same. Both contain uniform-hazard (equal probability) spectral response ordinates at natural periods of 0.3 and 1.0 seconds for a reference site condition (soil profile S_2). The probabilistic maps are for a 10 percent probability of exceedance for exposure times of 50 and 250 years (return periods of 474 and 2372 years). These maps were originally prepared for the 1994 and 1991 editions, respectively, of the *NEHRP Recommended Provisions for the Development of Seismic Regulations for New Buildings.* The 1994 revision gives increased recognition to the likelihood of occurrence of a large earthquakes on the Cascadia subduction zone.

The spectral ordinate maps in the appendices are for horizontal spectral response acceleration with 5 percent damping for periods of 0.3 sec and 1.0 sec for a reference site condition of soil. The probabilistic maps are for a 10 percent probability of exceedance for exposure times of 50 and 250 years (return periods of 474 and 2372 years). There are eight maps in each appendix. Four maps are for the 48 contiguous states and four maps are for California and Nevada. The latter four maps were prepared because the contour density in California makes it difficult to read them on a map of 48 states. Of the four maps two are for 50 year exposure times and two are for 250 year exposure; each of the exposure times has a 0.3 sec and 1.0 sec spectral ordinate map. The hazard model, source zones, and attenuation equations for ground motion are included in Appendix D. This material has been included in the appendix since thorough descriptions are available elsewhere.

Development of Design Spectra

A *design spectrum* is required for use in building codes. This spectrum needs to consider the site (geotechnical) properties, denoted by S, and properties of the structure, denoted by R. Traditionally, design values have also provided additional safety for longer-period structures. This is accomplished in current codes by using an exponent of $-2/3$ instead of -1.0 on the building period, T, outside the short period response region (flat portion of the approximate response spectrum). Two forms of a design equation were considered and compared to complete response spectra for cities typical of the two characteristic spectral shapes (San Francisco and Memphis), as shown in Figure 8. Both S and R are taken as unity in Figure 8 for the purpose of comparison with



(a) San Francisco (b) Memphis

Figure 8. Comparison of complete response spectra for two cities representative of Groups 1 and 2 with two forms of a design equation. S_A of a fraction of gravity.

the response spectrum. The first equation, based on an exponent of $-2/3$ on the period T and passing through the 1.0 sec ordinate, is about the same as current design practice. However, it was found in studying the shapes in Figures 8 that such an approach caused the design spectrum to result in values below the complete response spectrum for periods smaller than 1.0 second for spectral shapes in Group 2 (represented by Memphis in Figure 8b). Accordingly, a second equation was examined that consists of three segments, the constant short period region defined by the 0.3-second ordinate, a region varying as 1/T, and a region varying as $1/T^{2/3}$. This form is shown in Figure 10 and was considered satisfactory for both characteristic spectral shapes in Figure 8. It should be noted here that modification of the exponent on T from -1.0 to some other value, such as $-2/3$ in current use, has no particular technical basis (Algermissen and Leyendecker, 1992). It is based on the desire to provide additional safety in the design of buildings with longer periods (BSSC, 1995).

As a result of the above evaluation, the proposed form for the design equation shown in Figure 9 was included in the 1991 *NEHRP Provisions* for trial use. This is simply the approximate spectrum incorporating an S factor to account for site effects and an R factor, termed a response modification factor. The R factor incorporates construction material type and structural-behavior effects. Inclusion of the exponent of −2/3 on the period T was patterned after current practice in the *NEHRP Provisions* and the model codes.

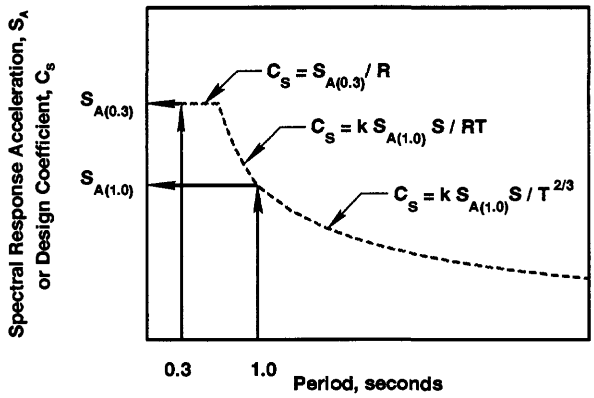


Figure 9. Proposed design equation.

Truncation

Current code practice allows truncation of the short-period response at a so-called effective peak acceleration of 0.4 g. This is roughly equivalent to a spectral response value of 1.0 g, obtained by multiplying the peak value by 2.5 as is done in the *NEHRP Provisions*. The effect of truncation in regions of high ground motion can be significant as may be seen in Figure 10 where San Francisco is used as the basis for comparison. The justification for truncation used by many designers is that the use of stringent ductile detailing requirements in current codes result in a structure that can absorb energy from the larger ground motions and thus it is not necessary to design for the larger ground motions. Further discussion of the rationale for and against truncation, or a specific value for truncation, is not possible in this paper, It is, however, an issue that needs to be considered in formulating code requirements. It may also be seen in the figure that the difference in lateral force coefficients between the requirements in the appendix and the main body of the *NEHRP Provisions* are minor when truncation is considered. On the other hand, when truncation is used the result is a poor approximation to the uniform hazard spectrum.

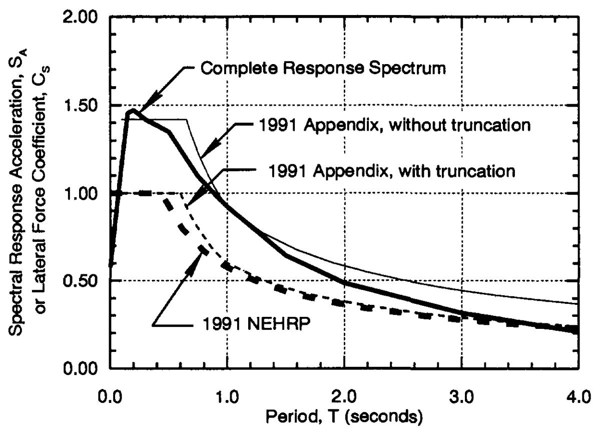


Figure 10. Comparison of response spectrum with design curves for San Francisco. S_A is in units of a fraction of gravity.

Truncation Multiplier

As mentioned earlier, the NEHRP Provisions use a multiplier of 2.5 applied to the effective peak ground acceleration to obtain the maximum value of the lateral force coefficient, which is applicable to short period structures. The UBC uses a multiplier of 2.75 for the same purpose. Neither document rigorously explains the origin of the multiplier. The difference between the two documents is pointed out since the direct use of probabilistic spectral ordinates to obtain a value of the lateral force coefficient circumvents arguments on the appropriate value for such a multiplier.

Conclusions and Future Plans

The spectral-ordinate maps discussed here provide an important new tool for the development of elastic response spectra for structures. It has been shown that these maps may be used to closely approximate a complete response spectrum for different areas of the U.S. Design equations based on using the spectral-ordinate maps have been proposed. The use of spectral maps appears to bypass such issues as the appropriate multiplier to convert peak ground acceleration or velocity to spectral values. It also directly addresses the well-known argument that peak values of ground motion are relatively poor measures of structural behavior. Finally, use of spectral values filters out the possible undue influence of large high-frequency spikes in measured ground motion. This examination of use of spectral ordinate maps in simple design equations shows that the equations appear to provide reasonable approximate uniform-hazard elastic response spectra when compared to the complete response spectra. While issues such as truncation need to be addressed, it appears possible to incorporate such issues in the design procedure in a straightforward manner.

It is recognized that the site classifications have been changed since this study of spectral shapes was done. Different site factors are now applied to the two ground motion parameters (BSSC, 1995). Since these are new factors, the influence of their use should be carefully examined prior to adoption in building codes. It is also recognized that attenuation functions are being revised in light of recent data (for example, Boore and others, 1993). There are also anticipated changes in direction of the USGS seismic hazard mapping program (Frankel and others, 1994 and Frankel, 1995). These current efforts will be considered in the new USGS national maps anticipated in 1996. Frankel (1995) has described the newmodel that will be used. In addition to spectral ordinates, the new series of maps will include peak ground acceleration for the convenience of those requiring such a map.

Acknowledgments

The authors wish to thank Erdal Safak and Edwin Zacher for their thoughtful reviews of this report. In particular, the first author wishes to thank Mr. Zacher for his time during their discussions with regard to the SEAOC activities in preparing a zone map for the 1988 Uniform Building Code.

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APPENDIX A - USGS PEAK GROUND MOTION MAPS AND MAPS IN BUILDING CODES AND RELATED DOCUMENTS

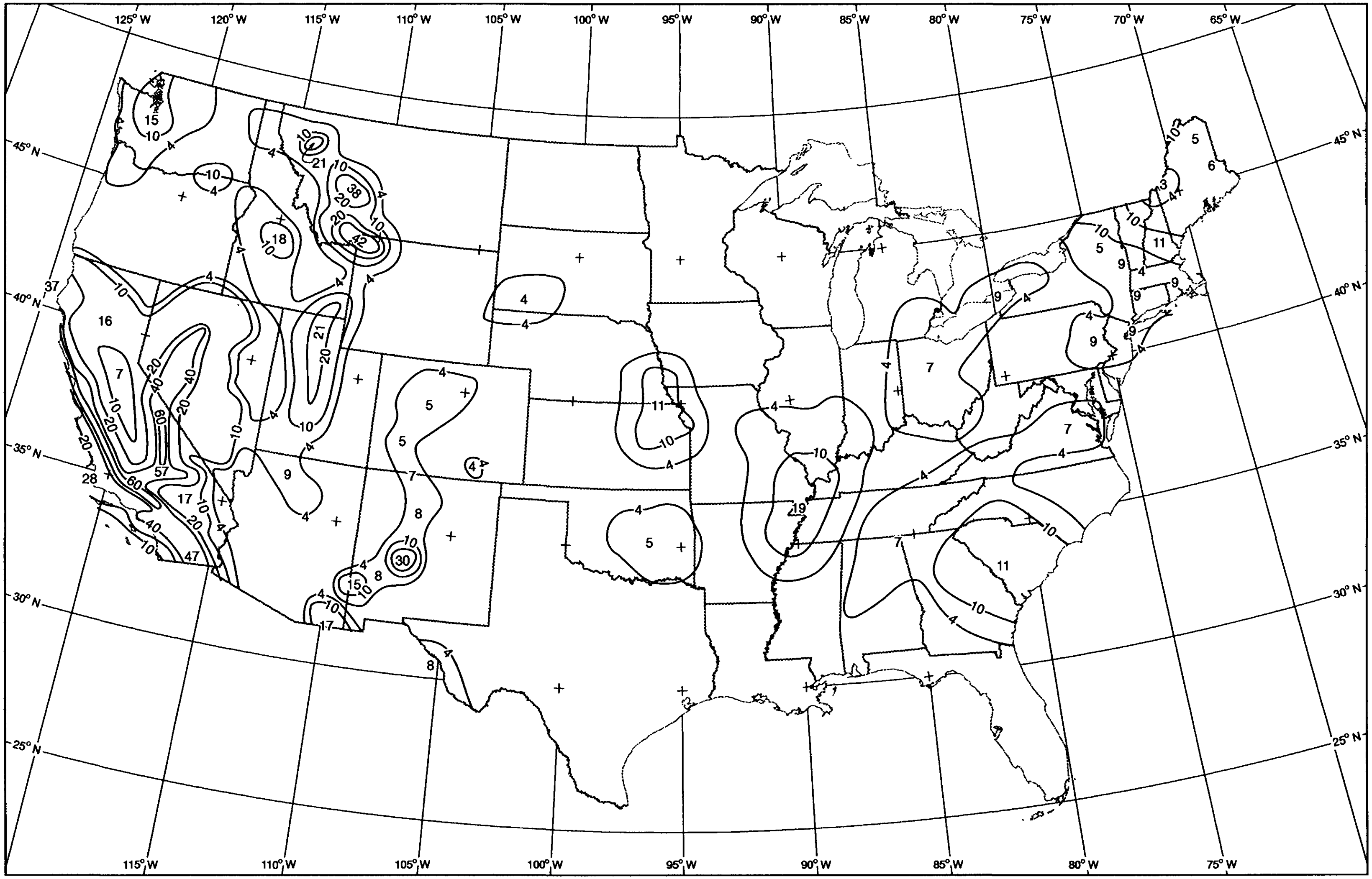


Figure A1. 1976 Contour map for peak horizontal acceleration (expressed as percent of gravity) in rock with 90 percent probability of not being exceeded in 50 years. The maximum acceleration within the 60 percent contour along the San Andreas and Garlock faults in California is 80 percent of gravity. After Algermissen and Perkins, 1976.

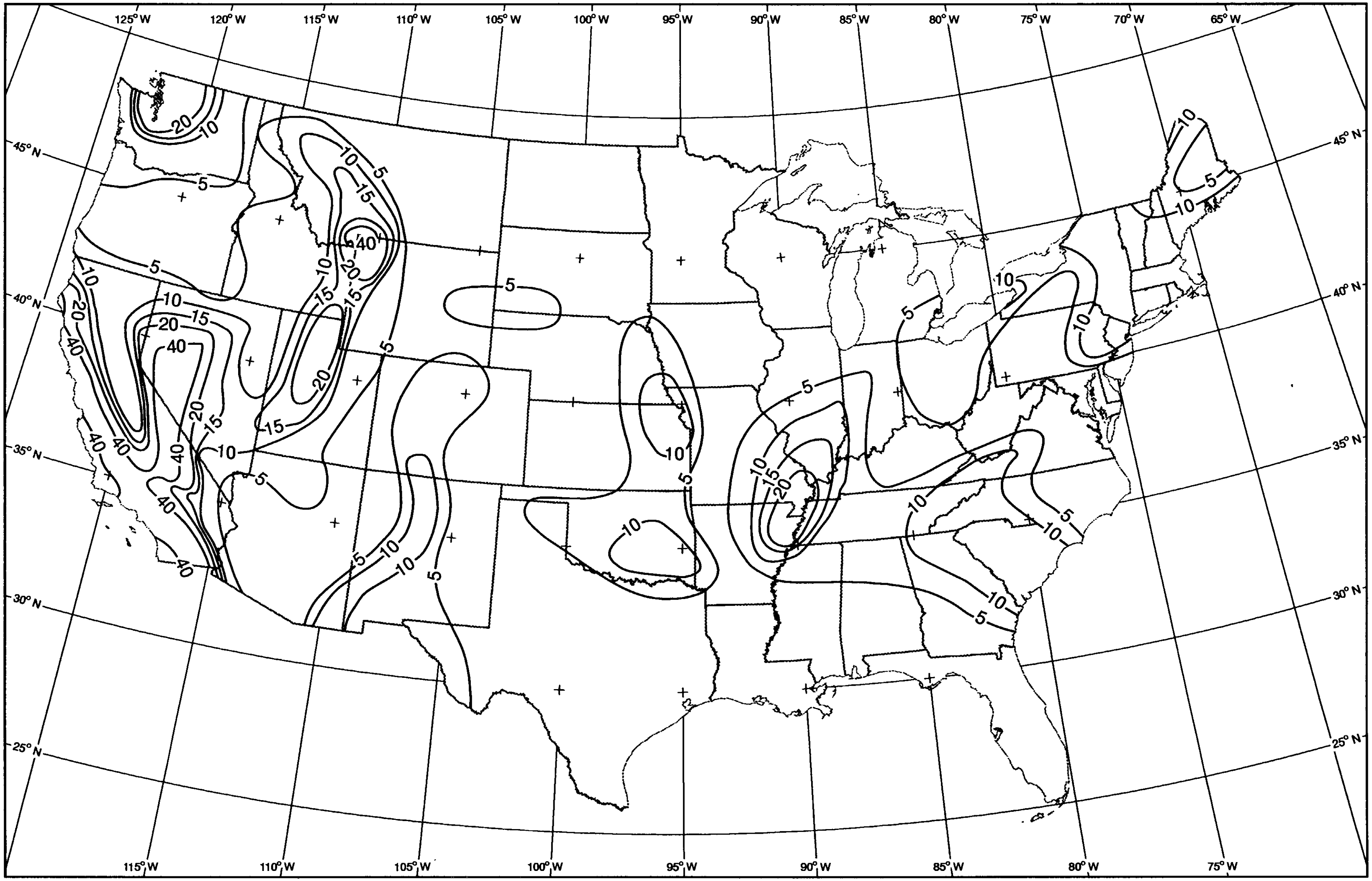


Figure A2. Contour map for effective peak accleration (EPA) coefficient, A_a, for the continental United States. The units of EPA are expressed as a percent of gravity. After BSSC, 1995 (This map was redrawn from the original source, if differences occur, the original source should be used).

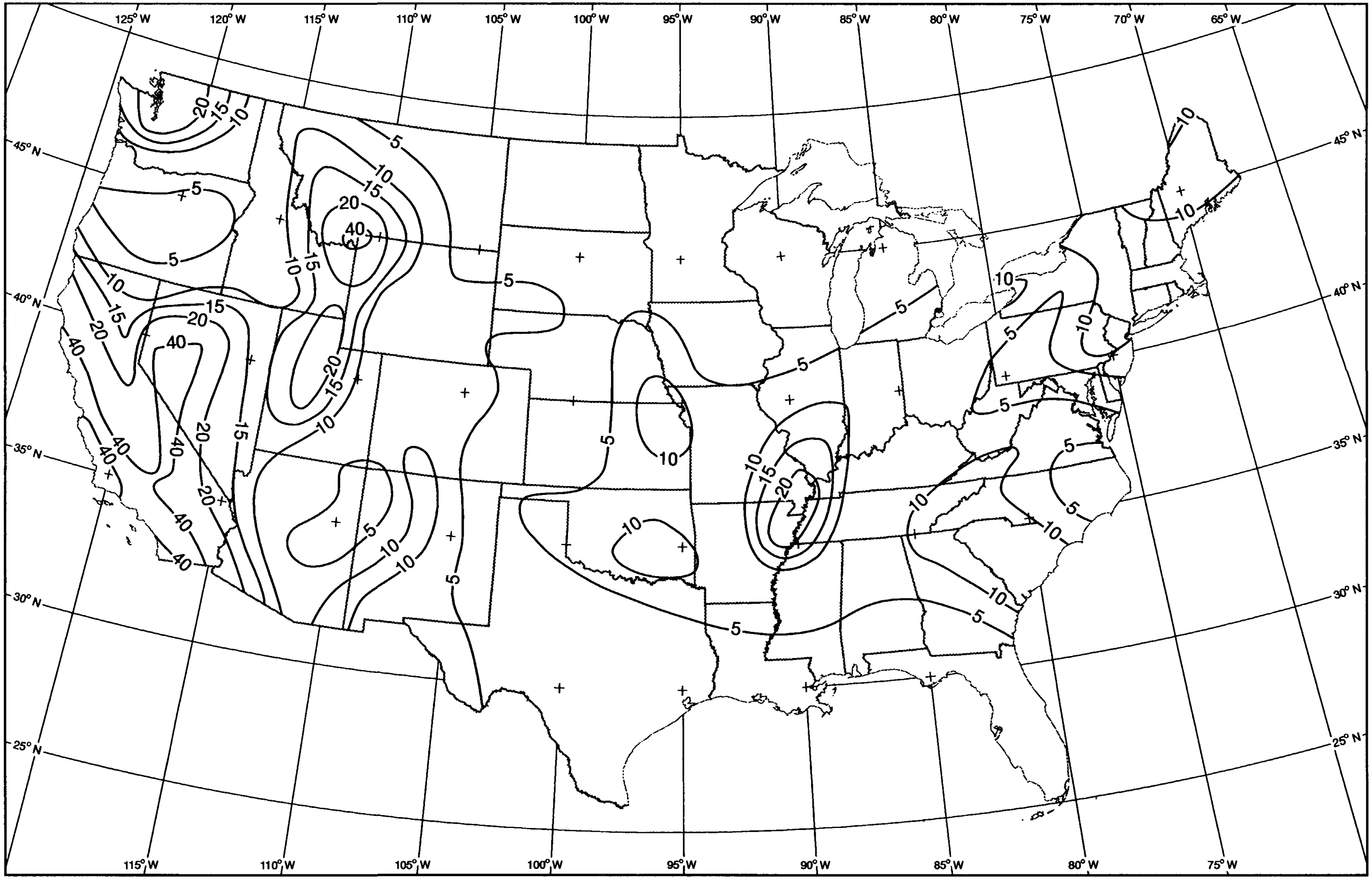


Figure A3. Contour map for effective peak velocity-related accleration (EPV) coefficient, A_v, for the continental United States. The units of EPV are expressed as a percent of gravity. After BSSC, 1995 (This map was redrawn from the original source, if differences occur, the original source should be used).

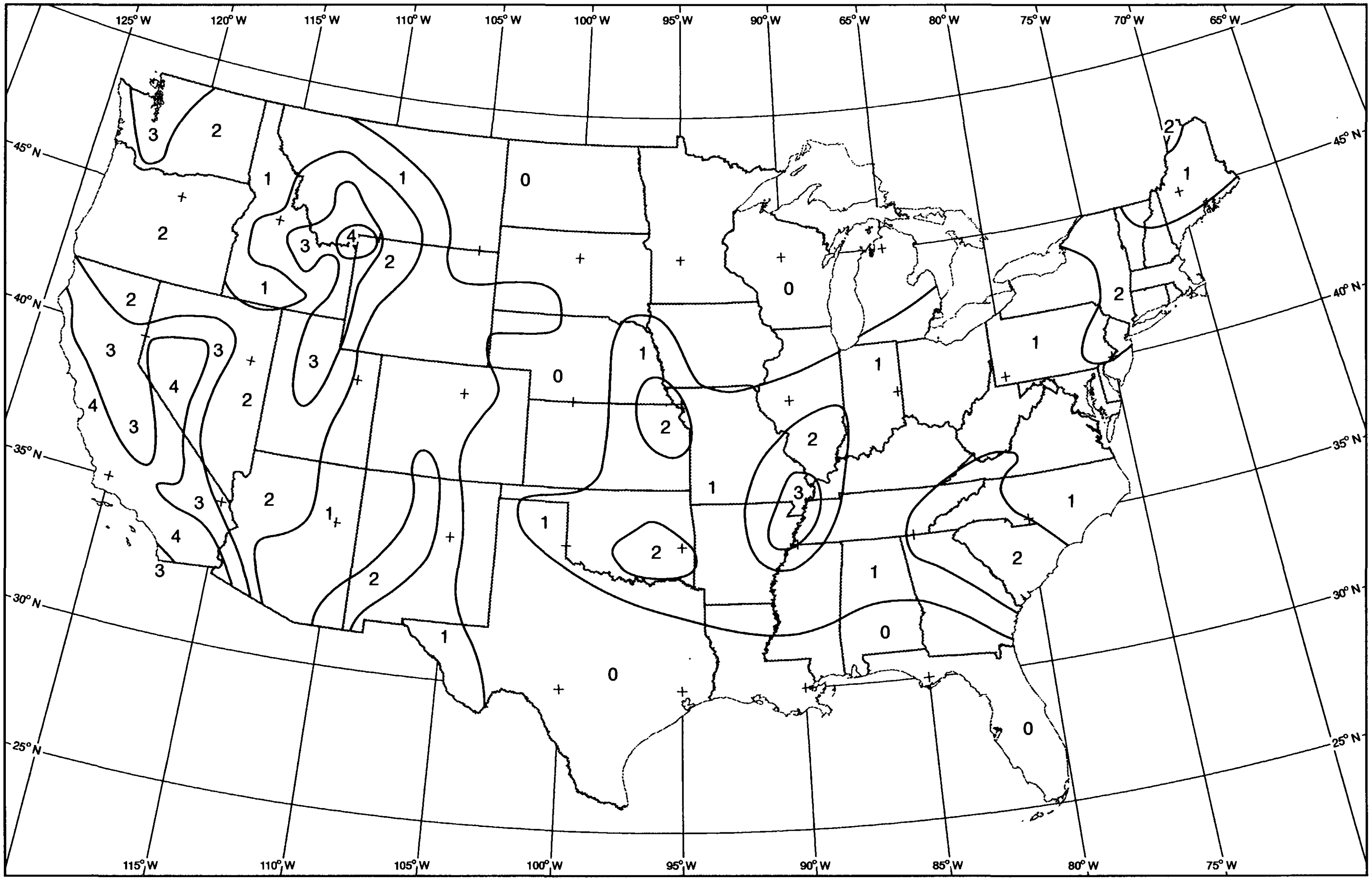


Figure A4. One of the SEAOC Seismology Committee proposals for the 1988 Uniform Building Code zone map. Zones are identified by the numbers from 0 to 4. Seismic zone factors are assigned to each zone; Zone 0 = 0, Zone1 = 0.1, Zone 2 = 0.20 (= 0.15 for Zone 2 east of the continental divide), Zone 3 = 0.3, and Zone 4 = 0.4. Each zone also has specific structural detailing requirements. After ICBO, 1986 (This map was redrawn from the original source, if differences occur, the original source should be used).

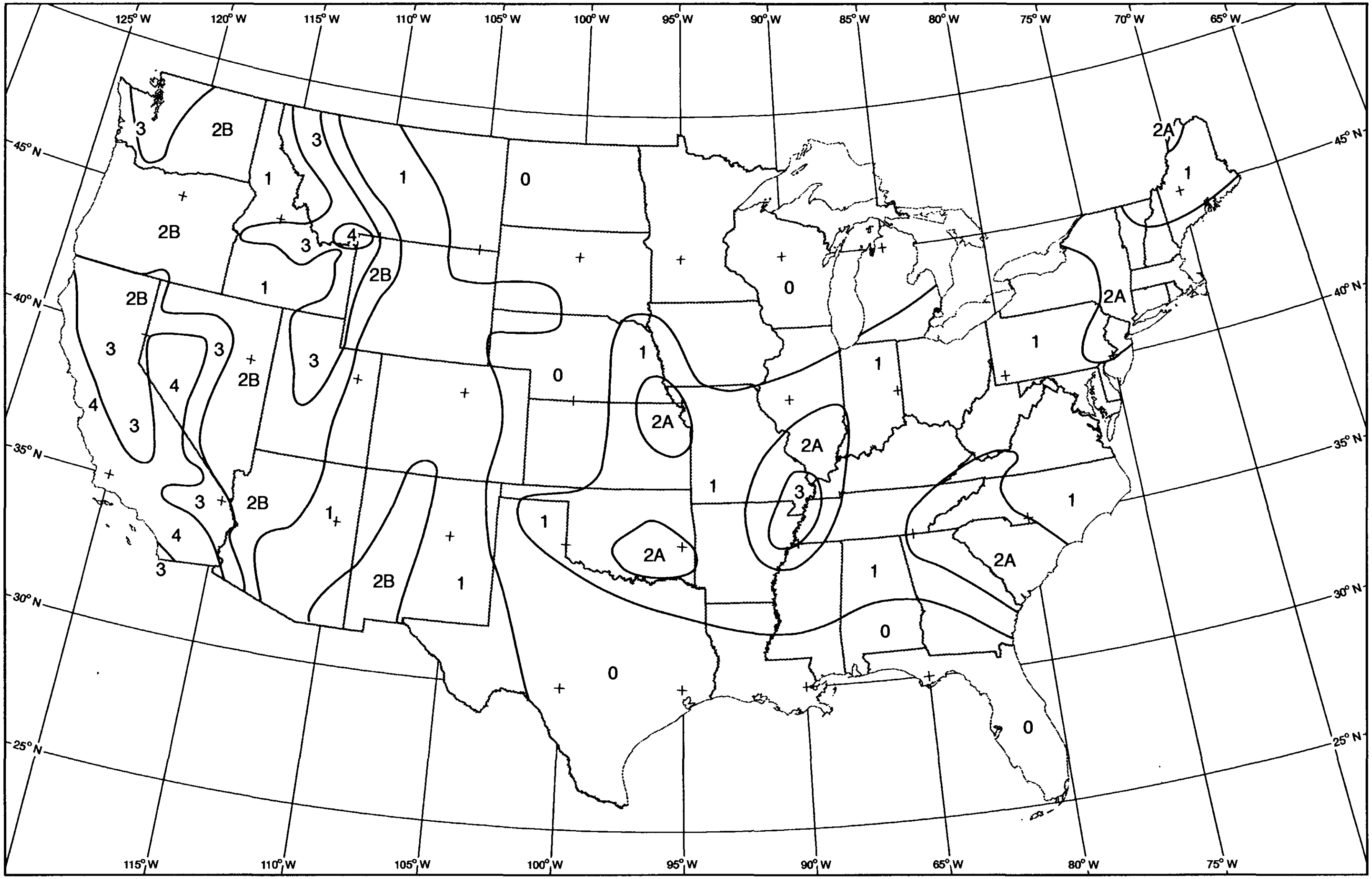


Figure A5. 1988 Uniform Building Code zone map. Zones are identified by the numbers from 0 to 4. Seismic zone factors are assigned to each zone; Zone 0 = 0, Zone1 = 0.075, Zone 2A = 0.15, Zone 2B = 0.20, Zone 3 = 0.3, and Zone 4 = 0.4. Each zone also has specific structural detailing requirements. After ICBO, 1988 (This map was redrawn from the original source, if differences occur, the original source should be used).

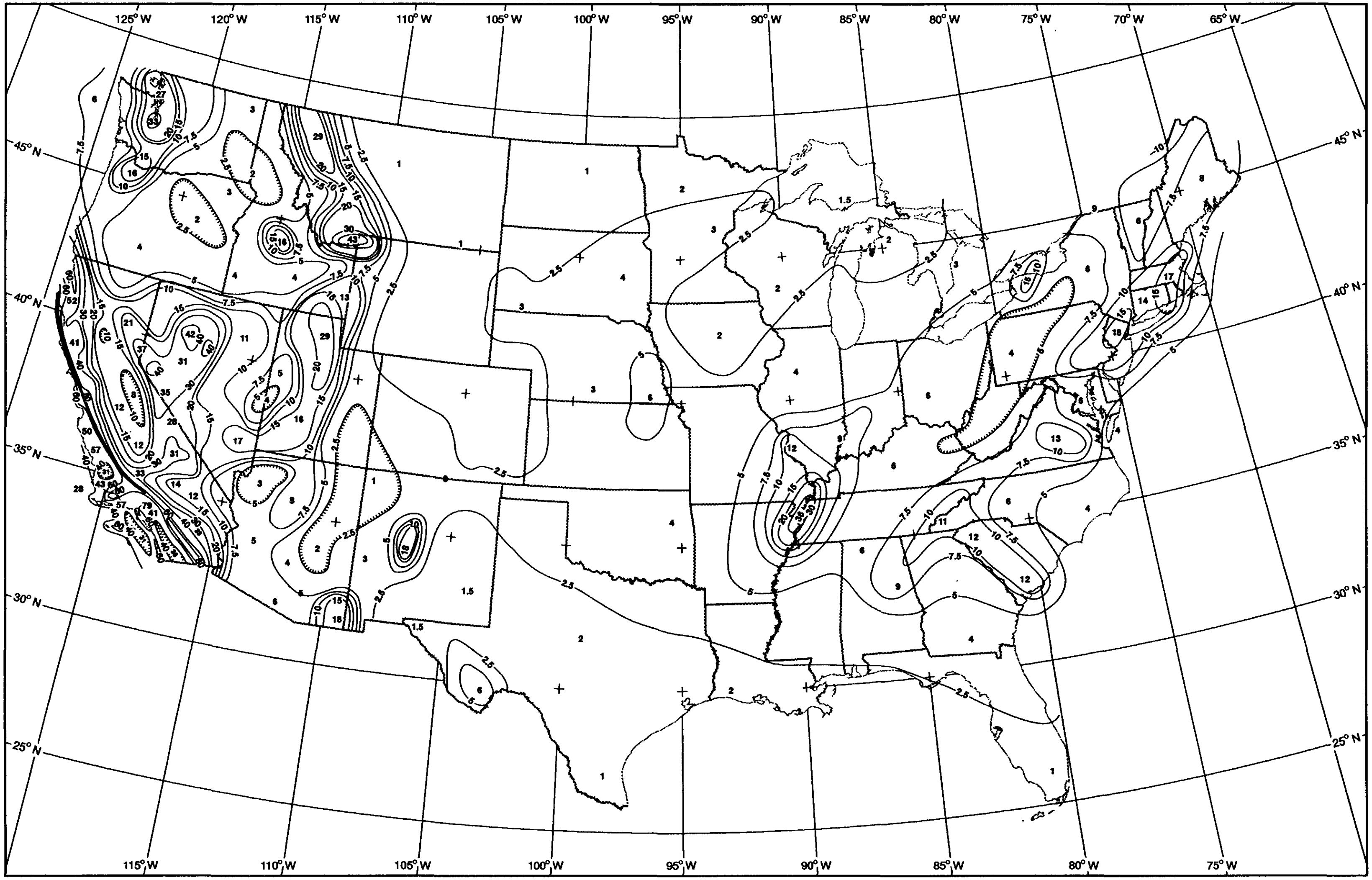


Figure A6. 1990 Contour map for peak horizontal acceleration (expressed as percent of gravity) in rock with 90 percent probability of not being exceeded in 50 years. After Algermissen et al, 1990.

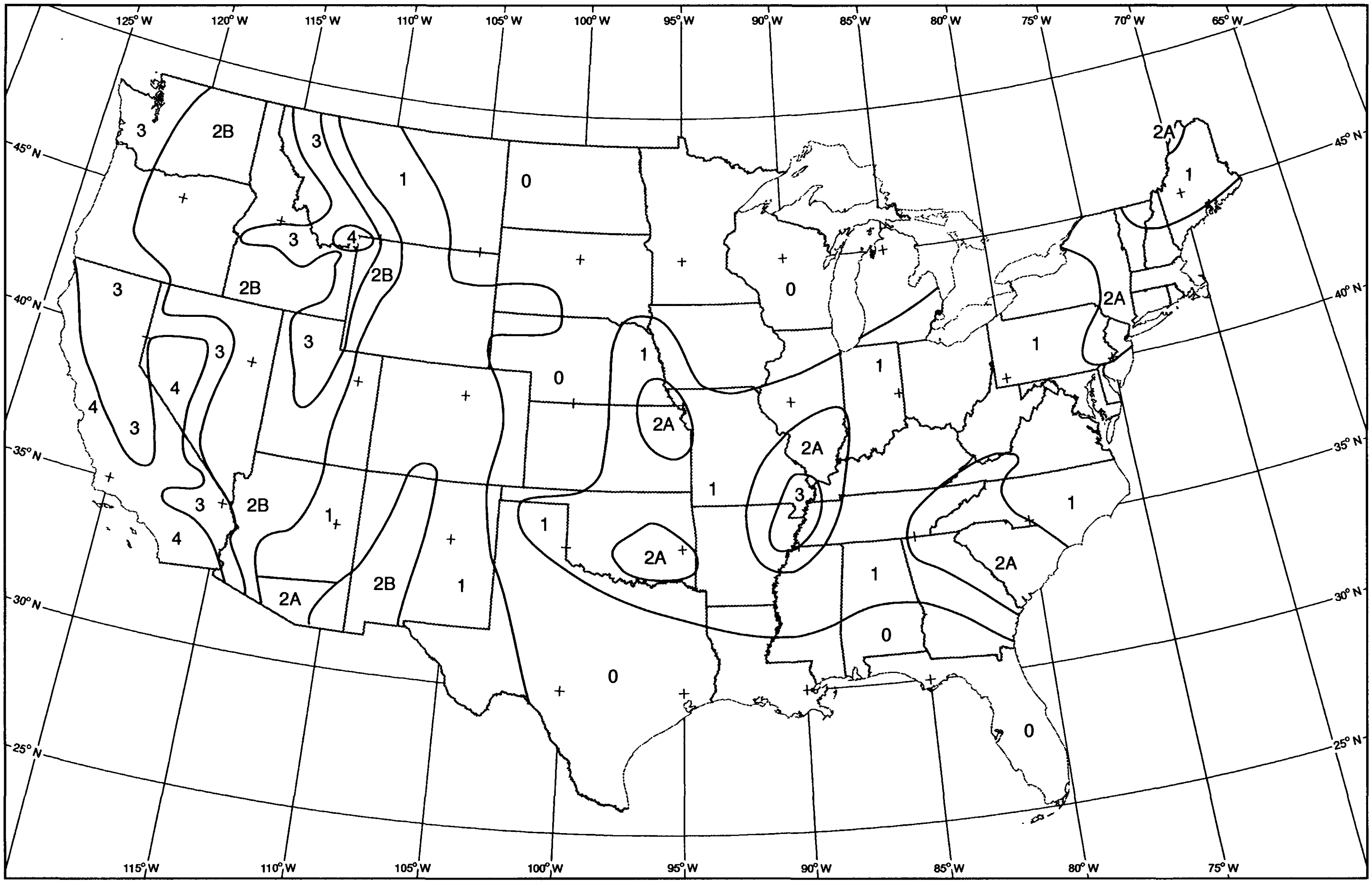


Figure A7. 1994 Uniform Building Code zone map. Zones are identified by the numbers from 0 to 4. Seismic zone factors are assigned to each zone; Zone 0 = 0, Zone1 = 0.075, Zone 2A = 0.15, Zone 2B = 0.20, Zone 3 = 0.3, and Zone 4 = 0.4. Each zone also has specific structural detailing requirements. After ICBO, 1994 (This map was redrawn from the original source, if differences occur, the original source should be used).

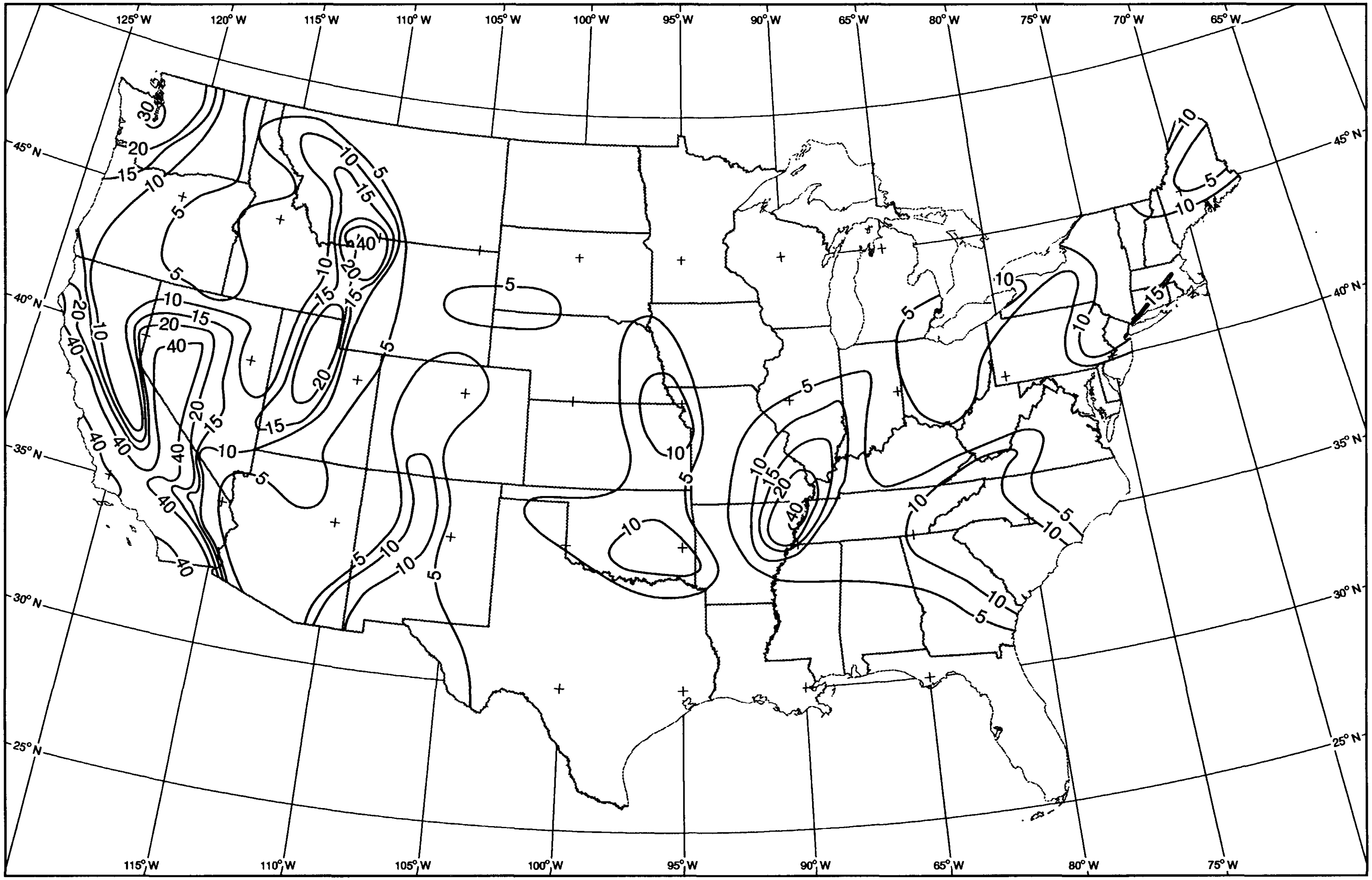


Figure A8. ASCE A7 contour map for effective peak accleration (EPA) coefficient, A_a, for the continental United States. The units of EPA are expressed as a percent of gravity. After ASCE, 1994 (This map was redrawn from the original source, if differences occur, the original source should be used).

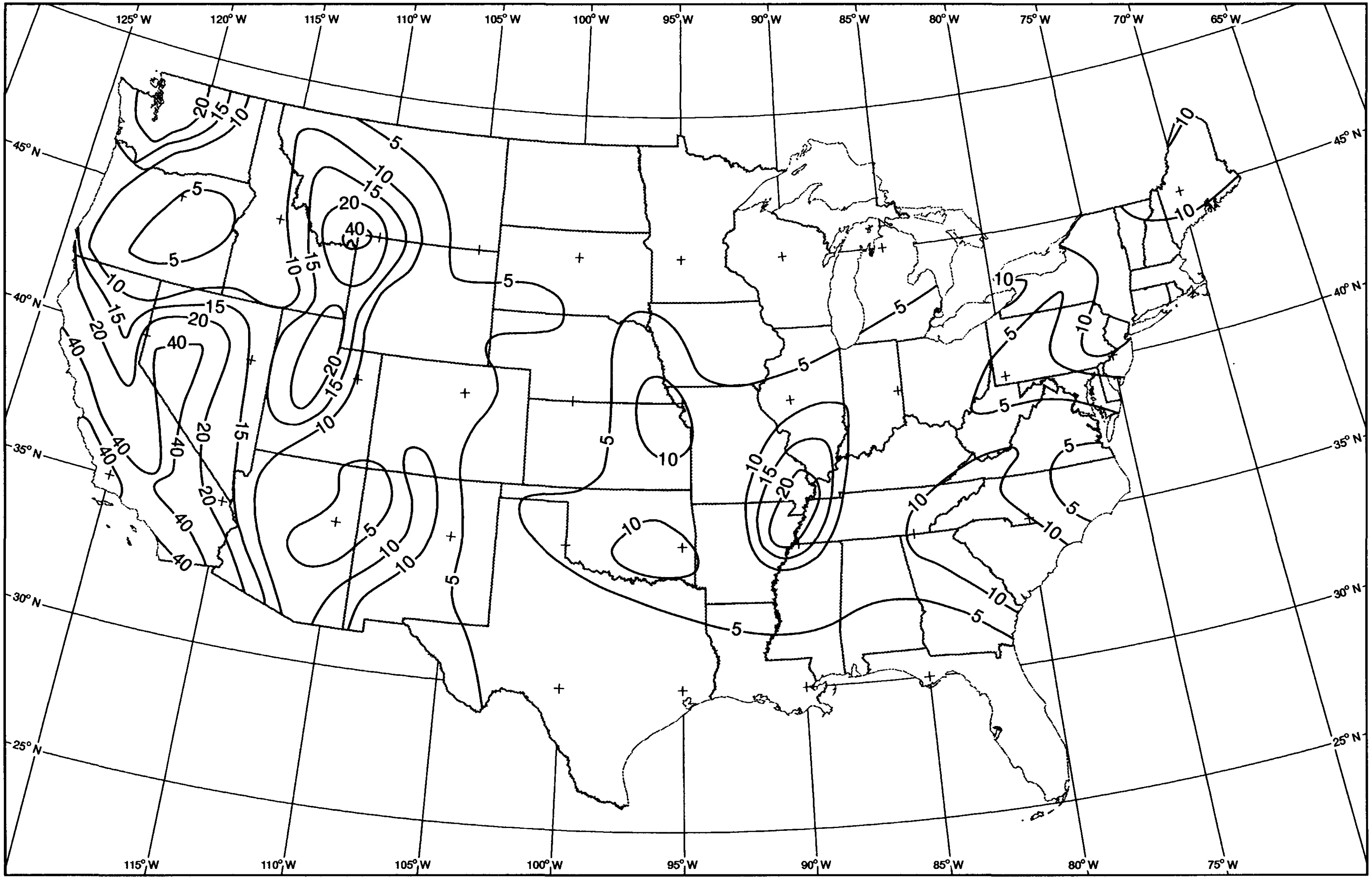


Figure A9. ASCE A7 contour map for effective peak velocity-related accleration (EPV) coefficient, A_v, for the continental United States. The units of EPV are expressed as a percent of gravity. After ASCE, 1994 (This map has been redrawn from the original source, if differences occur, the original source should be used).

APPENDIX B - 1994 SPECTRAL ORDINATE MAPS

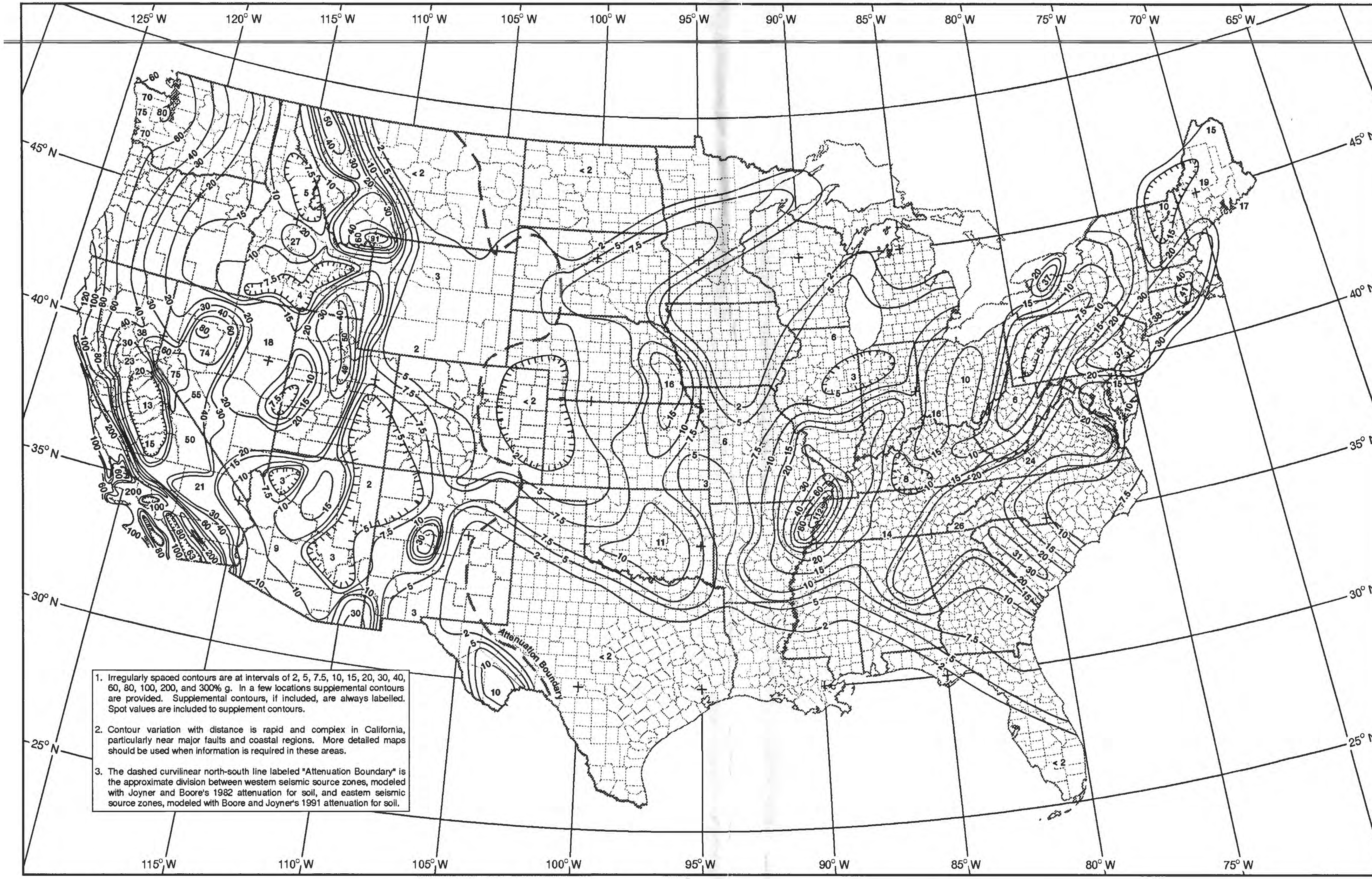
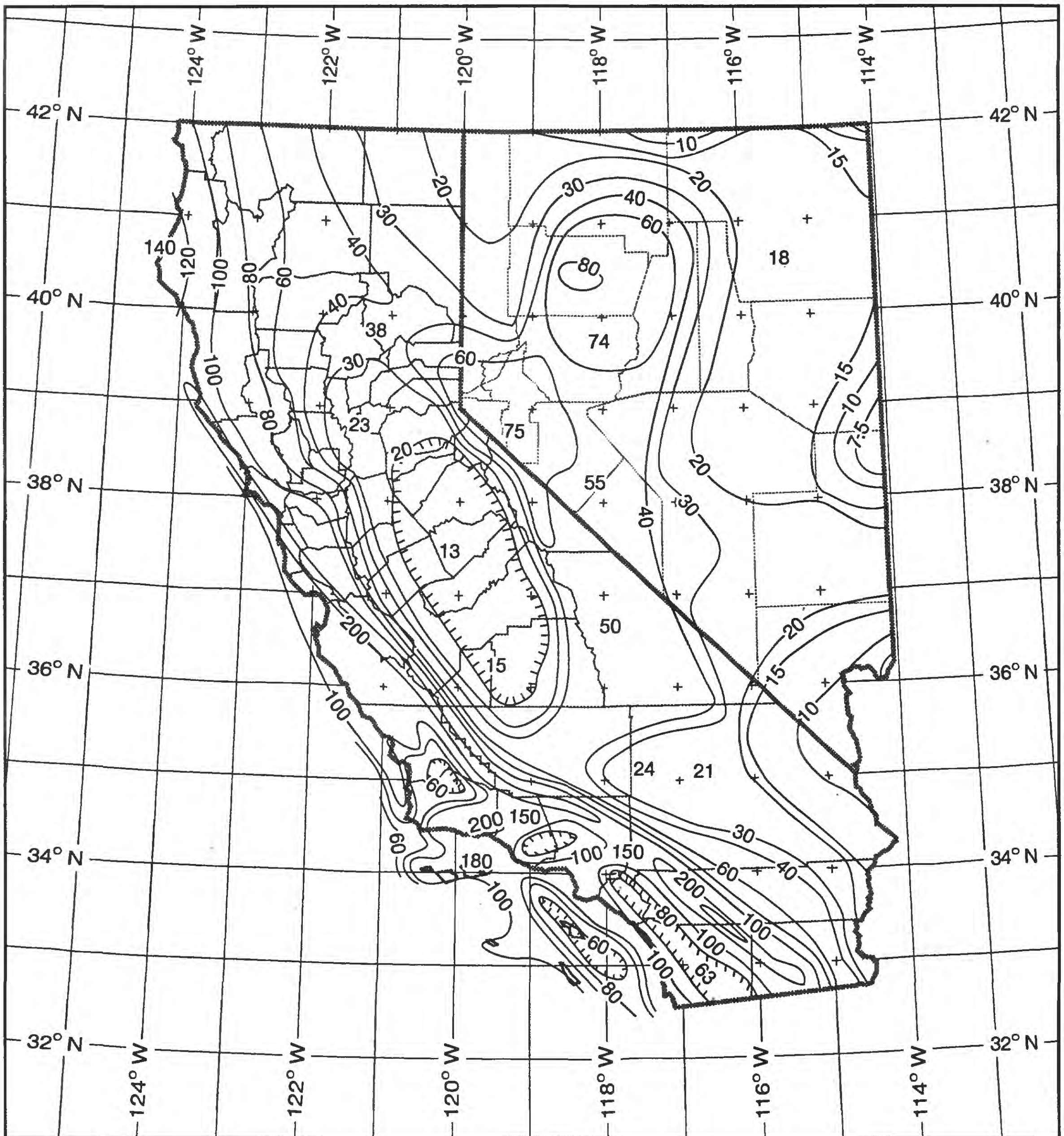


Figure B1. 1994 contour map of the 5 percent damped, 0.3 second pseudo-acceleration spectral response, expressed in percent of the acceleration of gravity, with a 10-percent probability of exceedance in 50 years. The map values include estimates of variability in the attenuation of spectral acceleration and in fault rupture length.

Figure B2. 1994 contour map of the 5 percent damped, 1.0 second pseudo-acceleration spectral response, expressed in percent of the acceleration of gravity, with a 10 percent probability of exceedance in 50 years. The map values include estimates of variability in the attenuation of spectral acceleration and in fault rupture length.

Figure B3. 1994 contour map of the 5 percent damped, 0.3 second pseudo-acceleration spectral response, expressed in percent of the acceleration of gravity, with a 10-percent probability of exceedance in 250 years. The map values include estimates of variability in the attenuation of spectral acceleration and in fault rupture length.

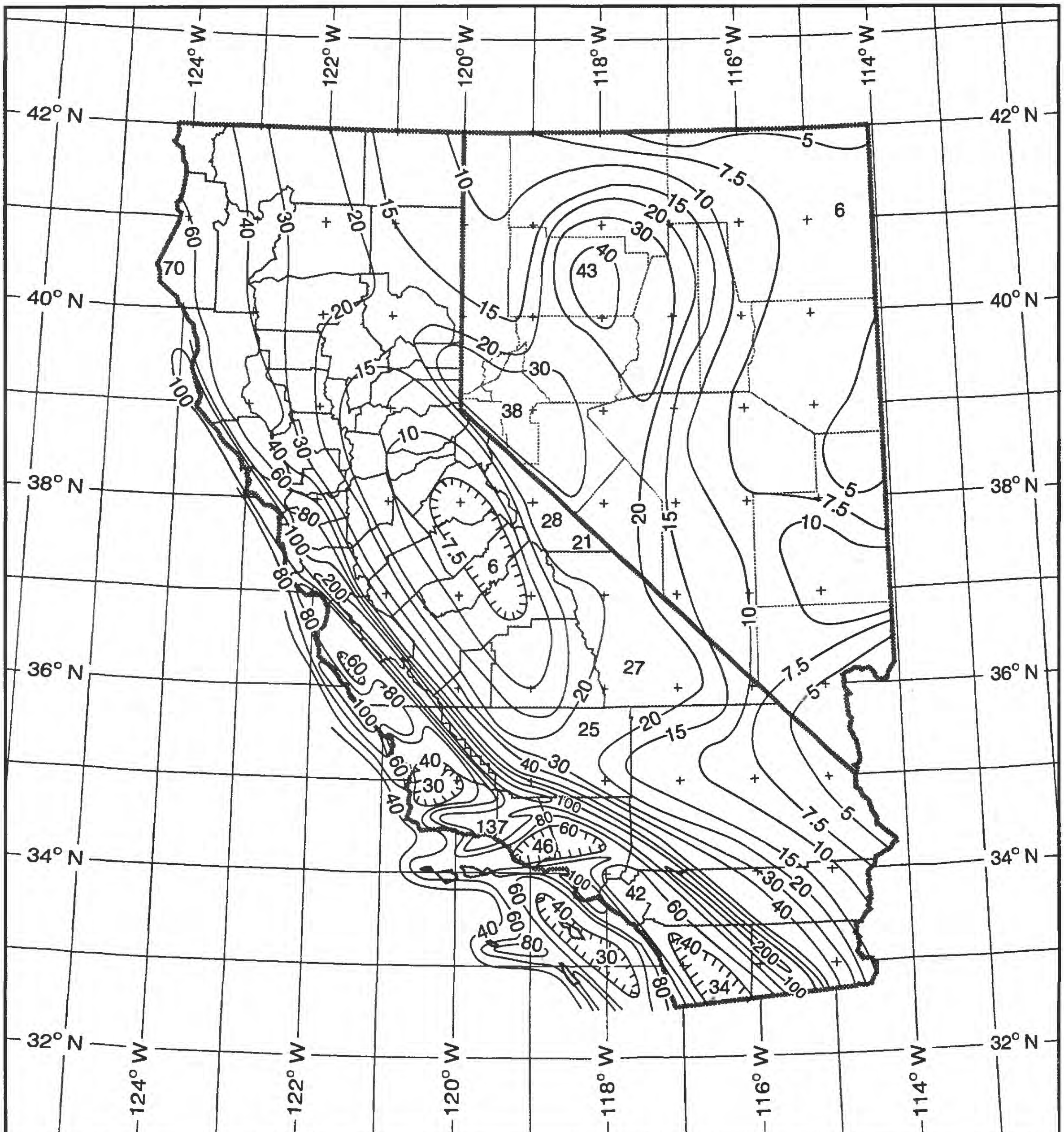
Figure B4. 1994 contour map of the 5 percent damped, 1.0 second pseudo-acceleration spectral response, expressed in percent of the acceleration of gravity, with a 10 percent probability of exceedance in 250 years. The map values include estimates of variability in the attenuation of spectral acceleration and in fault rupture length.



1. Irregularly spaced contours are at intervals of 2, 5, 7.5, 10, 15, 20, 30, 40, 60, 80, 100, 200, and 300% g. In a few locations supplemental contours are provided. Supplemental contours, if included, are always labelled. Spot values are included to supplement contours.

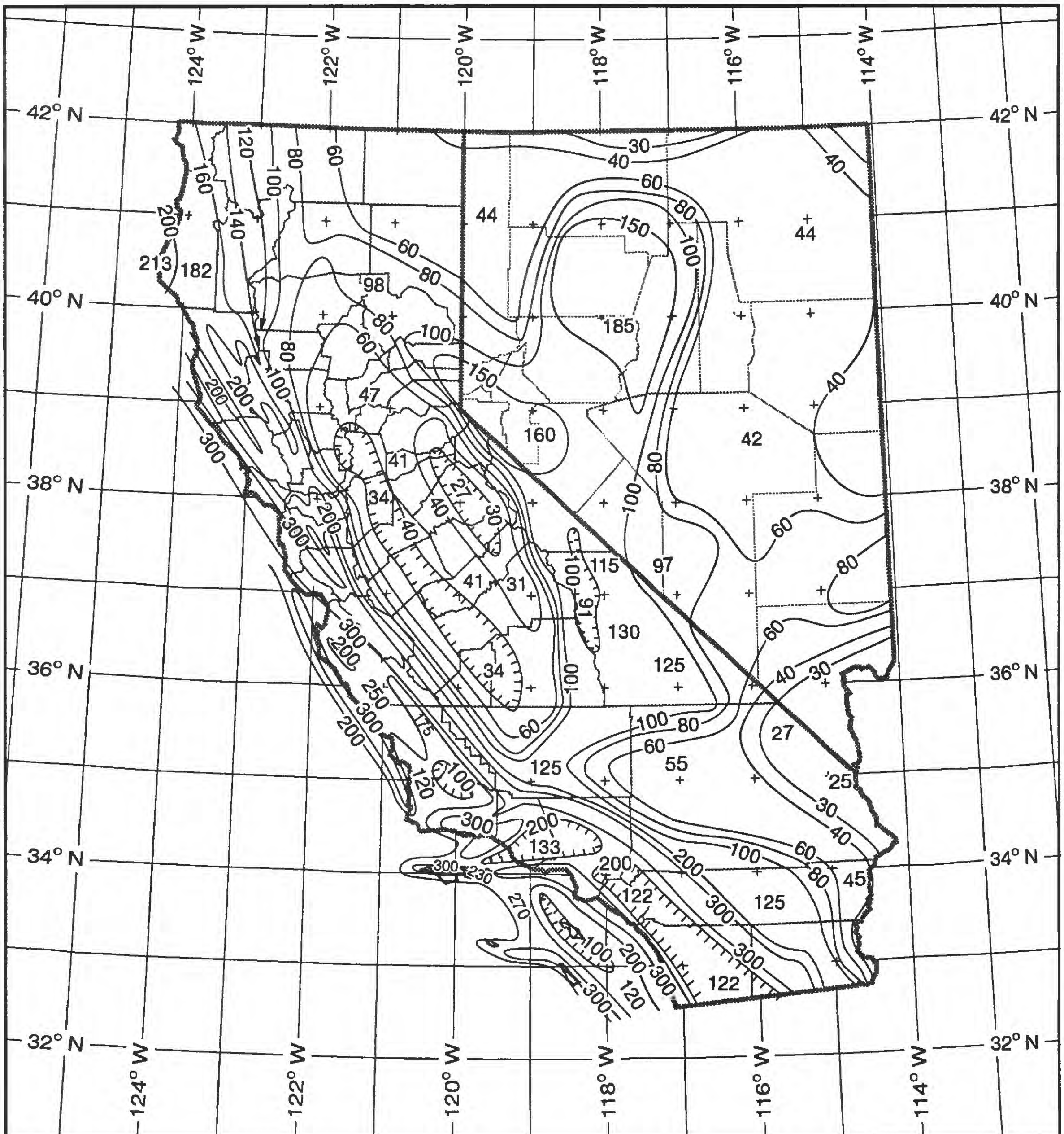
2. Contour variation with distance is rapid and complex in California, particularly near major faults and coastal regions. More detailed maps should be used when information is required in these areas.

Figure B5. 1994 contour map of the 5 percent damped, 0.3 second pseudo-acceleration spectral response, expressed in percent of the acceleration of gravity, with a 10-percent probability of exceedance in 50 years. The map values include estimates of variability in the attenuation of spectral acceleration and in fault rupture length.



1. Irregularly spaced contours are at intervals of 2, 5, 7.5, 10, 15, 20, 30, 40, 60, 80, 100, 200, and 300% g. In a few locations supplemental contours are provided. Supplemental contours, if included, are always labelled. Spot values are included to supplement contours.
2. Contour variation with distance is rapid and complex in California, particularly near major faults and coastal regions. More detailed maps should be used when information is required in these areas.

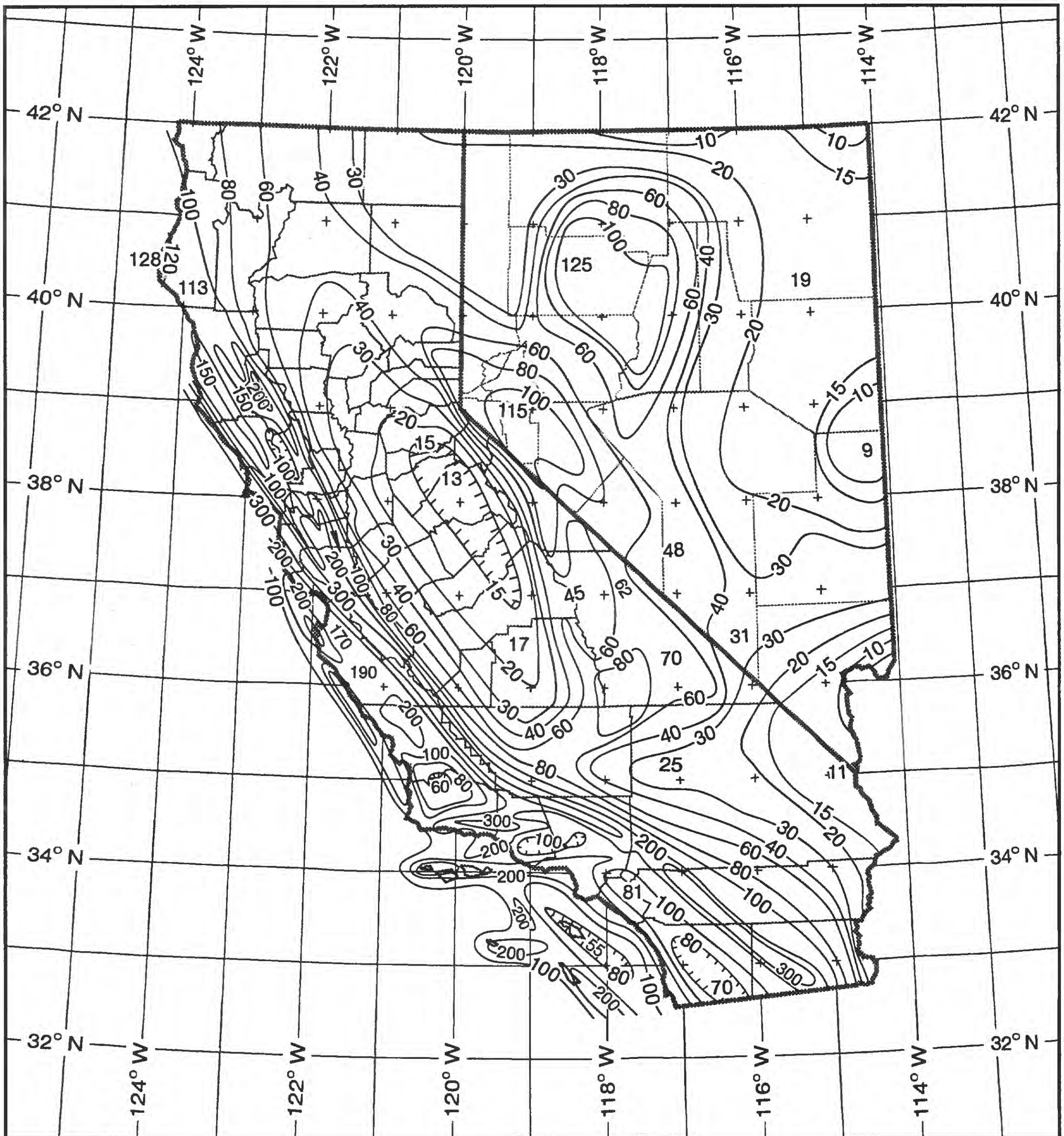
Figure B6. 1994 contour map of the 5 percent damped, 1.0 second pseudo-acceleration spectral response, expressed in percent of the acceleration of gravity, with a 10-percent probability of exceedance in 50 years. The map values include estimates of variability in the attenuation of spectral acceleration and in fault rupture length.



1. Irregularly spaced contours are at intervals of 2, 5, 7.5, 10, 15, 20, 30, 40, 60, 80, 100, 200, and 300% g. In a few locations supplemental contours are provided. Supplemental contours, if included, are always labelled. Spot values are included to supplement contours.

2. Contour variation with distance is rapid and complex in California, particularly near major faults and coastal regions. More detailed maps should be used when information is required in these areas.

Figure B7. 1994 contour map of the 5 percent damped, 0.3 second pseudo-acceleration spectral response, expressed in percent of the acceleration of gravity, with a 10-percent probability of exceedance in 250 years. The map values include estimates of variability in the attenuation of spectral acceleration and in fault rupture length.



1. Irregularly spaced contours are at intervals of 2, 5, 7.5, 10, 15, 20, 30, 40, 60, 80, 100, 200, and 300% g. In a few locations supplemental contours are provided. Supplemental contours, if included, are always labelled. Spot values are included to supplement contours.

2. Contour variation with distance is rapid and complex in California, particularly near major faults and coastal regions. More detailed maps should be used when information is required in these areas.

Figure B8. 1994 contour map of the 5 percent damped, 1.0 second pseudo-acceleration spectral response, expressed in percent of the acceleration of gravity, with a 10-percent probability of exceedance in 250 years. The map values include estimates of variability in the attenuation of spectral acceleration and in fault rupture length.

APPENDIX C - 1991 SPECTRAL ORDINATE MAPS

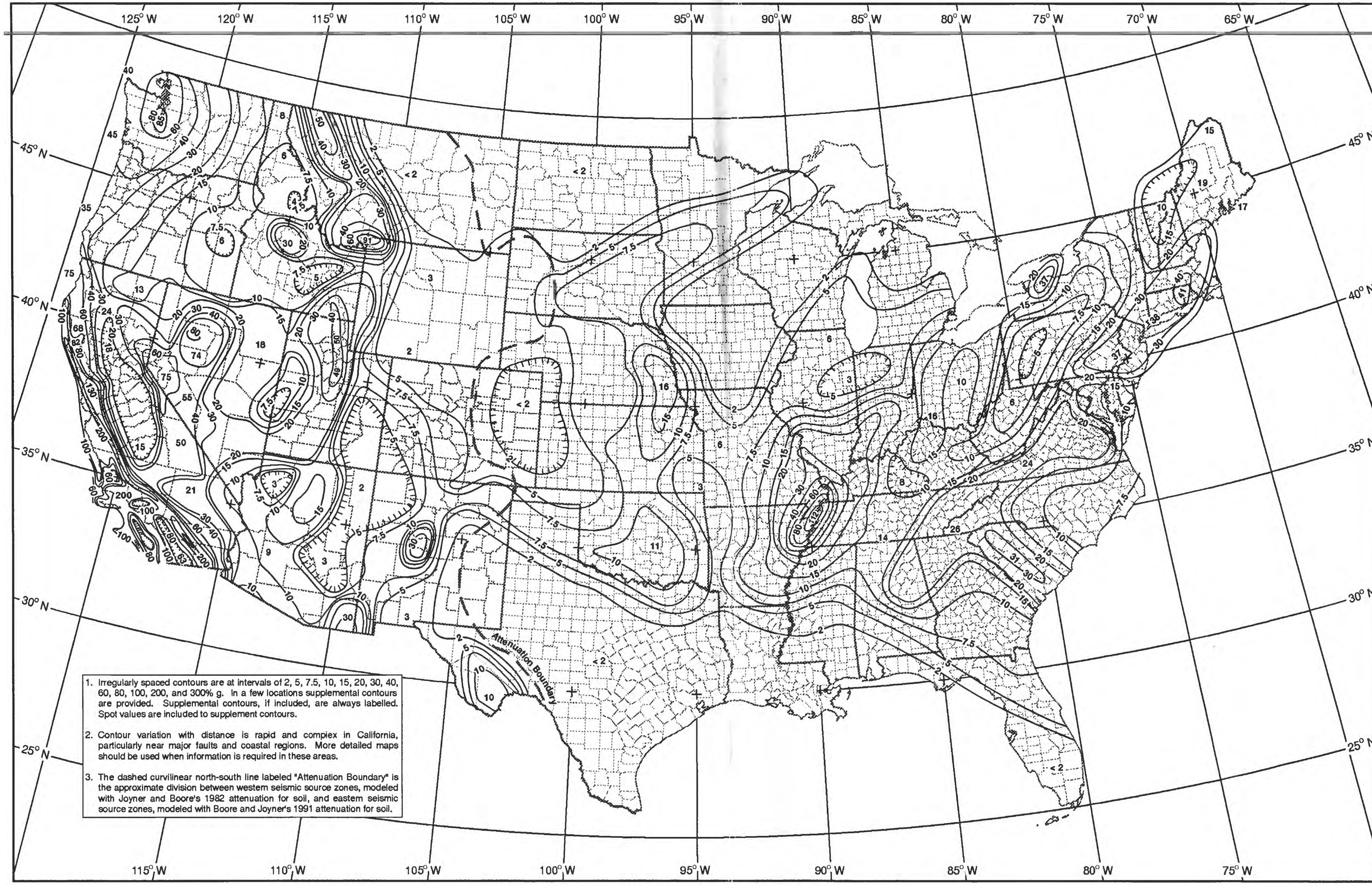


Figure C1. 1991 contour map of the 5 percent damped, 0.3 second pseudo-acceleration spectral response, expressed in percent of the acceleration of gravity, with a 10-percent probability of exceedance in 50 years. The map values include estimates of variability in the attenuation of spectral acceleration and in fault rupture length.

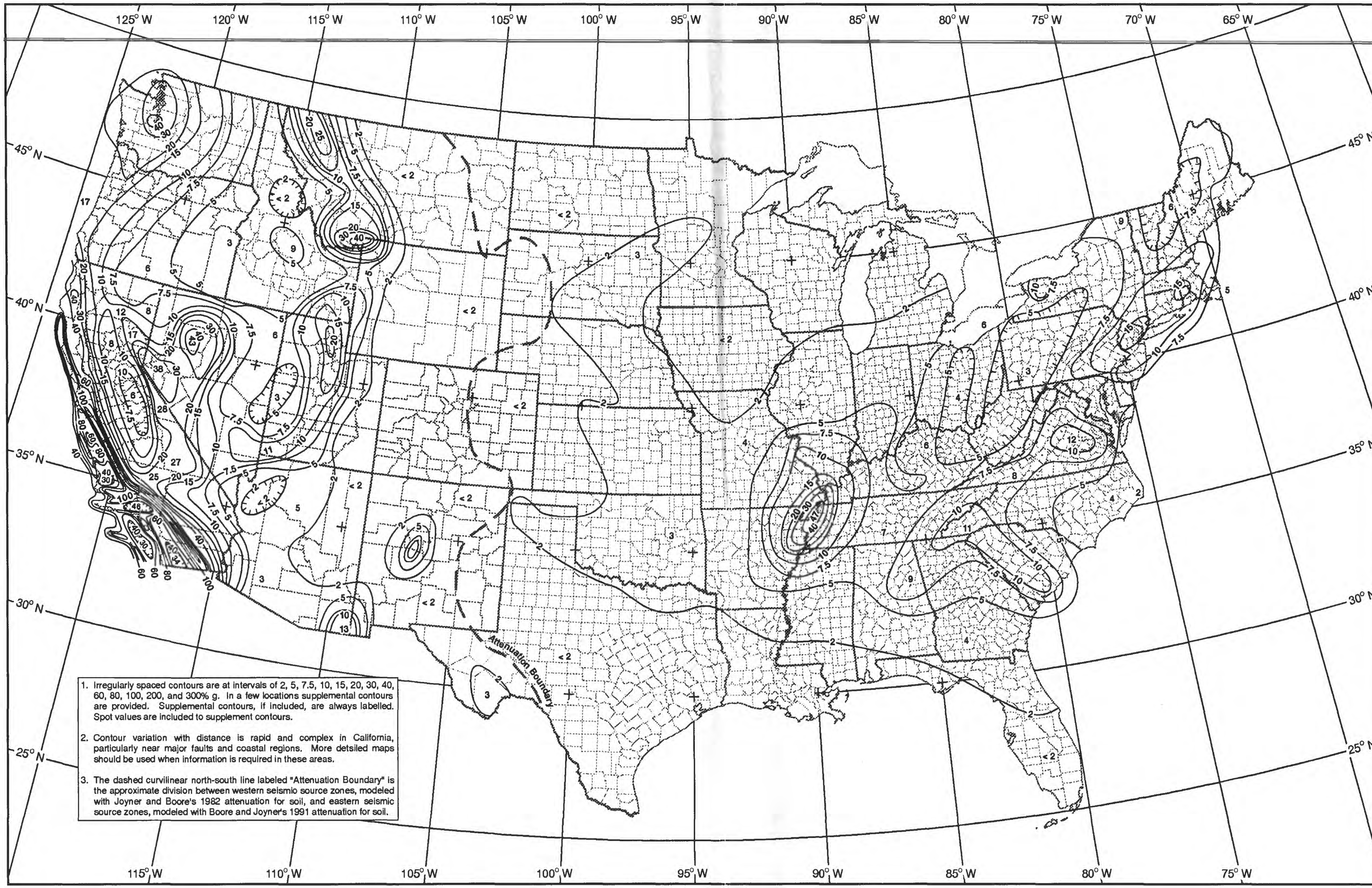
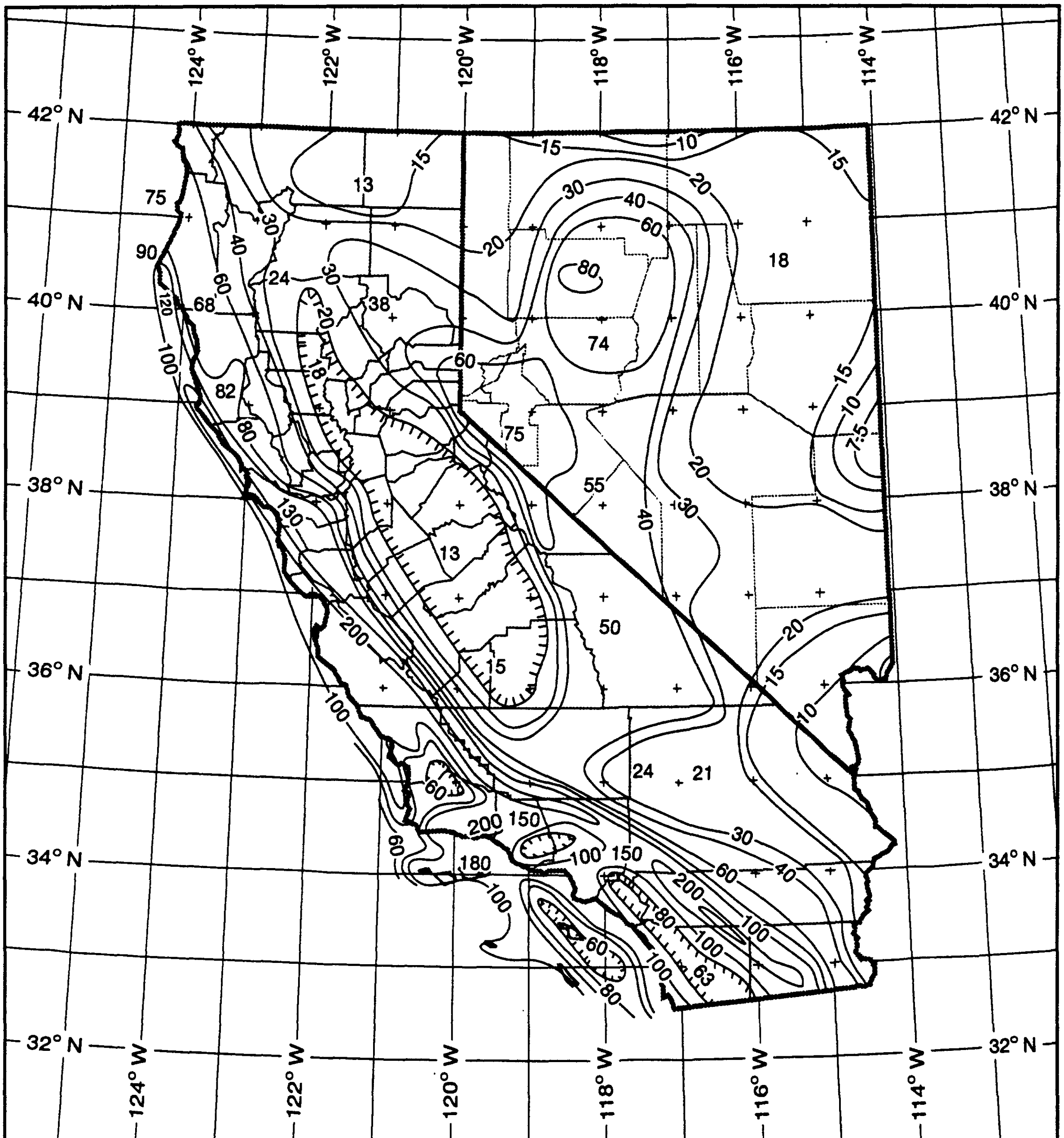


Figure C2. 1991 contour map of the 5 percent damped, 1.0 second pseudo-acceleration spectral response, expressed in percent of the acceleration of gravity, with a 10 percent probability of exceedance in 50 years. The map values include estimates of variability in the attenuation of spectral acceleration and in fault rupture length.

Figure C3. 1991 contour map of the 5 percent damped, 0.3 second pseudo-acceleration spectral response, expressed in percent of the acceleration of gravity, with a 10-percent probability of exceedance in 250 years. The map values include estimates of variability in the attenuation of spectral acceleration and in fault rupture length.

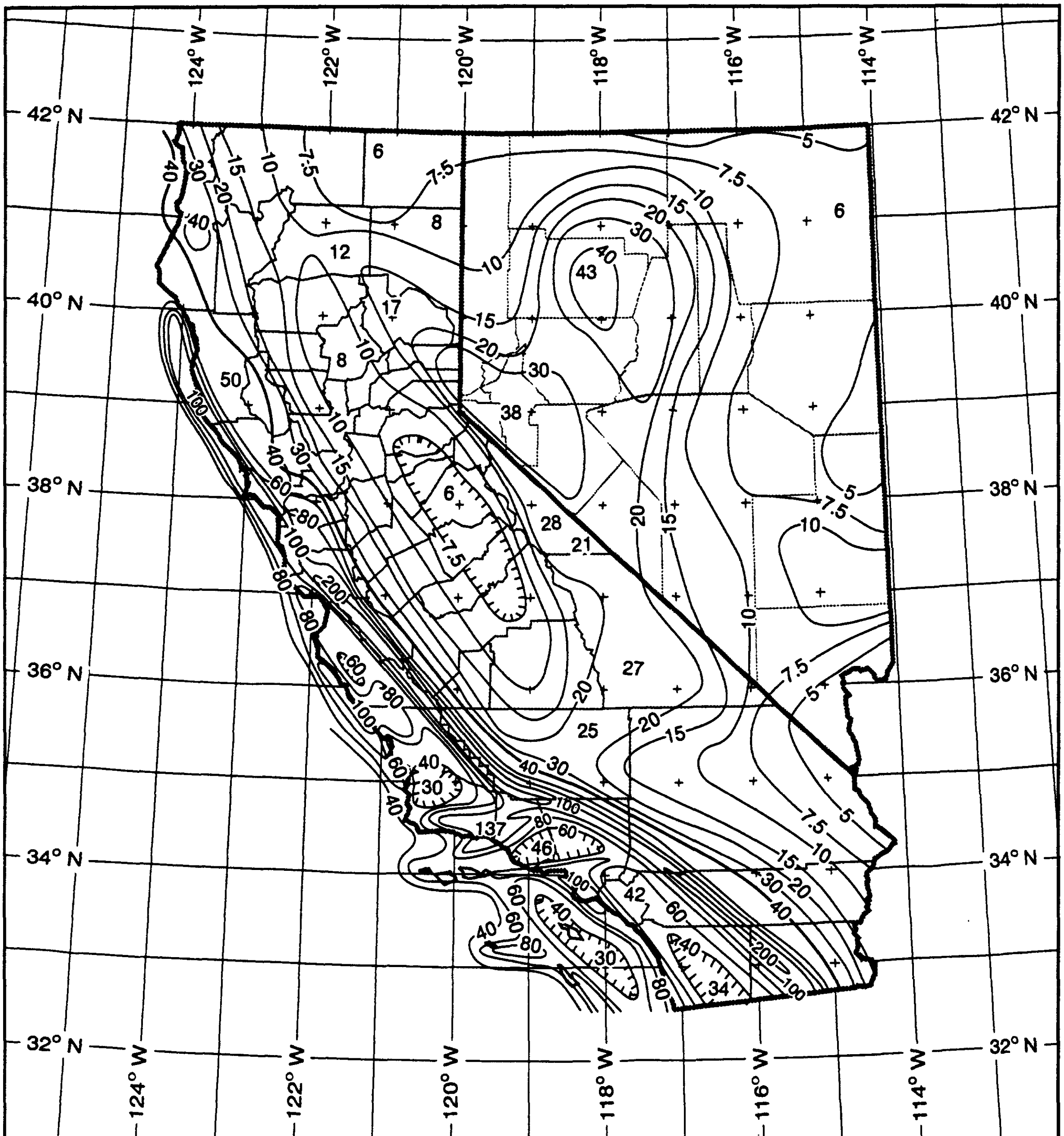
Figure C4. 1991 contour map of the 5 percent damped, 1.0 second pseudo-acceleration spectral response, expressed in percent of the acceleration of gravity, with a 10 percent probability of exceedance in 250 years. The map values include estimates of variability in the attenuation of spectral acceleration and in fault rupture length.



1. Irregularly spaced contours are at intervals of 2, 5, 7.5, 10, 15, 20, 30, 40, 60, 80, 100, 200, and 300% g. In a few locations supplemental contours are provided. Supplemental contours, if included, are always labelled. Spot values are included to supplement contours.

2. Contour variation with distance is rapid and complex in California, particularly near major faults and coastal regions. More detailed maps should be used when information is required in these areas.

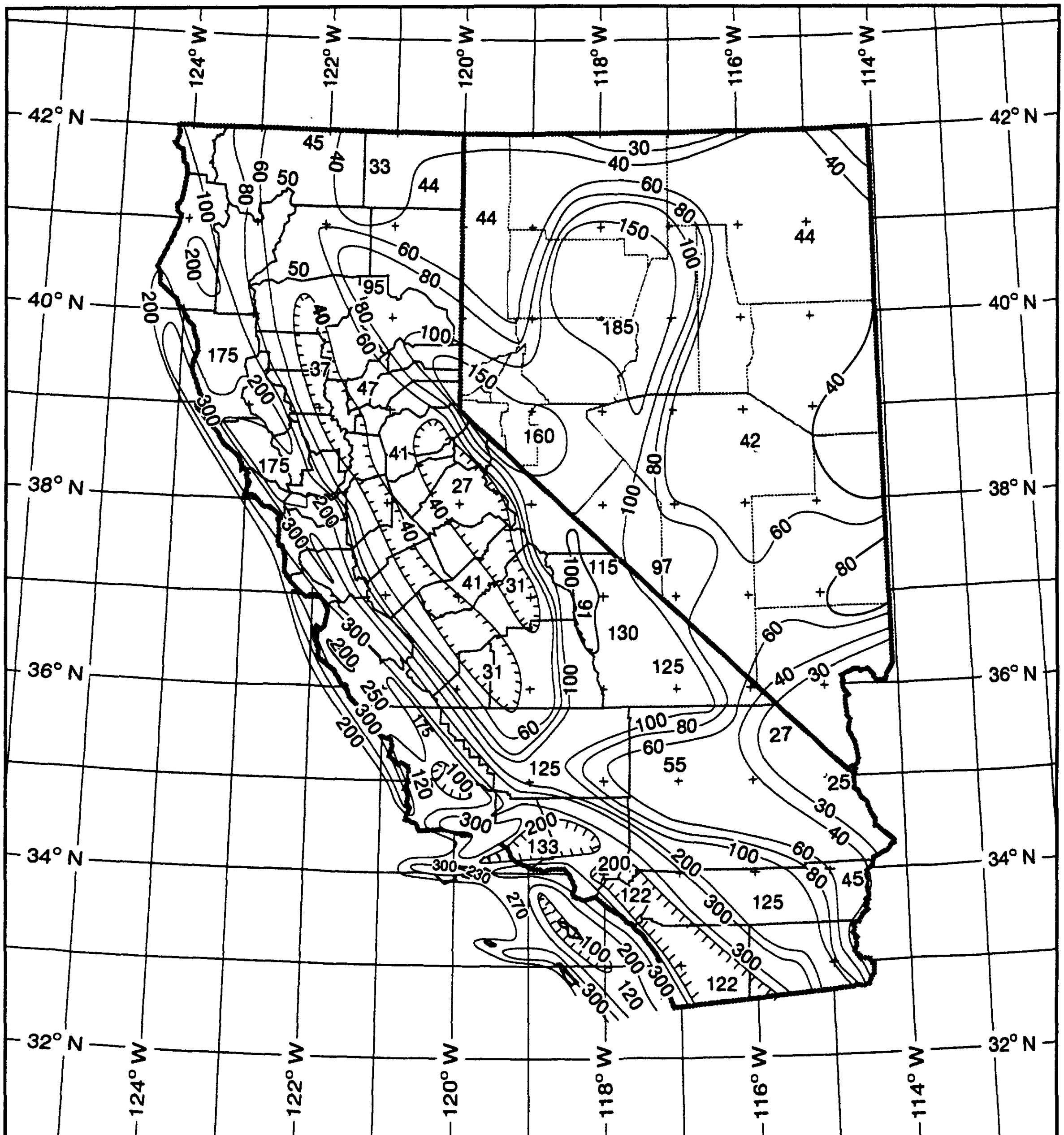
Figure C5. 1991 contour map of the 5 percent damped, 0.3 second pseudo-acceleration spectral response, expressed in percent of the acceleration of gravity, with a 10-percent probability of exceedance in 50 years. The map values include estimates of variability in the attenuation of spectral acceleration and in fault rupture length.



1. Irregularly spaced contours are at intervals of 2, 5, 7.5, 10, 15, 20, 30, 40, 60, 80, 100, 200, and 300% g. In a few locations supplemental contours are provided. Supplemental contours, if included, are always labelled. Spot values are included to supplement contours.

2. Contour variation with distance is rapid and complex in California, particularly near major faults and coastal regions. More detailed maps should be used when information is required in these areas.

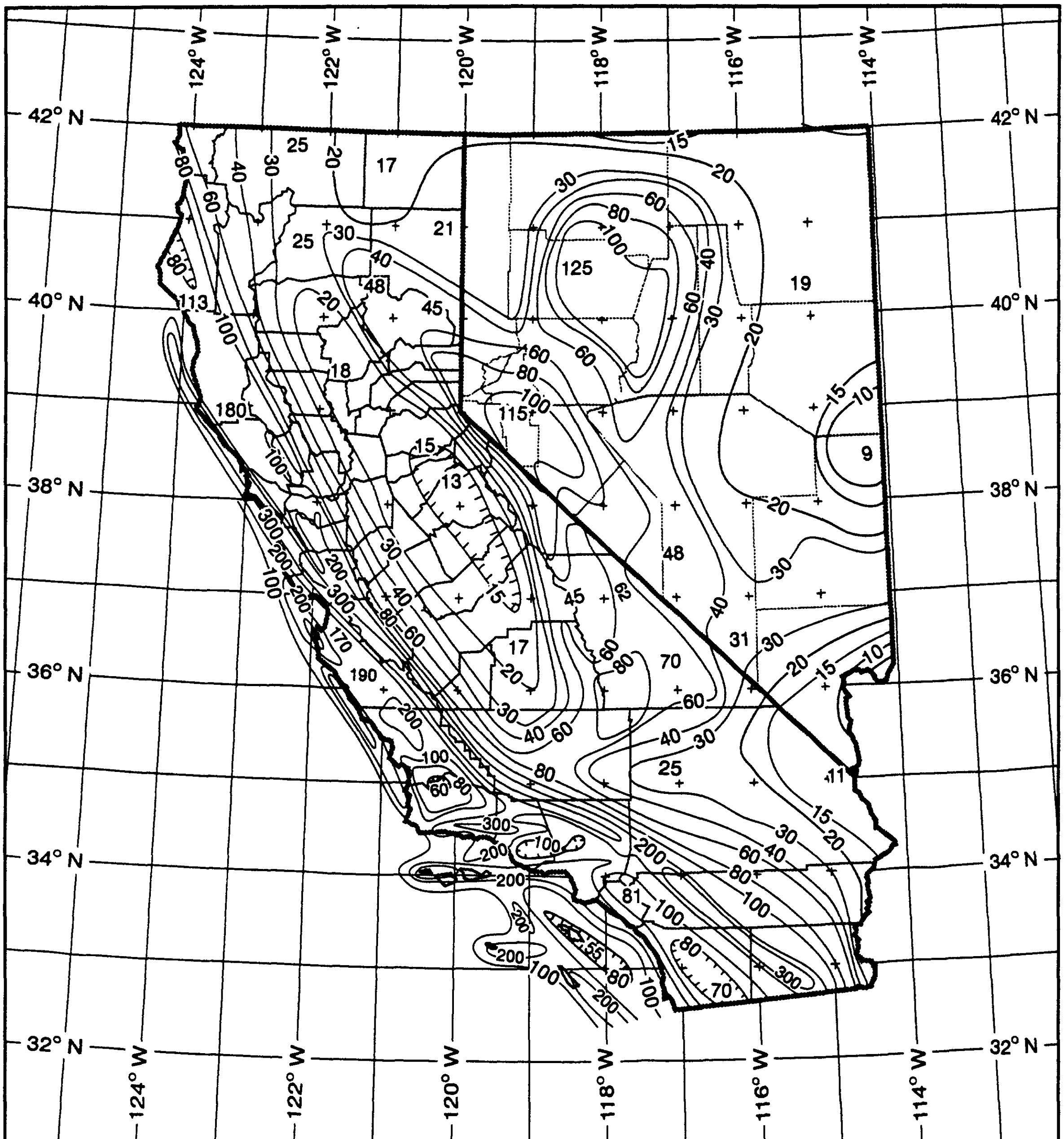
Figure C6. 1991 USGS map of the 5 percent damped, 1.0 second pseudo-acceleration spectral response, expressed in percent of the acceleration of gravity, with a 10-percent probability of exceedance in 50 years. The map values include estimates of variability in the attenuation of spectral acceleration and in fault rupture length.



1. Irregularly spaced contours are at intervals of 2, 5, 7.5, 10, 15, 20, 30, 40, 60, 80, 100, 200, and 300% g. In a few locations supplemental contours are provided. Supplemental contours, if included, are always labelled. Spot values are included to supplement contours.

2. Contour variation with distance is rapid and complex in California, particularly near major faults and coastal regions. More detailed maps should be used when information is required in these areas.

Figure C7. 1991 contour map of the 5 percent damped, 0.3 second pseudo-acceleration spectral response, expressed in percent of the acceleration of gravity, with a 10-percent probability of exceedance in 250 years. The map values include estimates of variability in the attenuation of spectral acceleration and in fault rupture length.



1. Irregularly spaced contours are at intervals of 2, 5, 7.5, 10, 15, 20, 30, 40, 60, 80, 100, 200, and 300% g. In a few locations supplemental contours are provided. Supplemental contours, if included, are always labelled. Spot values are included to supplement contours.

2. Contour variation with distance is rapid and complex in California, particularly near major faults and coastal regions. More detailed maps should be used when information is required in these areas.

Figure C8. 1991 contour map of the 5 percent damped, 1.0 second pseudo-acceleration spectral response, expressed in percent of the acceleration of gravity, with a 10-percent probability of exceedance in 250 years. The map values include estimates of variability in the attenuation of spectral acceleration and in fault rupture length.

APPENDIX D- USE OF PROBABILISTIC GROUND MOTION MAPS IN BUILDING CODES AND RELATED DOCUMENTS

Use of Probabilistic Ground Motion Maps in Building Codes and Related Documents					
Date	Publication (see reference list for complete citation)	Parameter(s) Mapped	Exposure Time(s) Mapped, years	Basis of Map	Comments
1976	Algermissen, S.T. and Perkins, D. M., 1976	PGA	50	10% probability of being exceeded in the 50 - year exposure time.	First national probabilistic map prepared by USGS. The attenuation function was for maximum peak acceleration. Variability on the attenuation function was not included. The map was included in the commentary to the 1978 ATC 3-06 and the 1985, 1988, 1991, and 1994 editions of the *NEHRP Provisions*. The map served as the basis for the A_a map in the *Tentative Provisions for the Development of Seismic Regulations for Buildings*.
1978	Applied Technology Council, 1978	A_a, A_v	NA	See comment.	The A_a map was based on the draft of the USGS 1976 PGA map with modifications by the committees preparing ATC 3-06. The principle difference was the truncation of the USGS contours for PGA at values at 0.4. This affected essentially values in California. Other contours were modified somewhat based on ATC committee review. Because of these changes, the map does not have a uniform probably of exceedance during a 50-year exposure time period although it is usually described as such. A_v was created from the A_a maps by a committee using some simple rules since attenuation functions for this parameter were not available at the time of its preparation. Although page-size contour maps for A_a and A_v were included in the commentary, the design approach used county-by-county maps to determine A_a and A_v factors.
1982	ANSI, 1982	Zones	NA	See comment.	Based on 1978 ATC 3-06 map for A_v. A zone map based on the A_v map was prepared since it was more conservative than the A_a map. Factors were applied to zones.
1982	Algermissen and others, 1982	PGA, PGV	10 50 250	10% probability of being exceeded in the mapped exposure times.	First national probabilistic maps for peak acceleration and peak velocity. The attenuation functions were for maximum peak acceleration and velocity. Variability on the attenuation functions was not included.
1985	Building Seismic Safety Council, 1986	A_a, A_v	NA	See comment.	Same county-by-county maps as in the 1978 ATC 3-06 Provisions.

Table D1. Chronology of Probabilistic Maps

Use of Probabilistic Ground Motion Maps in Building Codes and Related Documents

Date	Publication (see reference list for complete citation)	Parameter(s) Mapped	Exposure Time(s) Mapped, years	Basis of Map	Comments
1988	Building Seismic Safety Council, 1988	A_a, A_v	NA	See comment.	The maps used for the main approach to seismic design were the same maps as in the 1978 ATC 3-06 Provisions. Contour maps of A_a and A_v, the same size as the county-by-county maps were added. The design procedure was modified to allow use of either set of maps. An alternate approach, described below, was provided in an appendix for trial use.
		PGA, PGV	50 250	10% probability of being exceeded in the mapped exposure times.	These probabilistic maps for peak acceleration and peak velocity were prepared by the USGS for a BSSC committee for consideration in updating the A_a and A_v contour maps in the *NEHRP Provisions*. The basis of the maps was the same as the 1982 USGS maps(Algermissen and others, 1982) except that variability on the attenuation functions was included for the first time by USGS. The maps were published as an appendix to the 1988 NEHRP, along with a proposed design method. The appendix was intended for trial use and evaluation.
1988	*Uniform Building Code*, 1988	Zones	NA	See comment.	This is a zone map, similar to that used in *Minimum Design Loads for Buildings and Other Structures, 1982,* based originally on the contour map of A_v in the 1978 ATC 3-06 and the 1985 NEHRP. The zone coefficients are linked with detailing requirements and differ from contour values on the original maps. Specific contours differ from the original sources somewhat in the western states.
1988	American Society of Civil Engineers, 1988				Same as the 1982 ANSI Standard.
1988	Structural Engineers Association of California, 1988	Zones	NA	See comment for 1978 ATC 3-06.	This zone map, Figure A4, for California is based on the A_v contour map in the 1978 ATC 3-06 with modifications based on input from a number of organizations. The zone coefficients are linked with detailing requirements, which is the reason the 1988 UBC map differs from Figure A4.

Table D1 continued. Chronology of Probabilistic Maps

Use of Probabilistic Ground Motion Maps in Building Codes and Related Documents					
Date	Publication (see reference list for complete citation)	Parameter(s) Mapped	Exposure Time(s) Mapped, years	Basis of Map	Comments
1990	Algermissen and others, 1990	PGA, PGV	50 250	There is a 10% probability of being exceeded in the mapped exposure times.	National probabilistic maps for peak acceleration and peak velocity, variability on the attenuation function was included. Except for minor differences in source zones in the northeast, the maps are virtually the same as those published in the 1988 NEHRP Provisions.
1991	Building Seismic Safety Council, 1992	A_a, A_v	NA	See comment.	Same maps as in the 1978 ATC 3-06 Provisions. An alternate approach, based on the 1991 USGS maps, was provided in an appendix for trial use.
		$S_{A(0.3)}$, $S_{A(1.0)}$	50 250	There is a 10% probability of being exceeded in the mapped exposure times,	Probabilistic maps for spectral response acceleration for 0.3 and 1.0 sec periods. The attenuation functions were for the random horizontal component of the pseudo-velocity response. Variability on the attenuation was included. The maps were published in an appendix to the 1991 NEHRP. A proposed method for determination of equivalent lateral force using the maps was included for trial use and evaluation.
1993	*National Building Code*, 1993	A_a, A_v	NA	See comment.	Based on 1991 NEHRP Provisions. One addition contour was added and specific spot values of ground motion were included for interpolation purposes.
1994	*Standard Building Code*, 1994	A_a, A_v	NA	See comment.	Based on 1991 NEHRP Provisions with only minor differences.
1994	American Society of Civil Engineers, 1994	A_a, A_v	NA	See comment.	Same maps as in the 1978 ATC 3-06 Provisions. An alternate approach, based on the 1991 USGS maps, was provided in an appendix for trial use. (BSSC, 1986)Based on 1991 NEHRP Provisions. Two notable differences are that the ground motions are increased in Oregon and Washington and spot values of ground motion are included for interpolation purposes.

Table D1 continued. Chronology of Probabilistic Maps

Use of Probabilistic Ground Motion Maps in Building Codes and Related Documents					
Date	Publication (see reference list for complete citation)	Parameter(s) Mapped	Exposure Time(s) Mapped, years	Basis of Map	Comments
1994	Building Seismic Safety Council, 1995	A_a, A_v	NA	See comment.	Same maps as in the 1978 ATC 3-06 Provisions. It is anticipated that the maps will be included in a commentary, along with several other proposed maps, but design information will not be included.
		$S_{A(0.3)}$, $S_{A(1.0)}$	50 250	10% probability of being exceeded in the mapped exposure times.	Probabilistic maps for spectral response acceleration for 0.3 and 1.0 sec periods. The maps were published in an appendix to the 1994 NEHRP. The maps differed from the 1991 maps by modifying the Pacific Northwest.
1994	UBC (1994)	Zones	NA	See comment.	This is a zone map based originally on the A_v map in the 1978 ATC 3-06 and the 1991 NEHRP. The zone coefficients are linked with detailing requirements and differ from contour values on the original maps. Specific contours differ somewhat in the western states. The map was originally introduced in 1988. The 1994 map differs primarily with increased ground motion in Oregon and Washington.
1996	USGS	This effort is still in progress and thus these data are not yet determined. It is anticipated that probabilistic maps for several exposure times will be prepared for at least PGA and several spectral response values for a short and long period.			

PGA	Peak acceleration as a percent (or fraction) of gravity
PGV	Peak velocity cm/sec
A_a	Effective peak acceleration coefficient as a fraction of gravity A_v
A_v	Effective peak velocity-related acceleration coefficient as a fraction of gravity
$S_{A(0.3)}$	Spectral response acceleration at 0.3 sec as a percent (or fraction) of gravity
$S_{A(1.0)}$	Spectral response acceleration at 0.3 sec as a percent (or fraction) of gravity

Table D1 continued. Chronology of Probabilistic Maps

APPENDIX E - BASIS OF MAPS

Hazard Model used for the Spectral Ordinate Maps

The calculation of ground motion is based on the assumption that earthquakes are distributed exponentially 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 observations. 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 by clustering may depart significantly from a Poisson process. 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.

The seismic source zones, rates, and the magnitude distribution of earthquakes within each source zone that were used to prepare the "1991 spectral ordinate maps" are the same as those used to prepare the peak ground motion maps in *Probabilistic Earthquake Acceleration and Velocity Maps for the United States and Puerto Rico* (Algermissen and others, 1990). A complete description of the source zones and rates used in the preparing the 1990 peak value maps has been published by Hanson and Perkins (1995). In order to illustrate the level of detail involved in the source zones, the maps of the zones are included at the end of this appendix. It is necessary to refer to Hanson and Perkins to obtain other needed information such as coordinates, rates, and magnitudes.

The only difference between the 1991 and 1994 spectral ordinate maps is the treatment of the Cascadia subduction zone. The 1991 maps modeled the Cascadia subduction zone as a magnitude 8.5 earthquake occurring on the average about once every 500 years somewhere on the subduction zone. This event was modeled as a rupture 200 km long by 100 km wide occurring on a zone 1000 km long by 100 km wide. Comparison of the 0.3 sec spectral response acceleration, versus exposure time with and without a subduction zone showed that there was little effect in Seattle, which is removed from the subduction zone. The effect due west from Seattle on the coast was significant (Algermissen and Leyendecker, 1992). Instead the response at Seattle is governed by crustal sources modeled in the vicinity of the city.

Since preparation of the 1991 maps, geologists have discovered additional information supporting occurrence of large Cascadia subduction zone earthquakes off the coast of Washington and Oregon. Because of this, Perkins (1993) studied additional modeling scenarios for the 1994 maps. In addition to the minimal interpretation described above (for the 1991 maps), he examined two additional interpretations referred to here as an intermediate case and a worst case. The intermediate case assumes that the 100 km by 1000 km subduction zone is covered by magnitude 8.5 ruptures once every 500 years. This assumption quintuples the seismic rate on the zone. The scenario produces a significant increase in hazard for sites within 60 km of the coast, roughly doubling probabilistic ground motions for the northern Oregon coast and increasing those on the Washington coast by about 70 percent . However, because of the continuing domination of local sources, probabilistic response at Seattle is not appreciably increased, and the response at Portland is increased by only 25 percent.

As a worst case model Perkins assumed that a magnitude 9.2 event ruptures the entire subduction interface zone once every 500 years. In this case, the ground-motion hazard over the western two-thirds of Washington and Oregon is dominated by the subduction zone. Response in the central regions of these states increases almost 70 percent over that of the mediating case, but there is little increase in ground motion hazard over the intermediate case for the coastal portions.

The intermediate case was selected for the 1994 maps. Since this is the only difference between the 1991 and 1994 maps, the maps differ only in the Pacific Northwest.

The procedure used in calculating the hazard is described in detail in the report *Probabilistic Estimates of Maximum Acceleration and Velocity in Rock in the Contiguous United States* (Algermissen and others, 1982). The hazard analysis computer program is described in detail in the report *SEISRISK III: A Computer Program for Seismic Hazard Estimation* (Bender and Perkins, 1987).

Ground-Motion Attenuation

The spectral ordinates are based on different attenuation equations for different areas of the United States as shown in Figure D1. For example, the attenuation of spectral-response acceleration (S_A) for the western United States (west of the eastern front of the Rocky Mountains) is that of Joyner and Boore (1982); it allows development of response spectra using for twelve periods ranging from 0.1 to 4.0 seconds. Equation E.1 shows the general form of the attenuation function for computing spectral response velocity.

$$\log y = a + b(M-6) + c(M-6)^2 + d\log r + kr + \sigma \qquad \text{(E.1)}$$

where

y = ground-motion parameter to be predicted
M = moment magnitude
a, b, c, d, k = coefficients in Table *E1*
s = soil site correction coefficients in Table *E1*, for use at sites with 5 m or more of soil
$r = \sqrt{r_o^2 + h^2}$
r_o^2 = shortest distance from the site to the vertical projection of the earthquake rupture on the surface of the earth, km
h = coefficients in Table *E1*
σ = standard deviations in Table *E1*

Table E1 contains the coefficients for use with Equation 1 for each parameter. Thus, each ground motion parameter is predicted by a specific attenuation equation. Each spectral ordinate uses a different equations. Thus a response spectrum can be determined directly rather than by attempting to construct one based on some statistical relationship with peak ground acceleration as has been commonly done in the past.

Spectral response acceleration is then determined from spectral response velocity obtained from Equation 1 by using equation E.2 (see for example, Chopra, 1980).

$$S_A = \frac{2\pi}{T} y \left(\frac{1}{g} \right) \tag{E.2}$$

where

S_A = spectral response acceleration, as a fraction of gravity
y = spectral response velocity from equation 1, cm/sec
T = period corresponding to the spectral response velocity, sec
g = acceleration of gravity, cm/sec^2

The attenuation of spectral acceleration for the central and eastern United States (east of the eastern front of the Rocky Mountains, Figure E1) is that of Boore and Joyner (1991); it allows development of response spectra for 13 different periods - .05 sec plus the same periods as shown in Table E1. In this case, as suggested by the authors, the variability used is that of Joyner and Boore (1982) as shown in Table E1.

In the Pacific Northwest, the spectral-response acceleration attenuation used for the subduction zone and intraplate earthquakes is that given by Youngs and Coppersmith (1989); it allows development of response spectral ordinates for periods of 0.1, 0.2, 0.3, 0.5, 1.0, and 2.0 seconds. The attenuation of shallow earthquakes in this region was modeled using the previously described relation developed by Joyner and Boore (1982), the same attenuation used for shallow earthquakes throughout the rest of the western United States.

Although other attenuation functions might have been used, these were selected because they have a similar background and have enough spectral ordinates available so that a reasonable study of spectral shapes could be made. They had also been subject to peer review.

Period, T (sec)	a	b	c	h	d	k	s	σ
Pseudo velocity response, cm/sec								
0.1	2.16	0.25	-0.06	11.3	-1.0	-0.0073	-0.02	0.28
0.15	2.40	0.30	-0.08	10.8	-1.0	-0.0067	-0.02	0.28
0.2	2.46	0.35	-0.09	9.6	-1.0	-0.0063	-0.01	0.28
0.3	2.47	0.42	-0.11	6.9	-1.0	-0.0058	0.04	0.28
0.4	2.44	0.47	-0.13	5.7	-1.0	-0.0054	0.10	0.31
0.5	2.41	0.52	-0.14	5.1	-1.0	-0.0051	0.14	0.33
0.75	2.34	0.60	-0.16	4.8	-1.0	-0.0045	0.23	0.33
1.0	2.28	0.67	-0.17	4.7	-1.0	-0.0039	0.27	0.33
1.5	2.19	0.74	-0.19	4.7	-1.0	-0.0026	0.31	0.33
2.0	2.12	0.79	-0.20	4.7	-1.0	-0.0015	0.32	0.33
3.0	2.02	0.85	-0.22	4.7	-0.98	0.0	0.32	0.33
4.0	1.96	0.88	-0.24	4.7	-0.95	0.0	0.29	0.33
Peak acceleration, cm/sec^2								
-	0.43	0.23	0.0	8.0	-1.0	-0.0027	0.0	0.28

Table E1. Parameters in the predictive equations of Joyner and Boore (1982) for the randomly oriented horizontal component of pseudo velocity response (cm/sec) at 5 percent damping and for peak acceleration.

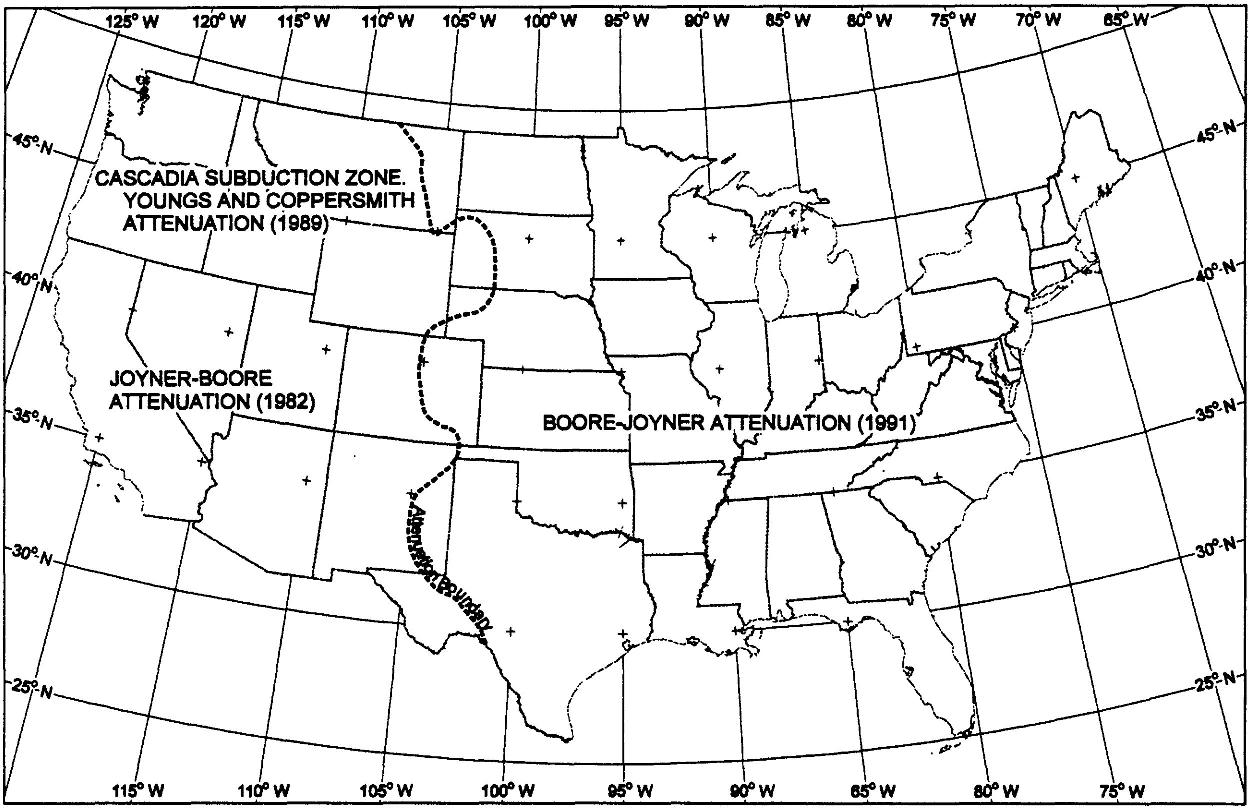


Figure E1. Location of the attenuation boundary between east and west. The Boore-Joyner attenuation (1982) is used for all sources west of the boundary except for the Pacific northwest. In the Pacific northwest, the Youngs and Coppersmith (1989) attenuation is used for the Cascadia subduction zone and intraplate earthquakes. However, the Joyner-Boore (1982) attenuation is used for shallow earthquakes in the Pacific northwest.

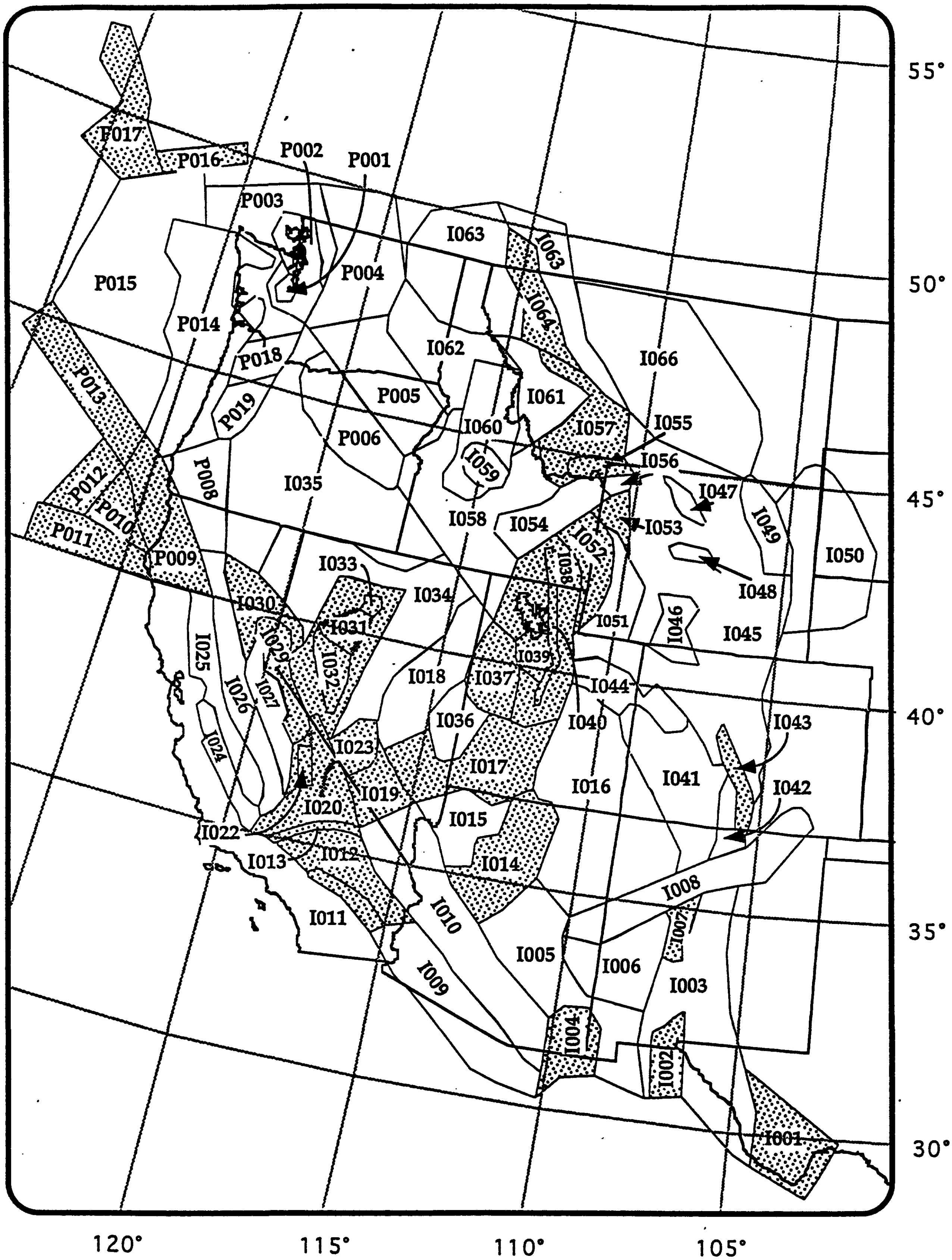


Figure E2. Pacific Northwest and Rocky Mountain region source zones with those areas that were also modeled using line sources, shown as shaded areas. From Hanson and Perkins (1995).

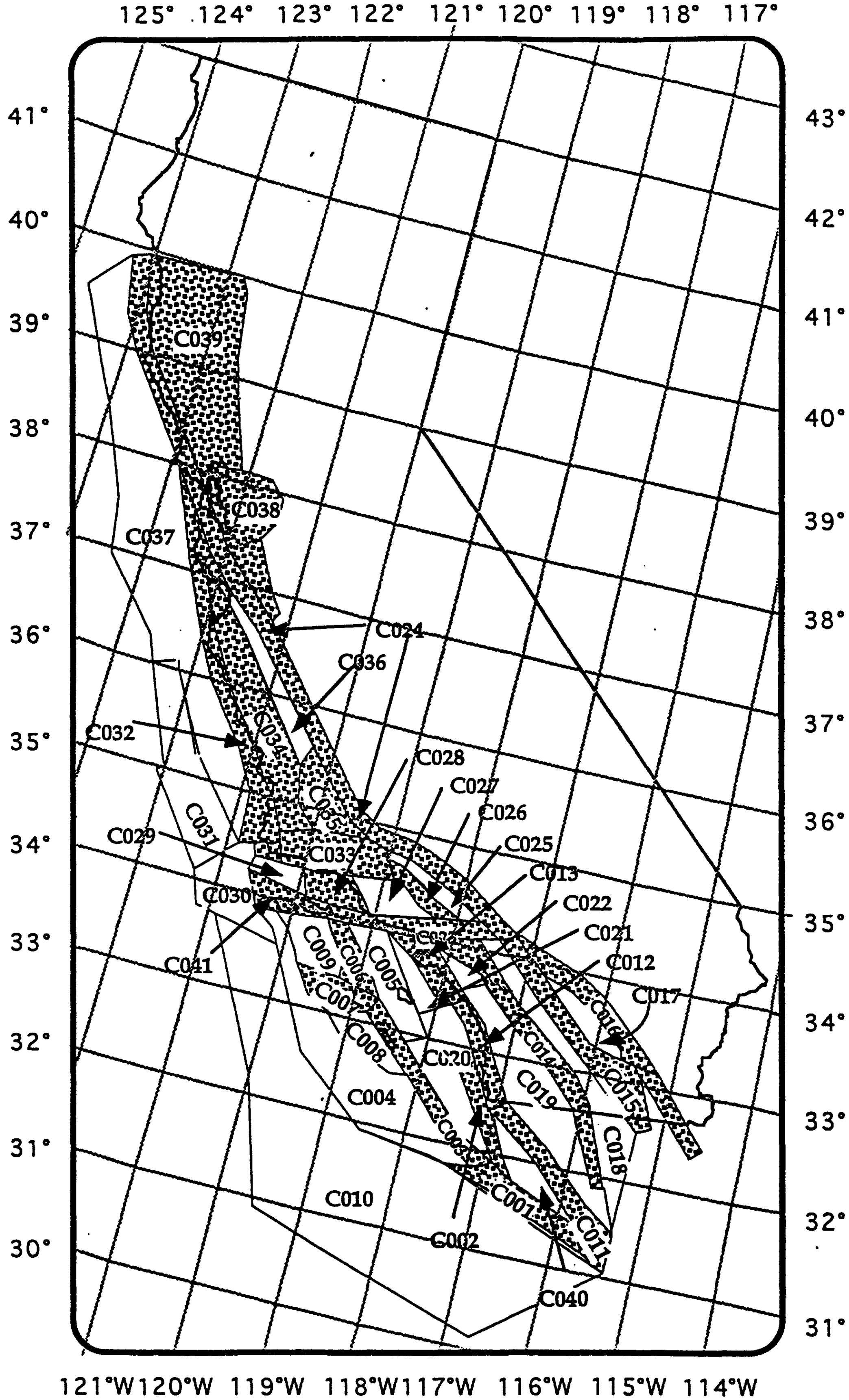


Figure E3. California source zones, with those shaded areas in which line sources were used to model finite ruptures for larger magnitude earthquakes. From Hanson and Perkins (1995).

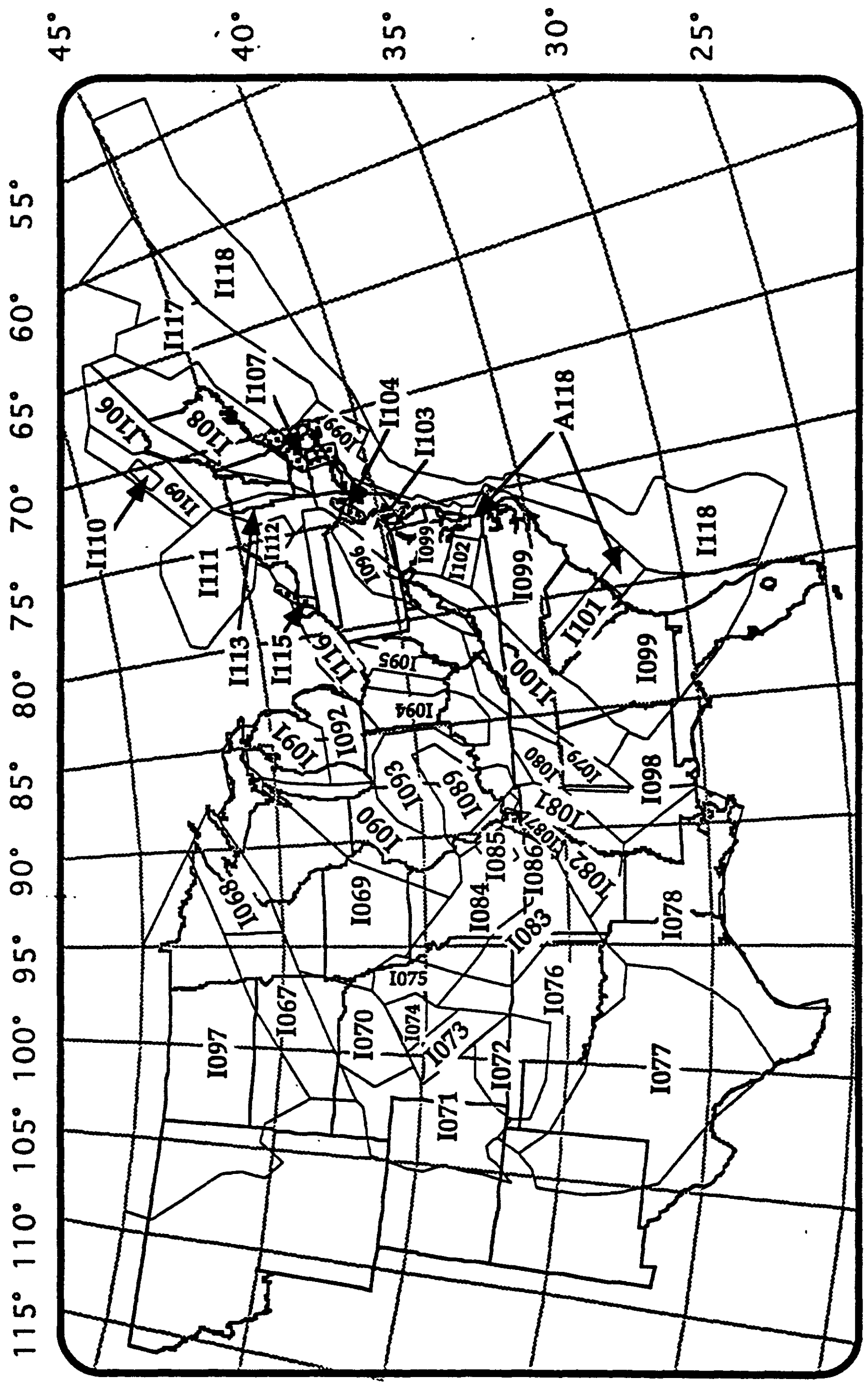


Figure E4. Central and Eastern U.S. source zones, with those areas that were also modeled using line sources shown as shaded areas. From Hanson and Perkins (1995).