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Probabilistic Estimates of Maximum Seismic Horizontal Ground Motion on Rock in the Pacific Northwest and the Adjacent Outer Continental Shelf

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ABSTRACT

Regional seismic hazard assessment of western Washington , Oregon and northwestern California and the adjacent Outer Continental Shelf is shown in a series of three peak horizontal acceleration maps and peak horizontal velocity maps for return-periods of 100, 500 and 2500 years. The mapped ground motions have a 90 percent probability of of not being exceeded in the corresponding exposure times of approximately 10, 50 and 250 years.

Descrimination of 19 seismogenic zones is made through a method that integrates historic seismicity with available geologic information. The seismogenic zones as defined are broad in character reflecting the current lack of knowledge concerning specific seismotectonic structures in the region.

Because many of the seismogenic zones do not have a sufficient number of earthquakes to make a reliable estimate of the underlying rates of seismic activity, all the

seismogenic zones were combined into one of five groups. The appropriate group was determined by contiguousness and general tectonic character. Procedures for determining seismicity parameters are those used by Algermissen and Perkins (1976).

The 100-year return-period acceleration map shows values between 4 percent g or less in the Washington Outer Continental Shelf and 49 percent g along the Mendocino Fracture Zone offshore of California. The 2,500-year return-period acceleration map shows values as high as 82 percent g along the northern San Andreas fault. Generally, where there is a low level of seismic activity, the accelerations double with a five-fold increase of return period. However, in the extremely active areas, a five-fold increase in return period increases the accelerations by a factor significantly smaller than two. As a function of return period, the increase in values on the velocity maps behave in the same manner.

INTRODUCTION

This report presents probabilistic estimates of extreme earthquake ground motions on rock in the Pacific Northwest OCS (Outer Continental Shelf). The estimates are presented in six maps (plates 2, 3, 4, 5, 6, and 7) at a scale of 1:2,500,000. The maps show peak horizontal ground acceleration and peak horizontal velocity on rock that has a 90.5% probability of not being exceeded in 10 years, 50 years, and 250 years, respectively. The corresponding return periods are 100 years, 500 years, and 2500 years.

The theory and methods used by Algermissen and Perkins (1976) in their acceleration map of the contiguous United States are generally followed in this study, with one modification: this study places greater emphasis on geologic factors in defining seismogenic zones.

The earthquake catalog compiled by Algermissen and Rothman and partially listed in Hays and others (1975) has been the source of earthquake data. Offshore, the catalog has been supplemented by data from the National Oceanic and Atmospheric Administration, Environmental Data Service. The combined catalog contains historic and instrumental seismicity dating from 1796 through 1974 in the Pacific Northwest.

AN APPROACH TO SEISMOGENIC ZONING

The earthquake hazard for the Pacific Northwest has been addressed in several earlier nationwide studies (Roberts and Ulrich, 1950; Algermissen, 1969; Algermissen and Perkins, 1976). Common to these studies is the defining of seismic source zones on the areal distribution of historic earthquake activity. Because the probabilistic method used in this study models earthquakes at a set of grid points within the source zones (Algermissen and Perkins, 1976), it seems more desirable to model events in areas of similar tectonic and geologic setting rather than in zones that are defined solely on the spatial distribution of seismicity. The assumptions implied by this preferred type of zoning form the definition of what we call seismogenic zoning. A seismogenic zone, as it appears on a map, is a planimetric representation of a three-dimensional domain within the Earth's crust. Each zone is assumed to have uniform earthquake potential; that is, earthquakes are randomly distributed throughout the zone and they share the same frequency-magnitude relationship.

In developing the seismogenic zones of the Pacific Northwest, we use an approach which is essentially the integration of two different methods. The first method depends predominantly on historic seismic activity to develop a zoning rationale. The basis for using historical epicenters for zoning is twofold: a) A resulting probabilistic ground motion map is face-valid in that it predicts likely future ground motions solely on the activity of the past. It is not unreasonable to expect the future activity to resemble that of the near past. b) In regions of poorly determined tectonics, the epicentral patterns suggest trends that may be representative of underlying unknown structural seismogenic features. The biases of seismicity-based zoning stem from shortcomings inherent in any earthquake catalog. These shortcomings are: relative briefness of seismic history as compared to the recurrence of large earthquakes, variations in the length of time that historic seismicity has been recorded owing to the nonuniform distribution of population with time; inaccurate locations of large- and medium-sized earthquakes (see for example Thenhaus, 1978); and the complete omission of many small earthquakes. In particular, because of these shortcomings, zoning on epicentral patterns alone may have the consequence of producing low hazard estimates for areas situated on what appears to be a currently aseismic section of a structural trend along which there are areas of higher seismicity. This is not prudent in areas where the seismotectonics are poorly understood, as in the Pacific Northwest.

The second method addresses the zoning problem from a geological point of view. The value of using geological evidence is that currently aseismic areas can be identified as areas of potential activity if they lie along or within structural trends that have historic seismicity at some distance removed from these areas of inactivity. Also, because the zones are defined on the basis of similar geologic character, one can transfer b-values and maximum magnitudes from active to inactive zones by analogy of physical setting. Zoning entirely on the basis of geologic evidence, however, is not flexible enough to be applied as a consistent rationale within various regions of interest. Throughout most of the United States, causes of earthquakes are not known; consequently, any attempt to relate all seismicity to physical models for the purpose of geological zoning would base entire probabilistic hazard studies on speculative theories concerning the seismotectonics of the area.

SEISMOGENIC ZONING METHOD

ZONING BASED UPON HISTORIC SEISMICITY

The seismic source zones used for Washington and Oregon by Algermissen and Perkins (1976) are shown in figure 1. The zones are based on historic activity and reflect both the relative density of epicenters and the variation in observed maximum magnitude. The zones also bear a remarkable resemblance to the strain release map, of Algermissen (1969). Unfortunately, the zones truncate structural geologic trends that are generally on strike with the source zones as defined. As a result, maximum magnitudes deemed credible within the zones are not recognized as credible events along the length of a geologic structural trend. In view of our lack of understanding of the tectonic setting in the Pacific Northwest, it is judicious, when modelling seismicity, to allow maximum magnitude events to occur along continuous structural trends or in areas of similar geologic or tectonic setting.

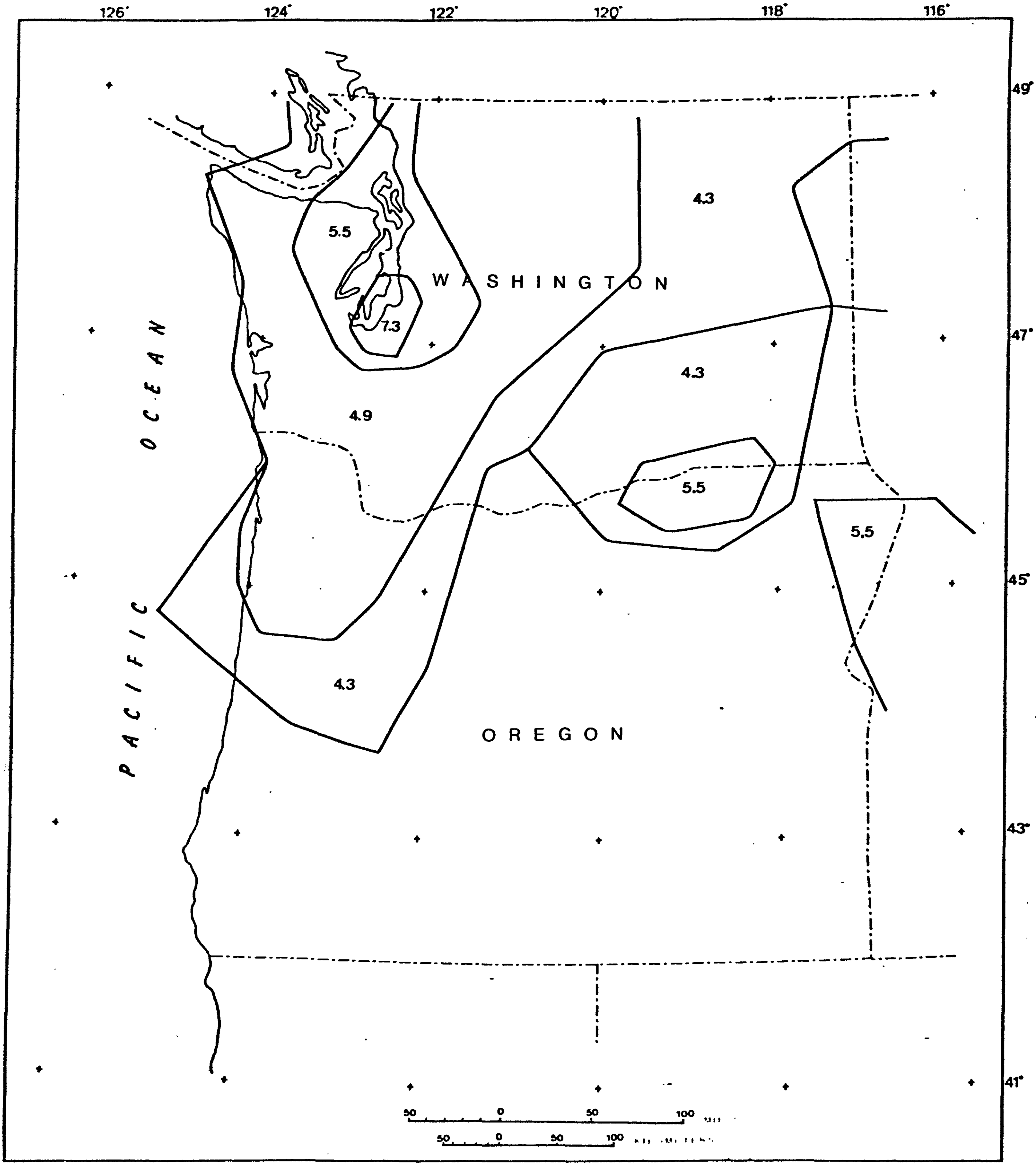

Figure 1.--Seismic Source Zones for Washington and Oregon (modified from Algermissen and Perkins, 1976). Numbers within zone boundaries are maximum magnitudes (M_c) assigned by Algermissen and Perkins (1976).

In developing zones based on seismicity, spatial character of the epicenters is of primary importance. The first method used in examining the spatial character of the historic seismicity is shown in figure 2. Using as a radius the average distance between epicenters of equal intensity, circles are drawn around the epicenters. The result is a "bubble map" showing the least common events (that is, the largest ones) with the largest circles. These largest events would be expected to aline with major structural trends, whereas the smaller events would be expected to confirm the major trends and to also indicate areas of more diffuse background seismicity. Notable features of this display of historic seismicity are:

1. a sharp contrast in the areal rate and distribution of seismicity between the areas east and west of the crest of the Cascade Range,

2. strong northwest epicenter trends in Washington with some trends having possible continuations into eastern Oregon,

3. less pronounced northeast epicenter trends in western Oregon, and

4. coincidence of seismicity with the Puget Sound-Willamette depression.

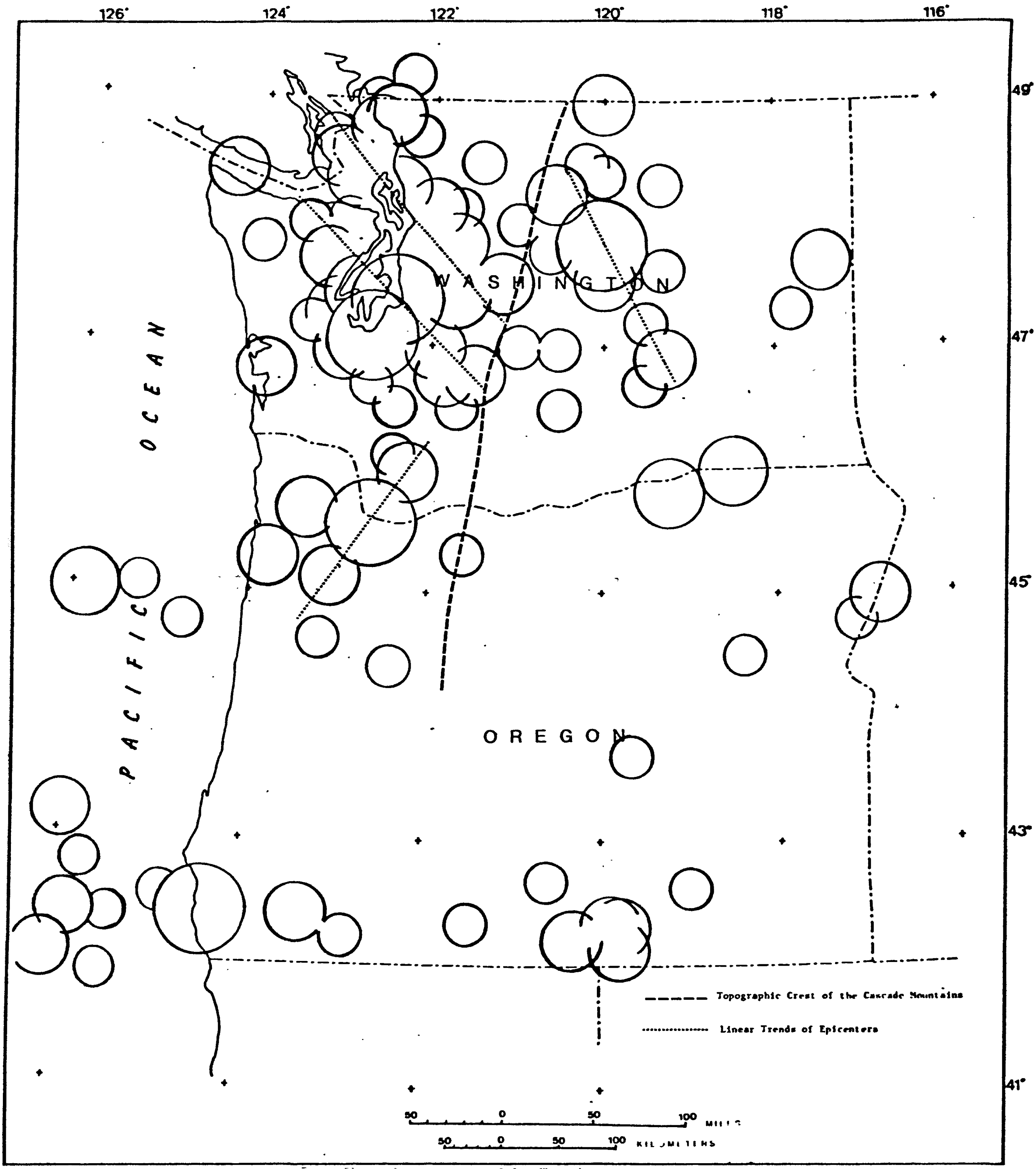

Figure 2.--"Bubble" map representing spatial distribution of historic seismicity. Largest circles represent largest, or least common, events.

A second method of examining spatial distribution of historic seismicity is to normalize the events to intensity VI. This is done by arbitrarily assigning a measure of 1 to an intensity VI event. Events of intensity I' greater-than or less-than intensity VI are assigned values of an equivalent number of intensity VI's that would be obtained from the intensity VI intercept of a line on a log-frequency versus intensity graph going through the point (N,I) = (1,I'). Summing these values, using an equal-area counting net adapted to an Albers-equal-area projection, produces on a map a grid of numbers that represent the equivalent number of intensity VI earthquakes occurring near the grid points. A contoured version of such a map of Washington and Oregon is shown in figure 3. Primary features of this map show:

1. a contrast in the spatial distribution of earthquake activity east and west of the crest of the Cascade Range,

2. a northeast-trending zone of activity that extends from the south end of the Willamette depression in Oregon through southwestern Washington where it merges with the activity southeast of Puget Sound,

3. a northwest trend of clusters of activity that extends through northeastern Oregon and south-eastern Washington; the trend becomes more north-south oriented just east of the Cascade Range, and

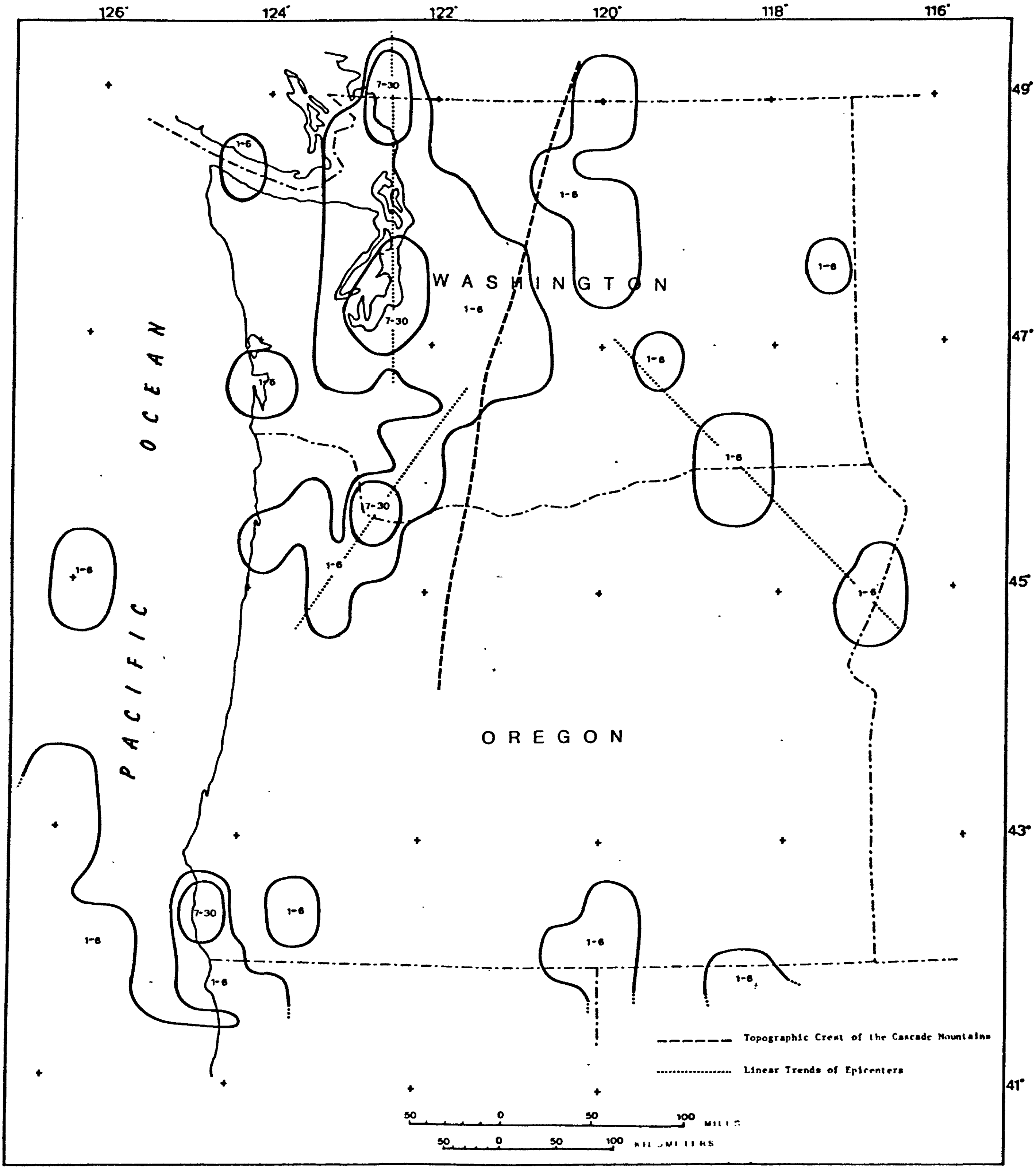

Figure 3.--Map representing regional seismicity in terms of equivalent number of intensity VI events as smoothed by a counting grid. Contours enclose those areas that have experienced the equivalent of 1 to 6 and 7 to 30 equivalent intensity VI events.

4. a strong north-south trend that is coincident with the Puget Sound area.

ZONING BASED ON GEOLOGY

A first-cut attempt at zoning the Pacific Northwest in terms of a geological approach is shown in figure 4. As can be seen, the map is primarily based on regional physiography with a few boundaries being defined by seismicity. The concept behind using physiography as the basis for zoning is a valid one in terms of seismogenic zoning because typically, a physiographic province has generally similar geologic structure throughout its area. The concept presupposes a physical model in which both physiography and seismicity are controlled by an underlying tectonic cause. This controlling association in the Puget Sound area, and its extension to the south (fig. 4), is confirmed by the features noted as points (1) and (4) on the lists derived from the two seismicity maps (figs. 2 and 3). The primary objection to the map of figure 4 is that it does not reflect the trends seen in the seismicity outside of the Puget Sound area and the Willamette Depression. A secondary, more general, objection is that such a map, with emphasis on bedrock geology, does not reflect continuation of geologic structure at depth. To correct these deficiencies of the map, we attempted several refinements. Quaternary volcanic rocks, Tertiary intrusives and basins having Quaternary alluviation are shown in figure 5. Also shown in figure 5 is a generalized version of the maps of seismicity clusters seen in figures 2 and 3. An apparent regional correlation exists between the seismicity and these geologic features. An outline enclosing these geologic features and the epicenter clusters is shown in figure 6. The primary objection to using figure 6 as a seismogenic zone map is that, in a broad regional sense, the epicenter clusters truncate geologic structural trends which might reasonably be inferred to be continuous.

The final consensus result of the progressive refinement of physiographic province maps and seismicity maps is shown in Plate 1. In the Puget Sound area and its extension to the south, certain boundaries have been made to coincide with the maximum gradient in Bouguer gravity anomaly in order to more accurately represent the zone in the Earth's crust. Also, within the province, seismicity boundaries have been used so as not to decrease the areal rate of persistent historic activity. Interestingly, the broadening of this province to the west in the south and to the east in the north (in order to encompass neighboring seismicity) coincides with the location of Tertiary intrusives in these areas.

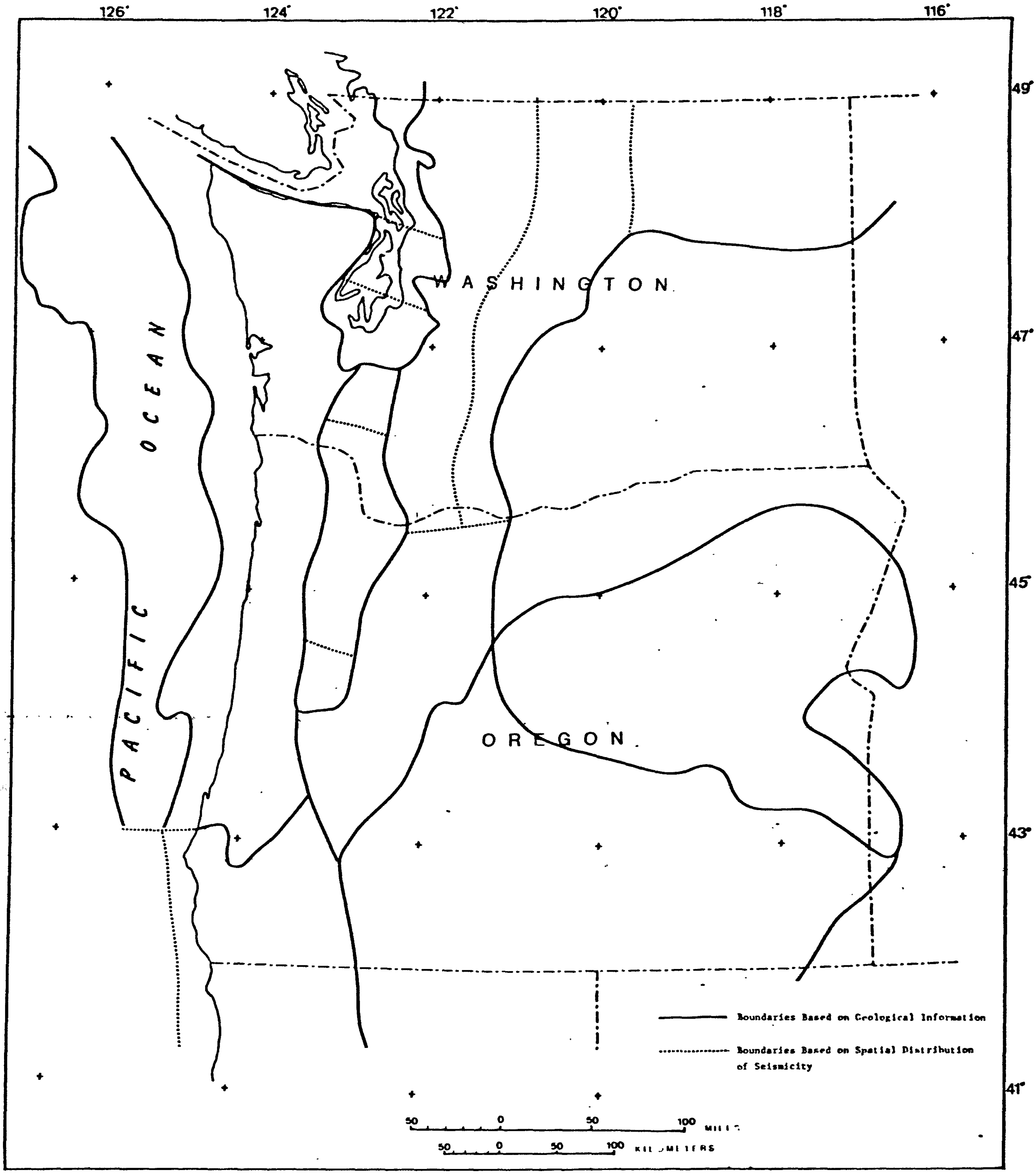

Figure 4.--First-cut attempt at a geological zoning scheme for the Pacific Northwest.

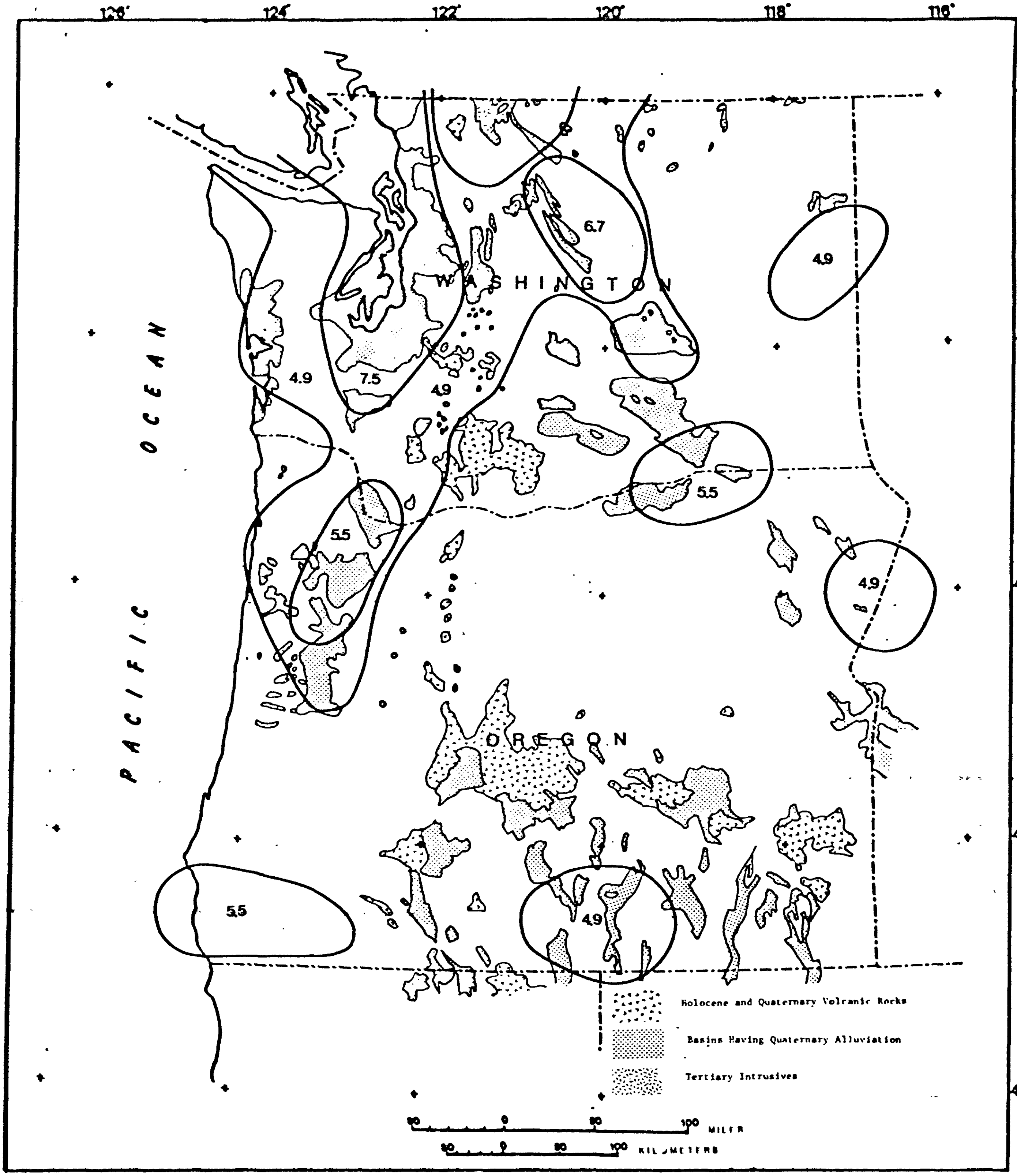

Figure 5.--Map of selected geological features in the Pacific Northwest (modified from King and Beikman, 1974) overlain by a generalized scheme of earthquake distributions from figures 1 and 2. Numbers indicate the magnitude of the largest event observed historically.

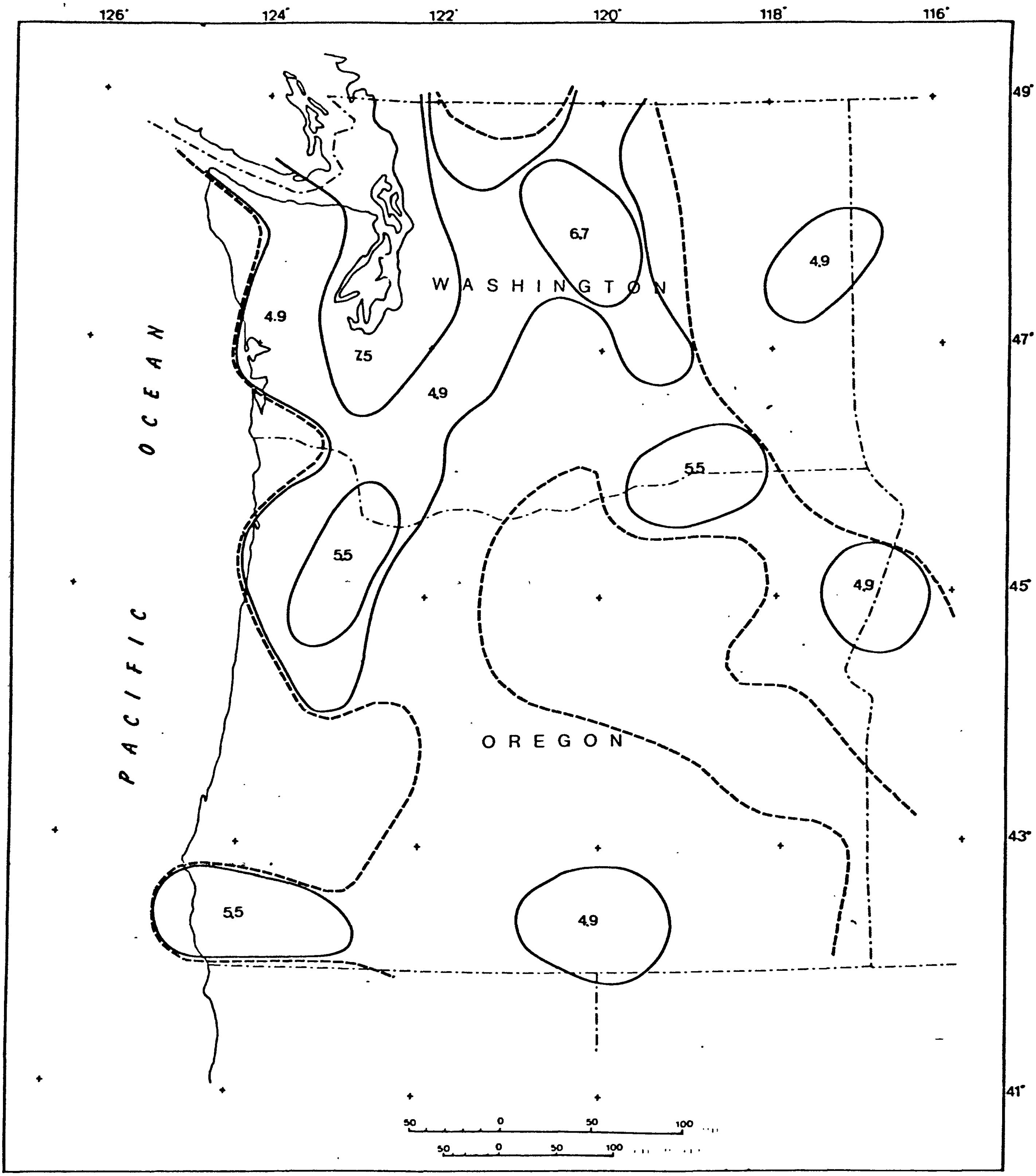

Figure 6.--Map showing a zoning scheme incorporating geological information and historic seismicity. Dashed lines enclose the geologic features of figure 5.

In the eastern half of Plate 1, the northeast boundary of the basin and range zone (zone 7, pl. 1) is Based on the Bouguer gravity change between the Basin and Range physiographic province and the Blue Mountains. An abrupt termination of Quaternary volcanism (Walker, 1973) and Basin and Range tectonic style occurs north of the boundary. Within the Basin and Range zone are three major zones of right-lateral shear trending to the northwest (Lawrence, 1976). The southern two shear zones offset the crest of the high Cascades by 10 to 20 km, whereas the northern shear zone (Brothers fault zone) does not extend that far to the northwest. The shear zones were not separated into individual seismogenic zones because it is not entirely clear whether the shear zones or the ubiquitous north-trending normal faults (the typical seismogenic feature farther to the south) are controlling the diffuse regional seismicity.

The northwest-trending zone across the Blue Mountains (zone 6) emerges as a distinct seismogenic zone when boundaries of the neighboring zones are established. Characteristic of zone 6, when compared to neighboring zones, is its relatively aseismic state and notable lack of Quaternary volcanism and its lack of large basins having Quaternary alluviation.

To the north of zone 6 is a second northwest-trending zone (zone 5). Northwest-trending, en echelon faulting, folding, and large basins of Quaternary alluviation (Newcomb, 1970) are the geological features typifying zone 5 (fig. 5 and plate 1). Lawrence (1976) located the northernmost of the northwest-trending shear zones in the Oregon segment of zone 5. This shear, estimated to have several kilometers of displacement, is on strike with other northwest-trending features that define the seismogenic zone. In Lawrence's report he referenced an oral communication in 1974 from Bowen and Fisher who indicate a drop in regional heat flow across the shear zone. The northwest-trending Olympic-Wallowa lineament also lies within zone 5 and is expressed by the en echelon faults and folds. Skehan (1965) attributed the lineament to a juxtaposition of continental crust (to the north) and oceanic crust (to the south). He also related the lineament to a northwest trend in seismic activity, and noted fault scarps of Pleistocene or Holocene age. We have not delineated the lineament as a seismogenic structure in itself because of the current vague understanding of the neotectonics of the area; rather, we include it as a component in a suite of geologic features that serve to define the seismogenic zone. The zone coincides with the northwesterly seismicity trend discussed previously.

The Cascade Range was not treated as a seismogenic zone in itself. The low incidence of seismicity in the southern Cascades (Westhusing, 1973) as opposed to the higher level of activity in the northern Cascades (figs. 2 and 3) and the fact that the spatial character of seismicity differs from east to west in the northern Cascades provide no clear evidence that the Cascade Range is a distinctive seismogenic zone. The southern Cascades have been included in the basin and range seismogenic zone based on the occurrence of Holocene and Quaternary volcanism in both regions. Also, two northwest-trending major shear zones extending from the Basin and Range offset the Pleistocene-to-Holocene trend of the high Cascades by 10 to 20 km (Lawrence, 1976). The implication is that the north-trending mountain range in itself may not be significant feature in the seismotectonic pattern.

In the Pacific Northwest OCS area (zone 14), the distinction between continental slope and the continental shelf has been eliminated. Although geological information indicates that the shelf and upper slope are characterized by north- to northwest-trending folds, whereas the lower slope is dominated by large-scale faulting (Spigai, 1971; Kulm and Fowler, 1974; Snavely and others, 1977), the lack of seismic activity precludes seismic-parameter distinction in the area. More detailed zones have been added to the northern California-southern Oregon offshore area (pl. 1) defining the Mendicino and Blanco fracture zones and the Gorda ridge (Dehlinger, and others, 1968; Silver, 1971; Phipps, 1974). The potentially large earthquakes on these features could have some effect on shaking on the Pacific Northwest OCS. In the Northern California OCS area, Hopper and others (1975) related a northwest seismicity trend across the Gorda basin (within our zone 9) to a new stage in the deformation of the Juan de Fuca plate. Recently, Herd (1978) has inferred the northwest-trending en echelon faults contained in zone 9 to be a continuation of the Hayward-Lake Mountain fault zones farther to the south. Zone 9 closely coincides with what Herd (1978) has called the Humboldt plate. Our zone truncates the extreme western edge of the inferred plate off Mendocino, owing to our reliance on seismic activity to define the Mendocino fracture zone.

The farthest northwest zone (zone 17) groups epicenters that occur near the Sovanco Fracture Zone, Paul Revere Ridge, and Winona Ridge (Pacific Geoscience Centre, 1978). A thin rectangular zone (zone 16) extends northeast from the base of zone 17. Zone 16 serves to locate a number of epicenters in line with a conjectural Juan de Fuca-America plate boundary (Barr, 1974). To the south, zone 15 represents the diffuse seismicity of the Juan de Fuca plate. To the east, the northern parts of zones 3 and 14 mark seismicity boundaries.

The controversial subject of subduction in the Pacific Northwest has not been addressed in our zoning scheme. Riddihough (1977, 1978), Riddihough and Hyndman (1977), Kulm and Fowler (1974), and Atwater (1970), among others, provided geophysical, stratigraphic, or tectonic arguments as to why present-day subduction should be occurring in the northwest; however, seismological (Crosson, 1972; Hill, 1978), petrologic (White and McBirney, 1978), and tectonic evidence (Stacy, 1973) argue against present-day subduction. Because of the paucity of seismicity along coastal Washington and Oregon and the neighboring OCS, the controversy has little bearing on the zoning of most of the region. Owing to the lack of seismicity in the past, regardless of the zones adopted, the ground motions will be relatively low. To substantially increase the ground motions over what the historic rates indicate, would be unreasonable in light of the confused tectonic picture. The subduction question is of importance to the Puget Sound area because of the relatively deep earthquakes that have occurred in the area; however, until more information comes to bear on the tectonic model of the Puget Sound area, we feel that continuing to zone the area based on the historic seismicity will reasonably portray the hazard for the area.

DETERMINING ANNUAL RATES OF OCCURRENCE

Annual rates of occurrence for the magnitude intervals shown in table 1 were derived from the observed historical seismic activity. Because many of the seismogenic zones do not have a sufficient number of earthquakes to make reliable estimate of the underlying rates of activity, all seismogenic zones were combined into one of five groups. The appropriate group was determined by contiguousness and general tectonic framework. Thus, the central two Puget Sound zones were combined (zones 1 and 2, pl.1) into one group; the remaining Puget Sound zones were placed in another group (zones 3, 18, and 19); the four zones east of the Puget Sound zones were combined into a third group (zones 4, 5, 6, and 7); the zones between Puget Sound and the active plate boundaries constituted a fourth group (zones 8, 14, 15, and 16); and, finally, the active plate boundary zones made up the fifth group (zones 9, 10, 11, 12, 13, and 17). These latter six zones each had enough historical earthquakes for independent determination of the seismic parameters but because the individual b-values were so similar, it was decided to combine them so that they all would share the same b-value.

For each group a table was constructed showing the observed number of earthquakes for each magnitude range during each decade, going back to the first decade in which an earthquake was observed in the group. For each magnitude range an annual rate of occurrence was determined by the average of the values from two methods. In the first method, one estimates the number of decades (beginning from the present and going into the past) for which the earthquakes are completely reported. The historical rate is then the total number of earthquakes during these decades, divided by the total number of years in this time span. The second method of determining annual rates is fundamentally the same as the first, except that the second method uses a technique published by Stepp (1972) to display the trend and variability of the decade rates as they are averaged backward in time. The historical rates averaged from the two methods are then smoothed by fitting them to the relationship

$$\log N = a + b\,Ms$$

where N is the estimated annual rate of earthquakes occurring within the magnitude interval specified in table 1. Because the catalog largely consists of epicentral intensities, we used the relationship

$$Ms = 0.6\,Io + 1.3$$

to convert from epicentral intensity to magnitude. The resulting smoothed annual rates were then back-allocated to individual constituent zones so that the amount of seismic activity back-allocated was approximately equal to the proportion of the zone's original contribution of earthquake events to the combined smoothing process.

Even with the grouping, not all the groups had a sufficient number of earthquakes so that one could adopt the calculated a and b values. Our experiments with simulating earthquake data samples from a negative-exponential distribution of magnitude (the distribution implied by the Richter law) had shown that samples having fewer than 40 earthquakes yielded (on the average) low b-value estimates when compared to the actual b-value used in the negative-exponential simulation. Accordingly, for the group surrounding the central Puget Sound group and the group immediately to the west, we adopted b values 0.10 larger (in absolute value) than those derived in the smoothing process. Smoothed annual rates adopted for these two groups were derived from a weighted least-squares fit (with rates as weights) to the original observed annual rate estimates by a line having the adopted b-value. These group annual rates were then back-allocated as before.

MAXIMUM MAGNITUDES

In general, the largest earthquakes have been observed in our fifth group of zones (the plate boundary zones). There have been three earthquakes in the magnitude 7.0 to 7.6 category. No statistical case can be made for the impossibility of an earthquake larger than this, nor are we aware of a physical argument against such an earthquake. As there are several alinements of epicenters in some of these regions, it is possible that these represent structures capable of supporting larger magnitude earthquakes. Accordingly, in the fifth group of zones we have adopted maximum magnitudes in the 7.6 to 8.2 category.

For all the rest of the zones, we have adopted maximum magnitudes in the 7.0 to 7.6, intensity X, category, including zone 15, which contains the spreading center of the Juan de Fuca plate and which has experienced one earthquake in the 7.0 to 7.6 category. Zone 16 has experienced two in this category, and zone 1 has experienced one at depth. It is possible to interpret the December 14, 1872 north-central Washington earthquake as intensity X, possibly occurring at Lake Chelan in zone 4 (C. W. Stover, oral communication, 1978). In zone 14, faulting with offsets of 2 and 7 m have been found off the coast of Washington (Snavely and others, 1977). For the rest of the zones the 7.0 to 7.6 magnitude category is at least a magnitude unit above the observed maximum magnitude; however, the overall low seismicity for most zones does not allow us to come to a statistical conclusion about this absence of moderate-magnitude earthquakes.

MODELLING THE EARTHQUAKES

The maximum magnitude of 7.3, along with the generally low annual probabilities of these events, allowed us to model the earthquakes in the mapping procedure (see below) by point sources, except at the plate boundary zones. The basis for this approximation depends on the fact that low accelerations and velocities are produced at a great distance from the epicenter of large-magnitude earthquakes. The large area of the low-ground motion isoseismal is not significantly increased by making the earthquake source a line instead of a point, if the line is small compared to the isoseismal radius. A magnitude 7.3 event could be expected to have a linear source dimension in the low tens of kilometers, whereas accelerations of 10 percent g could be experienced at significantly larger radii from the source. Because the low seismicity rates of most of the zones result in low extreme ground motions at the return periods mapped, the assumption of a point source is an appropriate approximation.

For the plate boundary zones, where we have chosen a higher maximum magnitude and where the seismicity rates are quite high, we have had to provide linear faults rather than point sources to model earthquakes whose magnitudes are larger than Ms = 6.4. In zones 11 and 13, linear faults were arbitrary lines parallel to the strike of the zone and were separated by 30 km spacing. For zones 10, 12, and 17, the faults were placed parallel to the direction of epicenter trends. In zone 9, three faults were placed in the general direction of the strike of the zone, but alined so as to be extensions of fault trends of the abutting California zone.

In zones 1 and 2, earthquakes having magnitudes larger than 6.4 were assumed to occur at 50 km depth. The acceleration attenuation function used was derived from the surface attenuation functions of Schnabel and Seed (1973) by assuming a point source at 50 km depth and and by assuming that the two attenuation functions would be identical for the same hypocentral distances. One-quarter of the earthquakes greater than magnitude 6.4 were assumed to occur at the surface, in accordance with a proposal of Algermissen (oral communication, 1978) and the observance by Gower (1978) of Holocene surface faults west of Puget Sound. All earthquakes of magnitude less than 6.4 were assumed to lie at the surface.

MAPPING PROCEDURE

The acceleration mapping procedure (Algermissen and Perkins, 1976) distributes earthquakes uniformly throughout a source zone (for smaller magnitudes the distribution of earthquakes is uniform, but for larger magnitudes, earthquakes are represented as linear ruptures, located uniformly over all fault lines modelled in the zone). (The rupture length is given by the equation,

$$l = .00063\exp(1.52M_s),$$

from curve A of Wallace, 1970.) Then, at every point on a map grid, the accelerations produced by these earthquakes are calculated, using the California acceleration attenuation functions of Schnabel and Seed (1973). For the velocity maps, an interim velocity attenuation by Perkins, Harding and Harmsen (written communication, 1979) was used. These ground motions have the same annual occurrence rates as the magnitudes that produce them. The successive application of this elementary procedure for every possible earthquake location in the zone, for every magnitude at these locations, for every zone in the region, produces a histogram of acceleration (or velocity) occurrences at every map grid point. This histogram can be turned into a cumulative probability distribution, which then is used to calculate exceedance probabilities for various exposure times. Each map is the result of contouring the values of the ground motion at each grid point for a given probability of exceedance during a given exposure time. In this report we present maps showing accelerations and velocities having only a 9.5 percent probability of being exceeded in 10, 50, and 250 years. For convenience the maps (pls. 2-7) have been titled with their corresponding return periods (the inverse of annual rate of exceedance). The relationship between exceedance probability, r, of a ground motion value, m, in exposure time, T, and the return period, R, of ground motion, m, is given by the equation

$$1-r(m)=\exp(-t/R(m))$$

$$=\exp(-t\ (\text{annual rate of exceedance of } m))$$

A handy rule of thumb when $T < 0.1 (R(m))$ is

$$r(m)=T/R(m) \ .$$

GENERAL CHARACTER OF THE MAPS

1. The maps (pls. 2-7) are dominated by high ground motions in the plate boundary zones, especially near the coast of southern Oregon and northern California. Except for zone 9, ground motion values within the plate boundary

zones have been averaged, removing the ripple effect expected from the modelled faults. In zone 9, because we believe the modelled faults have a basis for existence at these locations, we have contoured the actual ground motion values plotted. The 500- and 2500-year maps show alternate but equally valid methods of contouring the results. The 2500-year map depicts an interpretation in which the major eastern fault of zone 9 could break across the border into zone 13. Both maps show the results of the assumption that the faults in zone 9 will not break over the southern boundary into the abutting California zone.

2. Earthquakes in the plate boundary zones do not shake significantly into the OCS of northern Oregon and Washington; ground motion levels here are governed by the low local seismic rate that has been assumed. In accordance with the fact that the continental slope and continental shelf were not distinguished by rate differences in the zoning, no hazard difference appears in the maps.

3. On shore, significant shaking is expected in the Puget Sound area, the area immediately to the east between Puget Sound and the crest of the Cascades, and in the historically active spot in the southern extension of the Puget Sound-Willamette depression around Portland, Oregon.

4. Detailed contours have not been attempted in the vicinity of zones in Canada. There is significant decrease in historical seismic activity at the north boundary of zone 3. It is unlikely, however, that alternative zonings of Canada in this vicinity will significantly change the map values in the United States.

A comparison of the 100- and 500-year return-period maps shows that in areas dominated by point sources a rough "rule-of-thumb" is present: an increase by a factor by five in return period roughly doubles the ground motion. This rule-of-thumb bespeaks a general insensitivity to minor changes in seismic rates in maps of this type. Also, in application to the design of structures, doubling the design ground motion reduces the likelihood, by a factor of five, that the design ground motion will be exceeded during the lifetime of a structure. In areas dominated by fault sources and in the comparison of the 2500- to 500-year return-period maps, the increase in ground motion is significantly less than double. This is due to the fact that maximum ground motions are being approached. In consequence, the log acceleration or log velocity versus log return period curve, at each point, becomes much flatter at high ground motions, especially at points in the vicinity of fault sources.

MAPPED GROUND MOTIONS AS LOWER-BOUND HAZARD ESTIMATES

Given the source zones and their seismicity estimates, we must point out that the ground motion values we derive from them are not conservative. The calculations were made without taking into account statistical variability in the attenuation function. Incorporating an estimate of this variability would result in the spreading of the ground-motion histograms and, therefore, cause an increase in the mapped ground motion at a given level of extreme probability. We believe that the maps (pls.2-7) represent suitable values for a baseline estimate of seismic ground-shaking hazard on the rock below a site (site ground motions will have to be increased to account for soil response). More detailed, site-dependent studies, in order to get lower values, will need to establish that

1) Earthquakes do not occur relatively uniformly in a zone but preferentially at some distance removed from the site.

2) Earthquakes occur at an average rate significantly (say, 30 percent) smaller than the historical rate (to produce a ground motion 15 percent smaller than mapped).

3) Maximum magnitudes in the vicinity of a site are significantly smaller than 7.3. Sensitivity studies (Perkins, 1978) indicate that for point sources, extreme ground motions are relatively insensitive to

changes in maximum magnitude, if the maximum magnitude is above 6.0.

Table 1.-- Annual earthquake occurrence rates of the Pacific Northwest and the adjacent Outer Continental Shelf

		Magnitude levels (Ms)						
Zone[1]	b-value	4.0<M<4.6 4.3	4.6<M<5.2 4.9	5.2<M<5.8 5.5	5.8<M<6.4 6.1	6.4<M<7.0 6.7	7.0<M<7.6 7.3	7.6<M<8.2 7.9
1	-0.66	0.110	0.0442	0.0178	0.0714	0.0288	0.00116	-----
2	-.66	.435	.175	.0702	.0282	.0114	.00457	-----
3	-.90	.124	.0359	.0104	.00296	.00082	.00027	-----
4	-1.04	.348	.0828	.0197	.0046	.0012	.0003	-----
5	-1.04	.124	.0294	.0070	.0016	.0004	.0001	-----
6	-1.04	.0283	.00673	.00161	.00038	.00009	.00002	-----
7	-1.04	.118	.0280	.00669	.00158	.00039	.00011	-----
8	-.70	.0164	.0062	.0024	.0009	.0003	.0001	-----
9	-.47	.208	.109	.0569	.0297	.0155	.0081	0.0042
10	-.47	.452	.236	.123	.0644	.0337	.0176	.0092
11	-.47	.964	.503	.262	.137	.0717	.0375	.0195
12	-.47	.371	.194	.101	.0529	.0276	.0144	.0075
13	-.47	.690	.361	.188	.0984	.0514	.0269	.0140
14	-.70	.109	.0417	.0159	.0060	.0023	.0008	-----
15	-.70	.345	.131	.0500	.0190	.0072	.0026	-----
16	-.70	.0493	.0188	.0071	.0027	.0010	.0004	-----
17	-.47	.879	.459	.240	.125	.0654	.0342	.0178
18	-.90	.188	.0543	.0157	.00450	.00126	.00041	-----
19	-.90	.0409	.0118	.00342	.00098	.00027	.00008	-----

[1]locations shown in plate 1

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