A PRELIMINARY GEOLOGICAL INVESTIGATION OF THE GROUND EFFECTS OF EARTHQUAKES IN THE PORTLAND METROPOLITAN AREA, OREGON

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O-74-01

Sponsored by the U.S. Geological Survey
Contract No. 14-08-0001-13458

Effective Date of Contract: June 22, 1973
Contract Expiration Date: June 30, 1974, extended to August 31, 1974
Amount of Contract: $15,000

Submitted to:
Mr. Howard D. Gower, Technical Officer
Branch of Western Environmental Geology
U.S. Geological Survey
Menlo Park, California 94025

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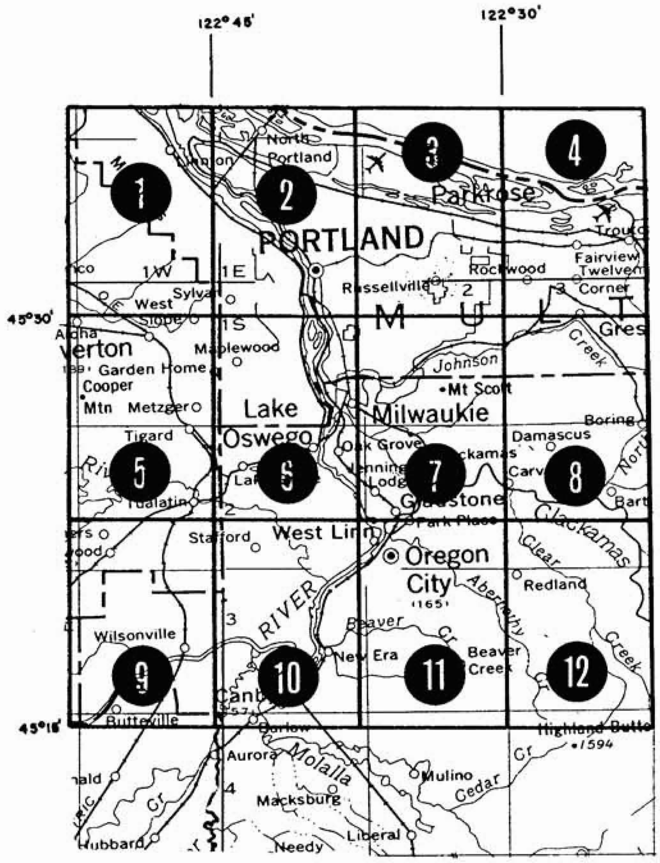
INTRODUCTION

This report is the summary of a year's study into the surface effects of earthquakes in the greater Portland area. The area encompassed in the study is shown in Figure 1. The project was funded by the U. S. Geological Survey, managed by the Oregon Department of Geology and Mineral Industries, and conducted by several students and some faculty members of the Department of Earth Sciences at Portland State University. Several lines of investigation were followed. Results of these investigations, considered preliminary in an evaluation of the geology and geologic hazards of the Portland area, are summarized in sections below, accompanied by figures or a plate.

Individuals responsible for the data portrayed are acknowledged in the plates. Those responsible for the written sections are as follows: Portland earthquake history - Dan J. Cash, Preliminary tectonic map of greater Portland area - G. T. Benson, Slopes - L. A. Palmer; the other parts were written by Paul E. Hammond. Crack analysis and development of the tectonic map were by Jan Donovan; crack analysis and portraying of landslides were by Tom Reilly; interpretation of the slope map was by Brian Gannon; cartographic shading of the slope map was by Peter G. Madsen; and the drafting of the entire set of plates was by Lynne Lawson. The staff of the Department of Geology and Mineral Industries is thanked for the final drafting, preparation, and assembling of the report. And, lastly, the U. S. Geological Survey is thanked for the financial support in making this study available to the residents of the Portland metropolitan area.



1. Linnton
2. Portland
3. Mt. Tabor
4. Camas
5. Beaverton
6. Lake Oswego
7. Gladstone
8. Damascus
9. Sherwood
10. Canby
11. Oregon City
12. Redland

Figure 1. Index map of the Portland area showing 15' topographic map coverage.

PORTLAND EARTHQUAKE HISTORY

Available information on the seismicity of Portland is mainly limited to historical accounts of damage and other effects. Only since the November 1962 earthquake have instrumental analyses been published. Most of the information on earthquake chronology for this report comes from Berg and Baker (1963), Couch and Lowell (1971), and Treasher (1938, unpublished data: Oregon Dept. Geology and Mineral Industries). A synthesis of the chronology from 1877 to 1970 is given in Table 1. Only earthquakes with epicenters within 50 kilometers (30 miles) of downtown Portland are included. Where possible, the distance and direction from downtown to each epicenter is given. Maximum intensity is expressed in Roman numerals on the Modified Mercalli (MM) Scale of 1931. Six earthquakes also have instrumental magnitudes expressed in Arabic numerals on the unified magnitude scale.

Damage in Portland has been relatively slight. The greatest amount of damage occurred during the shock of November 5, 1962, which was felt over a 20,000 square mile area of Oregon and Washington. The maximum intensity experienced was MM VII at the Veterans Administration Hospital, according to Couch (1973), and somewhere in North Portland, according to Dehlinger and others (1963). However, a U. S. Coast and Geodetic Survey report (1964) described several instances of cracked, broken, and fallen chimneys in the north, southeast, and southwest parts of the city. These occurrences are included in the definition of MM VII (Richter, 1958); thus, several places in Portland were at least on the verge of experiencing an intensity MM VII. The Veterans Administration Hospital locality may have been close to intensity MM VIII since "damage considerable to brick" and "chimney turned at an angle of about 20 degrees" were reported (U. S. Coast

Table 1. Portland earthquakes 1877-1970.

DATE (PST)	INTENSITY[1]	MAGNITUDE[2]	EPICENTER LOCATION
12OCT1877	III(?)[3]		Portland area
30NOV1877	III		Portland
? 1879	IV		Portland
1MAY1882	III		Portland
28SEP1883	?		Portland
3JAN1884	IV		Portland
10OCT1885	III		Portland
3FEB1892	VI		Portland
21FEB1898	IV		Portland
22FEB1898	III		Portland
16JUN1904	IV		Portland
16JUN1904	?		Portland
27MAY1907	III		Portland
30DEC1909	IV		Portland
7FEB1910	?		Portland
15FEB1910	IV		Portland
22MAR1914	IV		Portland
5SEP1914	III		Portland
18MAY1915	V		Portland
12FEB1918	III		Portland
9NOV1920	III		Portland
4MAR1921	III		Portland
22SEP1921	IV		Portland
26SEP1922	IV		Portland
15MAY1922	IV		Portland
14JAN1932	IV		Portland
23NOV1933	III		Portland
23APR1939	III		Portland
15NOV1939	III		Portland
16FEB1941	III		Portland
26JUL1941	IV		Tigard
29DEC1941	VI		Portland
1NOV1942	V		Portland

Table 1. (continued)

DATE (PST)	INTENSITY	MAGNITUDE	EPICENTER LOCATION
25MAR1951	II		Portland
1FEB1954	?		Canby
23APR1954	IV		45.1 N, 122.9 W, Near Woodburn
28NOV1957	III		Portland
12MAR1958	II		Portland
18NOV1958	III		Gresham
4AUG1959	III		Portland
3JAN1961	IV		18 km NW of CC (City Center)
6NOV1961	VI		45.3 N, 122.9 W
7NOV1961	V		Portland
29NOV1961	IV		Portland
15DEC1961	III		Scappoose, 32 km NNW of CC
17OCT1962	II		West Linn
6NOV1962	VII	5.0[4]	45.6 N, 122.6 W; 12 km NE of CC
2MAR1963	IV		Portland
27DEC1963	VI	4.5[4]	45.7 N, 123.4 W; 50 km WNW of CC
1OCT1964	V		45.7 N, 122.8 W; 22 km NW of CC
27JAN1968	IV	3.7[4]	45.6 N, 122.6 W; 11 km NE of CC
13MAY1968	IV	3.8[4]	45.6 N, 122.6 W; 14 km NE of CC
5MAR1969	III	3.5[4]	45.6 N, 122.8 W; 16 km NE of CC
25JUN1970	IV	3.6[4]	West Portland

[1] Modified Mercalli Scale of 1931.

[2] Unified magnitude (m).

[3] Although Berg and Baker (1963) report the intensity as III, Schlicker, et al. (1964) give the intensity as VIII. In a list compiled by Treasher, (1938, unpublished data) he mentions "overthrown" chimneys and surmises the intensity to be about VIII.

[4] From Couch and Lowell (1971).

and Geodetic Survey, 1964); Richter (1958), in his version of the Mercalli scale, includes these effects under intensity MM VIII.

Earthquakes originating outside the Portland area have also had their effects on the city. In 1949, an earthquake magnitude $m = 7.1$ with its epicenter near Olympia, Washington, about 200 kilometers from Portland, produced an intensity of MM VI. A second example, a shock $m = 6.5$ in 1965 near Tacoma, Washington, was experienced by Portland at an intensity MM V. In 1941, Portland experienced an intensity MM IV from an earthquake of magnitude $m = 5.5$ whose epicenter was at sea about 300 kilometers west of Cape Blanco, Oregon. While the effects on Portland of nonlocal shocks has not been serious so far, they cannot be ignored. Couch and Deacon (1972) prepared a seismic risk map for a portion of Western U. S. in which the maximum probable intensity predicted for the Portland area is MM VIII - IX as a consequence of possible shocks originating in either the Puget Sound area or the area immediately around Portland.

Epicenters and Focal Depths

Epicenters for instrumentally located Portland shocks are shown in Figure 2, from Couch and Peterson (1972), who determined the positions using travel time curves published by Dehlinger and others (1965) for the Pacific Northwest. The circles drawn about each epicenter represent the uncertainty in epicentral locations; in several cases the circle of uncertainty is approximately the size of the city. Estimates of focal depths in Portland vary from 4 to 35 kilometers (Couch and others, 1968; Heinrichs and Pietrafesa, 1968). Uncertainty in focal depth determination runs as high as $\pm$ 15 kilometers (Couch and Lowell, 1971); even so, the focal depths are sufficiently well known that Portland earthquakes probably originate within the crust. Until a network of seismographs is installed close to and within Portland, greater accuracy in the location of active zones of faulting is impossible.

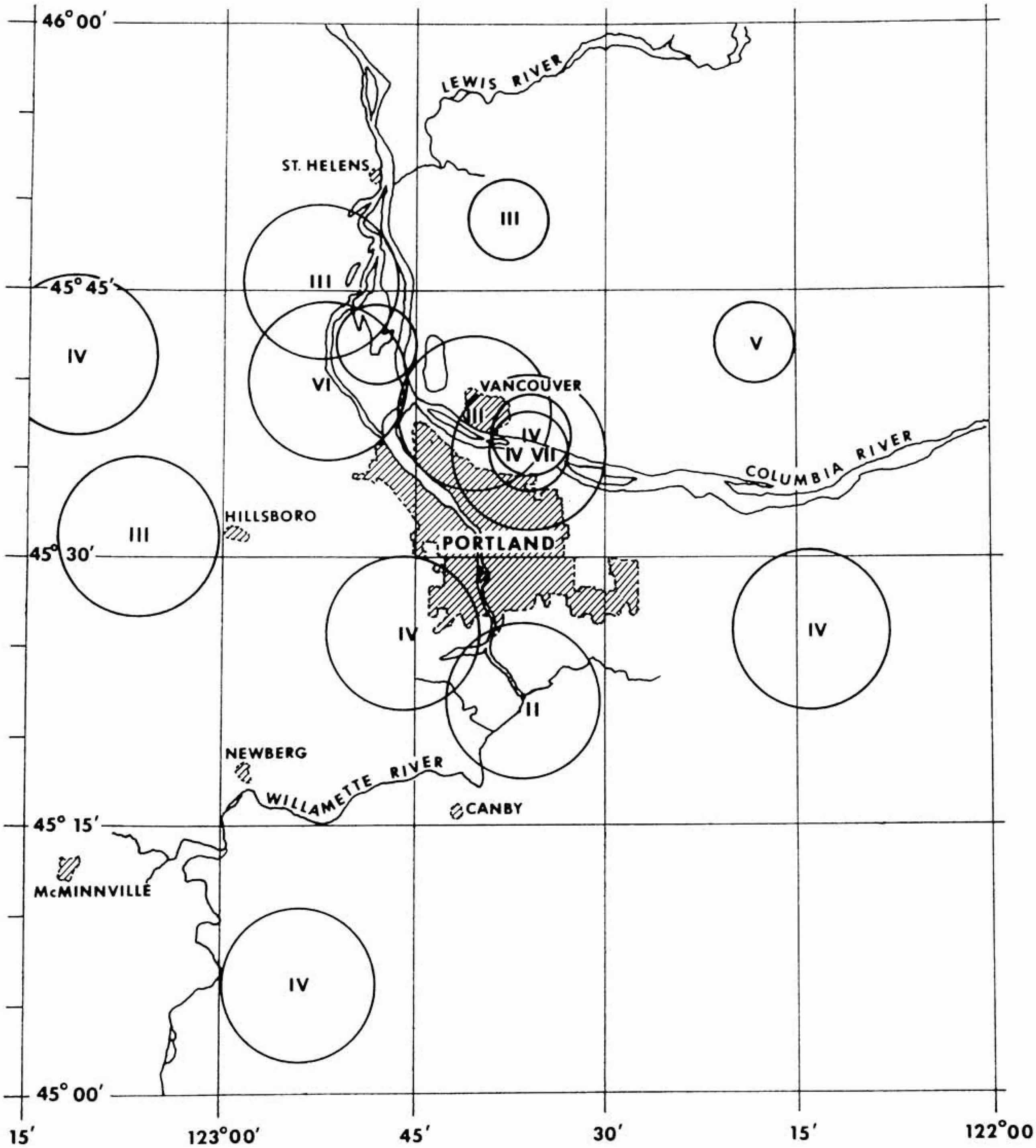


Figure 2. Earthquake epicenters in the Portland area. Roman numerals indicate maximum intensity. Size of circle indicates relative uncertainty of epicentral location (from Couch and Peterson, 1972, with permission).

Relationship Between Magnitude and Intensity

Except for six of the more recent shocks in Table 1, only maximum intensities were reported. Assuming a depth of focus of 15 kilometers for Portland earthquakes, the following relationship between MM intensity and unified magnitude is derived (Stacey, 1969, p. 72):

$$m = 0.43\, I_{max} + 2.9 \qquad (1)$$

The dashed line in Figure 3 illustrates that relationship.

The solid line in Figure 3 is the relationship between unified magnitude and intensity for the six Portland earthquakes for which both values were reported (Cash, 1974). The equation for the solid line is:

$$m = 0.43\, I_{max} + 2.0 \qquad (2)$$

The difference between Equations 1 and 2, or between the two lines of Figure 3, means that the maximum intensities of Portland shocks tend to be about two scale units higher for any given magnitude than would be expected from the standard formula.

Couch and Peterson (1972) have demonstrated anomalously high intensities in Portland. They produced "intensity anomaly" maps by plotting and contouring the differences between expected and observed intensities at a number of locations in Portland. These maps are reproduced in this paper as Figures 4 and 5. Figure 4 is the intensity anomaly map for local shocks. The anomalies generally range from -2 to +2 (MM). One locality, in the vicinity of Veterans Administration Hospital, has an anomaly of +3. That is in general agreement with Figure 3 and the discussion of the effects at Veterans Administration Hospital found in this paper.

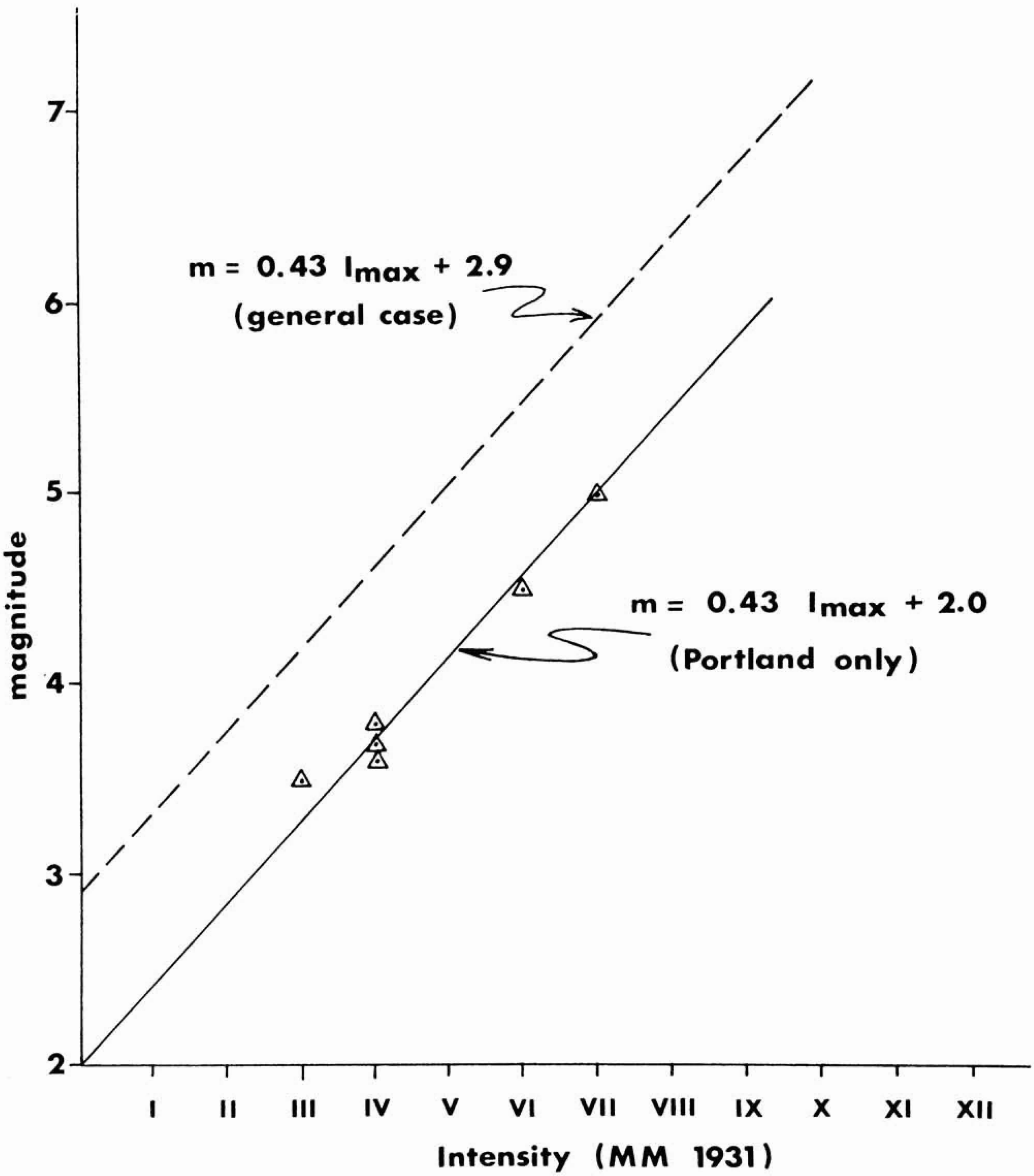


Figure 3. Relationship between magnitude and intensity (Cash, 1974).

Even more striking are the intensity anomalies for distant shocks found in Figure 5, in which the anomalies generally range from +1 to +5 (MM). That is additional good reason to carefully investigate and consider the potential effects of shocks originating in the Puget Sound area and off the Oregon Coast.

The cause of these anomalies in uncertain, but is most likely related to the following factors:

(1) Thickness and composition of surficial lithology and soil. Generally speaking the greatest intensities of earthquakes appear to occur on thick, loosely or poorly consolidated surface deposits. Some theoretical work indicates that the amplitude of ground displacement, velocity, and acceleration is a function of the relationship between the peak frequencies of the seismic radiation, the thickness, and the acoustic impedance of the surficial rock and soil units (see, for example, Alcock, 1969). In addition, certain types of materials tend to be unstable during cyclic motion, especially when wet, and therefore more prone to downslope movement and differential settling. The effects of this upon structures is obvious.

(2) Slope of topography. During shaking, differential movement of the ground on sloping surfaces can be expected, especially on deposits of unstable materials such as wet loess, silt, or sand, which are prone to downslope movement. The Portland Hills (Tualatin Mountains) on the west side of the city have steep slopes and deposits of loess and silt; however, no correlation is obvious in either Figure 4 or 5 between high intensity anomalies and the Portland Hills.

(3) Epicentral distance. The attenuation of seismic waves is greatest for high frequencies. Thus, by the time seismic radiation has traveled some distance it contains relatively more low-frequency (long-period) components, which tend to have relatively

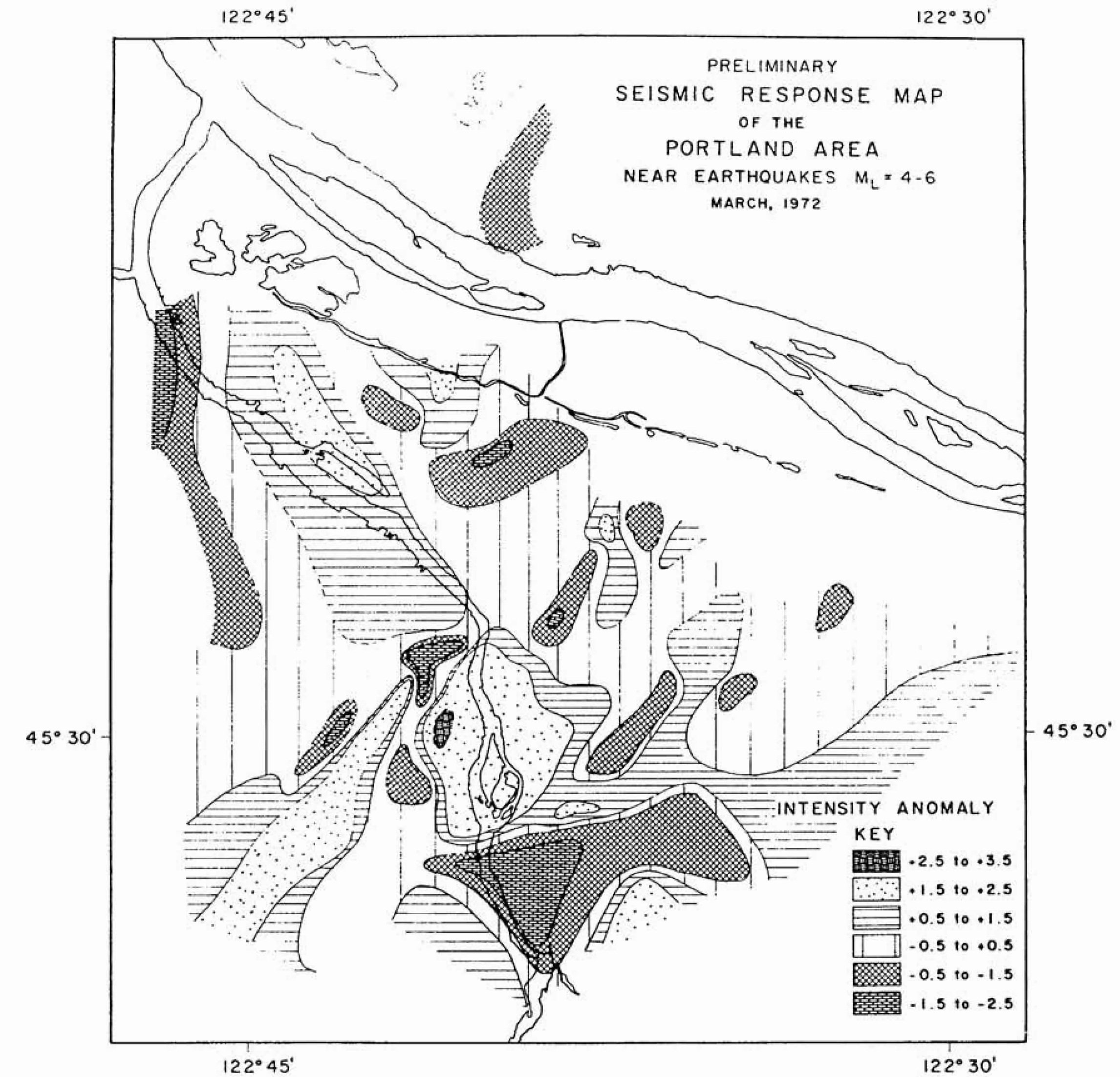


Figure 4. Intensity anomaly map for local earthquakes, magnitudes (M_L) 4 to 6 (from Couch and Peterson, 1972, with permission).

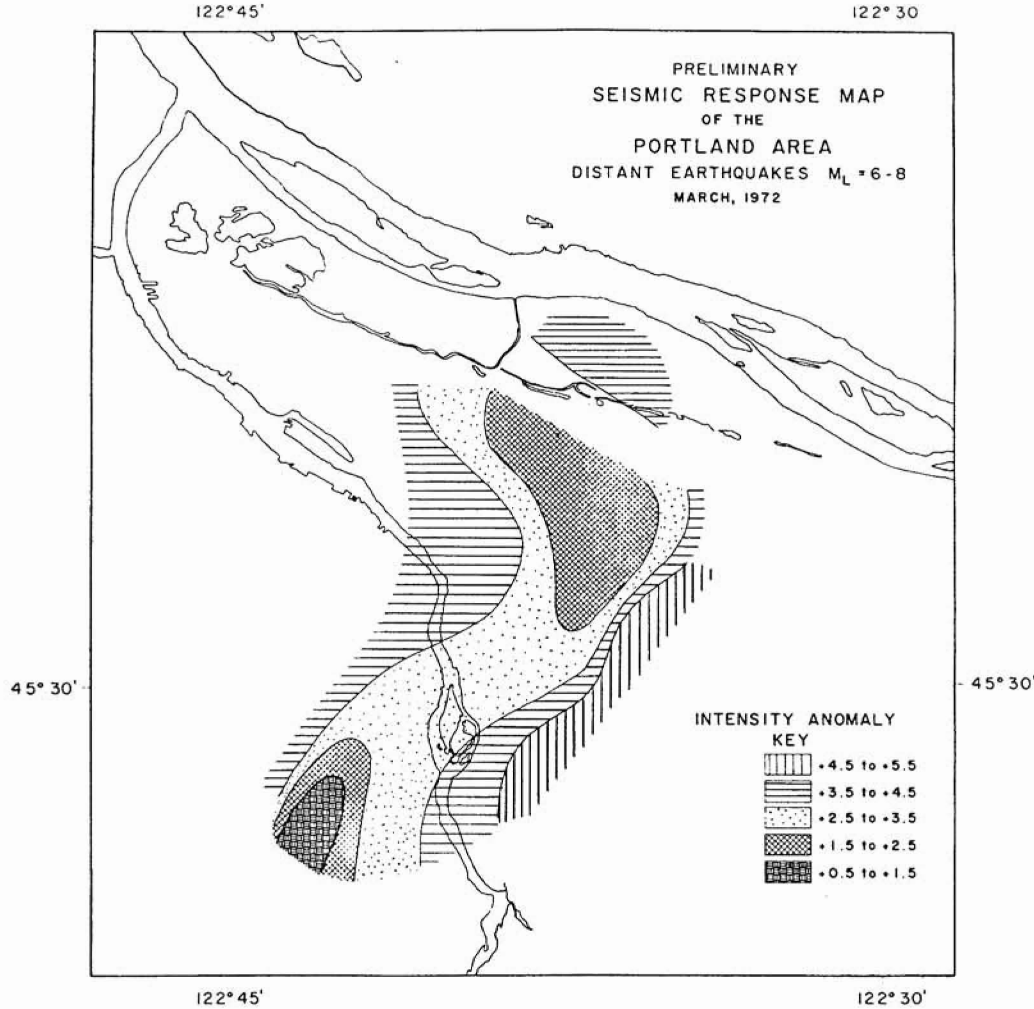


Figure 5. Intensity anomaly map for distant earthquakes, magnitudes (M_L) 6 to 8 (from Couch and Peterson, 1972, with permission).

greater influence on thicker layers of materials. Therefore, distant shocks can be expected to produce different seismic excitation patterns than local shocks. In addition, because of wave dispersion, earthquakes of distant origin tend to shake the ground for longer times than shocks of local origin. The duration of shaking is almost certainly among the most important parameters which determine the degree of damage.

Energy and Strain Release

For the purpose of energy calculations, the intensity of a Portland shock can be converted to unified magnitude m using Equation 2. Then the energy release of each event is calculated from a relationship given by Richter (1958):

$$\log E = 2.4\,m + 5.8 \qquad (3)$$

where "log" is the common logarithm, E is energy in ergs, and m is unified magnitude. In practice, equation 3 alone was used for those events whose unified magnitudes were already known, and Equations 2 and 3 were combined for use with those events for which only intensities are known, forming the single equation,

$$\log E = 1.03\,I_{max} + 10.6 \qquad (4)$$

The magnitudes and energies thus calculated are presented in Table 2. The total energy released in the 94-year period is 9.23×10^{17} ergs. This is 9.82×10^{15} ergs/year, equivalent to one earthquake of magnitude m = 4.2 (MM V) each year. The equivalent annual magnitude and average annual energy release have little physical significance, however. The single largest event, m = 5, released 6.5×10^{17} ergs of energy (6.9×10^{15} ergs/year), more than half the total released, and either energy value is equivalent to one magnitude m = 4.2 per year using Equation 3.

Couch and others (1968) convert the energy release to strain release, which they plot as a function of time. That plot shows that the seismicity of Portland increased markedly about 1950. Prior to that time the average annual strain release was 1.2×10^8 ergs $^{\frac{1}{2}}$/year, and it rose to 3.7×10^8 ergs $^{\frac{1}{2}}$/year after 1950, a three-fold increase. The seismic history of Portland is too brief to tell whether this apparent increase in seismicity portends serious consequences or is merely a part of a brief and minor cycle in local seismicity.

Maximum Probable Earthquake

The frequency of earthquake occurrence drops with increasing magnitude. This fact is seen in Table 2. An effective way to express this relationship is by a formula of the form,

$$\log N = A - b \cdot m,$$

where N is the annual number of earthquakes of magnitude m or greater, and A and b are constants. Figure 6 is the plot of log N versus m for Portland earthquakes during the 94-year record (Cash, 1974). Values of m were determined from the Portland magnitude-intensity equation (Equation 2). The equation for the curve is

$$\log N = 2.91 - 0.93\, m. \qquad (5)$$

The value of $b = 0.93$ is very close to the world-wide value of $b = 0.92$ determined by Gutenberg and Richter (1954) for earthquakes $m<7.1$. The maximum probable shock for a specific time period (called the recurrence interval) can be determined from either Figure 6 or Equation 5. In Equation 5, the maximum probable shock for a 100-year period is found by substituting 0.01 (=1/100) for N and solving for m. The value obtained is $m = 5.3$. The same value is obtained directly from Figure 6 by choosing m where the line

Table 2. Statistics of intensity, magnitude, and energy.

Maximum Intensity (MM)	II	III	IV	V	VI	VII
Magnitude (unified)	2.9	3.3	3.7	4.2	4.6	5.0
Energy, E (ergs)	4.6×10^{12}	4.9×10^{13}	5.2×10^{14}	5.6×10^{15}	6.0×10^{16}	6.5×10^{17}
Number of Events	3	19	19	4	4	1
Total Energy ΣE (ergs)	1.4×10^{13}	9.3×10^{14}	9.9×10^{15}	2.2×10^{16}	2.4×10^{17}	6.5×10^{17}

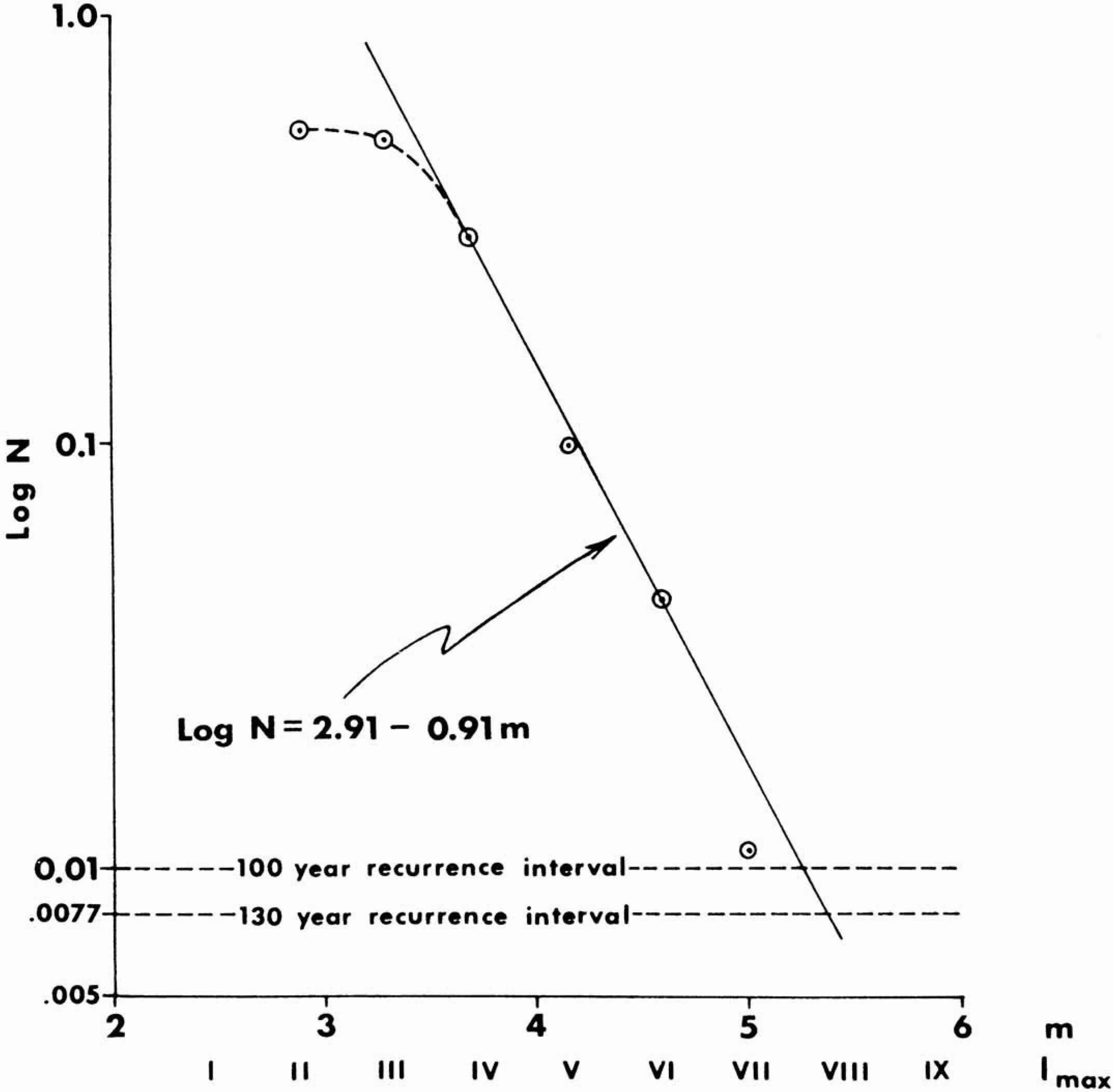


Figure 6. Frequency-magnitude relationship for Portland earthquakes (Cash, 1974).

crosses the abscissa at N = 0.01. Also marked on the abscissa are approximate values of intensity. The maximum probable 100-year shock for Portland, according to this graph, will produce a maximum intensity of VII to VIII. Couch and Deacon (1972) used a recurrence interval of 130 years, based on the observation that the recurrence interval for large quakes in analogous studies in part of the Arctic Ocean, a region somewhat similar to the northwestern United States structurally and tectonically, was 130 years.

Focal Mechanism and Local Stress

The stress conditions accompanying the faulting process during an earthquake can be determined by the construction of focal mechanism diagrams from first motions on seismograms. According to Couch and Lowell (1971), "Focal mechanism studies by Couch and MacFarlane (1971) and Dehlinger and others (1970) characterize a regional stress field which produces the earthquakes of Oregon. The minimum compressive stress is aligned approximately east-west. The maximum compressive stress varies from an approximate north-south alignment to a vertical alignment. Faults, hence earthquakes, occur when the stress differential exceeds the strength of the crustal rocks. Three fault types are expected under a stress field aligned as above:

1) right lateral strike-slip, oriented northwest-southeast
2) left lateral strike-slip oriented northeast-southwest
3) normal, oriented north-south.

"Geologic heterogeneities and old lines of weakness may modify the anticipated fault directions and/or cause mixed faulting to occur. The stress field and consequent faults and associated earthquakes in Oregon suggest a gradual dilation or stretching of Oregon in a general east-west direction."

Because of the lack of adequate seismograph coverage, the most that can be said about the mechanism of Portland earthquakes is that the least principal stress (so-called "tension" axis) is horizontal and east-west (Couch and Lowell, 1971). Not enough data points are available to determine the direction of the maximum principal stress, or whether the faulting process was, say, strike-slip or dip-slip faulting. Both mechanisms can be made to fit the available data. An east-west tension axis agrees with focal mechanisms of earthquakes off the coast of Oregon (Couch and Pietrafesa, 1968), and in southern Oregon (Couch and Johnson, 1968).

PRELIMINARY TECTONIC MAP OF GREATER PORTLAND AREA

In order to develop a picture of the structural geology of the Portland area, a preliminary map (Plate 1) showing contours on the top surface of the Columbia River Basalt was prepared by G. T. Benson and Jan Donovan. Data were developed through study of available outcrops, well log records, and gravity surveying.

Surface Data

Contacts of the Columbia River Basalt are taken from the various published geologic maps which cover parts of the greater Portland area, notably Trimble (1963), Hart and Newcomb (1965), and Schlicker and Deacon (1967). Numerous discrepancies between these maps are attributed to paucity of bedrock outcrops and the presence of a weathered zone of variable thickness at the top of the basalt.

In projecting contours "into the air" over outcrop areas of Columbia River Basalt, adjacent subsurface slopes have been followed, a few attitudes noted, and a rough assumption made that up to 100 feet of basalt has been eroded from ridge tops. The interpretation is, of course, subject to considerable error, but it is useful in that the top of the basalt generally could not have been lower than shown.

Well Data

Although water well logs provide most of the data for the map, their quality ranges from excellent to poor. Obvious inaccuracies have been noted in reported well locations, surface elevations, and depths of the top of the basalt. Well data have been used, although in some instances of glaring errors, elevations from topographic maps were used.

Gravity Data

Gravity measurements were made at quarter- to half-mile intervals along some 115 miles of traverses in basin areas, supplemented by 77 miles of traverses by Dan J. Cash, and 22 miles by Schmela (1971) with the hope of defining structural trends (such as basin axes) and possibly local variations in the top of the basalt. The profiles do not show expected detailed variations, either because the top of the basalt is relatively smooth beneath the basins, or more likely because the spacing and accuracy of our observations are inadequate for useful resolution. However, even the most general trends of the gravity residuals are not entirely in agreement with the large surface features of the area: the Tualatin Valley is marked by a gravity low, but a broad (poorly defined) north-trending gravity high obliquely crosses the Portland Hills structural trend. The source of this gravity high is probably 15 km or more deep. For contouring the map, general gravity trends have been followed.

Interpretation

The Tualatin Valley in the western part of the region is a fairly well-defined elliptical basin with a major axis trending roughly N 65° W. The Portland Hills are the physiographic expression of a relatively long and narrow uplift which trends approximately N 35° W. The shape of Portland Basin to the east is very poorly controlled; the interpretation reflects the Portland Hills and Tualatin trends for lack of other control. The high in the eastern part of the map is based largely on data from one well. A well in the southeast corner of the map and several more wells farther southeast are compatible with the interpretation.

The area south of the Tualatin basin and west of the Portland Hills uplift is perhaps the most informative on the map. Here outcrops and wells together give a maximum density of useful data. These data require either abrupt changes in both strike and dip, or the presence of considerable faulting, or both. Indeed, both faults and strongly curved fold axial trends have been mapped in this area (Hart and Newcomb, 1965). A few faults have been added only to avoid extreme inconsistencies in pattern.

Probably the most striking thing about the map as a whole is lack of consistent pattern, and it is even more apparent in the southwestern area, where fold axis trends differ from block to block. It would seem that the structure of the Portland Basin could not have been produced by a simple stress system (such as one constant direction of maximum compressive stress). The rock units involved in this study, the Columbia River Basalt and the overlying cover, are Miocene and younger, which argues against superposed deformations. The most practical interpretation, it seems to us, is that the relatively rigid Columbia River Basalt has been broken into separate blocks which have been deformed independently. The causes of this deformation and higher symmetry must be sought in the underlying section, perhaps deep in the crust. Perhaps a larger regional pattern of simple shear has been active, at least in the later part of the Cenozoic. The shallow structure is of immediate interest as it dominates the geological environment of Portland.

LINEATIONS

Three orders of lineations are shown in Plate 2. The first order includes known or suspected faults, shown in maps of published reports (Westphal, 1962; Schlicker and others, 1964; Schlicker and Deacon, 1967; and Baisille and Benson, 1971). They are the supposed northwest-trending Portland Hills fault, its extended or parallel segments, and the northeast-trending Sherwood fault, referred to as the Lake Oswego-Troutdale lineation. The second order lineations are possible fault and/or fracture zones inferred from study of aerial photographs and topographic maps. Field data so far obtained neither proves nor disproves the existence of faults or fracture zones at these lineations. The third order lineations are topographic lineations which may be related to fault and/or fracture zones. Many appear to be stream-cut features. Only limited field checking has been made of these lineations. In addition, all three orders of lineations are shown in grades of strength: well-defined, moderately well-defined, and least well-defined lineations, as they could be traced on aerial photographs. For example, the northeastern end of the Sherwood fault cannot be traced in the alluvial floor of the Tualatin Valley. The fault is suspected of existing here because of the geologic evidence for the fault about three miles southwest of the edge of the map. Apparently no movement has occurred on the fault in about the last 19,000 years, since deposition of the alluvium (Glenn, 1965). In contrast, the erosional scarps separating land surfaces at different elevations, e. g., the Portland surface overlooking the Columbia River floodplain, and the surface break northwest of Gresham, are very well defined on aerial photographs.

Many second- and third-order lineations, instead of being fault and/or fracture traces, could be bedding planes (strike), aquifer boundaries in alluvium, or topographic features such as ridge lines and slope breaks.

Aerial photography, taken in 1935, 1945, and 1965 was studied equally and compared. The northeast-trending Tryon Creek lineation and the segment between Lake Oswego and West Linn showed equally well on all photographs, strongly suggesting tectonic break in this area, yet no field data in support could be found.

More lineations appeared on the 1965 photography than the earlier. The younger lineations may be caused by construction, old fence lines, pipelines, power, and telephone lines, and altered ground water flow patterns. Also, the newer photography has better resolution, thereby enabling recognition of subtle linear features.

Note that most lineations trend either northwest or northeast. The city street grid obscures the east-west and north-south lineation pattern. Yet, on the other hand, in areas where streets are few, only a very small number of lineations east-west or north-south could be found, indicating that the pattern on the map (Plate 2) represents the condition in Portland.

The lineations in east Portland were partly checked for evidence of displacement of man-made structures along their traces. The results are summarized in Plate 3, Crack Analysis of Lineations in East Portland.

CRACK ANALYSIS OF LINEATIONS IN EAST PORTLAND

An investigation was made by several members of the study group of the better lineations in the flat terrain of east Portland in order to determine if recent movement had occurred on any lineations. The east Portland area was selected as the ideal site because of (1) its levelness, and (2) the recency of its surface, formed as recently as about 19,000 years ago at about the time of formation of the broad floor of the Willamette Valley following the last Missoula flood (Glenn, 1965, p. 182, 197). A study of this nature could not be conducted on the mapped faults, e. g., the possible Portland Hills fault, because the east slope of the hills is irregularly covered by vegetation and colluvium.

After several experimental traverses at the eastern foot of the Portland Hills and in west Portland, the study group found that groups of parallel cracks or fractures, crossing streets and/or curbs and sidewalks but not necessarily parallel to the previously determined lineations on aerial photographs, could be statistically summarized in numbers of cracks per 200-foot interval. The intervals were traversed along streets crossing some of the lineations. No cracks were found to enter or pass through buildings. Consequently, the map (Plate 3) was prepared to show the concentration of cracks in increments of 0-5, 6-10, and over 10 per 200-foot interval.

In addition to the street studies, power transmission lines and railroads were sighted for alignment where they crossed the lineations, and in no case were they found to bend or be offset at the lineation.

The study of cracks in the streets, sidewalks, and curbs proved frustrating in attempts to relate the cracks to recent tectonic movement. In street crossings of some good lineations, no cracks were found. And in other examples, recent street improvements or repavings concealed possible evidence of displacement. There is also no correlation of number of repavings to lineations. Most cracks were found to be caused by differential settlings of the subbase of streets or sidewalks, and these settlings were not found to be attributable to movement along lineations.

In studying the Crack Analysis Map (Plate 3), note the number of lineations crossed which reveal 5 or less cracks in the immediate area. Also, note the number of intervals with greater than 10 cracks which do not occur adjacent to the lineations. Instead, the higher concentration of cracks appears to be situated to one side or be removed some distance from the lineation.

In only four areas does there appear to be a correlation, weak at best, between lineations and crack concentrations. These areas are: the northernmost plot between Columbia Boulevard and Fremont Street, with respect to a northeast lineation; in the area of the intersection of Fremont Street and Sandy Boulevard, with respect to three parallel northwest lineations; west of 82nd and south of Burnside streets on intersecting lineations; and along Foster Road south of Powell Boulevard on northeast lineations.

No indications of ground displacement on lineations in these areas exist. We conclude that any ground movement associated with earthquakes in the recent past in Portland have not resulted in ground displacement. At least, there is no indication of ground displacement at the surface.

SLOPES

Four ranges of slope steepness are mapped (Plate 4). They define the amount and distribution of land of variable susceptibility to ground instability. Seismic shaking may trigger or accelerate extensive landsliding and other ground movements. Such secondary ground breakage is frequently the major cause of damage from earthquakes in steep terrain.

Relative slope is also useful to define limitations for land use planning and development, including potential for erosion and drainage, waste disposal, foundation stability, and forest and watershed management.

Slopes mapped as shown in Figure 7 and on the Slope Map (Plate 4) are 0-15% (0° - 8°32'), 15-35% (8°32' - 19°18'), 35-60% (19°18' - 30°58'), and greater than 60% (greater than 30°58'). The four slope areas represent areas of low, moderate, high, and extreme susceptibility to downslope earth movement. Steeper slopes are shaded as progressively darker map areas. No attempt has been made to relate steepness of slope to underlying surficial deposit or bedrock, or to susceptibility to landsliding.

Slope provides a general guide to distribution of ground instability, but specific site investigations are required to determine safety of a given location. Strength and wetness of soil and rock also affect stability, and flat areas adjacent to steep-unstable slopes are subject to failure.

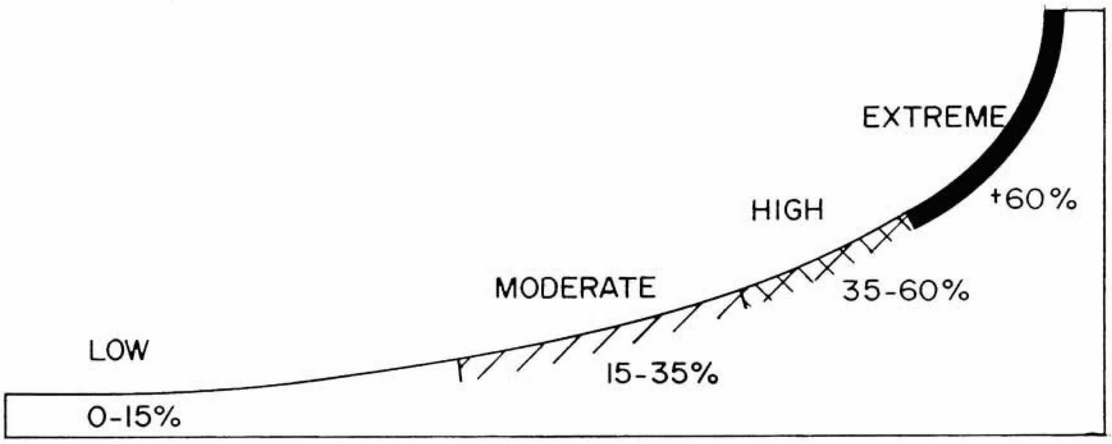


Figure 7. Slope steepness and relative susceptibility to down-slope earth movement, such as landslides.

LANDSLIDES

All landslides, including slumps and earthflows, so far delineated in Portland are shown in Plate 5. The arrow shows the direction of movement. The slides occurred in the recent past, within the last 10,000 years; some are presently active. Some are attributable to natural geologic processes described below; others were triggered by construction, such as the Washington Park Reservoir slide (Clarke, 1904) and the Zoo-OMSI slide (files of Oregon Division of Highways and Shannon and Wilson, Inc., Portland; Palmer and Redfern, 1973). Detailed reports, including geologic and engineering data, are available on a few slides from consulting engineering geologists in Portland.

The many small slides in the northwestern Portland Hills are slumps or earthflows, locally referred to as "pop-outs", occurring in soil or underlying upland silt. These slides are attributed to high degree of water saturation during winter months on oversteepened slopes, especially if followed by a prolonged freeze. The initial area of failure is generally less than 100 feet wide, but once activated, the mass behaves as a fluid and flows downslope until arrested, thus damaging a much larger area. The depth of the mass is less than 20 feet in most slides examined.

Larger slides in the Portland Hills involve greater thicknesses of upland silt, fine-grained sedimentary rocks atop Columbia River Basalt, and basalt. All or parts of these rock units may be involved. The Washington Park Reservoir slide contains about 20 feet of upland silt underlain by 50 to 500 feet of clayey sedimentary rocks and broken basalt. All three rock units are contained within the Zoo-OMSI landslide (Palmer and Redfern, 1973). The large ancient slide east of Washington Park also contains all three rock units.

Most of the slides in the southern Portland Hills and along the Willamette River consist of Columbia River Basalt and interbedded clayey sedimentary beds. Undercutting of the slopes, by both man and nature, are the cause here.

The landslides southeast of Portland, located mostly along the Clackamas River, are the result of undercutting in soft conglomerate and sandstone beds of the Troutdale Formation, beneath cappings of Boring Lava.

The large number of slides in the Portland Hills and along the deeper stream valleys indicate a high degree of susceptibility to landsliding. The process is considered the greatest geologic hazard in Portland. Considerable attention must be devoted to stability of landslides or landslide-potential slopes in all types of construction.

The study has not revealed any evidence of coincidence of landslide and earthquakes in Portland; nevertheless, the presence of upland silt and clayey sedimentary beds atop Columbia River Basalt, abundant fractures and interbedded clayey sedimentary rocks in the Columbia River Basalt, and easily eroded Troutdale strata flanking the basalt create an unstable situation, one highly susceptible to massive landsliding and property damage should extensive ground shaking occur during the winter months when soils are saturated.

POTENTIAL GEOLOGIC HAZARDS RELATED TO EARTHQUAKES

Three geologic hazards related to earthquakes are shown in Plate 6:

1. Approximate outline of alluvial plain. Area subject to possible strong ground shaking during earthquake.
2. Approximate outline of areas (belts) subject to possible ground displacement (sudden uplift, subsidence, or lateral shifting) during earthquake.
3. Approximate outline of areas subject to possible landsliding caused by earthquake.

Areas of alluvial plains are subject to intense ground shaking in the event of an earthquake at or near Portland. The alluvial plains are the flat-lying areas adjacent to the major streams. They occur up to elevations of about 250 feet, as much as 150 feet above present day flood plain (approximate 100-year flood level). The plains are underlain by partly compacted to unconsolidated gravels, sand, and silt deposited 19,000 years ago or less (Glenn, 1965). Some of these materials are water saturated during the winter and early spring months, and parts of them may be subject to liquefaction during ground shaking associated with earthquake activity.

Areas of ground displacement are belts enclosing major lineations or suspected major fault zones. They are identified as the northwest-trending Portland Hills lineation and the northeast-trending Lake-Oswego-Troutdale lineation. Note that these belts do not include several inferred faults on the preliminary Tectonic Map (Plate 1) because (1) no faults have been recognized at the surface by earlier mapping, principally that of Schlicker and Deacon

(1967), (2) the faults are short and are not considered active or hazardous at present without corroborating data, and (3) the faults shown on the tectonic map are interpreted as questionable and may not exist. The Lake Oswego-Troutdale lineation is not shown as a fault zone on the Preliminary Tectonic Map (Plate 1) because of lack of subsurface or well data. The structure contouring is subparallel to the lineation and indicates a structurally higher block to the southeast in relation to the block underlying the Portland basin. Furthermore the abundance of Boring Lava volcanic centers immediately southeast of the belt and the paucity to the northwest suggest that a structural demarcation possibly exists along a northeast trend in this area.

Ground surface within these belts may disrupt during an earthquake. Disruption may be either by uplift of a few feet or less along one side of a rupture or by horizontal displacement of a few feet or less. The rupture and displacement may not necessarily be confined to the center of the belt; they could occur discontinuously along a part of the total length and to one side of the belt.

Areas subject to possible landsliding caused by earthquakes are located near major lineations or belts of possible ground displacement. These areas include slopes as low as 35 percent, depending on local conditions and rock type.

Geologic materials underlying these slopes consist of three types:

1. Columbia River Basalt occurs beneath the Portland Hills and the hills adjacent to the Tualatin Valley and Willamette River. The rock is well jointed and has a well-developed longitudinal joint set parallel to the long direction of the hills, especially the eastern slope of the Portland Hills. The layers of basalt are commonly interstratified with unstable palagonite breccia, and they dip

toward the adjacent valleys. These characteristics tend to make the basalt unstable on steep slopes especially during an earthquake.

2. Upland silt, consisting mostly of wind-blown detritus, caps all hill surfaces above 350 feet elevation in the Portland area. The silt is compacted, stands up well in fresh excavations, is impermeable yet capable of retaining a high percentage of water. This material is quite susceptible to landsliding in areas of recent excavations for large dwellings or for sewer or water pipe lines. Uncompacted silt collects water and when saturated tends to flow. Excavations divert surface water run-off; water collects in filled excavations, leading to landslide potential. If an earthquake occurs at or near areas of water-saturated upland silt, large masses of the silt may liquefy and flow downslope.

3. Alluvium in river bluffs is also subject to landsliding if the material is moderately to poorly consolidated and contains a high percent of water at the time of an earthquake.

SUMMARY

On the basis of this preliminary investigation into the surface evidences for the effects of earthquakes in the greater Portland area, several tentative conclusions can be made.

1. Earthquake damage in Portland has fortunately been slight so far, although the city experiences an earthquake averaging 4.2 magnitude each year. However, since 1950 the seismicity appears to have increased. Calculations indicate that Portland will experience one earthquake of approximate magnitude 5.4 (intensity VII - VIII) about every 100 to 130 year interval.
2. The location of earthquake epicenters and active zones of faulting within or near Portland is at best uncertain; therefore, a network of seismographs installed close to or within Portland is strongly needed in order to determine active fault zones.
3. Several poorly defined areas of anomalous intensities or potentially high ground shaking do exist in Portland. These areas do not conform to presently known geologic structures, surficial deposits, or specific landforms. Considerably more investigation and data are necessary in order to predict with a fair degree of accuracy the amount of ground shaking to be experienced in Portland in response to near or distant earthquakes.
4. A tectonic investigation of the area reveals that the main bedrock (Columbia River Basalt) extends irregularly through the area and lies at different depths beneath basins. The surface atop the basalt appears to be broken into a number

of separate structural blocks that are separated from each other by faults, some possibly active.

5. The greater Portland area is interlaced by many well-defined lineations, primarily topographic but many trending across valley floors with no obvious surface indications. A few lineations can be related to known faults; most cannot. Several lineations in east Portland were closely examined for evidence of off-set of manmade structures that might indicate recency of movement. In no individual lineation could it be established that the lineation is the trace of a fault with recent movement. Instead, cracking of manmade structures in the area of the lineation was attributed to differential ground settling not related to fault movement.

6. Compilation of the slope isopleth map indicates that much of the upland areas of Portland have slopes of 35 percent or more. Consequently, for this terrain to be developed, on-site investigations into the stability of the slope and drainage will be necessary.

7. Landslides occur extensively in the greater Portland area and represent the greatest geologic hazard to man. The slides range in size from small slumps to massive earth failures 2 or more square miles in area. Portland is susceptible to landslide because of: (a) The hilly terrain and steep slopes, (b) the great extent of relatively unconsolidated silt and other sedimentary rocks of geologically youthful age mantling the hills and bordering the steeply sloping valleys, and (c) the high precipitation during the winter and high water saturation percentage of the unconsolidated sediments. Should a major earthquake occur in Portland after a period of heavy rains, the city could experience extensive damage.

8. Areas of greatest geologic hazards related to earthquakes are:

   a. Alluvial plains adjacent to rivers, underlain by unconsolidated water-bearing sediments (subject to intense ground shaking and/or liquefaction, depending upon the magnitude and location of the earthquake epicenter).

   b. Linear zones at base of ridges or hills, where major faults of recent geologic age may be present (subject to possible ground displacement both vertically and horizontally).

   c. Steep slopes overlain by unconsolidated sediments and/or thick soils adjacent to the belts of suspected ground displacement (subject to landslides).

RECOMMENDATIONS

The results of this preliminary study reveal the need for several additional investigations to ascertain the extent of geologic hazards in the greater Portland area. These investigations, grouped in order of priority, are:

High Priority

a) A detailed seismic survey of lowlands and hills to determine ground response (shaking) to earthquakes, in conjunction with a compilation of the subsurface stratigraphy of the Tualatin and Portland basins (using drill-hole records in the files of geologic engineering firms, etc.). Data would be related with information on intensity anomaly maps.

b) Geologic mapping at scale 1:12,000 of the upland terrain in the area, in conjunction with partial subsurface studies, through the use of drill-hole data and geophysical surveying--seismic, gravity, and magnetic--in order to refine the tectonic map and to catalogue the landslide terrain of the area.

c) The initiation of a comprehensive and thorough program of better informing the land developer and home owner regarding the landslide potential in the area, in concert with a parallel program informing the developer and owner of the limits and techniques available in minimizing the hazards through planning and engineering.

Moderate Priority

a) Determination of flow-by-flow stratigraphy of the Columbia River Basalt in the area by "finger printing" individual flows by trace element content and petrographic characteristics, and establishing a data center in cooperation with engineering firms in order to compare and record individual basalt flows at depth, to eventually plot an accurate structure contour map of the bedrock configuration and tectonic map of the area.

b) Establishment of a seismic station network in the Portland-Vancouver area with direct ties to the networks established in other parts of Oregon by Oregon State University and the Puget Sound area by the University of Washington.

Low Priority

a) The initiation of a program to study the better defined lineations by trenching and by an on-going program of observing trenches excavated for other purposes as they are dug (sewer lines, gas lines, other utilities), in an attempt to more adequately investigate the possibility of recent movement on the surface in the Portland area.

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PRELIMINARY TECTONIC MAP OF THE GREATER PORTLAND AREA

LEGEND

Contours on top of Columbia River Basalt (contour interval is 100 feet)

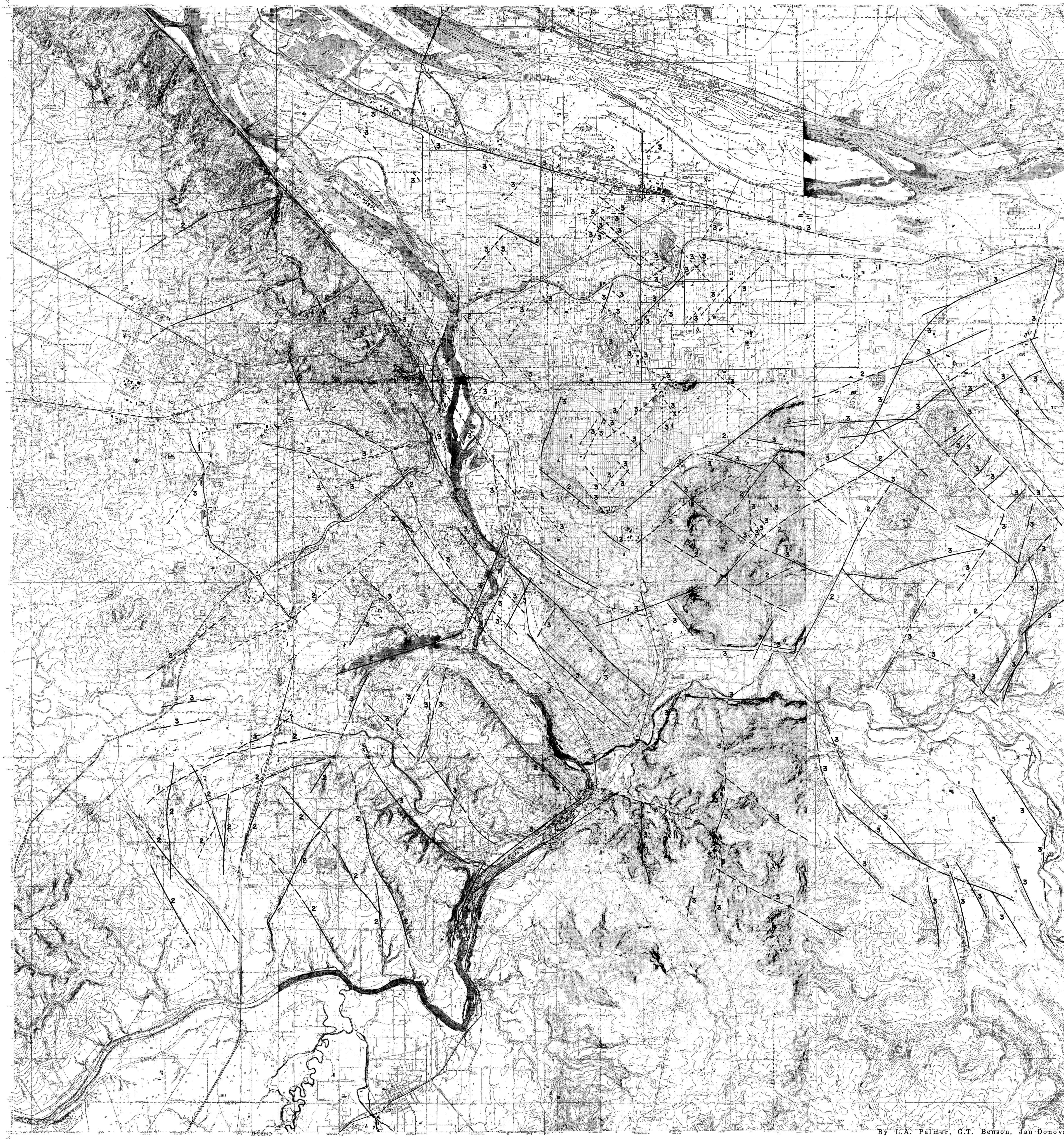
- Contour
- Inferred contour
- Projected contour
- Trend of axis to residual gravity anomaly
- Well to basalt

Faults

- Mapped fault based on previous geologic reports
- Probable faults based on interpretations of structure contours
- Questionable fault
- Line of exposure of Columbia River Basalt
- Edge of Columbia River Basalt

By G. T. Benson and Jan Donovan
Cartography by Lynne Lawson
Cartographic Editing by S. R. Renoud

LINEATIONS IN THE PORTLAND AREA



LEGEND

Base maps from U.S. Geological Survey
Control by USGS, USC&GS, USCE, and State of Oregon
7.5-minute series (topographic) of the following quadrangles: Linnton, Portland, Mt. Tabor, Camas, Beaverton, Lake Oswego, Gladstone, Damascus, Sherwood, Canby, Oregon City, and Redland
Photo revised in 1970
Topography from aerial photographs by photogrammetric methods
Aerial photographs taken 1952. Field check 1954.
Revised from aerial photographs taken 1960
Field check 1961

———	Well-defined lineation on aerial photographs
— —	Moderately well-defined lineation on aerial photographs
- - - -	Less well-defined lineation on aerial photographs
1	First order lineations - faults shown on maps of published reports
2	Second order lineations - possible faults or fractures, inferred from aerial photographs and topographic maps
3	Third order lineations - topographic lineations which may be related to fault and/or fracture zones

SCALE 1:48,000

Contour interval 10 feet
Datum is mean sea level

APPROXIMATE MEAN DECLINATION, 1974

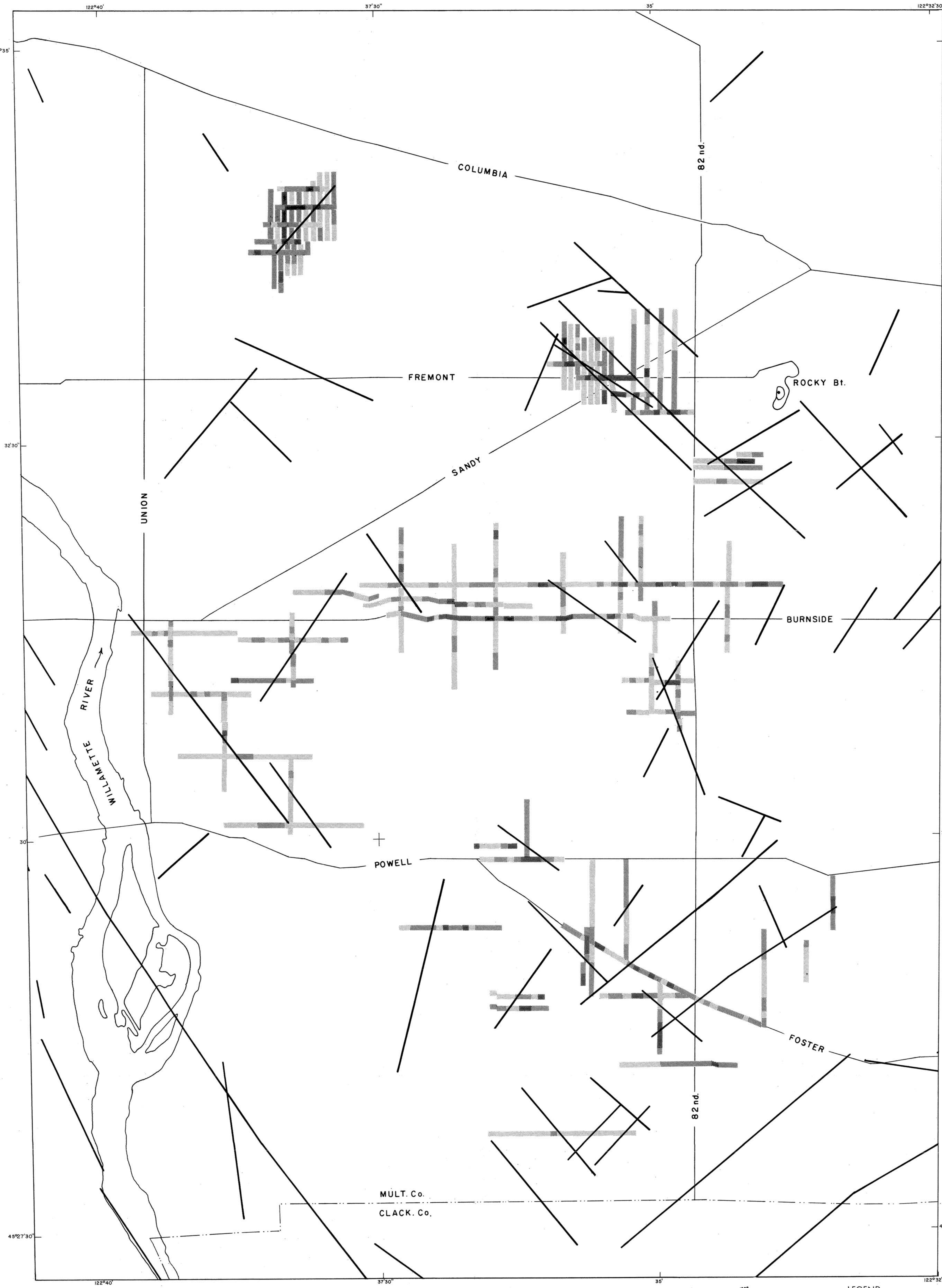
LOCATION

By L.A. Palmer, G.T. Benson, Jan Donovan, Tom Reilly, and P. E. Hammond 1974

Cartography by Lynne Lawson, and W. H. Pokorny
Cartographic Editing by S. R. Renoud

CRACK ANALYSIS OF LINEATIONS IN EAST PORTLAND

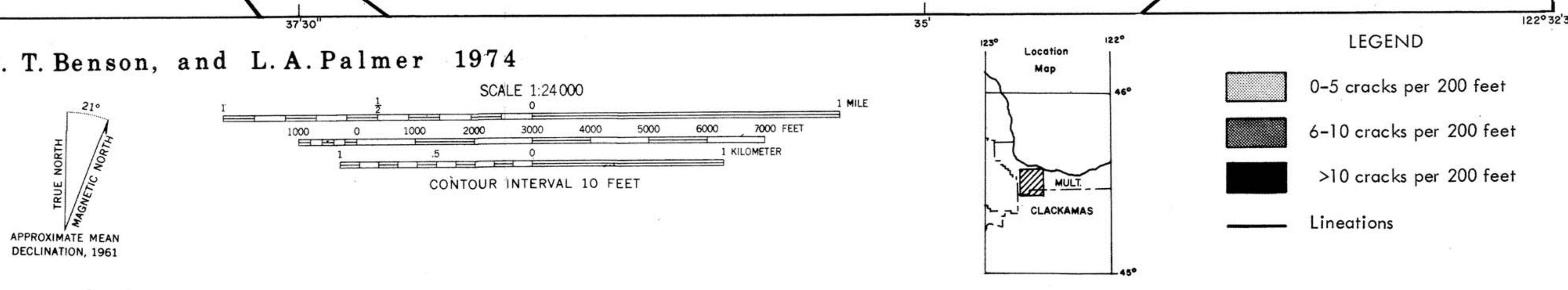
PLATE 3



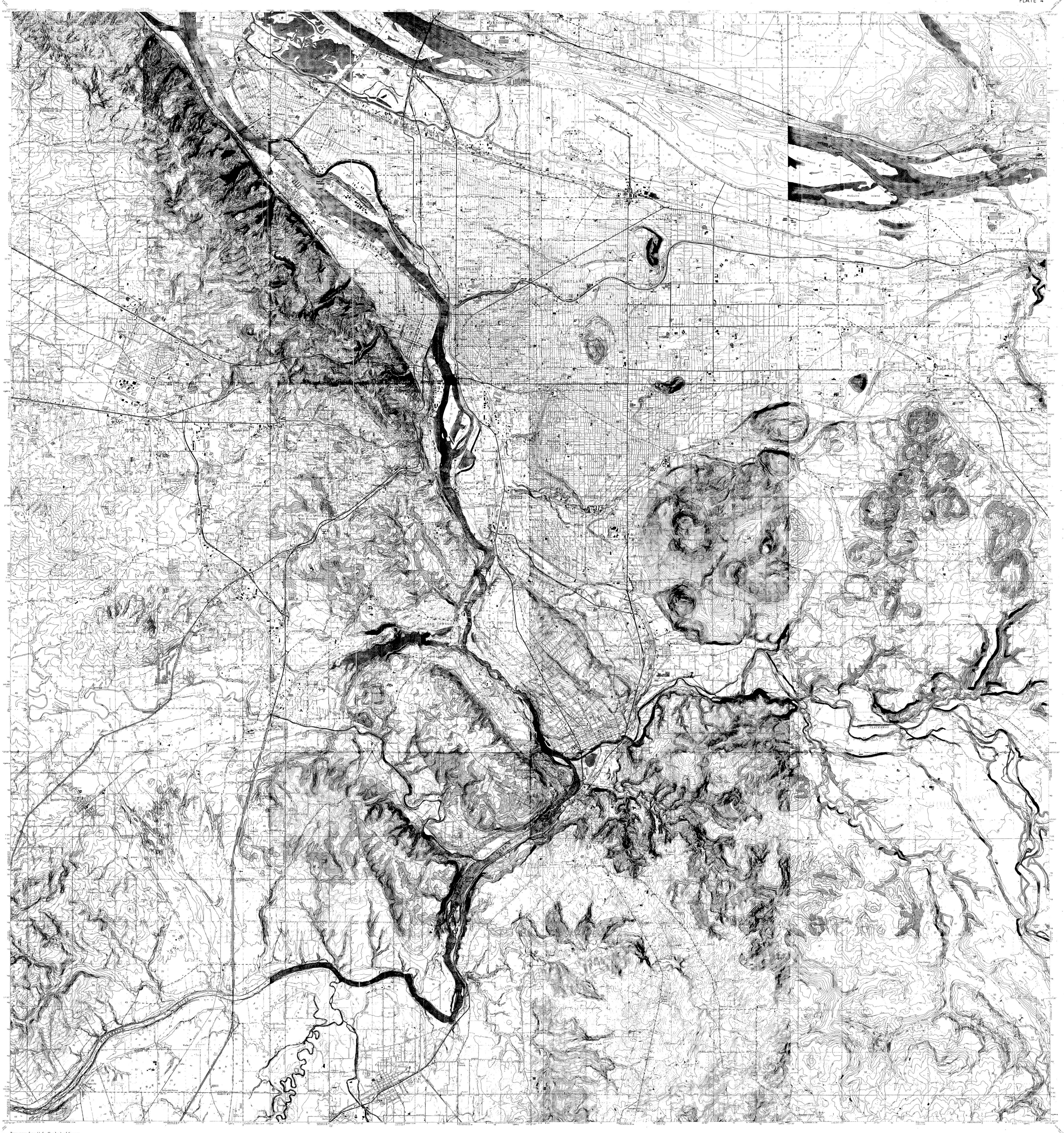
By Jan Donovan, Tom Reilly, G. T. Benson, and L. A. Palmer 1974

Cartography by Brian Gannon

Cartograpic Editing by S. R. Renoud



SLOPE MAP OF THE PORTLAND AREA



Base maps from U.S. Geological Survey

Control by USGS, USC&GS, USCE, and State of Oregon

7.5-minute series (topographic) of the following quadrangles: Linnton, Portland, Mt. Tabor, Camas, Beaverton, Lake Oswego, Gladstone, Damascus, Sherwood, Canby, Oregon City, and Redland
Photo revised in 1970

Topography from aerial photographs by photogrammetric methods

Aerial photographs taken 1952. Field check 1954.
Revised from aerial photographs taken 1960
Field check 1961

LEGEND

- > 60% (30°58')
- 35-60% (19°18' - 30°58')
- 15-35% (8°32' - 19°18')
- 0-15% (0° - 8°32')

SCALE 1:48,000

4 MILES

21000 FEET

5 KILOMETERS

Contour interval 10 feet
Datum is mean sea level

TRUE NORTH
MAGNETIC NORTH
21°
APPROXIMATE MEAN DECLINATION, 1974

OREGON
LOCATION

By Brian Gannon 1974

Cartography by Brian Gannon, Peter G. Madson, and W. H. Pokorny

Cartogrraphic Editing by S. R. Renoud

PRELIMINARY LANDSLIDE MAP OF THE PORTLAND AREA

Base maps from U.S. Geological Survey

Control by USGS, USC&GS, USCE, and State of Oregon

7.5-minute series (topographic) of the following quadrangles: Linnton, Portland, Mt. Tabor, Camas, Beaverton, Lake Oswego, Gladstone, Damascus, Sherwood, Canby, Oregon City, and Redland
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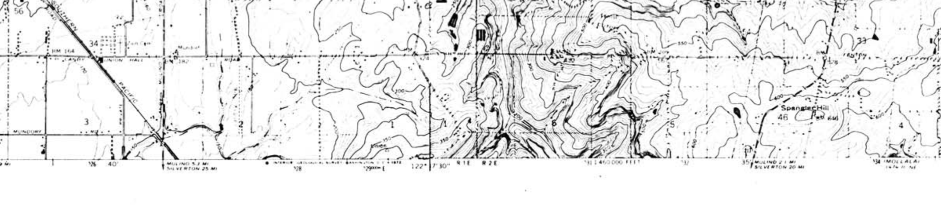

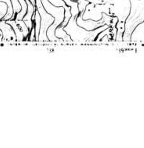

By Paul E. Hammond 1974

Cartography by Lynne Lawson and W. H. Pokorny

Cartographic Editing by S. R. Renoud

MAP OF POTENTIAL GEOLOGIC HAZARDS RELATED TO EARTHQUAKES IN THE PORTLAND AREA

PLATE 6

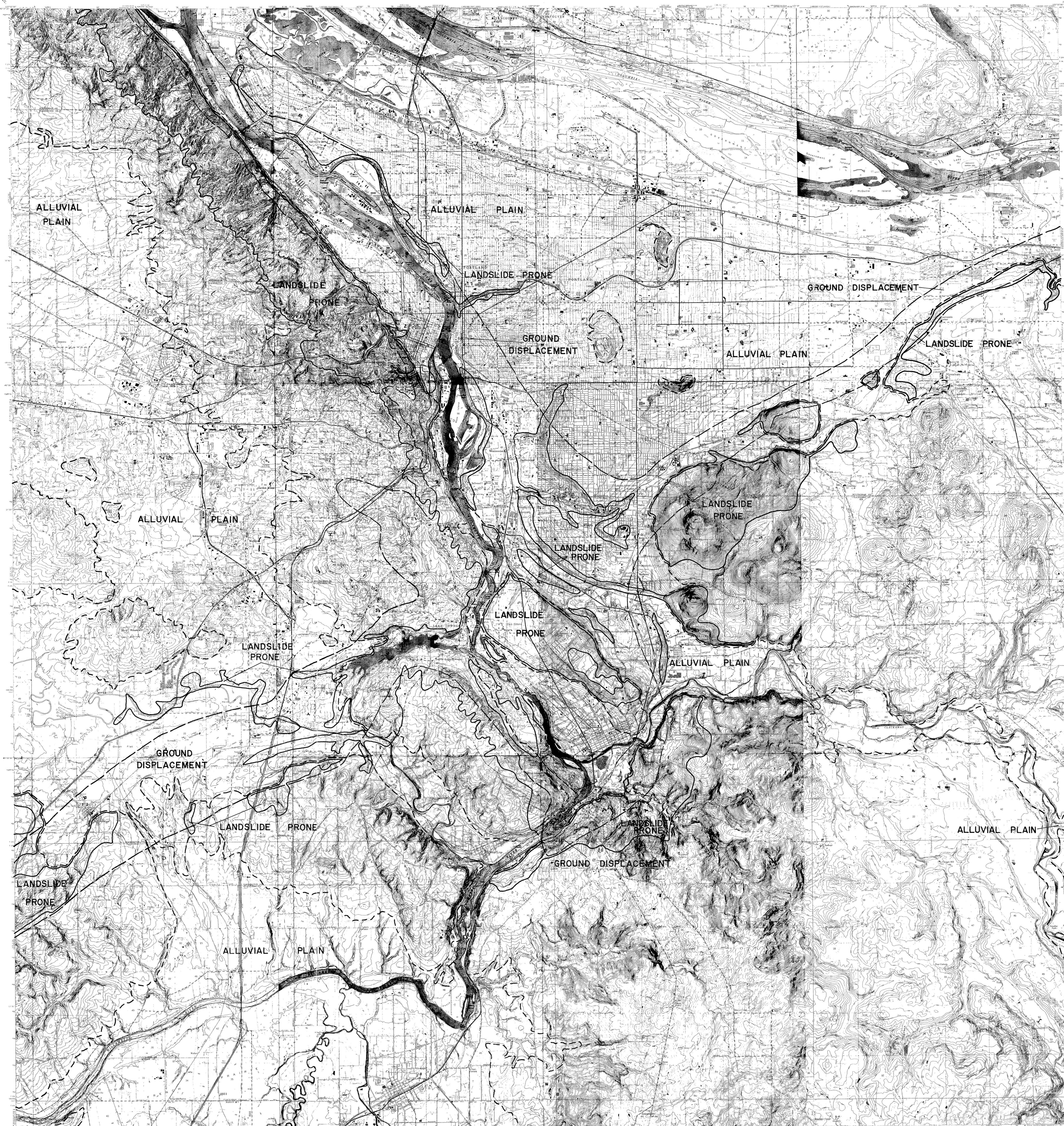

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Photo revised in 1970

Topography from aerial photographs by photogrammetric methods

Aerial photographs taken 1952. Field check 1954.
Revised from aerial photographs taken 1960
Field check 1961

LEGEND

Ground shake area:
Approximate outline of alluvial plain. Area subject to possible strong ground shaking during earthquake.

Ground displacement area:
Approximate outline of area (belts) subject to possible ground displacement (sudden uplift, subsidence, or lateral shifting) during earthquake.

Landslide prone area:
Approximate outline of areas subject to possible landsliding caused by earthquake.

SCALE 1:48,000

Contour interval 10 feet
Datum is mean sea level

APPROXIMATE MEAN DECLINATION, 1974

LOCATION

By L. A. Palmer, Tom Reilly and Paul E. Hammond

Cartography by Lynne Lawson and W. H. Pokorny
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