WASHINGTON STATE EARTHQUAKE HAZARDS

by
LINDA LAWRANCE NOSON, ANTHONY QAMAR,
AND GERALD W. THORSEN

WASHINGTON DIVISION OF GEOLOGY AND EARTH RESOURCES
INFORMATION CIRCULAR 85

1988

WASHINGTON STATE DEPARTMENT OF
Natural Resources
Brian Boyle - Commissioner of Public Lands
Art Stearns - Supervisor

Division of Geology and Earth Resources
Raymond Lasmanis, State Geologist

Cover photo:

Damage to an unreinforced masonry building in downtown Centralia in 1949. A man was killed by the falling upper walls of this two-story corner building. Unreinforced masonry walls, gables, cornices, and partitions were the most seriously damaged structures in the 1949 and 1965 earthquakes. Inferior mortar and inadequate ties between walls and floors compounded the damage. (Photo from the A. E. Miller Collection, University of Washington Archives)

WASHINGTON STATE EARTHQUAKE HAZARDS

by

LINDA LAWRANCE NOSON, ANTHONY QAMAR,
AND GERALD W. THORSEN

WASHINGTON DIVISION OF GEOLOGY AND EARTH RESOURCES

INFORMATION CIRCULAR 85

1988

WASHINGTON STATE DEPARTMENT OF
Natural Resources
Brian Boyle - Commissioner of Public Lands
Art Stearns - Supervisor

Division of Geology and Earth Resources
Raymond Lasmanis, State Geologist

The authors gratefully acknowledge review of the manuscript of this publication by members of the Geophysics Program, University of Washington.

This report is available from:

Publications
Washington Department of Natural Resources
Division of Geology and Earth Resources
Mail Stop PY-12
Olympia, WA 98504

The printing of this report was supported by U.S. Geological Survey Earthquake Hazards Reduction Program Agreement No. 14-08-0001-A0509.

This publication is free, but please add $1.00 to each order for postage and handling. Make checks or money orders payable to the Department of Natural Resources. Because we have a limited number of copies, please write or telephone [(206) 459-6372] the Division if you wish to place a large order.

This book is printed on acid-free paper.

Printed in the United States of America.

CONTENTS

Summary 1
Introduction 3
What are earthquakes? 5
How are earthquakes measured? 11
What causes earthquakes? 15
  Plate tectonics theory 15
  Plate tectonics and earthquakes in the northwestern United States 15
Where do earthquakes in Washington occur? 21
  Washington's largest reported earthquakes 21
  Earthquakes recorded by the University of Washington seismograph network 21
When and where will the next big earthquake occur? 27
What causes damage? 29
  Direct causes 29
  Secondary causes of earthquake damage 30
Where has earthquake damage occurred in Washington State? 49
  1872 North Cascades earthquake 49
  1936 Milton-Freewater earthquake 49
  1939 Puget Sound earthquake 49
  1945 Puget/Cascades border region earthquake 49
  1946 Puget Sound earthquake 49
  1949 Olympia and 1965 Seattle-Tacoma Puget Sound earthquakes 50
How can we reduce earthquake losses in Washington? 53
  Understanding earthquake risk 53
  Risk reduction 59
  Risk reduction policy 61
Glossary 63
References cited 67
  Selected catalogs containing information about earthquakes in Washington and adjacent areas 73
  Publications of the Federal Emergency Management Agency 77

ILLUSTRATIONS

Figure 1. Block diagrams of fault types 5
Figure 2. Diagrams of near-surface ground motions produced by seismic waves 6
Figure 3. Map showing location of active seismograph stations in the Pacific Northwest in 1987 7
Figure 4. Sketch of components and dimensions of a typical remost seismograph station 8
Figure 5. Seismograms illustrating the range of ground motions commonly recorded in Washington and Oregon 9
Figure 6. Method for calculating epicentral distance and magnitude of an earthquake 12
Figure 7. Isoseismal map for the Seattle-Tacoma earthquake of 1965 14
Figure 8. Map showing relation between major tectonic plates and earthquakes 16
Figure 9. Cutaway view of the Earth 17
Figure 10. Diagram illustrating three types of plate boundaries 17
Figure 11. Cross sections of Washington showing plate convergence and earthquake hypocenter locations 18
Figure 12. Map showing epicenters of selected earthquakes in the Pacific Northwest since 1960 19
Figure 13. Map showing epicenters and dates of the largest Pacific Northwest earthquakes between 1872 and 1987 .23
Figure 14. Map showing epicenters of Washington earthquakes recorded from 1982 to 1987 ($M_c \geq 2.0$) 24

ILLUSTRATIONS, continued

Figure 15. Map showing faults in Washington known to be active or thought to have been active in the last 10,000 years 25
Figure 16. Aerial view of the Saddle Mountain faults near Lake Cushman, Olympic Peninsula 30
Figure 17. Photograph showing evidence for subsidence in coastal Washington, buried marsh 31
Figure 18. Photograph showing evidence for subsidence in coastal Washington, ghost forest 31
Figure 19. Photograph of a landslide in fill near Olympia, 1965 32
Figure 20. Photograph of landslide, Tacoma Narrows, 1949 34
Figure 21. Photograph of road damage caused by liquefaction, Olympia, 1965 34
Figure 22. Photograph of sand blows, Olympia, 1965 35
Figure 23. Tide gage records showing tsunami waves from the 1964 Alaska earthquake 37
Figure 24. Map showing tsunami damage in coastal Washington from the 1964 Alaska earthquake 38, 39
Figure 25. Photograph of stripped dunes, coastal Washington 39
Figure 26. Diagram showing structural components of a building 40
Figure 27. Photograph showing failure of unreinforced masonry during the 1965 earthquake 40
Figure 28. Photograph of damage at the Fisher Flouring Mills, 1965 41
Figure 29. Photograph of collapsed roof, Puyallup High School, 1949 42
Figure 30. Photograph of a collapsed parapet wall, Olympia, 1949 43
Figure 31. Photograph of a damaged chimney, Kelso, 1949 44
Figure 32. Photograph of fallen light fixtures in an Olympia school, 1965 44
Figure 33. Photograph of fallen library shelves, 1949 44
Figure 34. Photograph of Boeing Company tapes scattered by the 1965 earthquake 45
Figure 35. Photograph of windows broken in a Tacoma store by the 1965 earthquake 45
Figure 36. Photograph of government files disturbed by the 1965 earthquake 45
Figure 37. Photograph of damaged radio tower, 1949 46
Figure 38. Photograph of damage at Lower Van Norman Dam, California, 1971 47
Figure 39. Photograph of shifted ground in Seattle, 1965 50
Figure 40. Photograph of damage at school entrance, Castle Rock, 1949 50
Figure 41. Photograph of damage to Lafayette School, Seattle, 1949 51
Figure 42. Photograph of damage at Washington State Training School for Boys, Chehalis, 1949 51
Figure 43. Photograph of damaged arch, Capitol Building, Olympia, 1949 52
Figure 44. Map prepared for Uniform Building Code showing Seismic Risk Zones, 1988 56
Figure 45. Photographs of unreinforced masonry buildings in Port Townsend 57
Figure 46. Sketch showing method of securing a home water heater 58
Figure 47. Sketch of a child in the "drop and cover" position 59

TABLES

Table 1. Modified Mercalli Intensity Scale 13
Table 2. Largest known earthquakes felt in Washington 22
Table 3. Wave heights of some recent tsunamis recorded at selected West Coast tide gages 36
Table 4. What to do during an earthquake 60
Table 5. What to do after the shaking stops 60

WASHINGTON STATE EARTHQUAKE HAZARDS

by
Linda Lawrance Noson[1], Anthony Qamar[2], and Gerald W. Thorsen[3]

SUMMARY

Washington is earthquake country. More than 1,000 earthquakes are recorded in the state each year; a dozen or more of these produce significant shaking or damage. Large earthquakes in 1949 and 1965 killed 15 people and caused more than $200 million (1984 dollars) property damage.

Earth scientists believe that most earthquakes are caused by slow movements inside the Earth that push against the Earth's brittle, relatively thin outer layer, causing the rocks to break suddenly. This outer layer is fragmented into a number of pieces, called plates. Most earthquakes occur at the boundaries of these plates. In Washington, the small Juan de Fuca plate off the coast of Washington, Oregon, and northern California is slowly moving eastward beneath a much larger plate that includes both the North American continent and the land beneath part of the Atlantic Ocean. Plate motions in the Pacific Northwest result in shallow earthquakes widely distributed over Washington and deep earthquakes in the western parts of Washington and Oregon. The movement of the Juan de Fuca plate beneath the North America plate is in many respects similar to the movements of plates in South America, Mexico, Japan, and Alaska, where the world's largest earthquakes occur.

We cannot predict precisely where, when, and how large the next destructive earthquake will be in Washington, but seismological and geological evidence supports several possibilities. Large earthquakes reported historically in Washington have most frequently occurred deep beneath the Puget Sound region. The most recent and best documented of these were the 1949 Olympia earthquake and the 1965 Seattle-Tacoma earthquake. The pattern of earthquake occurrence observed in Washington so far indicates that large earthquakes similar to the 1965 Seattle-Tacoma earthquake are likely to occur about every 35 years and large earthquakes similar to the 1949 Olympia earthquake about every 110 years. Such large earthquakes deep beneath the Puget Sound area will happen again.

The largest earthquake reported in the state did not occur in the Puget Sound region, but rather at a shallow depth under the North Cascade Mountains. Recent studies in the southern Cascades near Mount St. Helens indicate that other areas in the Cascades may produce large, shallow earthquakes, comparable in size to the 1949 and 1965 Puget Sound earthquakes. The average interval of time between occurrences of such earthquakes in the Cascade Mountains is uncertain because they have occurred infrequently. However, the 1872 North Cascade earthquake and earthquake activity in the southern Cascades are reminders that Puget Sound is not the only region in Washington having significant earthquake hazards.

[1] Federal Emergency Management Agency, Bothell, WA 98021
[2] Geophysics Program, University of Washington, Seattle, WA 98195
[3] Washington Division of Geology and Earth Resources, Olympia, WA 98504

The largest earthquake now considered a possibility in the Pacific Northwest is a shallow subduction-style earthquake similar to recent destructive earthquakes in Alaska and Mexico, which had magnitudes greater than 8. An earthquake this large would be expected to occur along the coast of Washington or Oregon. Although we have no record of such large earthquakes in the Pacific Northwest within the last 150 years, some scientists believe that rocks and sediments exposed along the coasts of Washington and Oregon show evidence that as many as eight such earthquakes have occurred in the last several thousand years. This evidence indicates an average interval of time between subduction earthquakes of several hundred years. A magnitude 8 subduction earthquake would not only cause widespread dangerous ground shaking but would also likely produce water waves capable of inundating coastal areas in a matter of minutes.

Earthquake damage is primarily caused by ground shaking. However, wood frame houses, well attached to their foundations and built on firm ground, generally sustain little structural damage during earthquakes. In contrast, unreinforced brick buildings commonly suffer severe damage. Ground shaking may also displace and distort the non-structural parts of a building—including windows, ceiling tiles, partitions and furniture—producing property damage and endangering life. Other hazards such as ground liquefaction are commonly triggered by strong ground shaking.

Future injuries and property losses from earthquake hazards can be reduced by considering these hazards when making decisions about land use, by designing structures that can undergo ground shaking without collapse, by securely attaching the non-structural elements of a building, and by educating the public about what to do before, during, and after an earthquake to protect life and property. Many businesses and corporations without earthquake emergency contingency plans fail following earthquake disasters. Earthquakes cannot be prevented, but practicing appropriate response actions and the mitigation of hazards will reduce their impact on people.

Now is the time to prepare. Establishing earthquake safety policy, both governmental and organizational, will provide guidelines for the development of earthquake safety programs and ensure that programs are consistently carried out. Businesses that have earthquake emergency plans are less likely to fail following earthquake disasters.

More detailed information about earthquakes, local geology, and earthquake safety in Washington can be obtained from the following:

Washington State Department of Natural Resources
Division of Geology and Earth Resources
4224 6th Avenue SE, Lacey, WA 98504
Mail: MS PY-12, Olympia, WA 98504
(206) 459-6372

Washington State Department of Community Development
Division of Emergency Management
4220 E. Martin Way, Olympia, WA 98504
(206) 753-5255

Federal Emergency Management Agency, Region X
130 228th Ave. SW
Bothell, WA 98021
(206) 487-4694

Branch of Distribution
U.S. Geological Survey
Box 25286, Federal Center
Denver, CO 80225
(303) 234-3832

Public Inquiries Office
U.S. Geological Survey
Room 122, Bldg. 3, (MS 33)
345 Middlefield Road
Menlo Park, CA 94025
(415) 329-4396

County and city emergency management offices
(For information, consult local telephone books for emergency services.)

See also a list of sources of technical information following the references cited at the end of this report.

INTRODUCTION

Washington is well-known for snowclad mountains, white-water rivers, and thick rain forests. Some of the hazards of such an environment—avalanches, drowning, and fires—are obvious and the precautions necessary to deal with them well understood. The hazard from earthquakes in Washington is less well recognized, yet damage and loss of life during a large earthquake are certain. A 1975 study (U.S. Geological Survey, 1975) of six counties in the Puget Sound area, now considered by some to be too conservative, projects as many as 2,200 deaths and 8,700 injuries in the next magnitude 7.5 earthquake.

Each year more than 1,000 earthquakes are recorded in Washington. Fifteen to twenty of these earthquakes cause ground shaking strong enough to be felt. However, major destructive earthquakes occur much less often. The last earthquake to cause widespread damage in Washington occurred in 1965. Since that time the state's population has increased by nearly 50 percent. Washington residents have largely forgotten the 1965 earthquake, and this has contributed to a general lack of public awareness of the state's earthquake hazards. Some scientists suggest that even larger earthquakes have occurred every several hundred or thousand years in the Pacific Northwest and that the most recent such earthquake occurred about 300 years ago.

This publication contains answers to the most commonly asked questions about earthquakes in Washington: Why do we have earthquakes? Can we predict when and where the next big earthquake will occur? Where are the earthquake faults? What would happen if we had a large earthquake today? What can be done to prepare for an earthquake?

By understanding the causes and effects of Washington earthquakes, individuals can take appropriate actions to reduce loss of life and property. Many of the necessary actions are identified and described in this report. A glossary of technical terms (in bold print in the text) is included at the end of the text.

WHAT ARE EARTHQUAKES?

An **earthquake** is the shaking of the ground caused by an abrupt shift of rock along a fracture in the Earth, called a **fault** (Fig. 1). Within seconds, an earthquake releases stress that has slowly accumulated within the rock, sometimes over hundreds of years.

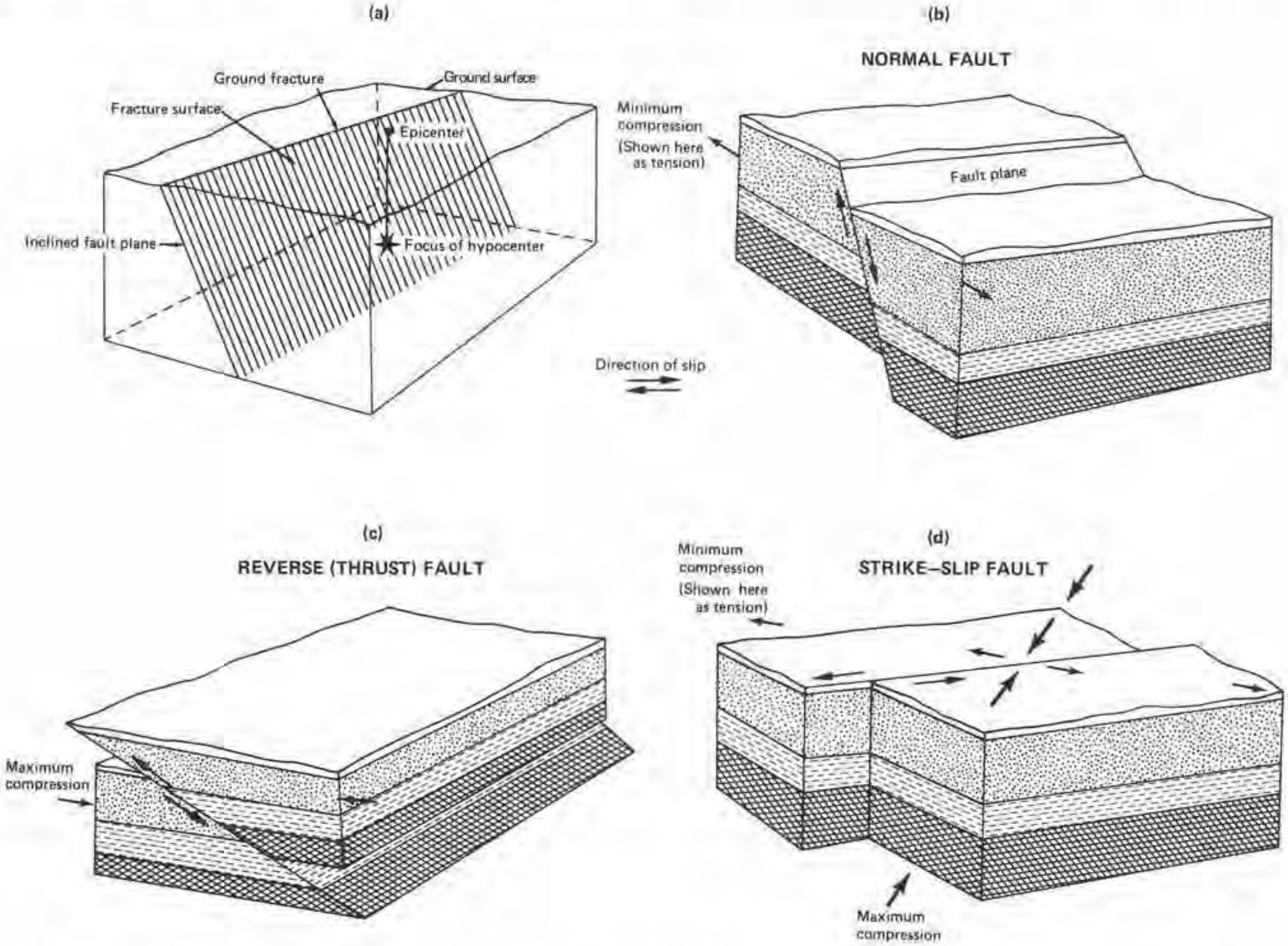


Figure 1. Block diagrams of fault types. (a) An earthquake is caused by the sudden fracturing of rock along part of a fault surface, shown here as a plane. If the fault reaches the surface, a visible ground fracture is created. The **focus** or **hypocenter** is the point on the fault plane where fracturing begins. The **epicenter** is the point on the ground surface directly over the focus. If the fault plane is inclined, the position of the epicenter will not coincide with the ground fracture. Simple fault motions are shown in (b), (c), and (d); directions of compressive stress are indicated. In a normal fault, (b), adjacent blocks of rock behave as if they were being pulled apart; the upper block slides downward along the fault relative to the other. In a thrust fault, (c), the blocks behave as if they were being pushed together; the upper block rides up the fault plane. In a strike-slip fault (d), one block moves horizontally past the other. Oblique motion of the blocks (not illustrated) combines thrust or normal fault motion with strike-slip motion. From an analysis of the seismic waves generated by an earthquake, called a **fault-plane solution**, scientists can determine the type of fault motion that occurred.

It is also possible for the accumulated stress to be released more gradually, by continuous slippage along a fault; this movement may amount to only a few millimeters a year. Such faults are said to undergo **aseismic fault creep** because the stress release occurs without earthquakes.

Faults are a record of past earth movements, just as fossils are a record of plants and animals that once inhabited the Earth. However, like volcanoes, faults may be extinct or active. Some faults are continuously active, while others may have occasional earthquakes and long periods of quiescence. Thousands of "extinct faults" have been mapped in Washington. A few active faults have also been mapped; these active faults are said to be active because they have experienced surface movement in the last 10,000 years. However, in the last 100 years earthquakes in Washington have not been associated with known active faults.

The earthquake process can be compared to the bending of a stick until it snaps. Stress accumulated during bending is suddenly released when the stick breaks. Vibrations are produced as the stick springs back to its pre-stressed position. In the Earth, **seismic waves** (Fig. 2) are the vibrations caused by the sudden release of stress built up in rocks on either side of a fault. The rupturing of a fault may release all or only some of the stress. Any residual stress is often released by later minor readjustments along the fault causing smaller earthquakes called **aftershocks.**

Earthquakes generate several kinds of seismic waves that vibrate the ground (Fig. 2). These seismic waves travel through the Earth at speeds of several **kilometers** per second, and they cause ground motions that can be detected by **seismographs** (or by **accelerographs**) far from the **epicenter** of the earthquake. In 1987, the University of Washington was operating more than 100 seismograph stations in Washington and northern Oregon (Fig. 3). Several thousand seismographs are operated throughout the world by other groups of seismologists.

Typical components of a modern seismograph station are shown in Figure 4. The signals produced by the seismographs in response to ground vibrations from an earthquake are commonly recorded on paper and magnetic tape. The display of ground motion versus time on a paper record is called a **seismogram** (Fig. 5). Seismographs can detect ground motions caused by sources other than earthquakes, such as explosions, volcanic eruptions, sonic booms, helicopters, and cars. Each of these sources can generally be identified from their characteristic signals recorded on seismograms.

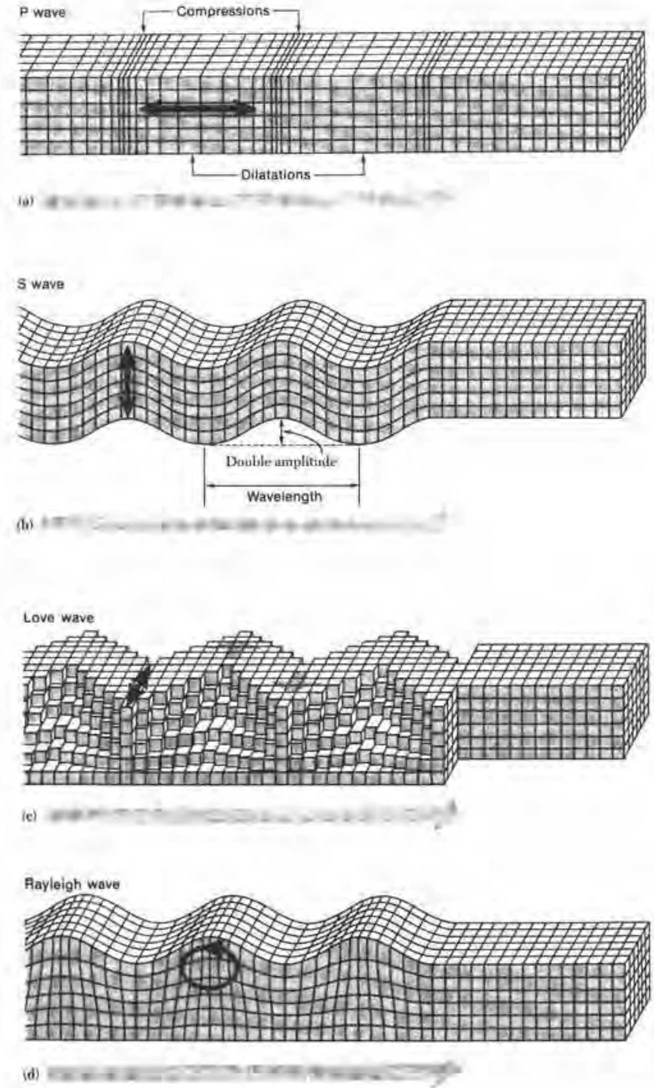


Figure 2. Diagrams of near-surface ground motions produced by seismic waves. The P and S waves, (a) and (b) respectively, travel through the earth in all directions from the focus of the earthquake; the first wave to reach an observer during an earthquake is the P wave. Two types of surface waves shown in (c) and (d), travel along the ground surface, somewhat like water waves, and arrive after the S waves. The direction the wave travels is indicated by the arrow below each diagram; the direction of ground movement caused by each wave is indicated by the solid arrows on the diagrams. P and S waves cause the ground to vibrate in mutually perpendicular directions. (Modified from "Earthquakes" by Bruce A.Bolt. Copyright ©1978, 1988 W.H. Freeman Company. Reprinted with permission)

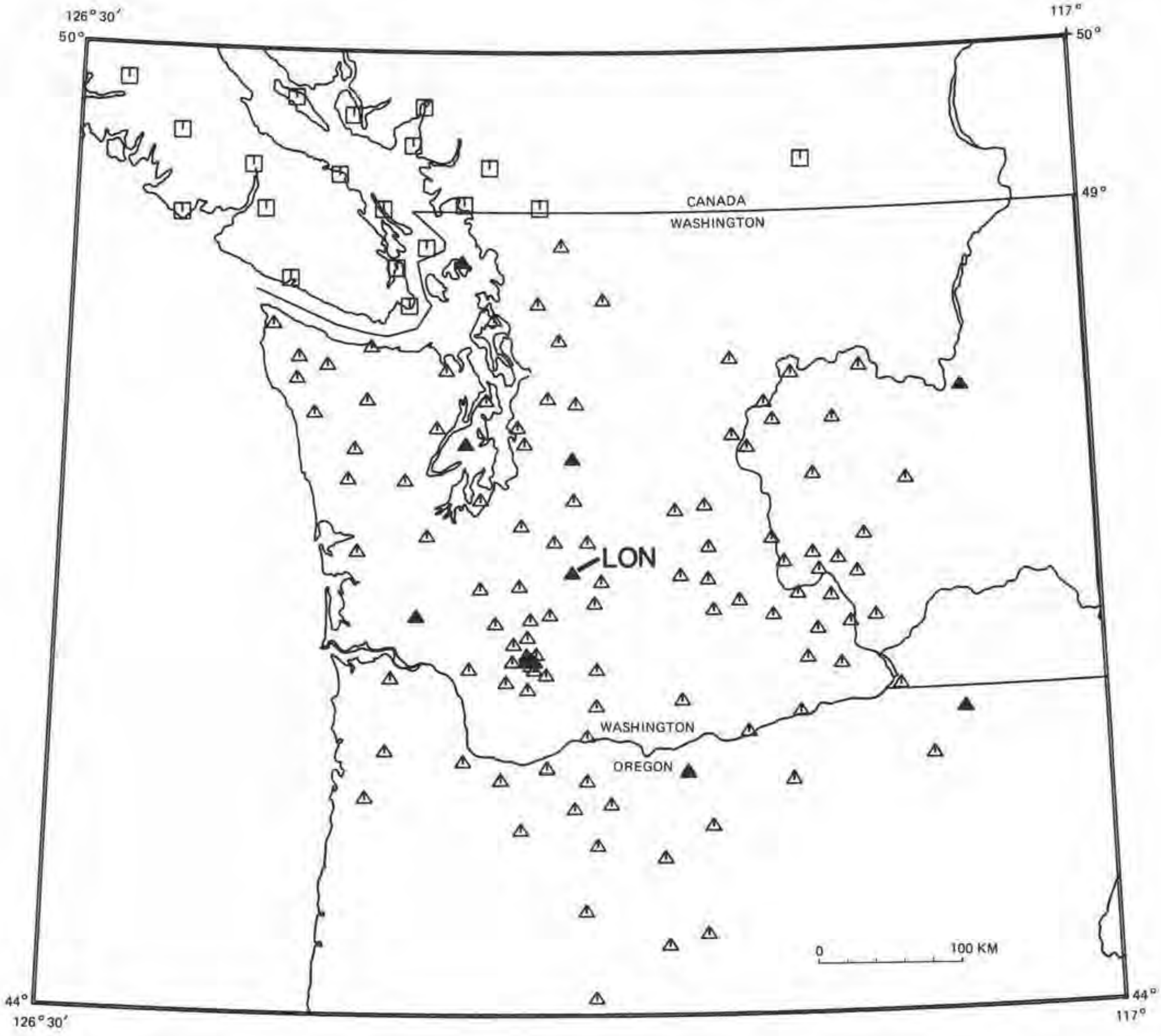


Figure 3. Active seismograph stations in the Pacific Northwest in 1987. Stations operated by the University of Washington are shown as triangles, Canadian stations as squares. Seismic signals from the University's stations are received in Seattle. Signals from stations shown as solid triangles are also transmitted to the National Earthquake Information Service in Golden, Colorado. Station LON, at Mount Rainier, is part of an international recording system known as the World Wide Standard Seismograph Station Network (WWSSN). At LON six seismometers measure the various kinds of seismic waves shown in Figure 2.

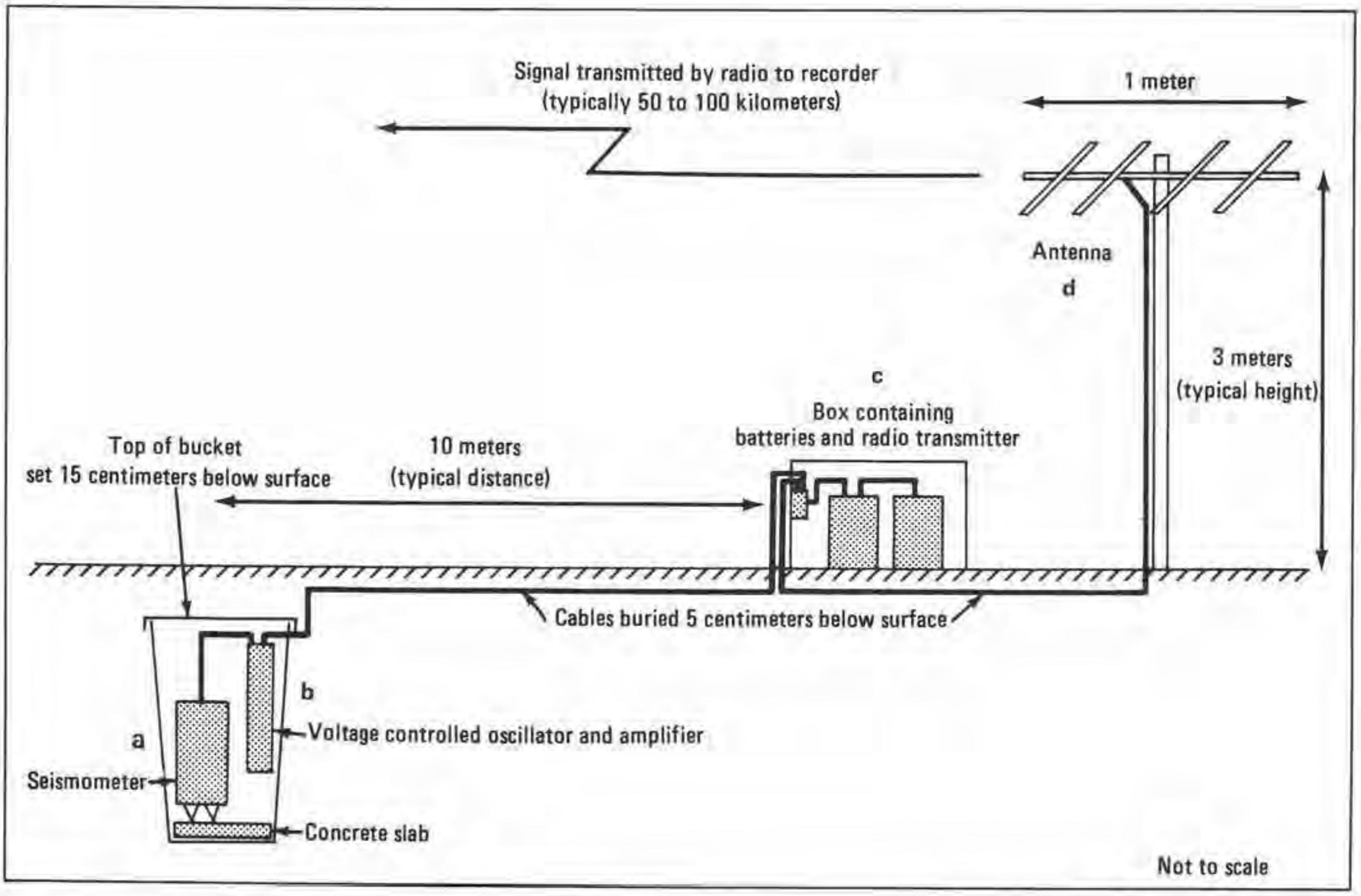


Figure 4. Components and dimensions of a typical remote seismograph station, similar to stations located on Figure 3. The seismometer (a) converts small ground motions into an electric signal that has varying voltage. An amplifier and a voltage-controlled oscillator amplify this signal and convert it to a frequency-modulated (FM) tone. The radio transmitter (c) and the antenna (d) transmit the tone signal to the recording site.

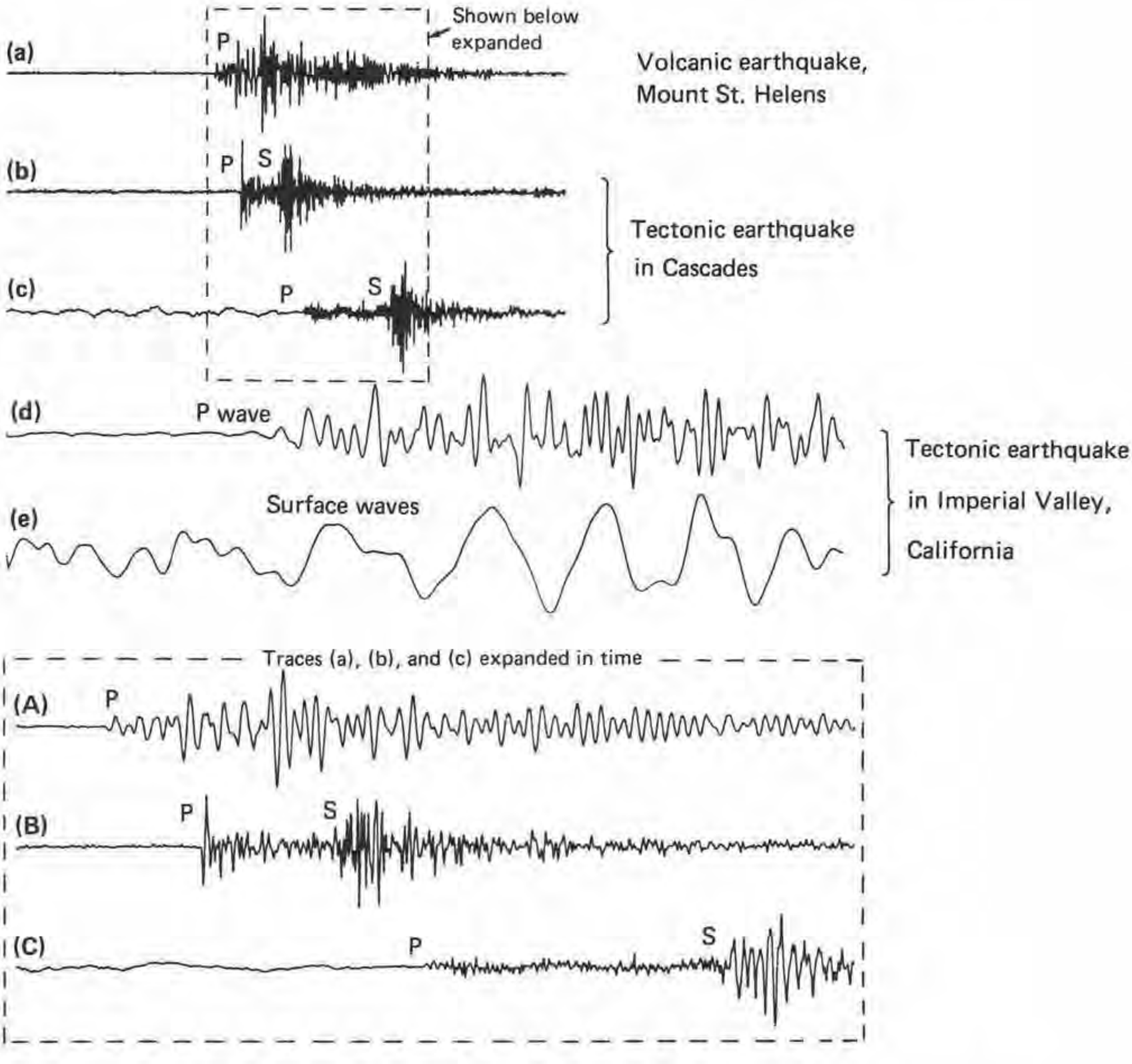


Figure 5. Seismograms (a) through (e) were recorded by stations in Washington and Oregon and illustrate the range of ground motion frequencies commonly recorded. The seismometers that recorded these motions are similar, and all had natural periods of 1.0 second. The seismograms for (a), (b), and (c) are expanded as (A), (B), and (C) in the lower part of the figure. P and S waves are marked on all seismograms. (a) Seismogram of a small (magnitude 1.2) volcanic earthquake at Mount St. Helens on November 23, 1987. The focus was less than 1 km below the surface, and the epicenter was less than 1 km from the station. (b) and (c) Seismograms of a magnitude 0.9 earthquake in the Cascade Range on November 18, 1987. The focus was at a depth of 17 km, and the epicenter was 13 km from the station that recorded (b) and 47 km from the station that recorded (c). (d) and (e) Seismograms from a magnitude 6.3 earthquake in the Imperial Valley of California on November 24, 1987 (d) shows the P wave as recorded at a station in northern Oregon, 1427 km from the epicenter. (e) shows the surface waves, which have lower frequencies, recorded at the same station. The surface waves arrived about 5-1/2 minutes after the P waves.

HOW ARE EARTHQUAKES MEASURED?

The size of an earthquake is indicated by a number called its **magnitude**. Magnitude is calculated from a measurement of either the **amplitude** or the duration of specific types of recorded seismic waves. Magnitude is determined from measurements made from seismograms and not on reports of shaking or interpretations of building damage. In general, the different magnitude scales (for example, local or **Richter magnitude** and **surface wave** magnitude) give similar numerical estimates of the size of an earthquake, and all display a logarithmic relation to recorded ground motion. That means each unit increase in magnitude represents an increase in the size of the recorded signal by a factor of 10. Therefore, a magnitude 7 earthquake would have a maximum signal amplitude 10 times greater than that of a magnitude 6 earthquake and 100 times greater than that of a magnitude 5 earthquake. Seismologists sometimes refer to the size of an earthquake as moderate (magnitude 5), large (magnitude 6), major (magnitude 7), or great (magnitude 8). Figure 6 shows how the Richter magnitude of an earthquake is calculated by measuring the amplitude of the maximum wave motion recorded on the seismogram.

The **intensity** of an earthquake is a measure of the amount of ground shaking at a particular site, and it is determined from reports of human reaction to shaking, damage done to structures, and other effects. The **Modified Mercalli Intensity Scale** (Table 1) is now the scale most commonly used to rank earthquakes felt in the United States. If magnitude is compared to the power output of a radio broadcasting station, then the intensity of an earthquake is the signal strength at a particular radio receiver. In practice, an earthquake is assigned one magnitude, but it may give rise to reports of intensities at many different levels. The magnitude 6.5 April 29, 1965, Seattle-Tacoma earthquake produced intensity VII to VIII damage near its epicenter, intensity V damage 150 kilometers away, and intensity I and II (barely felt) 300 to 500 kilometers from the epicenter (Fig. 7). Although the greatest damage, and thus highest intensity, is usually near the earthquake's origin, damage to buildings depends on many factors, such as the type of construction, distance from the epicenter, and type of soil beneath the building. (See Structural Failure of Buildings, in the section titled What Causes Damage?) Therefore, maps of earthquake intensity commonly show complex patterns.

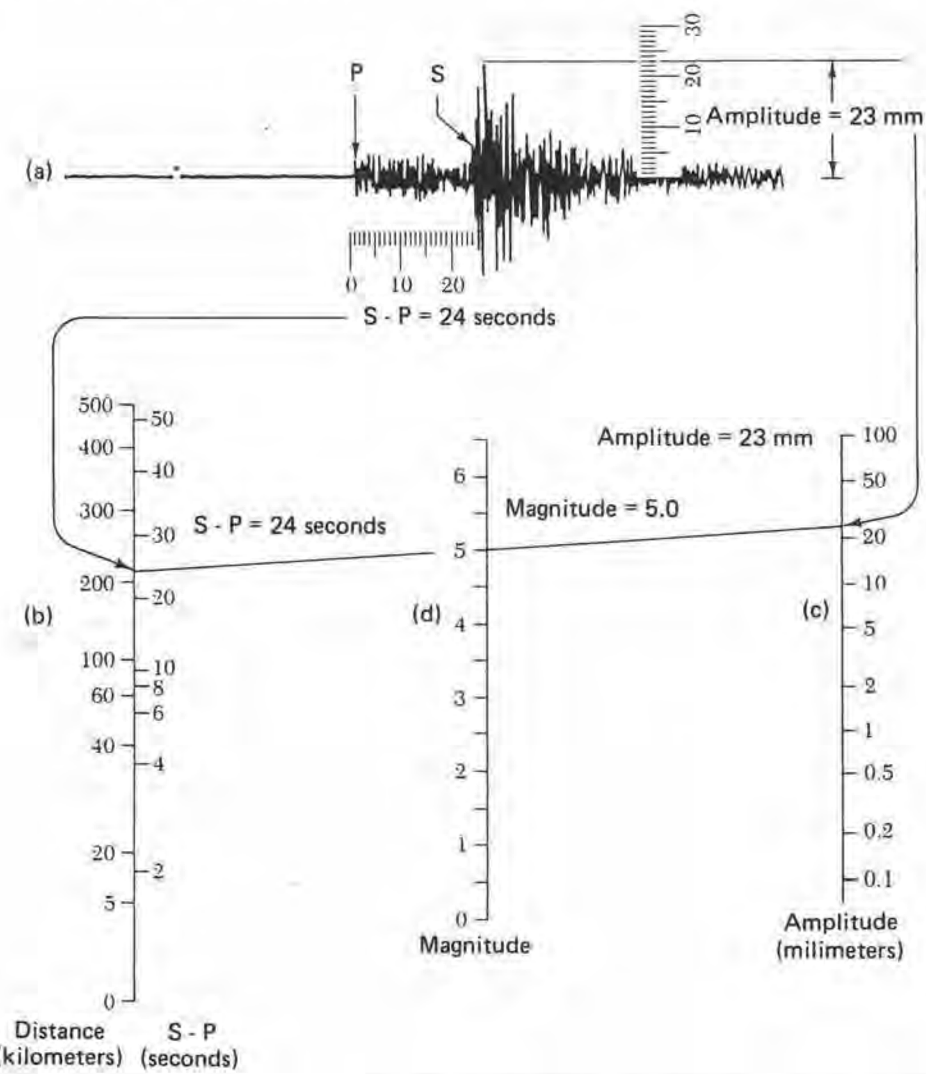


Figure 6. A method for calculating the epicentral distance and magnitude of a local earthquake (M_L) from the wave amplitude recorded on a seismogram. The seismograph that recorded this seismogram is a standard Wood-Anderson seismograph. In this example, the ruler below the seismogram in (a) indicates the time in seconds between the arrivals of the P and S waves; here, S - P = 24 seconds. This difference between arrival times can be used to calculate the distance between the epicenter and the recording station. The arrival-time difference is shown on the vertical scale (b) and corresponds to an epicentral distance of about 214 km. The amplitude of the seismic waves, 23 mm, is measured on the vertical scale in (a); this measurement is noted on the vertical scale (c, on the right). The magnitude is determined by drawing a line that connects the points on vertical scales (b) and (c). This line passes through 5 on vertical scale (d), corresponding to a magnitude of 5.0 (Modified from "Earthquakes" by Bruce A. Bolt. Copyright ©1978, 1988 W. H. Freeman and Company; reprinted with permission)

Table 1. Modified Mercalli Intensity Scale. From a pamphlet "The severity of an earthquake" prepared by the U.S. Geological Survey in 1986. See Wood and Neumann (1931) for complete details.

I. Not felt except by a very few under especially favorable circumstances.

II. Felt only by a few persons at rest, especially on upper floors of buildings. Delicately suspended objects may swing.

III. Felt quite noticeably by persons indoors, especially on upper floors of buildings. Many people do not recognize it as an earthquake. Standing motor cars may rock slightly. Vibration similar to the passing of truck. Duration estimated.

IV. Felt indoors by many, outdoors by few during the day. At night, some awakened. Dishes, windows, doors disturbed; walls make cracking sound. Sensation like heavy truck striking building. Standing motor cars rocked noticeably.

V. Felt by nearly everyone; many awakened. Some dishes, windows broken. Unstable objects overturned. Pendulum clocks may stop.

VI. Felt by all; many frightened. Some heavy furniture moved; a few instances of fallen plaster. Damage slight.

VII. Damage negligible in building of good design and construction; slight to moderate in well-built ordinary structures; considerable damage in poorly built or badly designed structures; some chimneys broken. Noticed by persons driving motor cars.

VIII. Damage slight in specially designed structures; considerable in ordinary substantial buildings with partial collapse. Damage great in poorly built structures. Fall of chimneys, factory stacks, columns, monuments, walls. Heavy furniture overturned.

IX. Damage considerable in specially designed structures; well-designed frame structures thrown out of plumb. Damage great in substantial buildings, with partial collapse. Buildings shifted off foundations.

X. Some well-built wooden structures destroyed; most masonry and frame structures destroyed with foundations. Rails bent.

XI. Few, if any (masonry) structures remain standing. Bridges destroyed. Rails bent greatly.

XII. Damage total. Lines of sight and level distorted. Objects thrown into the air.

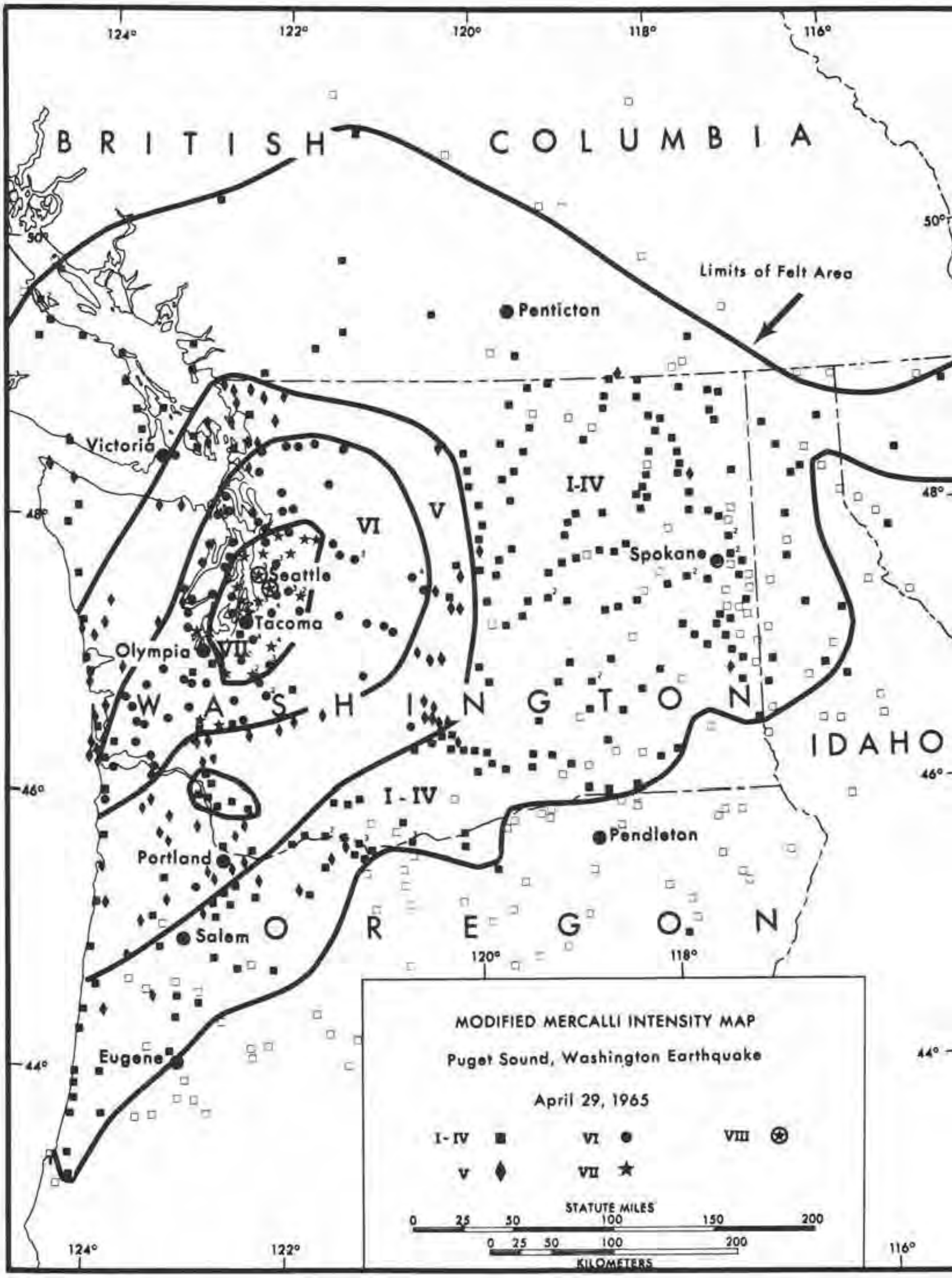


Figure 7. Isoseismal map for the Seattle-Tacoma earthquake of April 29, 1965. The lines enclose areas of equal intensity as designated on the Modified Mercalli Intensity Scale (Table 1). (From Algermissen and Harding, 1965)

WHAT CAUSES EARTHQUAKES?

Plate Tectonics Theory

The **plate tectonics** theory is a starting point for understanding the forces within the Earth that cause earthquakes. **Plates** are thick slabs of rock that make up the outermost 100 kilometers or so of the Earth (Fig. 8). Geologists use the term tectonics to describe deformation of the Earth's crust, the forces producing such deformation, and the geologic and structural features that result.

Earthquakes occur only in the outer, brittle portions of these plates, where temperatures in the rock are relatively low. Deep in the Earth's interior, **convection** of the rocks, caused by temperature variations in the Earth, induces stresses that result in movement of the overlying plates (Fig. 9). The rates of plate movements range from about 2 to 12 centimeters per year and can now be measured by precise surveying techniques. The stresses from convection can also deform the brittle portions of overlying plates, thereby storing tremendous energy within the plates. If the accumulating stress exceeds the strength of the rocks comprising these brittle zones, the rocks can break suddenly, releasing the stored elastic energy as an earthquake.

Three major types of **plate boundaries** are recognized (Fig. 10). These are called **spreading, convergent,** or **transform**, depending on whether the plates move away from, toward, or laterally past one another, respectively. Subduction occurs where one plate converges toward another plate, moves beneath it, and plunges as much as several hundred kilometers into the Earth's interior. The Juan de Fuca plate off the coasts of Washington and Oregon is subducting beneath North America (Fig. 11).

Ninety percent of the world's earthquakes occur along plate boundaries (Fig. 8) where the rocks are usually weaker and yield more readily to stress than do the rocks within a plate. The remaining 10 percent occur in areas away from present plate boundaries—like the great New Madrid, Missouri, earthquakes of 1811 and 1812, felt over at least 3.2 million square kilometers, which occurred in a region of southeast Missouri that continues to show seismic activity today (Schnell and Herd, 1984).

Plate Tectonics and Earthquakes in the Northwestern United States

The Cascadia **subduction zone** off the coasts of Washington, Oregon, and northern California is a **convergent boundary** between the large North America plate and the small Juan de Fuca plate to the west (Figs. 11, 12). The Juan de Fuca plate moves northeastward and then plunges (subducts) obliquely beneath the North America plate at a rate of 3 to 4 centimeters per year (Chase and others, 1975; Adams, 1984; Riddihough, 1984).

Washington has features typical of convergent boundaries in other parts of the world. These are illustrated in Figure 11:

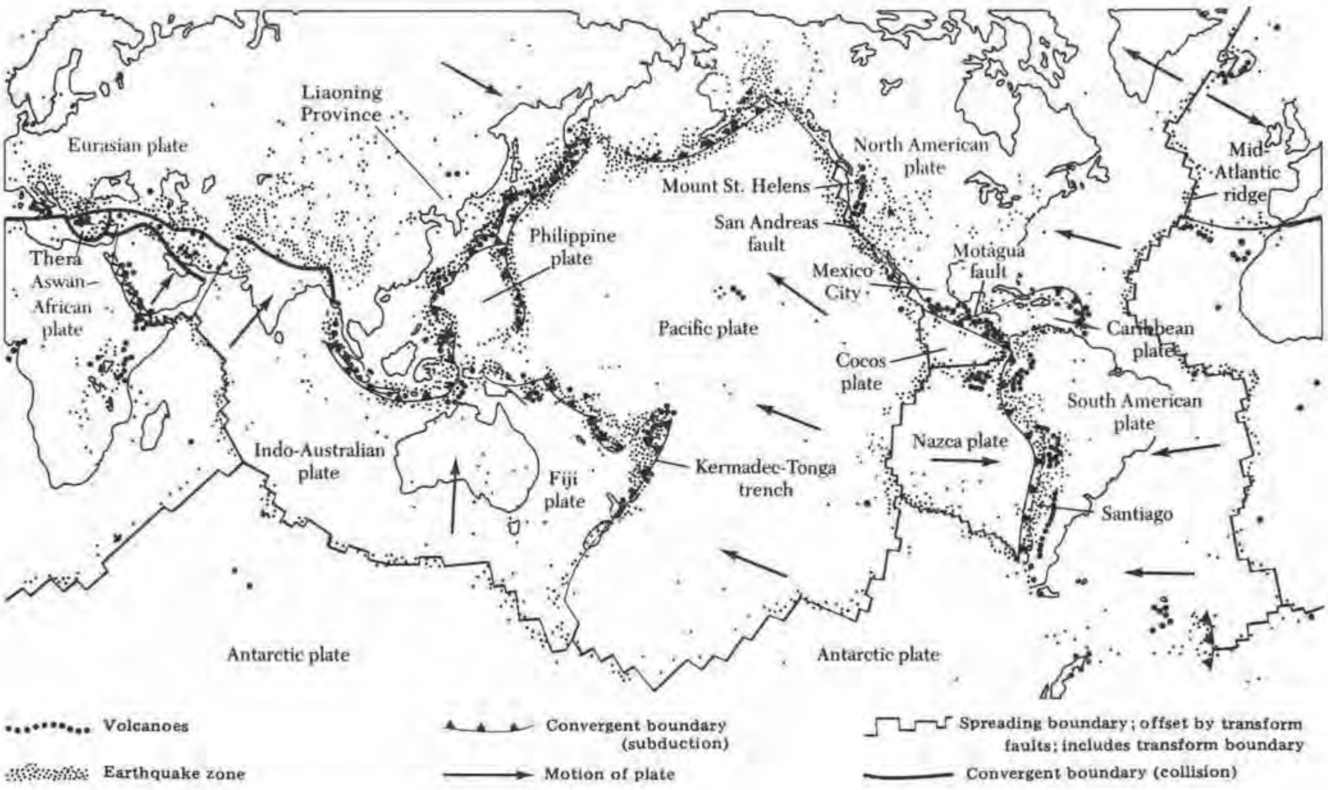
(1) A zone of deep earthquakes near the probable boundary between the Juan de Fuca plate and North America plate (Crosson, 1983; Taber and Smith, 1985; Weaver and Baker, 1988). The 1949 magnitude 7.1 Olympia earthquake and the 1965 magnitude 6.5 Seattle-Tacoma earthquake occurred within this deep zone.

(2) The active or recently active volcanoes of the Cascade range created by the upward migration of magma (molten rock) above the Juan de Fuca plate. Rock in the subducting plate may melt at depths of 100 kilometers or more in the Earth. Because melted rock is lighter, it can sometimes rise to the surface through weakened areas in the overlying materials.

(3) Young, highly deformed mountains composed of formerly oceanic rocks scraped off the Juan de Fuca plate during subduction and piled up on the Olympic peninsula (Tabor and Cady, 1978).

(4) Deformed young sediments offshore in the Pacific Ocean where the converging plates meet (Barnard, 1978).

In sum, the subduction of the Juan de Fuca plate beneath the North America plate is believed to directly or indirectly cause most of the earthquakes and young geologic features in Washington and Oregon.



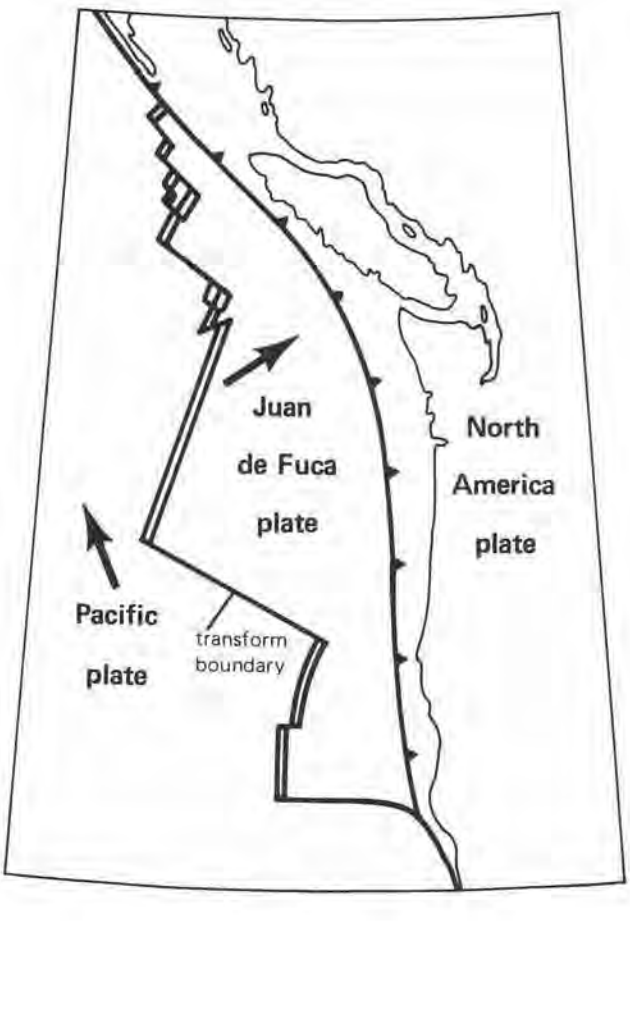


Figure 8. Relation between major tectonic plates and earthquakes. The Earth's surface is made up of 10 major plates and several smaller plates. Most earthquakes occur along plate margins. Small dots represent earthquake epicenters; large dots indicate locations of volcanoes. An enlargement (left) shows tectonic plates along the Pacific coast of North America. Arrows show motions of the Pacific and Juan de Fuca plates relative to North America. (World plate map from "Earthquakes" by Bruce A. Bolt. Copyright ©1978, 1988 W. H. Freeman and Company. Reprinted with permission; the explanation has been modified)

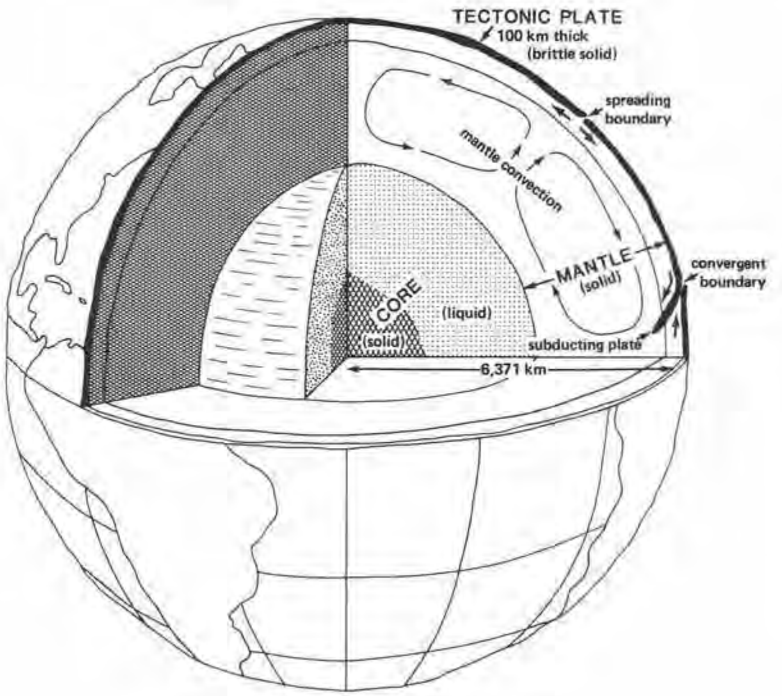


Figure 9. Cutaway view of the Earth showing the rocky mantle and iron core. The outermost layer consists of tectonic plates that are commonly about 100 km thick. Earthquakes occur within or at the boundaries of these plates. Although the mantle is solid, the rocks that comprise it act like a very viscous liquid and may move a few centimeters a year in great convection cells driven by temperature differences in the Earth. The plates move slowly with these currents. Spreading plate boundaries are thought to lie above areas of upwelling currents, and converging plate boundaries above areas where the currents move towards the center of the Earth. (See also Figure 10.)

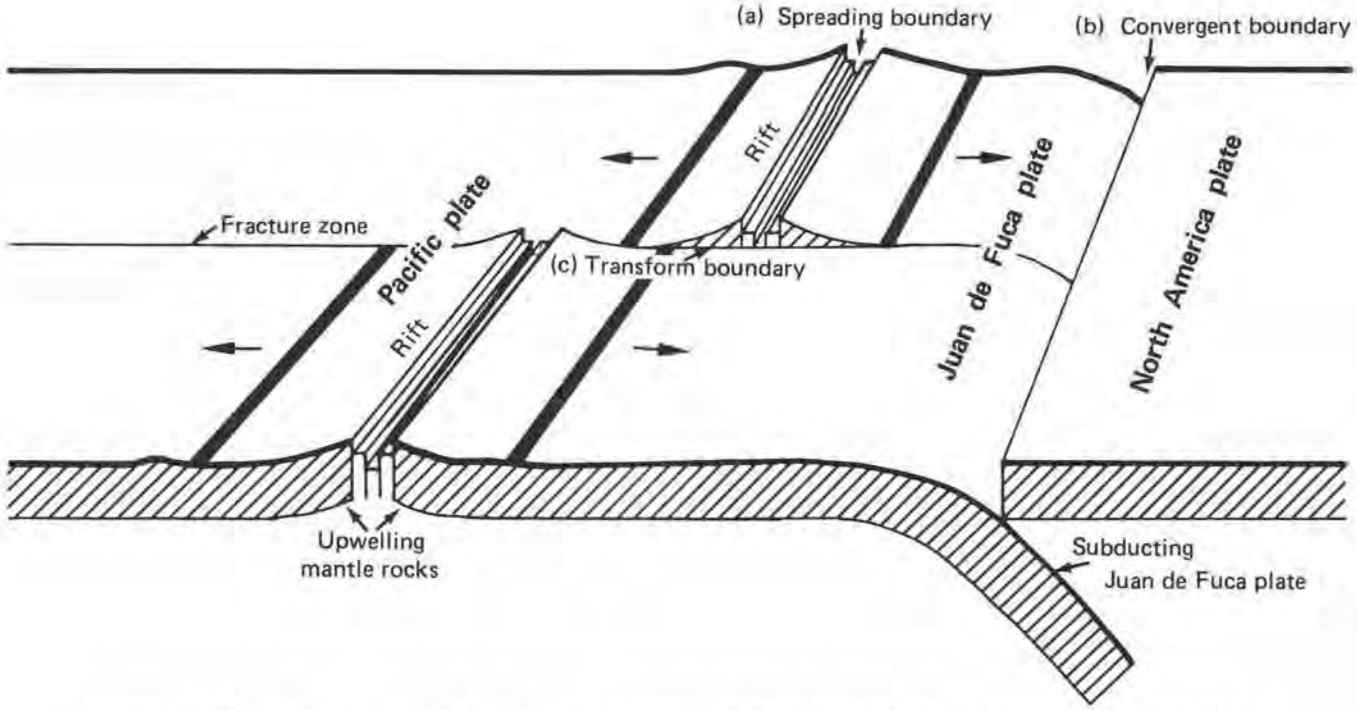


Figure 10. Three types of plate boundaries. A spreading boundary (a) marks the divergence of two plates. Material welling up from the mantle creates a rise or ridge bordering the rift between separating plates. A convergent boundary (b) occurs where one plate moves towards another. If one of these plates slides beneath the other, the motion is called subduction. A transform boundary (c) occurs where relative plate motion is neither divergent or convergent, but is parallel to the plate edges. The geometry of plates off the coast of Washington is schematically shown in this figure; plate locations are shown in Figure 8.

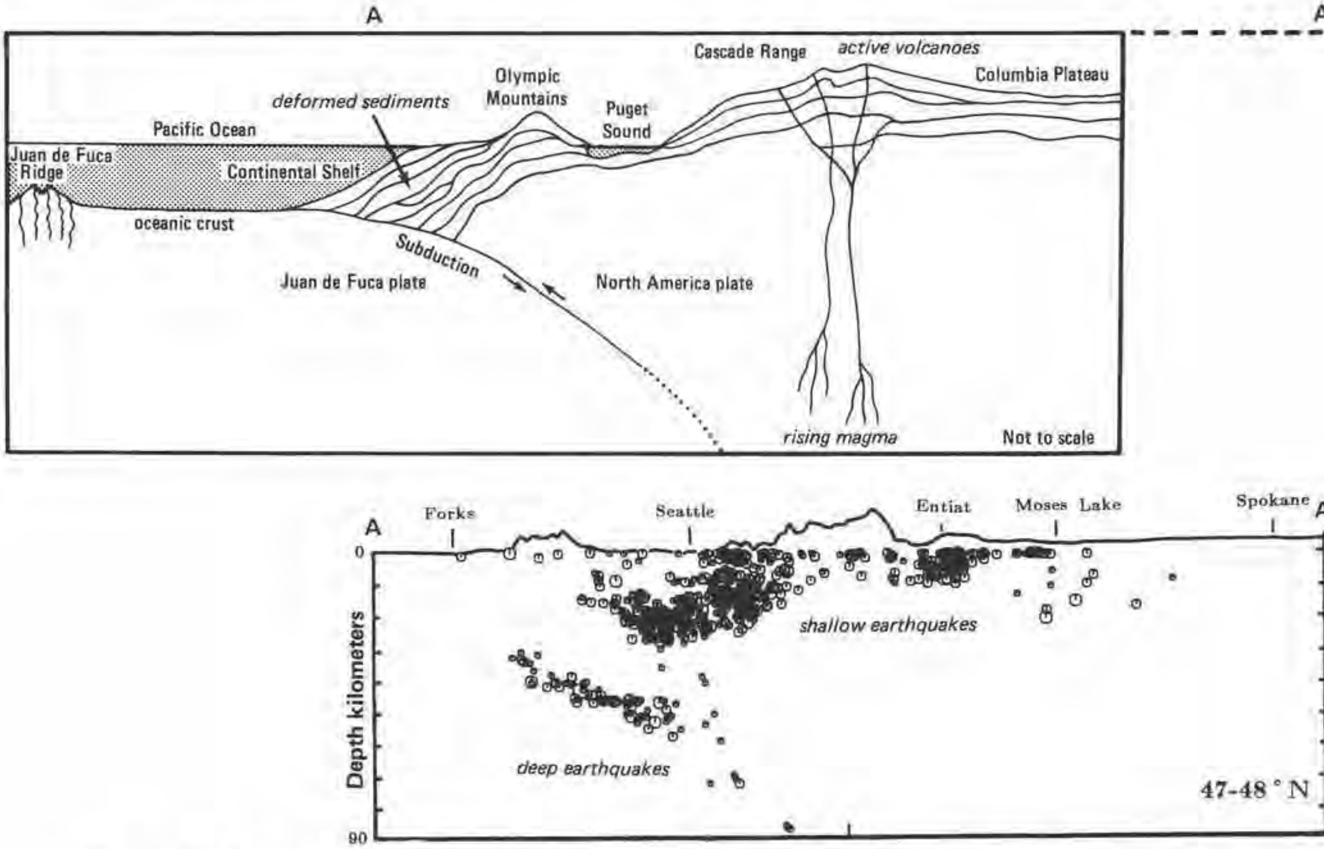


Figure 11. Cross sections of Washington showing plate convergence (top figure) and earthquake hypocenter locations. Some major topographic features and underlying geologic structures of Washington are shown diagrammatically in the upper figure. In the lower figure, selected hypocenters of earthquakes that occurred in 1982 through 1986 between latitudes 47° and 48°N are projected onto a vertical plane that generally corresponds to the diagram in the upper figure. Because of the great number of shallow earthquakes that occurred between 1982 and 1986, only hypocenters of those having magnitudes equal to or greater than 1.8 are shown in the lower figure. Below 30 km, hypocenters of all earthquakes having magnitudes of 1.0 or greater that occurred during this period are shown. The distribution of deep earthquakes indicates the slope of the zone of subduction. In the lower figure there is a vertical exaggeration of 2 to 1 below sea level; this creates the illusion that the subducting Juan de Fuca plate dips more steeply than it actually does. Topography indicated on the lower figure has a vertical exaggeration of 12 to 1.

The major plate boundaries in the Pacific Northwest are graphically delineated by the locations of recent earthquakes (Fig. 12). Narrow zones of shallow offshore earthquakes result from the movement of the Juan de Fuca plate relative to the Pacific plate, particularly along transform boundaries such as the Blanco Fracture Zone off the coast of Oregon. As expected, a few shallow offshore earthquakes occur along the Juan de Fuca Ridge, a **spreading boundary** between the Juan de Fuca and Pacific plates. Scattered earthquakes occur to the east in Washington, Oregon, and northern California, both in the subducting Juan de Fuca plate and in the overlying North America plate.

The world's greatest earthquakes occur on **subduction-zone boundaries**. These magnitude 8+ thrust-type earthquakes, sometimes called **subduction earthquakes**, occur from time to time as the two converging plates jerk past one another. There are no reports of such earthquakes in Washington since the first written records of permanent occupation by Europeans in 1833 when the Hudson Bay Trading Company post was established at Fort Nisqually (Hawkins and Crosson, 1975). And, since the installation in 1969 of a multistation seismograph network in Washington, there has been no evidence of even small thrust-type earthquakes between the plates in Washington and Oregon and offshore.

In fact, few earthquakes of any kind or size have been recorded along the coastal region of the Pacific Northwest. However, parts of subduction zones in Japan and Chile also appear to have had very low levels of

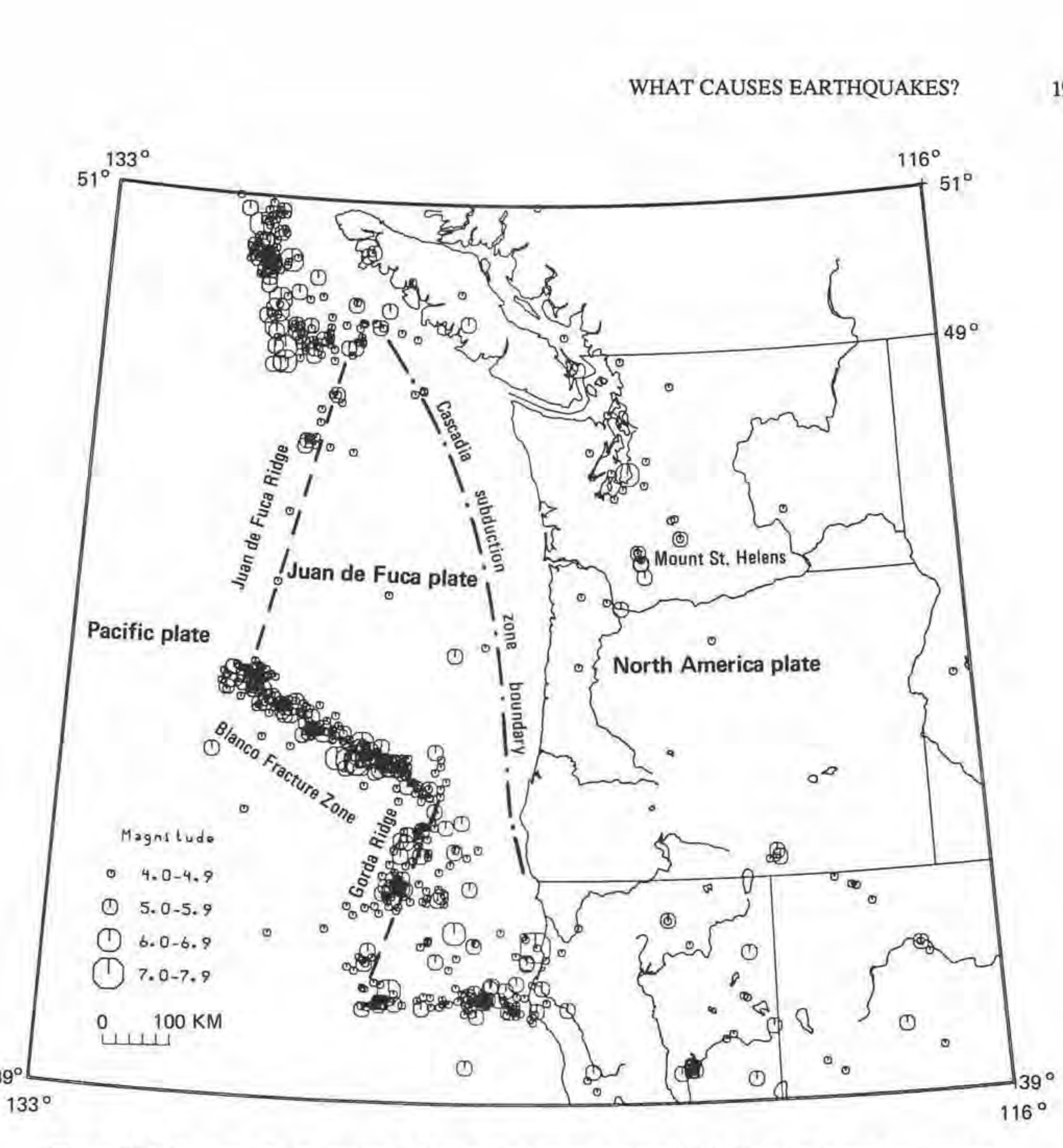


Figure 12. Epicenters of earthquakes in the Pacific Northwest since 1960. Only the largest earthquakes near Mount St. Helens are indicated. Note the position of the Cascadia subduction zone relative to Washington's coast and that epicentral locations mark plate boundaries shown in Figure 8. (Data from the National Oceanic and Atmospheric Administration and the University of Washington.)

seismicity prior to great subduction earthquakes (Heaton and Kanamori, 1984; Heaton and Hartzell, 1986). Therefore the seismic quiescence observed historically along coastal region of Washington and Oregon does not refute the possibility that an earthquake having a magnitude of greater than 8 could occur there. Heaton and Hartzell (1986) note the problem of incomplete seismic data when comparing one subduction zone with another, but they still conclude that available data support the finding that low levels of seismicity may exist in subduction zones prior to a magnitude 8 earthquake.

The convergence of the Juan de Fuca and North America plates is quite slow, so great subduction earthquakes may be rare. Savage and others (1981) interpret geodetic strain measurements near Seattle as indicating that compressional strain is accumulating parallel to the direction of convergence between the

Juan de Fuca and North America plates, as would be expected prior to a great, thrust earthquake off the coast of Washington and British Columbia.

Atwater (1987) has found geologic evidence that he believes shows that the last great subduction earthquake in Washington occurred as recently as 300 years ago.

Historically, many earthquakes have occurred in the subducting Juan de Fuca plate deep beneath Puget Sound and at shallow depths in many places in Washington, Oregon, and British Columbia in the overlying North America plate. It is reasonable to expect future earthquakes in these areas to have magnitudes comparable to the magnitudes of past earthquakes. The biggest historical earthquakes include the shallow magnitude 7.4 earthquake in the North Cascades in 1872 and the deep magnitude 7.1 earthquake in the southern Puget Sound area in 1949 (Rasmussen, 1967; U.S. Geological Survey, 1975; Malone and Bor, 1979). Therefore, even without the occurrence of great subduction-style earthquakes in the Pacific Northwest, Washington is still earthquake country.

WHERE DO WASHINGTON EARTHQUAKES OCCUR?

Washington's Largest Reported Earthquakes

Most of the largest earthquakes felt in Washington (Table 2) have occurred in the Puget Sound region between Olympia and the Canadian border, in the Cascade mountains, and along the Washington-Oregon border. Figure 13 shows the locations of epicenters of the largest earthquakes reported in Washington from 1872 to 1987. The earthquakes whose epicenters are shown were felt over an area of at least 50,000 square kilometers or were rated VII or more on the Modified Mercalli Intensity Scale (Table 1). Two earthquakes whose epicenters were on Vancouver Island, British Columbia, are included on Figure 13 because they were widely felt in Washington.

The depths of the largest Washington earthquakes are not precisely known because calculations of depth require a number of seismograms for each earthquake. Before 1949, the number of earthquakes and their locations and sizes were determined almost entirely using newspaper accounts of reported damage. Even as late as 1969 there were only three seismograph stations in Washington and three in western British Columbia. As a result, information about early earthquakes is incomplete, and the locations, depths and sizes of these earthquakes are less precise than those of earthquakes recorded after 1969 by the University of Washington multistation seismograph network.

The 1949 magnitude 7.1 Olympia earthquake and the 1965 magnitude 6.5 earthquake between Tacoma and Seattle were large enough to be recorded at many seismograph stations around the world. Both of these Puget Sound earthquakes occurred within the subducting Juan de Fuca plate at depths of 54-63 kilometers (Langston and Blum, 1977; Baker and Langston, 1987). Neither earthquake had significant aftershock activity. Like the 1949 and the 1965 earthquakes, almost all large Puget Sound earthquakes have lacked aftershocks. The lack of aftershocks is considered characteristic of deep earthquakes (Algermissen, 1983; Page, 1968), and this has been taken as evidence that the early large earthquakes in the Puget Sound region were mostly deep (Algermissen, 1983). The 1880 earthquake may have been shallow because many aftershocks were reported.

Many aftershocks have been reported following large earthquakes in the Washington Cascade Mountains. The largest such earthquake (perhaps the largest in the state) occurred on Dec. 14, 1872, in the northern Cascade Mountains and was followed by many aftershocks. The estimated location, depth, and size of this earthquake are controversial. The location used in Table 2 and shown on Figure 13 was determined by Malone and Bor (1979) and was estimated using the intensity pattern determined from reports of damage. Other possible locations of the 1872 earthquake, ranging from the Canadian border to Lake Chelan, have also been calculated from the analysis of intensity patterns (Milne, 1956; Bechtel, 1976; Washington Public Power Supply System, 1977; Algermissen, 1983). The numerous aftershocks following this event have been interpreted as evidence that the source for the 1872 earthquake was shallow (Algermissen, 1983). Some argue, however, that a shallow earthquake of this magnitude would have caused a large identifiable surface rupture. Although the Straight Creek fault passes near this area, geological evidence does not support the conclusion that it has had recent movement (Vance and Miller, 1983). The 1872 earthquake is thus a reminder that Puget Sound is not the only site of large, damaging earthquakes in Washington.

Moderate, damaging earthquakes have been reported from eastern Washington. These include the 1893 Umatilla and 1936 Milton-Freewater earthquakes whose epicenters were located along the southeastern Washington-northeastern Oregon border and the 1959 Lake Chelan earthquake along the eastern border of the Cascades. Strong aftershocks followed each of these earthquakes.

Earthquakes Recorded by the University of Washington Seismograph Network

The geographic distribution of recent earthquakes located by the University of Washington seismograph network (Fig. 14) coincides broadly with the distribution of the largest Washington earthquakes shown on Figure 13. Most of Washington's earthquakes occur within the Puget Sound region and along the western side of the Cascade mountains. Eastern Washington is an area of generally low seismicity—except for the western side of the Columbia River Basin and the Oregon-Washington border (Malone and others, 1975). Numerous earthquakes occur in the Georgia Strait–northern Puget Sound areas of Canada. However, since the installation of regional seismograph networks in Washington and

Table 2. Largest known earthquakes felt in Washington. Numbers in parentheses give the number of the reference in last column. Earthquakes with epicenters outside Washington are flagged by *. See Table 1 for an explanation of the Modified Mercalli Intensity Scale.

Year	Date	Time (PST)	North latitude	West longitude	Depth (km)	Mag (felt)[1]	Mag (inst)[2]	Maximum Modified Mercalli Intensity	Felt Area (sq km)	Location	References
1872	Dec. 14	2140	48°48′00″	121°24′00″	shallow (2)	7.3 (4)	none	IX (3)	1,010,000(5)	North Cascades	(1) Algermissen, 1983; (2) M. G. Hopper and others 1982; (3) Bechtel, Inc. 1976; (4) Malone and Bor, 1979; (5) Rogers, 1983; (6) Slemmons and others, 1978; (7) Wash. Public Power Supply System, 1977
1877*	Oct. 12	1353	45°30′00″	122°30′00″ (8)	shallow (8)	5.3	none	VII (9)	48,000 (9)	Portland, Oregon	(8) Shannon and Wilson, 1975; (9) Thenhaus, 1978
1880	Dec. 12	2040	47°30′00″	122°30′00″ (11)	?	?	none	VII (10)	?	Puget Sound	(10) Rasmussen and others, 1974; (11) U.S.Army Corps of Engineers, 1983
1891	Nov. 29	1521	48°00′00″	123°30′00″ (10)	?	?	none	VII (10)	?	Puget Sound	(12) Rasmussen, 1967;(10)
1893	Mar. 06	1703	45°54′00″	119°24′00″ (8)	shallow	4.7	none	VII (8)	21,000 (8)	Southeastern Washington	(8)
1896	Jan. 03	2215	48°30′00″	122°48′00″ (13)	?	5.7 (11)	none	VII (12)	?	Puget Sound	(13) Ruth Ludwin, oral commun., 1987; (11,12)
1904	Mar. 16	2020	47°48′00″	123°00′00″ (5)	?	5.3	none	VII (5)	50,000 (5)	Olympic Peninsula, eastside	(5, 12)
1909	Jan. 11	1549	48°42′00″	122°48′00″ (5)	deep (5)	6.0	none	VII (5)	150,000 (5)	Puget Sound	(5)
1915	Aug. 18	0605	48°30′00″	121°24′00″ (5)	?	5.6	none	VI (5)	77,000 (5)	North Cascades	(5,12)
1918*	Dec. 06	0041	49°37′00″	125°55′00″ (5)	?	7.0	7.0 (17)	VIII (5)	650,000 (5)	Vancouver Island	(5)
1920	Jan. 23	2309	48°36′00″	123°00′00″ (5)	?	5.5	none	VII (14)	70,000 (5)	Puget Sound	(14) Earthquake History of the United States; (5)
1932	July 17	2201	47°45′00″	121°50′00″ (15)	shallow (15)	5.2	none	VII (15)	41,000 (15)	Central Cascades	(15) Bradford and Waters, 1934; (10)
1936	July 15	2308	46°00′00″	118°18′00″ (14)	shallow	6.4	5.75 (17)	VII (14)	270,000 (4)	Southeastern Washington	(16) Brown, 1937; (17) Gutenburg and Richter, 1954; (8, 14)
1939	Nov. 12	2346	47°24′00″	122°36′00″ (14)	deep	6.2	5.75 (17)	VII (14)	200,000 (5)	Puget Sound	(18) Coombs and Barksdale 1942; (4, 11, 17)
1945	April 29	1216	47°24′00″	121°42′00″ (14)		5.9	5.5 (17)	VII (14)	128,000 (14)	Central Cascades	(14)
1946	Feb. 14	1918	47°18′00″	122°54′00″ (10)	40 (10)	6.4	6.3 (10)	VII (14)	270,000 (14)	Puget Sound	(19) Barksdale and Coombs, 1946; (10, 14)
1946*	June 23	0913	49°48′00″	125°18′00″ (5)	deep (5)	7.4	7.3 (17)	VIII (4)	1,096,000 (5)	Vancouver Island	(5,14)
1949	April 13	1155	47°06′00″	122°42′00″	54 (20)	7.0	7.1 (17)	VIII(22)	594,000 (5)	Puget Sound	(20) Baker and Langston, 1987; (21) Gonen and Hawkins, 1974; (22) Nuttli, 1952; (23) Thorsen, 1986; (24) U.S. Army Corps of Engineers, 1949; (25) Weaver and Baker, 1988; (5, 10, 12, 17)
1949*	Aug. 21	2001	53°37′20″	133°16′20″ (5)		7.8	8.1 (17)	VIII	2,220,000 (14)	Queen Charlotte Is., B.C.	
1959	Aug. 05	1944	47°48′00″	120°00′00″ (4)	35 (4)	5.5	5.0 (4)	VI (12)	64,000 (14)	North Cascades, east side	(4,10,14)
1959*	Aug. 17	2237	44°49′59″	111°05′ (26)	10-12 (27)	7.6	7.5 (26)	X (26)	1,586,000 (26)	Hebgen Lake, Montana	(26) Stein and Bucknam, 1985; (27) U.S. Geological Survey, 1963
1962*	Nov. 05	1936	45°36′30″	122°35′54″ (29)	18 (28)	5.3	5.5 (30)	VII (14)	51,000 (14)	Portland, Oregon	(28) Berg and Baker, 1963; (29) Couch and others, 1968; (30) Dehlinger and Berg, 1962; (31) Dehlinger and others, 1963; (14)
1965	April 29	0728	47°24′00″	122°24′00″ (32)	63 (35)	6.8	6.5 (32)	VIII (14)	500,000 (5)	Puget Sound	(32) Algermissen and Harding, 1965; (33) Ihnen and Hadley, 1986; (34) Langston, 1981; (35) Langston and Blum, 1977; (36) MacPherson, 1965; (37) Mullineaux and others, 1967; (14)
1981	Feb. 13	2209	46°21′01″	122°14′66″ (38)	7 (36)	5.8	5.5 (38)	VII (39)	104,000 (40)	South Cascades	(38) Grant and others, 1984; (39) Qamar and others, 1987; (40) U.S. Earthquakes, 1981
1983*	Oct. 28	0606	44°03′29″	113°51′25″ (41)	14 (42)	7.2	7.3 (38)	VII (42)	800,000 (42)	Borah Peak, Idaho	(41) Richins and others, 1987; (42) Stover, 1987

[1] Mag (felt) = an estimate of magnitude, based on felt area; unless otherwise indicated, it is calculated from $\text{Mag (felt)} = -1.88 + 1.53 \log A$, where A is the total felt area; from Toppozada, 1975.

[2] Mag (inst) = instrumentally determined magnitude; refer to references listed in the table for magnitude scale used.

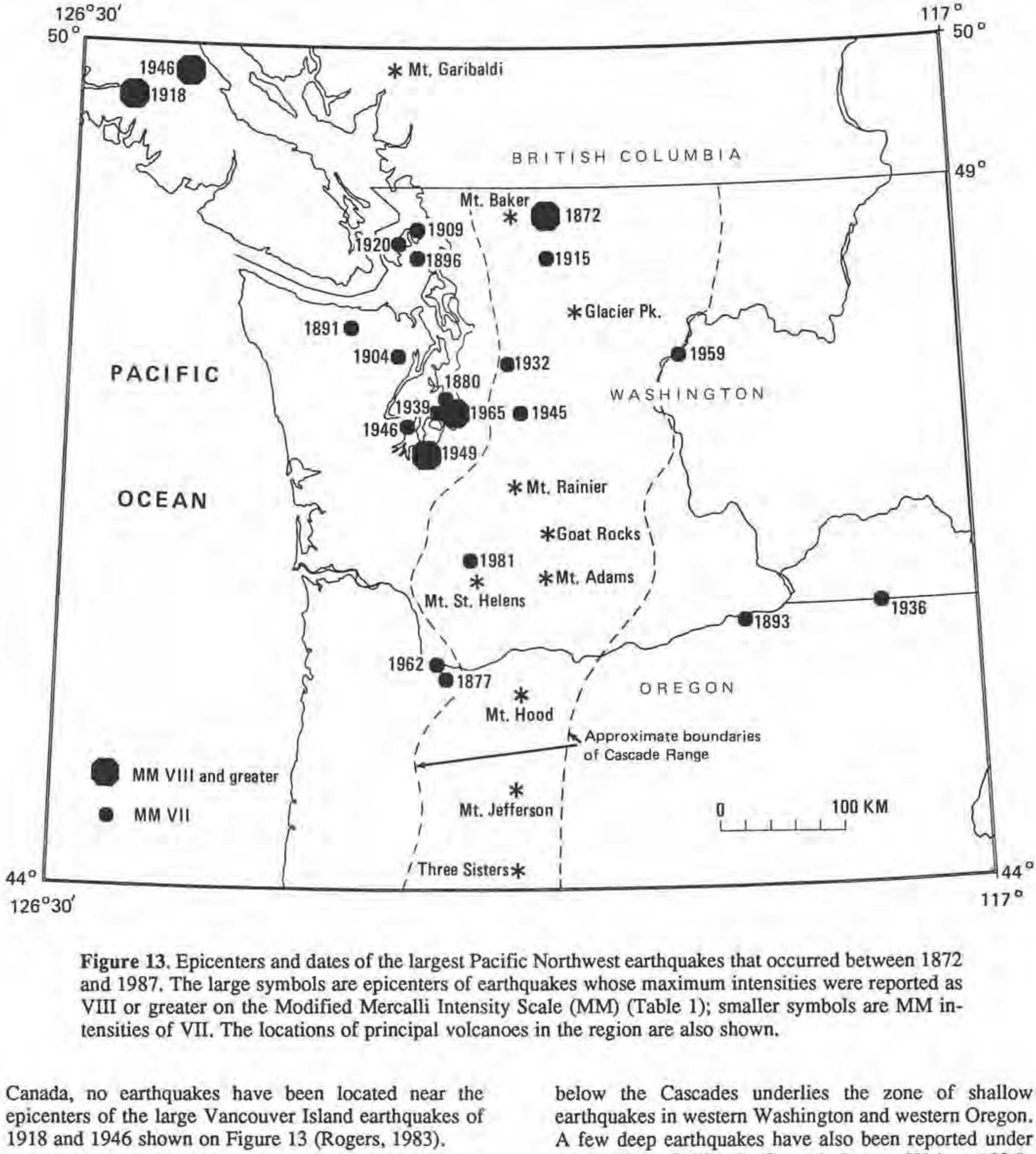


Figure 13. Epicenters and dates of the largest Pacific Northwest earthquakes that occurred between 1872 and 1987. The large symbols are epicenters of earthquakes whose maximum intensities were reported as VIII or greater on the Modified Mercalli Intensity Scale (MM) (Table 1); smaller symbols are MM intensities of VII. The locations of principal volcanoes in the region are also shown.

Canada, no earthquakes have been located near the epicenters of the large Vancouver Island earthquakes of 1918 and 1946 shown on Figure 13 (Rogers, 1983).

The east-west cross section shown in Figure 11 provides a subsurface view of Washington's earthquakes. Numerous shallow earthquakes occur in the crust of both eastern and western Washington within 30 kilometers of the Earth's surface. A thin zone of earthquake hypocenters that deepens toward the east from 30 kilometers under the coast to 100 kilometers below the Cascades underlies the zone of shallow earthquakes in western Washington and western Oregon. A few deep earthquakes have also been reported under the northern California Cascade Range (Walter, 1986). Although many small shallow earthquakes are recorded in the Puget Sound area today, no large shallow earthquakes have been recorded by the multistation seismograph network since 1969. The two largest Puget Sound earthquakes since 1969 were a magnitude 5.1 earthquake on May 16, 1976, located in the northern

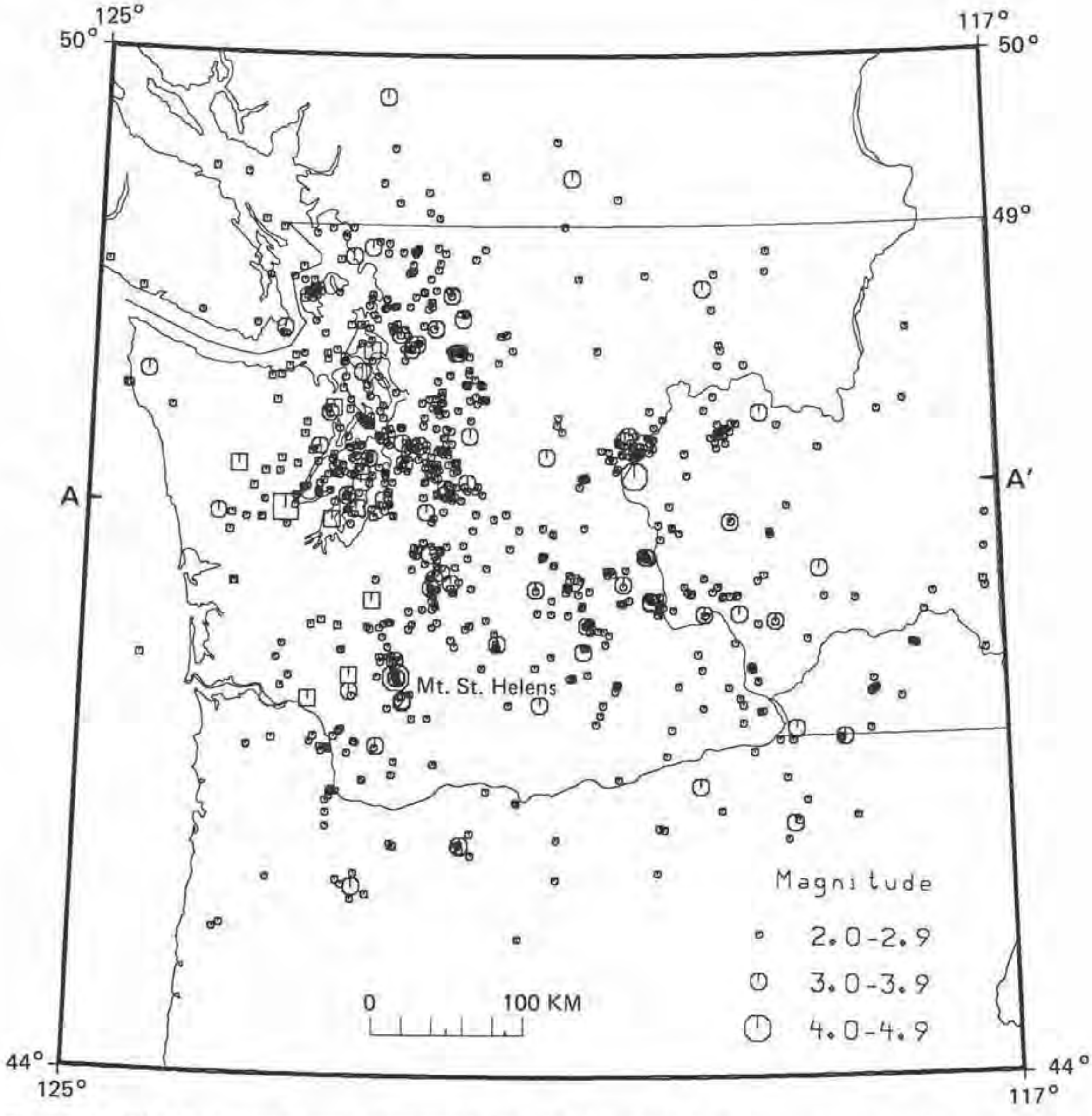


Figure 14. Washington earthquakes recorded from 1982 to 1987. Epicenters are shown for earthquakes having magnitude $M_c \geq 2.0$. Earthquakes deeper than 30 km are shown as squares. Only the largest earthquakes in the Mount St. Helens region are shown for clarity. Points A and A' are the endpoints of the vertical cross section shown in Figure 11b.

Puget Sound basin at a depth of 62 kilometers and a magnitude 4.5 earthquake on Sept. 8, 1976, located in the southern Puget Sound basin at a depth of 50 kilometers. Both these deep earthquakes were unaccompanied by aftershocks. In this respect, they were similar to the large, deep 1949 and 1965 earthquakes.

A magnitude 4.6 earthquake on March 11, 1978, near Bremerton, Washington, occurred at a depth of 24 kilometers, in the zone of shallow earthquakes above the subducting Juan de Fuca plate. The **mainshock** was followed by 44 aftershocks; this was the first well-documented mainshock-aftershock earthquake sequence in the Puget Sound basin (Yelin and Crosson, 1982). Considering the depth of this earthquake and the presence of thick overlying glacial deposits, it is not surprising that the fault producing this earthquake has not been identified at the surface.

Earthquakes in the Cascades are generally shallow—except for a few small deep earthquakes in the subducted Juan de Fuca plate. The two largest shallow earthquakes in Washington since 1969 occurred near Elk Lake and Goat Rocks in the southern Cascades. The magnitude 5.5 Elk Lake earthquake occurred on February 13, 1981, at a depth of only 7 kilometers and

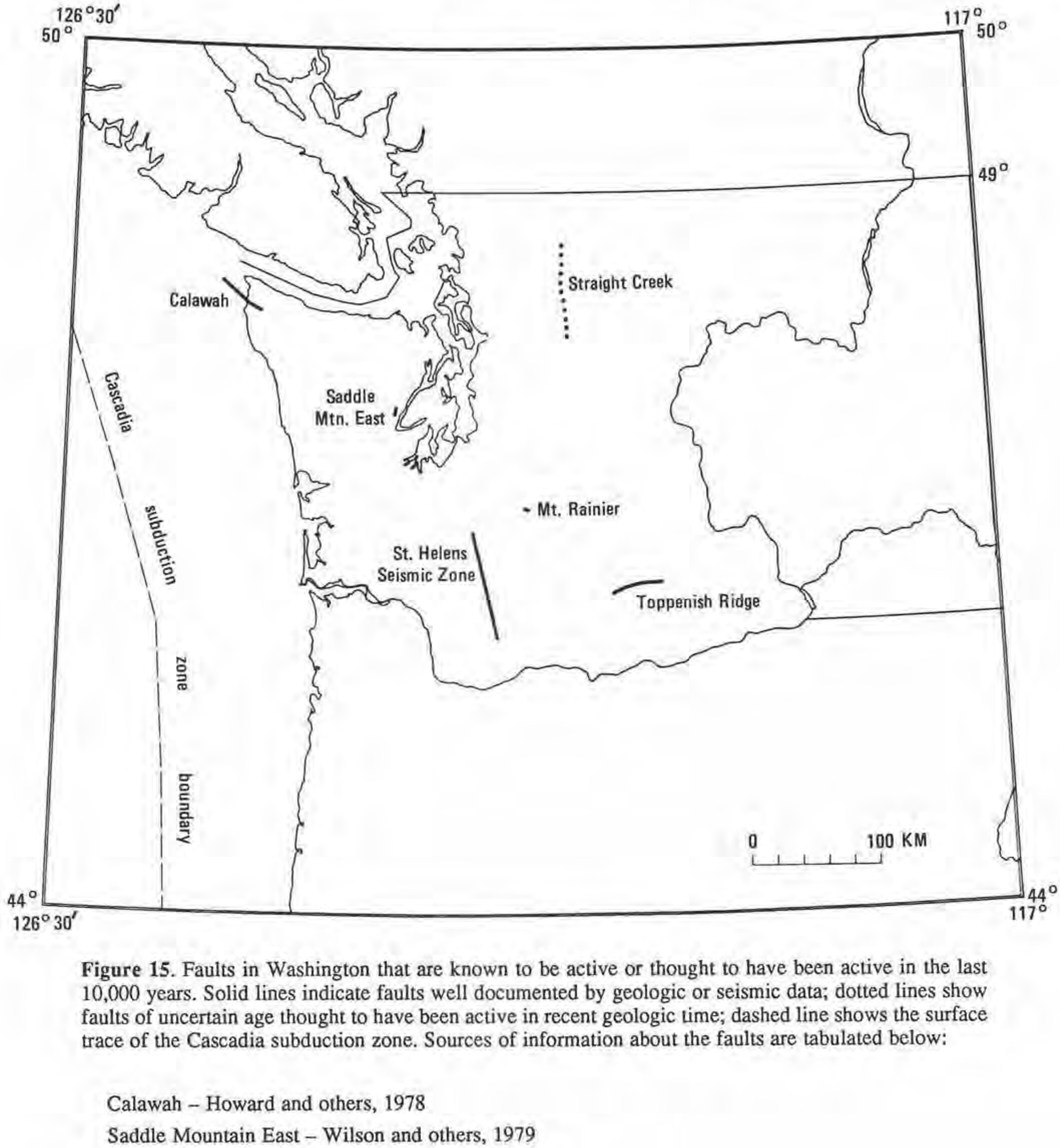


Figure 15. Faults in Washington that are known to be active or thought to have been active in the last 10,000 years. Solid lines indicate faults well documented by geologic or seismic data; dotted lines show faults of uncertain age thought to have been active in recent geologic time; dashed line shows the surface trace of the Cascadia subduction zone. Sources of information about the faults are tabulated below:

Calawah – Howard and others, 1978

Saddle Mountain East – Wilson and others, 1979

St. Helens Seismic Zone – Weaver and Smith, 1983

Toppenish Ridge – Campbell and Bentley, 1983

Mount Rainier – Crosson and Frank, 1975

Straight Creek – Slemmons and others, 1981
Vance and Miller, 1983

was felt over 102,000 square kilometers. It had more than 1,000 aftershocks (Grant and others, 1984) distributed on a vertical fault zone, called the St. Helens Seismic Zone by Weaver and Smith (1983), which did not break the Earth's surface (Fig. 15). Weaver and Smith (1983) suggest that the seismic zone, roughly centered on Mount St. Helens, may extend about 90 kilometers in a northwest-southeast direction. Scientists sometimes use the length of a fault to calculate the magnitude of the largest earthquake likely to occur on it. Weaver and Smith (1983) estimated that the St. Helens Seismic Zone could be capable of generating a magnitude 7.0 earthquake.

All earthquakes recorded in eastern Washington have been shallow, and most are at depths less than 6 kilometers. The largest earthquake in eastern Washington since 1969 was a shallow, magnitude 4.4 event northwest of Othello on December 20, 1973. Some of the most active earthquake areas in eastern Washington are near Entiat, south of Lake Chelan, and in the Saddle Mountains, south of Vantage. Many of the earthquakes in eastern Washington occur in clusters near the Saddle Mountains in folded volcanic rocks, which were extruded in southeastern Washington from 16.5 to 6 million years ago (Rothe, 1978; Malone and Bor, 1979).

WHEN AND WHERE WILL THE NEXT BIG EARTHQUAKE OCCUR?

The short answer is that we don't know, but several lines of evidence now seem to limit the number of possibilities. Ideally a prediction would specify the time, place, and magnitude of the next earthquake. With current information, this is about as easy as predicting the next traffic accident in a large city like Seattle. A specific traffic accident cannot be predicted, but experience shows that accidents are more likely during evening rush hours. They also occur more frequently on certain streets and more often involve two rather than ten cars. Similarly, the pattern of past earthquake activity can be used to estimate how often and where earthquakes of a given magnitude and location are likely to occur in the future. With the addition of geologic information, we can refine the estimate of where these earthquakes might occur.

Stepp (1973), for example, calculated earthquake **return times** versus earthquake size in the Puget Sound region by tabulating the maximum intensities reported from past earthquakes. (He used earthquake intensities rather than magnitudes because magnitudes were not generally calculated before 1960.) From this recurrence pattern, Stepp calculated that an earthquake of maximum intensity VII would occur in the Puget Sound region every 7 years on the average. Similarly, he estimated that the average return time of intensity VIII and IX earthquakes is 23 years and 73 years respectively; such earthquakes would be roughly equivalent to the ones in 1965 and 1949 (Table 2).

In the Puget Sound area, the activity of the deep earthquake zone in the subducted Juan de Fuca plate has differed significantly from the activity of the shallow earthquake zone in the overlying North America plate (depths less than 30 kilometers). Because earthquakes in Washington can now be clearly grouped into either the shallow or deep zone, seismologists have tried to make separate forecasts for each group. Puget Sound earthquakes recorded by the University of Washington network having magnitudes greater than 4 have been more numerous in the subducting Juan de Fuca plate. This observation agrees with studies suggesting that older large Puget Sound earthquakes are deep. This agreement supports the idea that an earthquake of magnitude 7 or greater in the Puget Sound region is much more likely to be deep than shallow. Similarly, a study by the U.S. Geological Survey (1975) proposed that the largest earthquake likely to occur in the Puget Sound region would have a depth of 50 kilometers and a magnitude as large as 7.5.

There is still no consensus on the probability of a large shallow earthquake, especially in the Puget Sound region. Based on information from the last 150 years, Rasmussen and others (1974) proposed that shallow earthquakes in the Puget Sound area would probably not have magnitudes exceeding 6.5. Only one of the largest Puget Sound earthquakes was reported to have had aftershocks; this event, in 1880, is very poorly documented. So far, however, estimates of the largest shallow Puget Sound earthquake suggest that the size would probably be smaller than the largest deep Puget Sound earthquake.

Large shallow earthquakes have occurred in the Cascades. The 1872 North Cascades earthquake was probably shallow. Weaver and Smith (1983) argue that the St. Helens Seismic Zone in the Cascades of southern Washington may also be capable of producing a large shallow earthquake having a magnitude of 7.0. Therefore, future earthquakes in the Cascades will likely be shallow and could have a magnitude of 7 or greater. In eastern Washington and Oregon, all earthquakes have been shallow, but no earthquakes having a magnitude exceeding 5.7 have occurred there in the past 150 years.

The largest earthquake proposed for Washington and Oregon is a subduction earthquake exceeding magnitude 8 located between the Juan de Fuca plate and the overlying North America plate (Heaton and Kanamori, 1984). Since the Juan de Fuca and North America plates are converging at a rate of 3 to 4 centimeters a year, Heaton and Hartzell (1987) have estimated an average return time of 400 to 500 years for a great subduction earthquake in the Pacific Northwest. Because of such a long return time, it is not surprising that we have not experienced such an earthquake within the last 150 years. Buried tidal marshes, newly discovered in bays and rivers along Washington's coast, were possibly submerged suddenly during large subduction earthquakes that struck western Washington as recently as 300 years ago. Atwater and others (1987) and Hull (1987) have used geologic evidence to show that such large earthquakes may have occurred at least eight times in the past 5,000 years.

To summarize: the maximum probable earthquake in Washington would be a subduction earthquake having a magnitude exceeding 8 and an epicenter near the coast; it would be caused by sudden slip between the Juan de Fuca and North America plates. From the dating of organic material preserved in rocks along the coast, some scientists believe that such earthquakes have occurred every 300 to 1,000 years. Other large earthquakes in the Puget Sound region can be expected to have magnitudes of at least 6.5 to 7.5 and depths greater than 40 kilometers. Rasmussen and others (1974) estimate 10-year return times for magnitude 6 earthquakes in the Puget Sound area. They also propose return times of 35 and 110 years for magnitude 6.5 and 7.0 earthquakes, respectively.

WHAT CAUSES DAMAGE?

Direct Causes

Ground Shaking

Factors Affecting Ground Shaking

Most earthquake damage is caused by ground shaking. The magnitude of an earthquake, distance to the earthquake **focus**, type of faulting, depth, and type of material are important factors in determining the amount of ground shaking that might be produced at a particular site. Where there is an extensive history of earthquake activity, these parameters can often be estimated; however, in many areas of Washington they are still poorly defined.

The magnitude of an earthquake influences ground shaking in several ways. Large earthquakes usually produce ground motions with large amplitudes and long durations. In addition, large earthquakes produce strong shaking over much larger areas than do smaller earthquakes. The 1949 magnitude 7.1 Olympia earthquake produced ground shaking lasting 30 seconds and was felt over an area of 550,000 square kilometers. In contrast, the 1964 magnitude 8.3 Alaska earthquake produced ground shaking for about 300 seconds and was felt over an area more than five times larger.

The distance of a site from an earthquake affects the amplitude of ground shaking. In general, the amplitude of ground motion decreases with increasing distance from the focus of an earthquake. The considerable depth of the 1949 and 1965 earthquakes put even the closest sites, those directly over the earthquake focus, at least 50 to 65 kilometers from the source of the ground shaking, a factor that contributed to the lower intensity experienced near the epicenter.

The frequency content of the shaking also changes with distance. Close to the epicenter, both high (rapid)- and low (slow)-frequency motions are present. Farther away, low-frequency motions are dominant, a natural consequence of wave attenuation in rock. The frequency of ground motion is an important factor in determining the severity of damage to structures and which structures are affected. (See Structural Failure of Buildings.)

Analyses of earthquake damage in Washington and elsewhere suggest that the severity of shaking depends on several factors besides the distance and magnitude of an earthquake. (See Structural Failure of Buildings.) These factors include the kinds and thicknesses of geologic materials exposed at the surface and the subsurface geologic structure (Rasmussen and others, 1974; Newmark and Hall, 1982). Natural and artificial unconsolidated materials, such as sediments in river deltas and materials used as landfill, commonly amplify ground motions relative to motion in consolidated sediments or bedrock. Such areas, in general, have had higher levels of ground shaking in past Washington earthquakes. The thickness of unconsolidated material may also affect the amount of ground shaking produced. Certain frequencies of ground shaking may generate disproportionately large motions because of wave resonance in sedimentary basins. Just as the pitch of sound from an organ pipe depends on the length of the pipe and the density and compressibility of air, the various frequencies at which a sedimentary basin will resonate when shaken by seismic waves depend on the thickness, density, and stiffness of the sedimentary layers.

Subsurface structures, such as sedimentary layers that vary in thickness or degree of consolidation, may increase ground motion by focusing seismic wave energy at a particular site. The curved surfaces of buried bedrock topography may also focus waves. Langston and Lee (1983) suggested focusing as a mechanism to explain why the severity of damage observed in West Seattle during the 1965 Seattle-Tacoma earthquake seemed unrelated to surface geology in many places (Mullineaux and others, 1967; Yount, 1983). The depth to bedrock changes from very near the surface in the West Seattle area to significantly deeper just a short distance away in downtown Seattle.

Estimating Future Ground Shaking

Studies of the 1949 and 1965 earthquakes have provided most of the data used to estimate future ground shaking in Washington (Langston, 1981; Langston and Lee, 1983; Ihnen and Hadley, 1986). The depths of these two earthquakes (54 and 63 kilometers below Puget Sound in the subducting Juan de Fuca plate), their magnitudes, and the reports of damage at sites in Washington having a variety of geologic materials have led to estimates of future ground shaking for similar events (U.S. Geological Survey, 1975). For example, the intensity of ground shaking in the epicentral area of a future large Puget Sound earthquake if that earthquake occurred at a depth comparable to those of the 1949 and 1965 earthquakes would be lower than the intensity that would be expected for a shallow earthquake of the same magnitude. The reduced intensity would be related to the effect of depth to the focus and the possible attenuation of ground shaking in some areas identified during past earthquakes caused by the nature of the geologic materials between the focus and the site.

A magnitude 8 subduction earthquake along the coast of Washington or a large shallow earthquake in the Puget Sound area or in the Cascade Mountains would not be expected to produce the same distribution of ground shaking observed during the large deep Puget Sound earthquakes. However, the expected motion can be estimated. For example, Heaton and Hartzell (1986) have estimated ground motions for a hypothetical magnitude 9 earthquake along coastal Washington.

Surface Faulting

The consequences of major fault rupture at the surface can be extreme. Buildings may be torn apart, gas lines severed, and roads made impassible. Damage by faults is more localized than the widespread damage caused by ground shaking. Nevertheless, the identification of active surface faults is an important part of estimating future earthquake losses.

Faults that have so far been identified as active or possibly active within the last 10,000 years are shown on Figure 15.

Many maps of surface faults in Washington have been published (for example, McLucas, 1980, and Gower and others, 1985). Most of the faults on these maps are presently inactive. Geologic evidence indicating active fault movement within the last 10,000 years has been reported for only a few small faults in Washington. The best documented active surface faults in the state are located near Lake Cushman in western Washington (Fig. 16). The most recent time of movement of many faults is unknown because, in many places, the faults are not covered by young geologic materials. Such material, if found to be disturbed, would provide geologic evidence of the time of movement.

Seismicity, another indication of active faulting, has only rarely been associated with recognized surface faults in Washington. However, seismic activity has been used to define faults that do not currently rupture the surface, such as the St. Helens Seismic Zone shown on Figure 15.

Subsidence and Uplift

Sudden elevation changes during earthquakes can have severe long-term economic impact on coastal development. Some parts of Prince William Sound were uplifted by several meters during the 1964 Alaska earthquake; the amount of rise was as much as 11 meters on Montague Island. Conversely, parts of the Kenai

Figure 16. Aerial view of Saddle Mountain faults (arrows) near Lake Cushman, Olympic Peninsula. Note sag ponds. Price Lake was created by the damming of a stream by the upthrown east side of the east fault. (U.S. Geological Survey aerial photo GS J 6 31)

Peninsula and Kodiak Island subsided as much as 2 meters during that earthquake (Plafker, 1969). Some raised harbors on Prince William Sound could no longer be used by boats. In other areas streets and buildings subsided so much that they were flooded at high tide (Plafker and others, 1969). Major subsidence or uplift of large regions often occurs as a result of great subduction-style, thrust earthquakes. Such elevation changes have been reported after earthquakes in New Zealand, Japan, Chile, and southeast Alaska (Plafker, 1969). Submerged marshlands in several estuaries along Washington's coast suggest that similar episodes of sudden subsidence have also occurred in the Pacific Northwest (Fig. 17). Preliminary dating indicates that many of the subsidence events at different sites in Washington occurred at the same time (Fig. 18). For this reason, Atwater (1987) and Hull (1987) have attributed these subsidence events to the occurrence of large subduction earthquakes.

Secondary Causes of Earthquake Damage

While earthquakes may produce ground shaking, surface faulting, and vertical movements that cause direct damage to buildings and land, damage and personal injury may also be caused by several additional factors.

Figure 17. Evidence for subsidence of coastal southwestern Washington that was probably induced by earthquakes (Atwater, 1987, 1988). This buried, and now partially exhumed marsh is exposed at low tide along the Johns River, a tributary of Grays Harbor. The buried marsh, forming the lighter toned bench on which the people are standing, dropped 3 or more feet about 300 years ago. (Photo by B. F. Atwater)

Figure 18. Evidence for subsidence of coastal southwestern Washington. A ghost forest of cedar snags protrudes through an intertidal marsh along the Copalis River. The man is standing on roots that mark the present level of the ghost forest floor. The forest was killed after being suddenly dropped into the intertidal zone about 300 years ago, perhaps at the same time as the subsidence of the marshland shown in Figure 17. (Photo by B. F. Atwater)

Earthquakes may trigger ground failures such as landslides, differential compaction of soil, and **liquefaction** of water-saturated deposits like landfills, sandy soils, and river deposits. Such ground failures may cause more damage to structures than the shaking itself. Earthquakes may also cause destructive water waves such as **tsunamis** and **seiches**. Non-structural building components like ceiling panels, windows, and furniture can cause severe injury if shaking causes them to shift or break. Broken or impaired lifelines (gas, water, or electric lines and transportation and communication networks) can produce hazardous situations and distress to a community. A reservoir can be a hazard, should shaking cause the dam to fail.

Ground Failure

Major property damage, death, and injury have resulted from ground failures triggered by earthquakes in many parts of the world. More than $200 million in property losses and a substantial number of deaths in the 1964 Alaska earthquake were caused by earthquake-induced ground failures. A 1970 earthquake off the coast of Peru triggered an ice and rock avalanche in the Andes that killed more than 18,000 people when it buried the city of Yungay. Earthquakes in the Puget Sound region have induced ground failures responsible for substantial damage to buildings, bridges, highways, railroads, water distribution systems, and marine facilities (Keefer, 1983; Grant, 1986). Ground failures induced by the 1949 Olympia earthquake occurred at scattered sites over an area of 30,000 square kilometers, and ground failures induced by the 1965 Seattle-Tacoma earthquake occurred over 20,000 square kilometers (Keefer, 1983).

In reviewing records of the 1949 and 1965 Puget Sound earthquakes, Keefer (1983) noted that geologic environments in the Puget Sound region having high susceptibilities to ground failure include areas of poorly compacted artificial fill, postglacial stream, lake, or beach sediments, river deltas, and areas having slopes steeper than 35 degrees. The types of ground failures associated with past Washington earthquakes and expected to accompany future earthquakes include landslides, soil liquefaction, and differential compaction. Such failures commonly occur in combination—for example, liquefaction may cause a landslide or accompany compaction.

Landslides

Washington has many sites susceptible to landslides, including steep bluffs of eroded glacial deposits in the Puget Sound region, steep rocky slopes along the Columbia River Gorge, and rugged terrain in the Cascade Mountains. Fourteen earthquakes, from 1872 to 1980, are known to have triggered landslides in Washington (Townley and Allen, 1939; Coffman and others, 1982; Bradford and Waters, 1934; Meyer and others, 1986).

Dozens of ancient landslides have been identified in the bluffs along Puget Sound, indicating their susceptibility to ground failure. The landslides may also be susceptible to further failure if the headwall or toe areas are steepened by erosion or excavation (Keefer, 1983; Harp and others, 1981). Ground shaking produced by recent large Puget Sound earthquakes generated 20 landslides, some as far as 180 kilometers from the epicenter of the 1949 Olympia earthquake, and 21 landslides as far as 100 kilometers from the epicenter of the 1965 Seattle-Tacoma earthquake (Keefer, 1983, 1984).

Figure 19 shows damage that occurred in 1965 to a railroad line between Olympia and Tumwater.

Washington's five stratovolcanoes (Mount Baker, Glacier Peak, Mount Rainier, Mount St. Helens, and Mount Adams) offer many sites for rock and ice avalanches, rock falls, and debris flows on their steep

Figure 19. A hillside slid away from beneath this 400-ft section of a Union Pacific Railway branch line near Olympia during the 1965 Seattle-Tacoma earthquake. (Photo by G. W. Thorsen)

slopes (Beget, 1983). The slopes of volcanoes are particularly vulnerable to landslides because of the layered and jointed volcanic rocks lying parallel to the mountain slopes, weakened by the effects of steam and hot ground water, and oversteepened by erosion. In addition, ice falls from glaciers can trigger landslides, and snow and ice add to the mobility of such slides (Dreidger and Kennard, 1986).

Landslides on Mount Rainier were reported for earthquakes in 1894, 1903, and 1917 (Townley and Allen, 1939). Crandell (1973) suggests that valley floors within a few kilometers of the base of Mount Rainier could be buried by rockfall avalanches triggered by a strong earthquake. The massive 2.8-cubic-kilometer rockslide/debris avalanche on the north side of Mount St. Helens during the catastrophic eruption of May 18, 1980, was triggered by a moderate (magnitude 5) earthquake that followed 8 weeks of intense earthquake activity beneath the volcano.

The impact of landslides on stream drainages and reservoirs also can pose significant danger to populations and developments downstream (Beget, 1983). Water ponded behind landslide-debris dams can cause severe floods when these natural dams are suddenly breached. Such outburst floods are most likely near volcanic centers active within the past 2 million years (Evans, 1986, p. 128). The Toutle River was blocked by a debris flow triggered by an earthquake during the 1980 eruption of Mount St. Helens. The debris flow dam raised the level of Spirit Lake by 60 meters. The U.S. Army Corps of Engineers constructed a tunnel through bedrock in order to lower the lake level and thereby reduce the danger of flooding from a sudden release of water and lessen the risk to persons living downstream.

Landslides or debris flows into reservoirs or lakes may displace enough water to cause severe downstream flooding (Crandell, 1973; Crandell and Mullineaux, 1976, 1978; Hyde and Crandell, 1978). Communities and developments located downstream of reservoirs and lakes along drainages from Mounts Baker, Adams, and St. Helens must all be considered at some risk from earthquake-induced landslides.

The sudden displacement of water by landslides can also generate destructive water waves. A 300-foot bluff along the Tacoma Narrows, thought to have been weakened by the 1949 earthquake, collapsed into Puget Sound 3 days after the 1949 earthquake (U.S. Army Corps of Engineers, 1949). Figure 20 shows the slide area. Minor wave damage occurred to houses adjacent to the slide; a slide-generated wave was directed against the opposite shore, but no property damage occurred because that shore was undeveloped at the time.

Future earthquakes in Washington are expected to generate more landslides and greater losses than reported for past earthquakes. Earthquakes with shallow focal depths or a longer duration of shaking will trigger more landslides than reported for the 1949 or 1965 earthquakes. In addition, a review of weather data indicates that precipitation during the rainy seasons preceding both the 1949 and 1965 events was near or below average throughout most of the Puget Sound area and may have been responsible for there having been fewer landslides than would have been expected in unusually wet weather. Continued population growth and development in areas of steep slopes further increase the possibility of substantial property damage and loss of life from landslides in Washington.

Liquefaction

Liquefaction occurs when saturated sand or silt is shaken violently enough to rearrange its individual grains. Such rearrangement has a tendency to compact the deposit. If the intragranular water cannot escape fast enough to permit compaction, the load of overlying material and structures may be temporarily transferred from the grains of sand or silt to the water, and the saturated deposit becomes "quicksand". The liquefied material may then cause lateral-spread landslides or loss of bearing strength under foundations or roadways, depending on the depth and thickness of the liquefied zone and local topography (Fig. 21).

If the liquefied layer is near the surface it may break through overlying "dry" deposits, forming geysers or curtains of muddy water that may leave sand blows as evidence (Fig. 22). Retaining walls may tilt or break from the fluid pressure of the liquefied zone. Shallow liquefaction zones can also cause severe damage to structures whose foundation support has suddenly become fluid. Liquefaction caused basement floors to break and be pushed upward in Seattle and Puyallup during the 1949 earthquake (Murphy and Ulrich, 1951). Other basements cracked open and completely filled with water and silt. Lighter structures may float in liquified soil. Buried fuel tanks, if sufficiently empty, may pop to the surface, breaking connecting pipes in the process. Pilings without loads may also float upwards. Heavy structures may tilt in response to the loss of bearing strength by underlying soil. During the 1964 Niigata, Japan, earthquake, four-story apartment buildings tilted on liquefied soils, one as much as 60 degrees!

If a thick section of unconsolidated deposits liquefies near the surface, it will tend to flow into and fill topographic depressions. For example, a stream channel may be narrowed as saturated and liquefied deposits on both sides of the stream flow into it. Compression resulting from such flow buckled or skewed spans and damaged abutments on more than 250 bridges during the 1964 Alaska earthquake (National Research Council, 1985). This form of liquefaction failure was so widespread that McCulloch and Bonilla (1970) coined the term "land spreading" to distinguish it from the more

Figure 20. This ground failure was initiated by ground cracking adjacent to the banks of the Tacoma Narrows during the 1949 Olympia earthquake; the slide occurred several days after the earthquake. The landslide endangered nearby homes and induced strong waves in the Narrows. (By permission of Wide World Photos, Inc., and Associated Press)

Figure 21. A road in Olympia that was damaged in 1965 by liquefaction. (Photos by G. W. Thorsen)

Figure 22. Sand blows at a site along Capitol Boulevard in Olympia, 1965. (Photo by G. W. Thorsen)

widely recognized lateral-spread landslides that tend to occur on slopes due to failure along a particular subsurface layer. Land spreading may have been responsible for the disabling of three drawbridges across the Duwamish Waterway in Seattle during the 1949 earthquake. The distance between the piers in the main span of the Spokane Street bridge was shortened by 6 to 8 inches, causing the bridge to jam in the closed position until the concrete and steel edges could be trimmed off sufficiently to permit reopening (Gonen and Hawkins, 1974). These and other drawspans over the Duwamish were also jammed by the 1965 earthquake (U.S. Coast and Geodetic Survey, 1967).

Earthquakes may trigger a phenomenon in certain clays that produces effects similar to liquefaction in water-saturated sand. When vibrated, these "quick" or "sensitive" clays undergo a drastic loss of shear strength. For example, a relatively thin sensitive zone in the Bootlegger Cove Clay, located about 25 meters below the surface, was blamed for the spectacular lateral-spread landslides that destroyed parts of Anchorage in 1964 (Hansen, 1966). The sensitive layer responsible for these landslides had been deposited in a marine environment, in contrast to the underlying and overlying fresh-water clays. Later leaching of the salt from the marine clay by fresh ground water may have increased the clay's sensitivity to vibration-induced loss of shear strength by shaking (Hansen, 1966). Glacial clays are present in the northern Puget Lowland, and Armstrong (1984) mentions one instance of a slide in such material that was apparently triggered by the vibration of a passing train. However, it is currently unknown whether all marine clays of the Puget Lowland have a significant susceptibility to such vibration-induced failure.

Differential Compaction

Structural damage commonly occurs to buildings underlain by foundation materials that have different physical properties. Materials such as tide flat sediments, glacial outwash sands, dredging muck, sawdust, and building rubble will settle by different amounts when shaken. These materials are prevalent under parts of the downtown and waterfront areas of Seattle, Tacoma, Olympia, and Aberdeen-Hoquiam. Dozens of water and/or gas line breaks occurred in these cities as a result of differential compaction during the 1949 earthquake (U.S. Army Corps of Engineers, Seattle District, unpub. report, May 12, 1949), and virtually every building along the Seattle waterfront was damaged by settling during the 1965 earthquake. Many waterfront areas around Puget Sound are underlain by material susceptible to differential compaction and are thus vulnerable to damage in future earthquakes.

Water Waves

Tsunamis

Tsunamis are long-wavelength, long-period sea waves generated by an abrupt movement of large volumes of water. In the open ocean, the distance between wave crests can be greater than 100 kilometers, and the wave periods can vary from 5 minutes to 1 hour. Such tsunamis travel 600-800 kilometers per hour, depending on water depth. Large subduction earthquakes causing vertical displacement of the sea floor and having magnitudes greater than 7.5 are the most common cause of destructive tsunamis. Large waves produced by an earthquake or a submarine landslide can overrun nearby coastal areas in a matter of minutes. Tsunamis can also travel thousands of kilometers across open ocean and wreak destruction on far shores hours after the earthquake that generated them.

Tsunami wave heights at sea are usually less than 1 meter, and the waves are not frequently noticed by people in ships. As tsunami waves approach the shallow water of the coast, their heights increase and sometimes exceed 20 meters. Table 3 summarizes the heights of recent tsunamis at Neah Bay, Washington, and some other sites in western North America. Figure 23 shows the effect of a tsunami on the water levels recorded at

Table 3. Wave heights of some recent tunamis recorded at selected West Coast tide gages. (Modified from Spaeth and Berkman, 1967. Heights are maximum rise or fall in feet.) M_s signifies surface-wave magnitude; M_w signifies moment magnitude

	Tsunami-generating earthquakes					
Selected tide stations	Eastern Aleutian 1946 M_s 7.4	Kamchatka 1952 M_w 9.0	Central Aleutians 1957 M_w 9.1	Southern Chile 1960 M_w 9.5	Southern Alaska 1964 M_w 9.2	Central Aleutians 1986 M_s 7.7
Tofino, B. C.	1.9	2.0		4.6	8.1	
Neah Bay, WA	1.2	1.5	1.0	2.4	4.7	0.6
Crescent City, CA	5.9	6.8	4.3	10.9	13.0+	0.03
San Francisco, CA	1.7	3.5	1.7	2.9	7.4	

+ = Tide gage went off scale.

four selected Pacific Northwest tide gage stations; this tsunami was caused by the March 27, 1964, Alaska earthquake.

Historically, tsunamis originating in the northern Pacific and in South America have caused more damage on the west coast of the United States than tsunamis originating in Japan and the South Pacific. The tsunami generated by the 1964 Alaska earthquake caused $85 million damage in Alaska, $10 million damage in Canada, $115,000 damage in Washington, $754,000 damage in Oregon, and $11 million damage in California (Wilson and Torum, 1972). Figure 24 summarizes the effects of the tsunami from the 1964 Alaska earthquake along the Washington coastline. In places, wave heights reached 4.5 meters. The wave heights varied considerably, depending on the local water depth and the shape of inlets. The 1964 tsunami destroyed a small bridge across the Copalis River (Grays Harbor County) by hurling log debris against supporting piles. The tsunami was also detected on the Columbia River as far as 160 kilometers from the ocean (Wilson and Torum, 1972). Besides causing property damage, the 1964 tsunami killed 103 people in Alaska, 4 in Oregon, and 12 in California. Newspaper accounts tell of narrow escapes along the Washington coast, but there were no fatalities there.

The regional variations in damage caused by a tsunami from a particular source region can be estimated for future earthquakes. The basis for such estimates, particularly the influence of near-shore bottom topography and irregular coastline on the height of an arriving tsunami wave, is described by Wiegel (1970) and Wilson and Torum (1972). Table 3 shows that tsunami waves at some locations are consistently higher, even from sources in opposite directions.

Past tsunamis have caused only minor damage in Washington. The damage caused in the state by the tsunami triggered by the 1964 Alaska earthquake occurred along small estuaries north of Grays Harbor. In some places south of Grays Harbor sand dunes protected developed areas from damage (Hogan and others, 1964). Parts of these dunes have since been cleared to enhance the view (Fig. 25); some homes behind the dune area may be exposed to greater risk from tsunami damage in the future.

What kind of tsunami might coastal Washington experience in the future? We can certainly expect another tsunami from a great earthquake in Alaska or other seismically active areas in the Pacific. One likely source area in the next two decades is the Shumagin Islands region of the Aleutians (Davies and others, 1981; Kowalik and Murty, 1984). A tsunami from the Shumagin Islands would reach Washington in about 3 hours. Preuss (1986) has estimated the impact this tsunami would have on the coastal community of Aberdeen, Washington.

In addition to a tsunami generated by a distant earthquake, a magnitude 8 or greater subduction earthquake between the Juan de Fuca and North America plates might create a large local tsunami on the coast of Washington. Atwater (1987) and Reinhart and Bourgeois (1987) have found evidence they believe indicates that a tsunami from a nearby great subduction earthquake did affect the coast of Washington about 300 years ago. In general, local tsunamis are much more destructive than tsunamis generated from a distant source. In addition, they may occur within minutes of the earthquake or landslide that produces them, allowing little time for evacuation. Estimates of the effect of a local tsunami in Washington are speculative because we have no written record of a large, shallow earthquake near the coast. However, the sudden submergence of coastal areas that may accompany great earthquakes might increase the amount of land in Washington susceptible to tsunami damage.

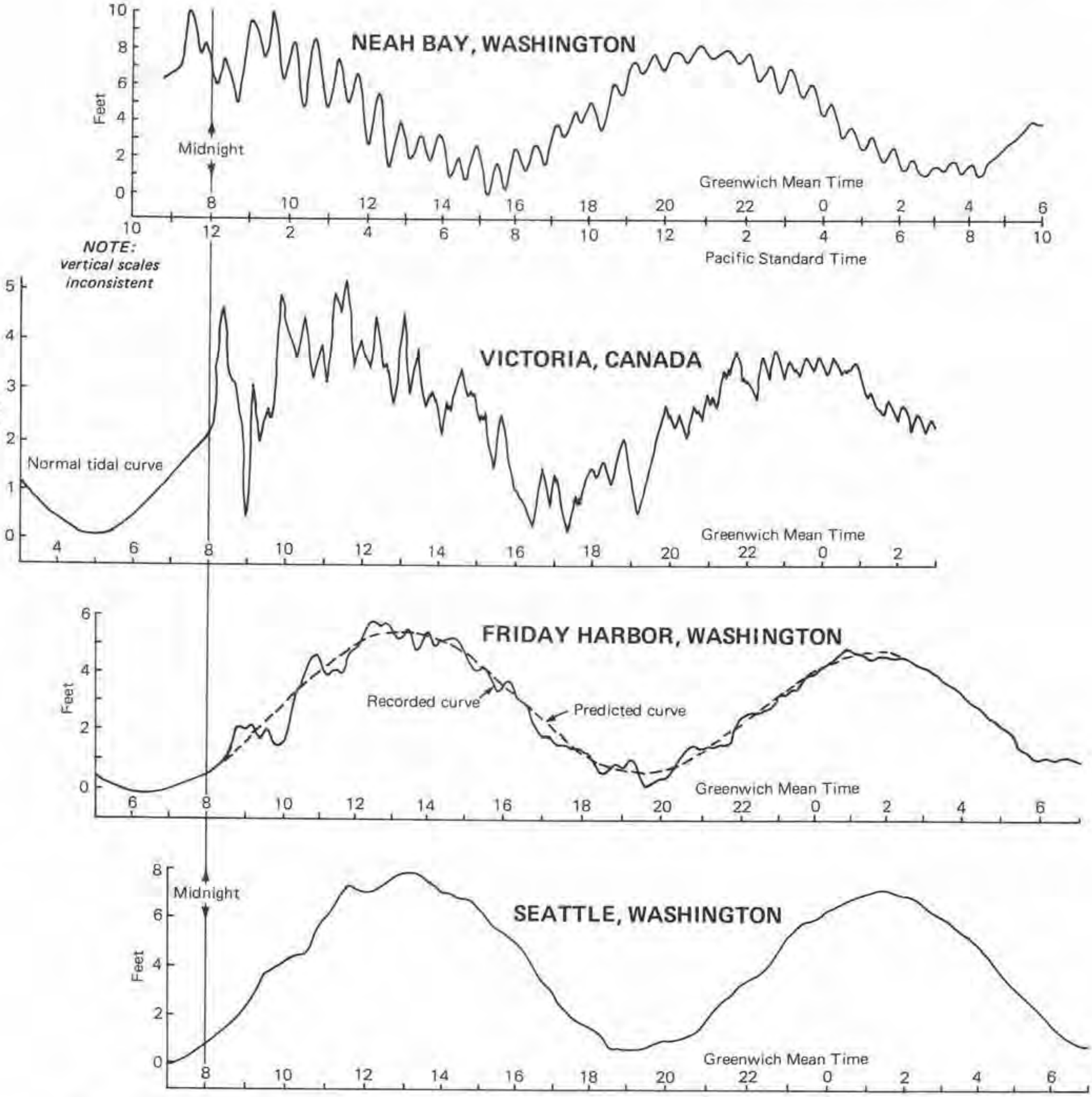


Figure 23. Tide gage records showing tsunami waves from the March 27, 1964, Alaska earthquake (magnitude 8.3) as recorded at four sites in the Pacific Northwest. Superimposed on the normal tide fluctuations having a period of about 12 hours (see predicted curve at Friday Harbor) are more rapid oscillations that have periods of about 1/2 hour that were caused by tsunami waves. Note the differences in tsunami wave amplitudes at different sites. (Modified from Spaeth and Berkman, 1972.)

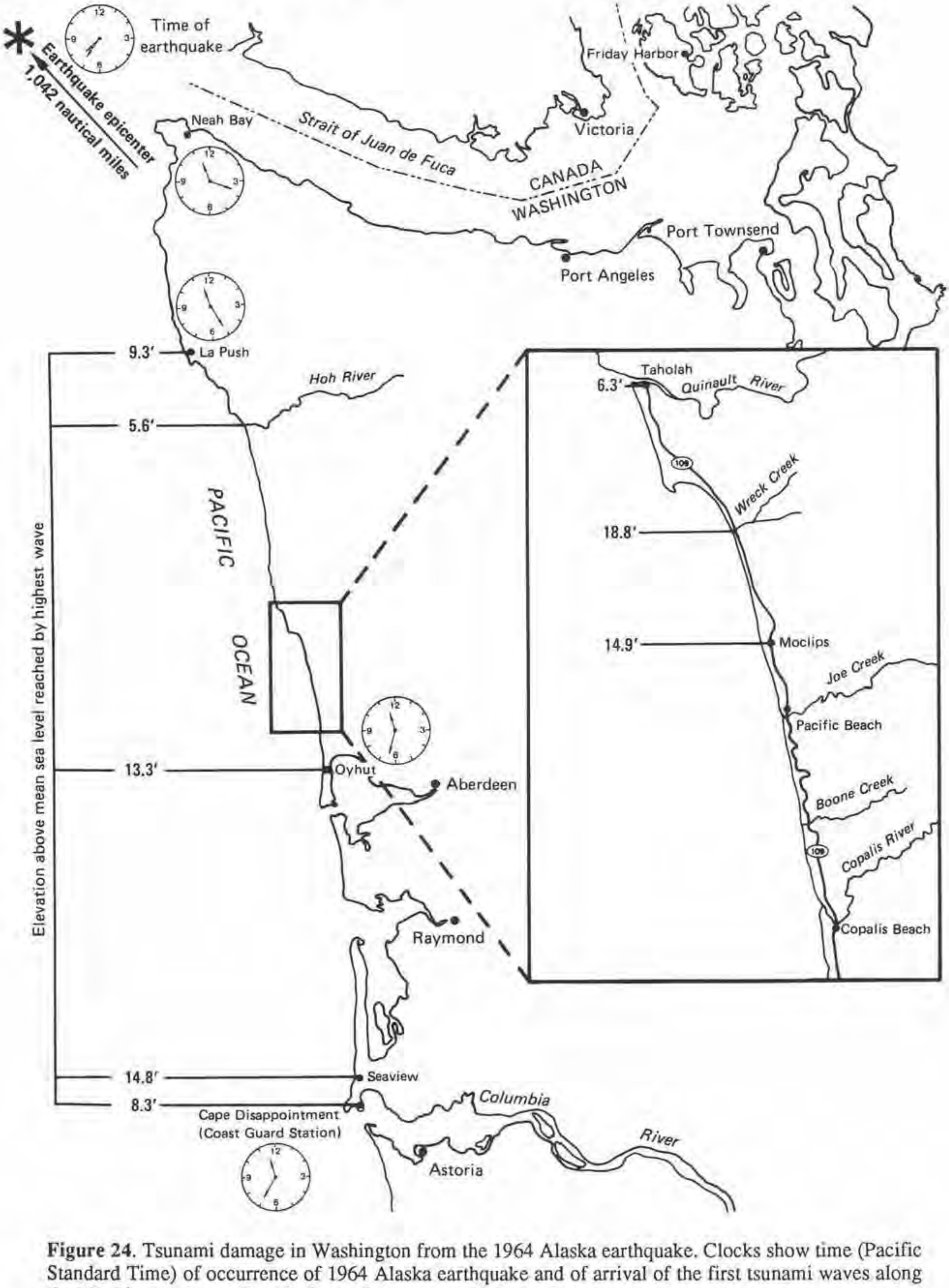


Figure 24. Tsunami damage in Washington from the 1964 Alaska earthquake. Clocks show time (Pacific Standard Time) of occurrence of 1964 Alaska earthquake and of arrival of the first tsunami waves along the Washington coast. Descriptions of damage on facing page.

La Push—Boats and floating dock broken loose, possible shoaling of channel.

Taholah—Crests below street level, no structural damage, loss of some nets and skiffs.

Wreck Creek—Debris on highway and bridge, washout of approach fills.

Moclips—Flooding 1 foot above ocean-front street, south end of town. Eight buildings damaged by drift logs or moved from foundation. Extensive damage to bulkheads and fills.

Pacific Beach—Dwelling* moved from foundation and destroyed, another building damaged.

Joe Creek—Logs and occupied home* slammed into bridge, three pile bents damaged or destroyed, two 20-foot spans lost.

Boone Creek—Debris on road, shoulder washout, dwelling flooded.

Copalis Beach—Damage to buildings, mobile homes.

Copalis River—Pile bents on bridge damaged, two bridge spans lost, others damaged.

Oyhut—Debris in yards and streets where dunes breached.

* Probably the same structure; see Washington Highway News, v. 11, no. 5, p. 2.)

Figure 24 (continued). Damage at towns along the coast of Washington caused by the tsunami generated by the 1964 Alaska earthquake (from Hogan and others, 1964, unless otherwise indicated).

Seiches

A seiche is a standing wave in an enclosed or partly enclosed body of water and is analogous to the sloshing of water that occurs when an adult suddenly sits down in a bathtub. Earthquakes may induce seiches in lakes, bays, and rivers. More commonly, seiches are caused by wind-driven currents or tides. Water from a seiche in Hebgen Reservoir caused by the 1959 earthquake near Yellowstone National Park repeatedly overtopped the dam, causing considerable damage to the dam and its spillway (Stermitz, 1964). The 1964 Alaska earthquake created a 0.3-meter-high seiche on the reservoir behind Grand Coulee Dam, and similar seiches were detected on 14 other bodies of water in Washington (McGarr and Vorhis, 1968). Several pleasure craft, houseboats, and floats sustained minor damage when a seiche caused some mooring lines to break on Lake Union in Seattle (Wilson and Torum, 1972). Seiches generated by the 1949 Queen Charlotte Islands earthquake were reported on Lake Union and Lake Washington in Seattle and on Commencement Bay in Tacoma. They separated boats from their moorings and stranded fish on the shore at Clear Lake in eastern Washington (Murphy and Ulrich, 1951). So far, no significant damage has been reported from seismic seiches in Washington caused by local or distant earthquakes.

Structural Failure of Buildings

A building's structure may be damaged if its vibratory response to ground motion exceeds design limits. The response depends on the interaction between structural elements of the building and the direction, frequency, and duration of ground motion. These factors

Figure 25. Dunes south of Grays Harbor have been stripped from beach property in order to enhance views. These dunes protected development on the beaches from tsunami damage in 1964 (Hogan and others, 1964). (Photo by G. W. Thorsen)

must be considered to produce a building design that prevents structural failure during earthquakes. In the absence of proper design, a building is exposed to greater risk of earthquake damage, particularly if the building has been subjected to prior strong earthquakes. The cumulative damage caused by prior earthquakes was stressed by Edwards (1951) in his analysis of structural damage by the 1949 Puget Sound earthquake.

Importance of Type of Construction to Building Damage

Usually, buildings can better withstand the vertical component of the earthquake-induced ground motion because they are designed to resist the large vertical loads generated by their own weight. Many are, however, vulnerable to large horizontal motions. Resistance to horizontal motion is usually accomplished by using lateral bracing and strong connections to hold structural elements together. Horizontal elements like floors can then distribute the building's weight to the building's strong vertical elements (Yanev, 1974). Figure 26 illustrates the basic structural components of any building.

Construction that provides a continuous path to transfer the lateral load from roof to foundation is more resistant to ground shaking than construction in which that path can be easily broken. For example, a well-nailed wood frame house resists ground shaking better than an unreinforced brick house because, once the brick cracks, the path along which the lateral load is transferred is broken. During both the 1949 and 1965 Washington earthquakes, buildings having unreinforced brick walls with sand-lime mortar suffered more damage than any other type of construction (Murphy and Ulrich, 1951, reprinted in Thorsen, 1986; U.S. Coast and Geodetic Survey, 1967). That damage was compounded by the lack of proper ties between the floors and walls (Fig. 27). Examples of structural damage in 1949 included: (1) Centralia—many walls collapsed, two schools were permanently closed, and one church was condemned; (2) Buckley—part of the high school collapsed; (3) Castle Rock—bricks and masonry from a gable over the main entrance of a Castle Rock high school collapsed, killing one student; (4) Chehalis—extensive damage to downtown buildings, schools, and churches (Murphy and Ulrich, 1951, reprinted in Thorsen, 1986); and (5) Seattle—1,900 brick walls that collapsed, fractured, or bulged were condemned and removed (Gonen and Hawkins, 1974). Other examples of structural damage include the collapse of unreinforced brick walls from the

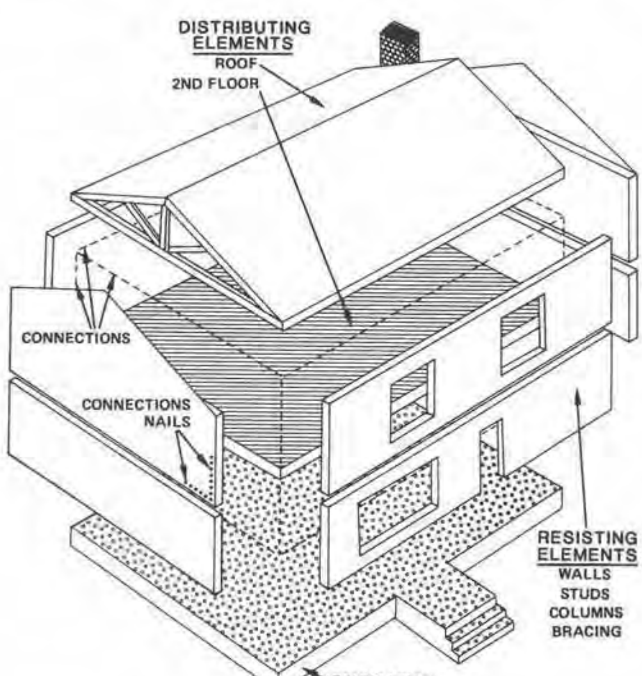


Figure 26. Structural components of a building.

Figure 27. Failure of unreinforced masonry used in a Seattle apartment building. Damage was caused by the 1965 earthquake. Note that the wood frame part of the building was undamaged. (Photo by The Seattle Times Co.)

sixth story of the Fisher Flouring Mills in Seattle (Fig. 28) and the severe cracking of unreinforced masonry walls in Issaquah school buildings.

Proper ties between the foundation and the structure and between the various elements of the structure are essential for good earthquake resistance. Buildings or other structures that are poorly attached or unattached to their foundations may shift off the foundation during an earthquake. In 1965, two 2,000-barrel aging tanks at the Rainier Brewing Company in Seattle fell off their foundations; one split and released its contents. Mobile homes merely resting on blocks have been especially vulnerable to damage during earthquakes (Yanev, 1974). Floors poorly attached to walls can pull away, permitting collapse of the wall or roof or a failure of the floor (Fig. 29). Because of the lack of proper ties, the third floor of the Seattle Union Pacific Railroad Station sagged after the 1965 earthquake.

Importance of Frequency of Ground Shaking to Building Damage

Building damage commonly depends on the frequency of ground motion. Damage can be particularly severe if the frequency of ground motion matches the natural vibration frequencies of the structure. In this case, the shaking response of the structure is enhanced, and the phenomenon is called resonance. Tall buildings, bridges, and other large structures respond most to low-frequency ground shaking, and small structures respond most to high-frequency shaking. Tall buildings in Seattle like the

Figure 28. Portions of the unreinforced brick walls on the sixth floor of the Fisher Flouring Mills collapsed to the ground during the 1965 earthquake. (Photo by The Seattle Times Co.)

Figure 29. The unanchored roof of the Puyallup High School gymnasium collapsed onto the stage during the 1949 Olympia earthquake. (Photo by The Seattle Times Co.)

Smith Tower responded strongly to the low-frequency ground motions produced by the 1946 Queen Charlotte earthquake located on Vancouver Island, 330 kilometers away. Other large earthquakes beyond the state borders have also caused damage in Washington—for example, earthquakes in British Columbia (Dec. 6, 1918, M=7.0; Aug. 21, 1949, M=8.1), in Montana (Aug. 17, 1959, M=7.5), and in Idaho (Oct. 23, 1983, M=7.5).

Tall buildings in sedimentary basins often suffer disproportionate damage because wave resonance in the basin amplifies low-frequency ground vibrations. During the September 19, 1985, Mexico earthquake (magnitude 8.1), 7- to 15-story buildings on unconsolidated sediments in Mexico City, 320 kilometers from the epicenter, collapsed because the low-frequency ground vibrations were enhanced by the sediments in a frequency range that matched the natural vibration frequency of the buildings (Rosenblueth, 1986).

Importance of Building Shape to Damage

The shape of a building can influence the severity of damage during earthquakes. Buildings that are L or U shaped in plan view (as seen from the air) may sustain more damage than a symmetrical building. This damage occurs because large stresses develop at the intersection between the building's segments, which respond differently to ground vibrations of different frequencies and different directions of motion. A building with sections that differ in height or width may develop large stresses at certain points because each section will vibrate at its own natural frequency in response to ground shaking. Separate buildings that vibrate at different frequencies can damage each other if they are built close together. During the 1985 Mexico earthquake, tall buildings in Mexico City swayed more slowly than shorter buildings, causing them to hit each other. This "hammering" of buildings on each other caused considerable damage and may have been responsible for the total collapse of some. Hammering was reported in both the 1949 and 1965 Puget Sound earthquakes (Edwards, 1951; U.S. Coast and Geodetic Survey, 1967).

Importance of Past Earthquakes to Building Damage

The history of a building and its exposure to prior earthquakes are also important in estimating the amount of damage it may sustain in future earthquakes. People often assume that a building that has survived an earthquake with no visible damage will likely not be damaged in subsequent earthquakes. However, ground shaking can weaken a building by damaging walls internally. Failure to detect and strengthen concealed damage can lead to complete destruction in a subsequent earthquake. For example, a 7-story reinforced-concrete refrigeration warehouse in Seattle had been damaged by previous earthquakes; a 20-foot-high concrete water tank platform atop this building collapsed during the 1949 earthquake (Edwards, 1951). The influence of the 1965 earthquake on buildings was difficult to evaluate due to previous structural damage caused by the 1949 earthquake (Gonen and Hawkins, 1974).

Importance of Building Remodeling to Damage

A building also may be weakened by structural alterations since its initial construction. For example, doors or other openings may have been cut through bearing walls, thereby increasing the risk of damage in future earthquakes.

Hazards of Non-structural Building Components

Non-structural Hazards

The non-structural elements of a building include parapets, architectural decorations (such as terra cotta cornices and ornamentation), chimneys, partition walls, ceiling panels, windows, light fixtures, and building contents. Displacement or distortion of these elements during ground shaking can be a major hazard to building occupants and result in extensive building damage. Damage to the non-structural elements of a building can include the destruction of costly equipment, such as computer systems, and the loss or extensive disorganization of important company records.

Displacement of non-structural elements occurs when they are unattached or poorly attached to the surrounding structure. The 1949 and 1965 Puget Sound earthquakes have provided several examples of damage and injury due to the displacement of non-structural parts of buildings. Many parapets collapsed, covering sidewalks with bricks (Fig. 30). A worker in the Fisher Flouring Mills was killed when a wooden water reservoir located on top of the building collapsed and fell in pieces to the ground. Cornices on Seattle's Franklin High School broke and dropped to the school yard below. Chimneys cracked and twisted, showering bricks on sidewalks, porches, school yards, and streets in many areas in the Puget Sound region (Fig. 31). In Chehalis, 75 percent of the town's chimneys were destroyed.

Light fixtures fell in many schools (Fig. 32). When a building shakes, objects like furniture may slide around violently. Many examples of shifted file cabinets, refrigerators, and overturned bookshelves were reported during the 1949 and 1965 earthquakes (Fig. 33). Objects on shelves also pose hazards if knocked to the floor or across a room. Books spilled from the shelves into the aisles of the Seattle Public Library, and most of the liquor bottles in the North Bend State Liquor Store fell to the floor. Magnetic computer tapes spilled from tape racks at the Boeing Company during the 1965 earthquake (Fig. 34).

Distortion of the non-structural elements occurs when the building flexes, putting extreme stress on rigid items like windows, panels, and built-in furniture (Bay Area Regional Earthquake Preparedness Project, 1985). In 1965 many windows in the Schoenfeld furniture store in Tacoma were shattered when glass was broken by the flexing of the window frames (Fig. 35). Other examples of this type of damage are noted in Thorsen (1986).

Economic loss during an earthquake is not confined to damaged building elements, equipment, and products. Loss of important company records, including inventory and customer lists, sales records, information about suppliers, and accounting, can contribute to disastrous business interruption costs (Fig. 36).

Damaged Lifelines

Lifelines include the utilities (power, water, gas), communication networks, and transportation systems that criss-cross and link our communities. Damage to these lifelines by earthquakes can create dangerous

Figure 30. A collapsed parapet wall and crushed canopy in downtown Olympia, 1949 earthquake. (Photo by Roger Easton, by permission Marie Cameron)

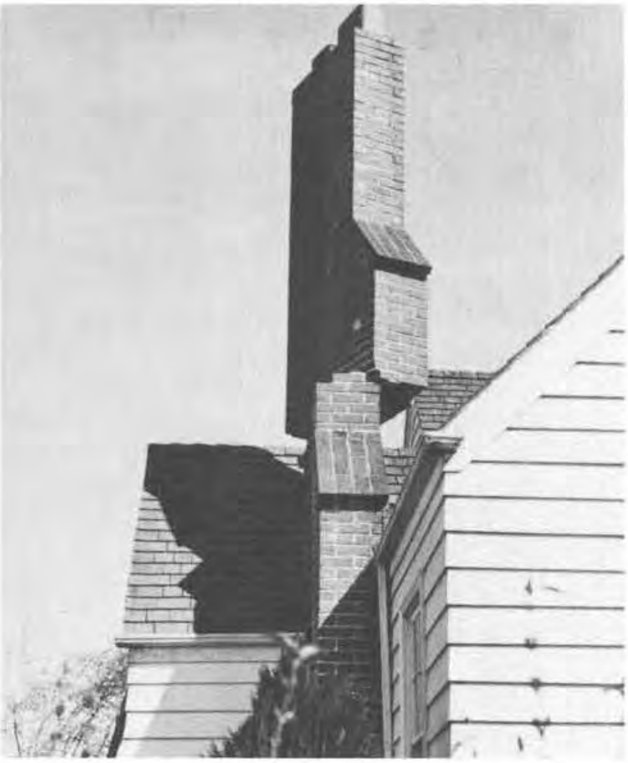


Figure 31. An unreinforced brick chimney in Kelso damaged during the 1949 Olympia earthquake. This chimney twisted on a mortar joint. (Photo from Edwards, 1951).

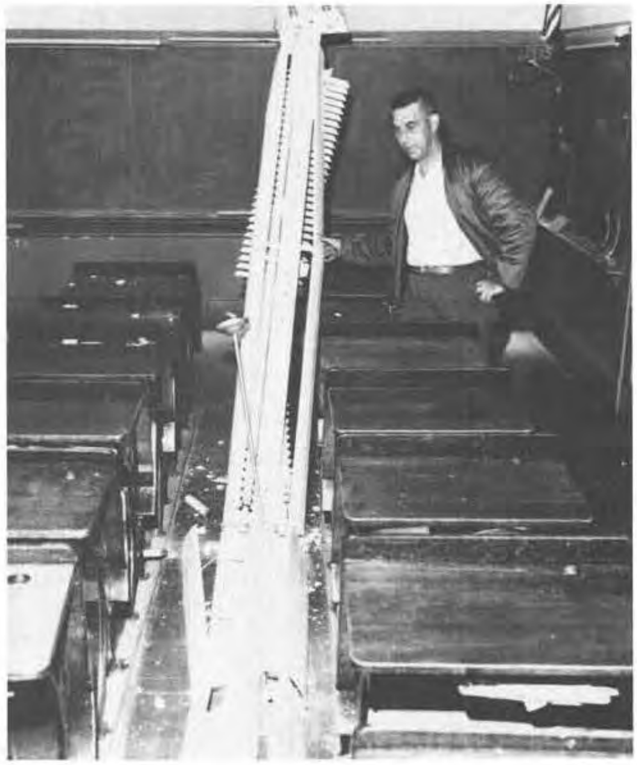


Figure 32. Fallen light fixtures in the aisle of an Olympia schoolroom; these were shaken loose during the 1965 Seattle-Tacoma earthquake. (Photo by Del Ogden, Daily Olympian)

Figure 33. Library shelves overturned as a result of the 1949 Olympia earthquake. (Photo by permission of the Seattle Times Co.)

Figure 34. Computer tapes scattered on floor of Boeing Company offices by the 1965 Seattle-Tacoma earthquake. (Photo courtesy of the Boeing Company)

Figure 36. Files scattered on the floor of the Department of Labor and Industries records section on the third floor of the General Administration Building in Olympia after the 1965 earthquake. (Photo by Del Ogden, Daily Olympian)

Figure 35. Glass windows broke on three sides of this ten-story building in Tacoma during the 1965 Seattle-Tacoma earthquake. (Photo by B. J. Morrill, from Steinbrugge and Cloud, 1965)

situations. Broken gas and power lines are serious threats to safety, largely because of risk of fire. Cracked water mains reduce the amount of water available for fire suppression. (See discussion of the 1949 and 1965 Puget Sound earthquakes.) Lack of communication isolates people from help and needed information (Fig. 37). Blocked or damaged transportation routes interfere with the ability of emergency personnel to respond promptly to requests for assistance.

Figure 37. Damage to the tower of Seattle radio station KJR caused by the 1949 Olympia earthquake. (Photo from A. E. Miller Collection, University of Washington Archives)

Other Hazards: Fires, Hazardous Spills, Dam Failures

Earthquakes may trigger many other hazards in a community. Damage to a dam caused by ground shaking could result in flooding downstream. Following the magnitude 6.4 San Fernando, California, earthquake in 1971, between 75,000 and 80,000 people were evacuated for 3 days from below the Lower Van Norman Dam. Damage occurred to both the Upper and Lower Van Norman Dams (Fig. 38), and authorities felt that a small amount of additional shaking would have caused both to fail (Subcommittee on Water and Sewerage Facilities, 1973).

The greater use and storage of hazardous materials in recent years increases the potential for loss of life and injury resulting from damage to storage or transport containers during an earthquake. A chemical spill in a general hospital at Santa Rosa, California, was caused by ground shaking produced by two earthquakes (magnitudes 5.6 and 5.7) that occurred nearby on October 1, 1969. A fire resulting from the spill spread to the surgery facility on the next floor (Reitherman, 1986). Bottles of chemicals stored on open shelves in a Coalinga, California, high school were shattered on the floor during the 1983 Coalinga earthquake. Sulfuric acid ate through from the second floor to the first floor and the mixing of other chemicals released toxic fumes throughout the building (Bulman, 1983).

Fires are a common problem during earthquakes. The devastating 1906 San Francisco earthquake is often called the San Francisco fire because of the tremendous damage caused by fires started during the ground shaking. Once fires are started, fire suppression may be hampered by damaged water distribution systems. Response to fires may be slow because of blocked transportation routes and damage to communication networks.

Figure 38. Damage at the Lower Van Norman Dam by the February 9, 1971, San Fernando, California, earthquake; view to the east. A massive slide into the reservoir broke off the east outlet tower and damaged the west outlet tower (foreground). No water overtopped the dam, and no leaks developed as a result of the shaking. More than 75,000 residents were evacuated from the area downstream for 3 days after the earthquake. (Photo by G. W. Thorsen)

WHERE HAS EARTHQUAKE DAMAGE OCCURRED IN WASHINGTON STATE?

The following sections briefly review property damage in Washington. Selected catalogs that contain chronological lists of earthquake locations, magnitudes, and damage for Washington earthquakes are listed following the references for this report. See also a compilation of out-of-print reports by Thorsen (1986) and Gonen and Hawkins (1974). Table 2 and Figure 13 give information about specific earthquakes causing damage in Washington. Reports of damage caused by earthquakes in Washington and northern Oregon provide examples of the location and kinds of damage to be expected in future earthquakes.

1872 North Cascades Earthquake

The earthquake of December 14, 1872, ranks as Washington's most widely felt earthquake. However, its occurrence in a relatively remote and sparsely populated part of the state during a period early in Washington's history limits the information available about damage near the epicenter. Severe damage to a log cabin was noted near Lake Chelan; ground sinking and upheaval were also observed nearby. Numerous landslides occurred near the lake and along the Columbia River. There were also reports of persons thrown to the ground near the mouth of the Wenatchee River.

1936 Milton-Freewater Earthquake

The northeastern Oregon Milton-Freewater earthquake of July 15, 1936, is the most destructive earthquake of the eastern Washington-Oregon border region since the late 1800s (Shannon and Wilson, Inc., 1975). Its intensity was greatest (VII) at Freewater, State Line, and Umapine in Oregon. Moderate damage occurred in Athena and Milton. Windows broke, walls cracked, a few chimneys collapsed, a two-story concrete house near Umapine lost part of the top of its second story, and some standing railroad cars near Milton were derailed (Brown, 1937). Two schools in Umapine were damaged. Water issued from cracks as much as 60 meters long. Numerous aftershocks were reported until November 1936 (Coffman and others, 1982). This earthquake was also felt widely in parts of Idaho.

1939 Puget Sound Earthquake

Damage from the November 12, 1939, Olympia earthquake was most severe in Centralia, Elma, and Olympia, where chimneys were broken, plaster cracked, and various objects overturned (Coombs and Barksdale, 1942). Swaying power lines caused short circuits that produced power failures in Olympia and Centralia. In Tacoma, a 200-pound terra cotta cornice that was attached to two buildings fell after being loosened by the differential movement between the buildings (Coombs and Barksdale, 1942).

1945 Puget/Cascades Border Region Earthquake

The earthquake of April 29, 1945, occurred near North Bend, Washington, along the western edge of the Cascades. The most severe damage reported included a broken water main and damaged chimneys in North Bend. Bricks were dislodged in a dozen or more homes in the Cle Elum area, and a Roslyn boy was struck on the head by a falling brick. At the Mount Si Ranger Station, near North Bend, "the earth buckled and heaved, and tons of rock and earth cascaded down the 4,000-foot cliffs of Mount Si" (Bodle and Murphy, 1947). The 1945 earthquake was thought to have occurred on a fault trending north from Mount Si to the Tolt River area (Bradford and Waters, 1934). However, recent mapping of the area indicates that the supposed fault trace along the west side of Mount Si is created by the differential resistance to weathering between the rocks forming Mount Si and those to the west (Tabor and others, 1982).

1946 Puget Sound Earthquake

The magnitude of the 1946 Puget Sound earthquake was nearly as large as that of the Seattle-Tacoma earthquake of 1965. In Seattle, the most severe damage caused by this earthquake was to industrial buildings built on filled ground in the Duwamish River valley and on the former tide-flat area at the south end of Elliott Bay. There was also heavy damage to waterfront structures built on pilings in Seattle (Barksdale and Coombs, 1946). In Olympia, fire trucks were moved to the street because of fear that the building would collapse; the firehouse doors were nearly jammed because of distortion suffered during the earthquake. Although damage in Tacoma was less spectacular than in Seattle or Olympia, six fires there were started when chimneys cracked during ground shaking.

1949 Olympia and 1965 Seattle-Tacoma Puget Sound Earthquakes

The best documented large earthquakes in Washington are the deep Puget Sound earthquakes of April 13, 1949, between Tacoma and Olympia, and April 29, 1965, between Seattle and Tacoma (Edwards, 1951). The damage patterns in both of these earthquakes were similar, although the 1949 earthquake was more destructive ($150 million damage versus $50 million damage, in 1984 dollars). Some of the damage sustained in 1965 was to buildings previously weakened by the 1949 earthquake.

In both the 1949 and 1965 earthquakes there was substantial damage to older masonry buildings with inferior mortar (Gonen and Hawkins, 1974) and to buildings with inadequate anchorage of framing to floor and roof joists (Seattle Fire Department, unpub. report, 1965; MacPherson, 1965). Differential ground settlement caused significant damage to both new and old buildings.

Most damage in Seattle during the 1949 and 1965 earthquakes was concentrated in areas of filled ground, especially in the Pioneer Square area, where there are many older masonry buildings, and along the waterfront (Fig. 39). In 1965 nearly every waterfront facility in Seattle was damaged. In Tacoma, damage occurred mainly to cornices and chimneys of older structures built on soft ground in lowland areas and on firmer gravel in highland areas. In Olympia, damage was primarily confined to the old part of the city and to areas of the port built on artificial fill. In 1949 a portion of Olympia's industrial area, built on fill extending into Puget Sound, settled 5 inches. Forty percent of business buildings and houses were damaged in Centralia in 1949. In Chehalis, four schools, the City Hall, the library, and the court house were damaged considerably, although all were built on solid ground.

Washington schools sustained a disproportionately high level of damage during the 1949 and 1965 earthquakes (Gonen and Hawkins, 1974). In 1949 and 1965, Seattle schools built prior to 1950 suffered extensive structural and non-structural damage. Thirty Washington schools, normally serving 10,000 students, were damaged in 1949. (See for example, Fig. 40.) Ten of these schools were condemned and permanently closed (Gonen and Hawkins, 1974). Three Seattle

Figure 39. The ground at this Harbor Island, Seattle, site dropped when the pier at the left shifted toward the water in the 1965 earthquake. (Photo by K. V. Steinbrugge, from Steinbrugge and Cloud, 1965)

Figure 40. This unanchored gable collapsed at the Castle Rock High School in the 1949 earthquake. The buidling is of unreinforced masonry construction. A student was killed by falling bricks. (Photo from A. E. Miller Collection, University of Washington Archives)

schools were torn down, and one was rebuilt (Martens, 1984). Following the 1965 earthquake, eight Seattle schools normally serving 8,800 students were closed until inspections could be carried out to determine their safety (Martens, 1984). In 1949, a large brick gable over the entry of Lafayette Elementary School in West Seattle collapsed directly onto an area normally used for assembly of pupils at the time of day the earthquake occurred (U.S. Geological Survey, 1975) (Fig. 41).

Figure 41. Lafayette School in Seattle after the 1949 earthquake. The gable fell because of lack of adequate anchorage and defective masonry. The masonry fell on the landing in front of the main entrance. (Photo from an article by C. N. Dirlam reproduced in Thorsen, 1986)

Similarly, the Washington State Training School for Boys, in Chehalis, sustained severe damage when a gable collapsed during the 1949 Olympia earthquake (Fig. 42). Fatalities and injuries to school children would have been much higher had many Puget Sound schools not been vacant because of spring vacation.

Wood frame residences were usually undamaged except for failures of brick fireplaces and chimneys extending above the roof. Experience in California and elsewhere shows that fireplaces and chimneys are one of the principal hazards to frame residences subjected to strong ground motion. Edwards (1951) estimated that more than 10,000 chimneys in northwestern Washington required repair after the 1949 earthquake. Seventy-five percent of the chimneys in Chehalis had to be replaced. Damage to split-level homes was greater than in other frame residences because the two sections of such homes vibrated at different frequencies, concentrating stress along the junction between the sections. Some split-level houses collapsed completely (Gonen and Hawkins, 1974).

Structural damage in multistory buildings was generally limited in both the 1949 and 1965 earthquakes. However, damage to the State Capitol in Olympia and other older structures in the capitol complex was severe due to the lack of lateral bracing and the collapse of brick and stone facing (Fig. 43). After the 1965 earthquake, the Capitol was temporarily closed, and government activities were moved to nearby motels.

Figure 42. Damage at the Washington State Training School for Boys, in Chehalis, caused by the 1949 Olympia earthquake. Typical of pre-1900 buildings, the thin wall and unanchored gable were easily knocked out by flexing of the wood structure. Cracks show that the left wall is about to fail. Two schools in Centralia were permanently closed because of damage sustained during this earthquake. (Photo from Edwards, 1951)

Figure 43. An unanchored keystone in an arch in the Capitol Building dome loosened by ground shaking in the 1949 Olympia earthquake. (Photo from the A. E. Miller Collection, University of Washington Archives)

Fortunately, fire was not a major problem in either the 1949 or 1965 earthquake even though numerous water mains broke. In the 1949 earthquake, 24 breaks were reported in water mains in Olympia, resulting in a temporary closing of the business district. In Tacoma, water mains broke because of landslides and settling of tide flats. A 60-inch main broke at the Seattle city reservoir. Centralia's gravity-feed water system was badly damaged. In 1965, three water mains (two 20-inch and one 12-inch) failed in Seattle, and two of three 48-inch water supply lines broke in Everett where the trestle carrying them crosses an area of poor soil. Pressure surges in pipes were reported in Tacoma but did not cause pipe failures.

In 1949, power failures occurred in Seattle when swinging transmission lines touched, causing circuit breakers to trip. In Tacoma, the transformer banks at the Bonneville Power Plant substation needed to be realigned. In Chehalis, electric power service was disrupted for about 2 hours. In 1965, two Bonneville Power Administration transmission towers toppled near Everett. These towers carried 230,000-volt electrical power from Chief Joseph Dam to the Snohomish substation.

In 1949, the Seattle gas distribution system broke at nearly 100 points, primarily because gas mains separated from connecting pipes where the pipes were buried in filled ground. Although a major break occurred in Olympia's gas mains, there was no crippling interruption of service.

After the 1949 earthquake, damaged lift bridges in Seattle and Tacoma would not open and close. Only minor damage occurred to the State highway system, and that was due mainly to ground settlement and a few small slides onto roadways and railway tracks. Landslides also occurred in 1965.

HOW CAN WE REDUCE EARTHQUAKE LOSSES IN WASHINGTON?

Earthquakes cannot be eliminated. However, the injury, loss of life, and property damage associated with them can be reduced and recovery accelerated by making earthquake-loss reduction part of an on-going program, rather than a hasty response to disaster. An earthquake-loss-reduction program entails three basic elements: (1) understanding the nature and extent of the earthquake risk, (2) taking actions to reduce the risks, and (3) establishing policy to guide the development of effective risk-reduction programs. Gori (1984) presents a collection of papers that provide practical information on improving the level of earthquake hazard mitigation and preparedness. Scott (1979) describes the elements of a state seismic safety program and the state policies needed to carry it out. The U.S. Geological Survey, the Federal Emergency Management Agency, the Washington Department of Natural Resources, and the Washington Department of Community Development, Division of Emergency Management began a multi-year cooperative earthquake hazards reduction program in 1985 to investigate earthquake potential, hazards mitigation, and preparedness efforts in the Puget Sound area. Workshops to review the results of these studies will be held periodically and workshop proceedings published in U.S. Geological Survey open-file reports (for example, Hays and Gori, 1986). The program was enlarged to include the Portland, Oregon, area in 1987.

Understanding Earthquake Risk

Risk can be numerically defined as the probability of a hazardous event multiplied by the cost of damage that would result should the event happen. Using this definition, the level of risk may be very high for a low-probability event if the consequences of the event are considered to be very costly. For example, although many safeguards exist to assure safe operation of nuclear power plants and although the likelihood of a major accident at a U.S. nuclear power plant is generally considered to be low, the cost of an accident involving release of radioactivity could be extremely high. On the other hand, a magnitude 8 earthquake occurring in a remote, unpopulated area might be considered a low-risk event because the consequences would have an impact on few people. A similar event in an urban area would involve high levels of risk. Therefore, the level of effort required to reduce earthquake losses will vary depending upon the severity of the hazard, the number of people that would be affected, and the amount and kind of property exposed.

The nature and extent of the earthquake risk in Washington is determined by estimating the level of expected ground shaking, identifying the sites susceptible to ground failures and tsunamis, and by combining such hazards information with information concerning the distribution of population, type of building construction, and technological hazards in the state. The present level of development of information identifying these factors is summarized below.

Maps have been published depicting expected levels of ground shaking in the United States. Recent maps (Algermissen and Perkins, 1976; Algermissen and others, 1982) show ground accelerations and velocities expected to affect structures with lifetimes of 10, 50, and 250 years. Since these maps are based on past earthquake activity, they most accurately estimate the level of ground shaking from earthquakes similar to those already experienced, like the 1949 Olympia earthquake in Washington. A large shallow earthquake in the Puget Sound region, a large shallow earthquake in southwestern Washington, or a great subduction-style earthquake along the coast have not been considered in the development of existing maps that depict expected levels of ground shaking. Ground shaking maps may need to be revised as new information on potential earthquake sources is developed.

Only a few maps are available that show areas in Washington that are susceptible to ground failure. Tubbs (1974) mapped potential landslide sites in Seattle. The Washington Surveying and Rating Bureau (1966) published maps showing areas of fill or unstable ground in Seattle, Bellingham, Everett, and Tacoma. County soil maps exist for areas throughout the state. Rasmussen and others (1974) used soil maps of counties in the Puget Sound region and estimates of ground shaking in past earthquakes to develop a method that can be satisfactorily used to identify sites likely to show the greatest damage to structures in future earthquakes. Maps indicating areas vulnerable to earthquake-generated waves and tsunamis or seiches do not exist.

Sociological factors that should be considered in the determination of earthquake risk in Washington include the distribution of people, businesses and industries, financial institutions, hazardous waste transportation routes and permanent storage sites, and the location of critical facilities such as nuclear reactors. Most of the state's population is concentrated west of the Cascade mountains in the Puget Sound region. Major businesses and industries like the Boeing Company are also in this area. Besides having significant earthquake activity, the Puget Sound region has many sites susceptible to ground failures. The lower population of eastern Washington somewhat limits the earthquake risk in that area even though moderate levels of ground shaking are anticipated. One matter of concern, however, is the impact of an earthquake on the storage of hazardous wastes in eastern Washington.

One attempt to estimate earthquake losses by combining the types of information described above was carried out by the U.S. Geological Survey (1975). This study focused on the potential impact of a major earthquake on six counties in the Puget Sound area. The study describes potential effects of earthquakes on buildings and other structures and estimates the impact of earthquakes on the availability of essential services, traffic patterns, communications, and other factors. Studies such as this can be used in combination with geotechnical data to develop risk reduction programs. Since the U.S. Geological Survey study was completed in 1975, the population of the Puget Sound area has increased by 25 percent, to 2.6 million in 1986. Capital investment increased 290 percent from 1975 to 1984 when assessed property valuation in the Puget Sound area reached $93.3 billion (Washington Seismic Safety Council, 1986). Social and economic changes in Washington combined with recent geologic evidence suggesting the possibility of earthquakes having magnitudes greater than 8 along the coast change the nature and extent of earthquake risk in the state. The 1975 U.S. Geological Survey report will be updated to take these changes into account.

Risk Reduction

Earthquake damage can be reduced by (a) taking account of earthquake hazards in land-use decisions, (b) using appropriate engineering and construction design to reduce the hazard, and (c) involving communities in earthquake preparedness programs.

Land-Use Decisions

Land owners, lenders, government officials, and others involved in land development need to understand the consequences of building in areas exposed to earthquake hazards. Those consequences should be carefully considered when making decisions on land use. Building in hazardous areas may necessitate a more expensive design, increased insurance coverage, or additional long-term maintenance. Individuals using property in hazardous areas may be at greater risk of injury and loss during an earthquake. Further, emergency response may be more difficult in areas developed in regions of high earthquake risk, and recovery following an earthquake may be slower and more costly.

Federal, state, and local regulatory laws can encourage some types of land use (Baker, 1976; Palm, 1981). The 1968 National Flood Insurance Act, the 1973 Flood Disaster Protection Act, the Flood Disaster Relief Act of 1973, and the Disaster Protection Act of 1975 make federally subsidized flood insurance and certain federal disaster relief funds available only to communities that control development within flood plains. Similar federal legislation providing federally subsidized earthquake insurance does not presently exist, and regions with high earthquake risk are not required to control development in order to qualify for federal disaster relief funds. However, the National Earthquake Hazard Reduction Act (PL-95-124) of 1977 established the **National Earthquake Hazard Reduction Program (NEHRP)** for the purpose of reducing the risks to life and property from future earthquakes. NEHRP objectives include the development and promotion of model building codes and the education of state and local officials about seismic risk. Some federal funds are provided under NEHRP to facilitate Washington state earthquake hazard mitigation and preparedness activities. Beginning in 1989, state participation, in the form of matching funds, will be required before other federal monies will be allocated. Federal regulations also guide siting of critical facilities, such as nuclear power plants, with respect to earthquake hazards and provide seismic design standards for federal hospitals and highways.

States can regulate land use by establishing policies to be followed at the state and local level. In California, state law requires that real estate agents disclose the presence of active faults (shown on state maps) prior to sale of property. The Washington State Environmental Policy Act of 1971 requires all state and local governmental agencies to consider environmental values both in undertaking their own projects and in licensing private proposals. Although the focus of this act is on the preservation and enhancement of the environment, an assessment of geologic factors affecting a proposal is required as part of the environmental impact statement. The Washington Energy Facility Site Evaluation Council considers earthquake hazards in the siting and licensing of state nuclear power plants and in the review of proposed oil pipeline routes.

Local governments can regulate land use through building permits, zoning provisions, and ordinances. The Seattle Greenbelt Ordinance is an example of a regulation that can be used to reduce earthquake hazards by limiting land use. The King County Sensitive Areas Ordinance 4365 can limit land use in certain areas, defined by the ordinance as those subject to landslides or significant earthquake hazard. (King County has mapped areas identified as unstable during ground shaking. However, if a property is in an unstable area not so identified by the county, the property owner is still required to follow Ordinance 4365.)

Engineering and Architectural Design

Although appropriate land use management may be an effective way to reduce earthquake risk, the benefits of utilizing a site may outweigh the risk. Significant earthquake hazards exist throughout the state, and not all high-risk sites can be avoided. Therefore, engineers have developed methods to increase the resistance of land and structures to the damaging effects of strong ground shaking.

Examples of engineering methods used to reduce earthquake hazards include the stabilization of landslide areas and compaction of soft-soil sites. Many landslides that occurred in King County following the January 19, 1986, rains might have been prevented by adequate drainage of the slide-prone areas. A landslide area along Perkins Lane in the Magnolia area of Seattle was improved by the installation of drain fields to reduce the water content of the slide material. This lowers, but does not remove, the susceptibility of the material to slip. A method called vibro-flotation can be used to compact the soil before a structure is built. This technique was used to compact the abutment area of the West Seattle bridge before the pier supports were emplaced.

Architects can contribute to the reduction of earthquake hazards by designing buildings with shapes that do not localize large stresses when the ground shakes and by considering ground shaking in the design of the non-structural elements of the building. Nonstructural hazards can be reduced in new or existing buildings by securely attaching ceiling panels, light fixtures, and shelving and by installing special equipment, like safety glass and automatic gas shut-off valves. Closed storage cabinets with secure latches should be used for loose objects whose movements during ground shaking might be dangerous.

The Uniform Building Code (prepared by International Conference of Building Officials) contains building design standards commonly used by architects and engineers in the western United States. These standards are periodically modified through experience and research. New versions of the Uniform Building Code apply only to new construction. Therefore, the age of a building provides a guide to the design criteria used at the time of construction and to the type of risk it offers.

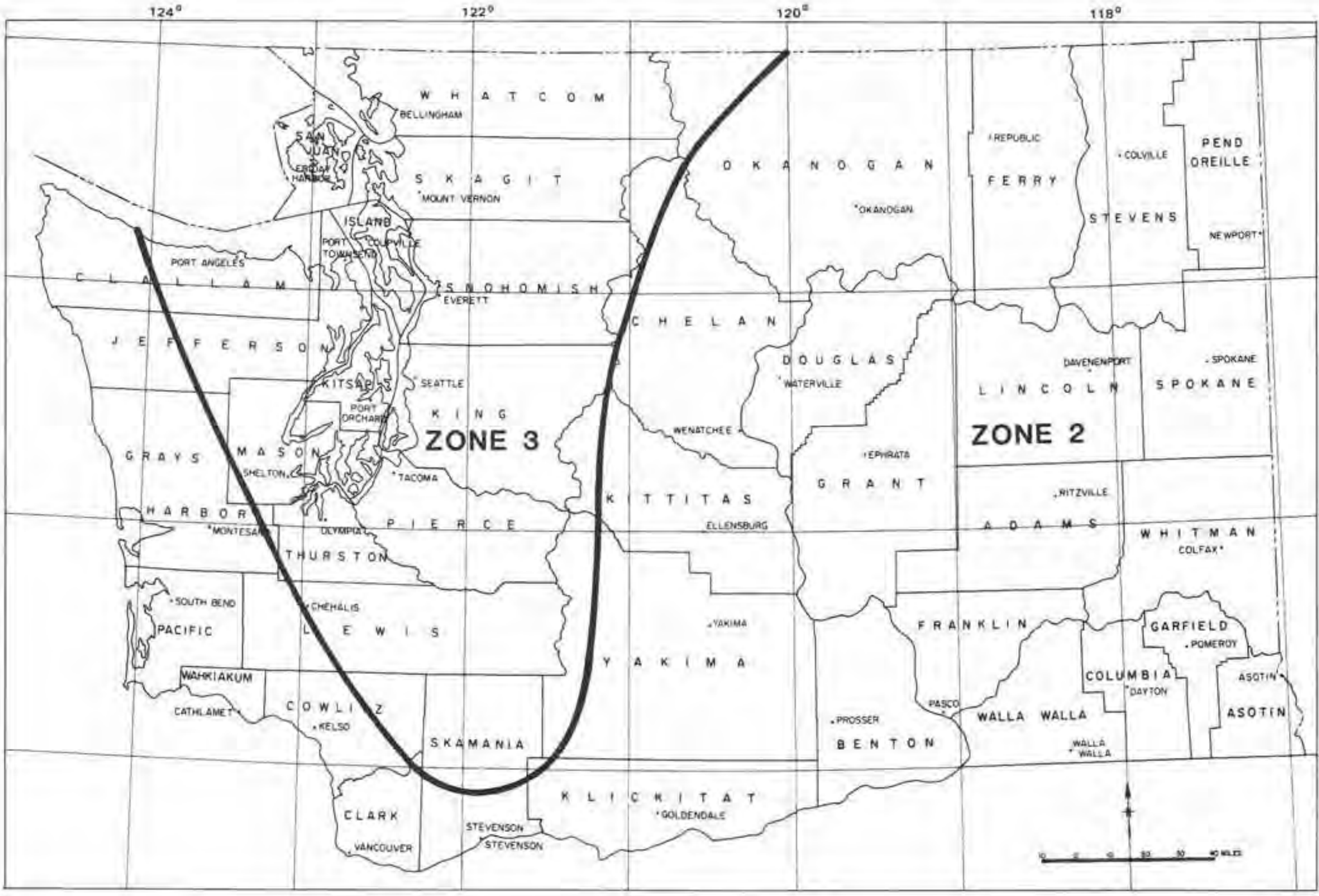
Before the first Uniform Building Code was developed in 1926, architects and engineers relied on design criteria that varied in different localities or with specific projects. From 1927 to 1946 the Uniform Building Code classified Washington state as an area where only minor earthquake damage was expected—the state was put in seismic zone 1 on a scale ranging from 0 to 3. In 1949, after the 1939 and 1946 Puget Sound earthquakes and the June 23, 1946, Canadian earthquake, Washington was reclassified and put in seismic risk zone 2. In 1952, the risk potential was upgraded again to seismic zone 3 because of the major 1949 Olympia earthquake.

Although Puget Sound is still classified as zone 3, the design requirements are much more stringent today than they were under the 1952 code. From 1952 to 1961 the recommendations for seismic design were included in an appendix to the Uniform Building Code as an optional consideration. In 1961, the seismic design section was moved from the appendix to the main text as a mandatory design requirement. Even though the Uniform Building Code was used by many jurisdictions in the state, doing so was not required by the State of Washington until January 1, 1975. At that time all jurisdictions were then required to adhere to the provisions of the most recently adopted version of the Uniform Building Code.

In 1976, the classification of seismic risk zones used in the Uniform Building Code was modified to range from 0 to 4. Seismic zone 4 includes areas expected to have major damage because of their proximity to major fault systems. In this classification, areas along the San Andreas fault and the Alaska subduction zone are in seismic zone 4. To date, no area of Washington has been proposed for inclusion in seismic zone 4.

A map of seismic zones in Washington (Uniform Building Code, 1988) is shown in Figure 44. It is a modification of the seismic zones depicted in the Uniform Building Code of 1985 and, like its predecessor, is based on Washington earthquake history. It illustrates the changes that recent studies have made in our assessment of earthquake hazards. For example, the St. Helens Seismic Zone (Fig. 15) has been placed in the higher risk zone 3; it was formerly in zone 2. More of the North Cascades is now included in seismic zone 3 because of recent studies of the severity of the 1872 North Cascades earthquake. Future revisions of the seismic risk zones in Washington could include placing part or all of the Cascadia subduction zone in seismic zone 4.

State regulations do not require structural improvement of buildings built prior to the required use of lateral resistance in building design. Strengthening older buildings is required only during extensive remodeling. However, the State of Washington has begun a program of improving the seismic safety of selected buildings. In 1979, the State of Washington spent $9.1 million strengthening the old state capitol building (now housing the Office of the Superintendent of Public Instruction). It also spent $3.4 million on the legislative office building in 1975, and $3.5 million on the insurance office building in 1973 and 1979. At the present time, however, no



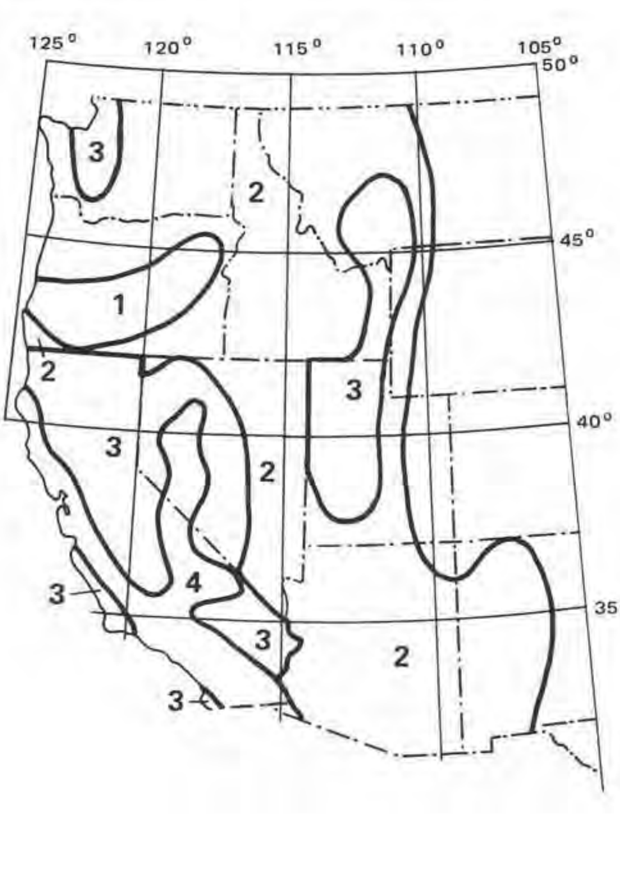


Figure 44. Uniform Building Code map of the Seismic Risk Zones of Washington (from International Conference of Building Officials, 1988). Compare this with the map to the left, which is from the 1985 edition of the code.

program exists to modify schools, hospitals, or fire stations built before 1949 so that they can resist ground shaking comparable to levels recorded during the 1949 and 1965 earthquakes.

Many older masonry buildings similar to those damaged during the 1949 and 1965 earthquakes exist throughout the Puget Sound region. Some examples are shown in Figure 45. Poor maintenance further weakens such buildings, creating significant hazards to building occupants or passersby.

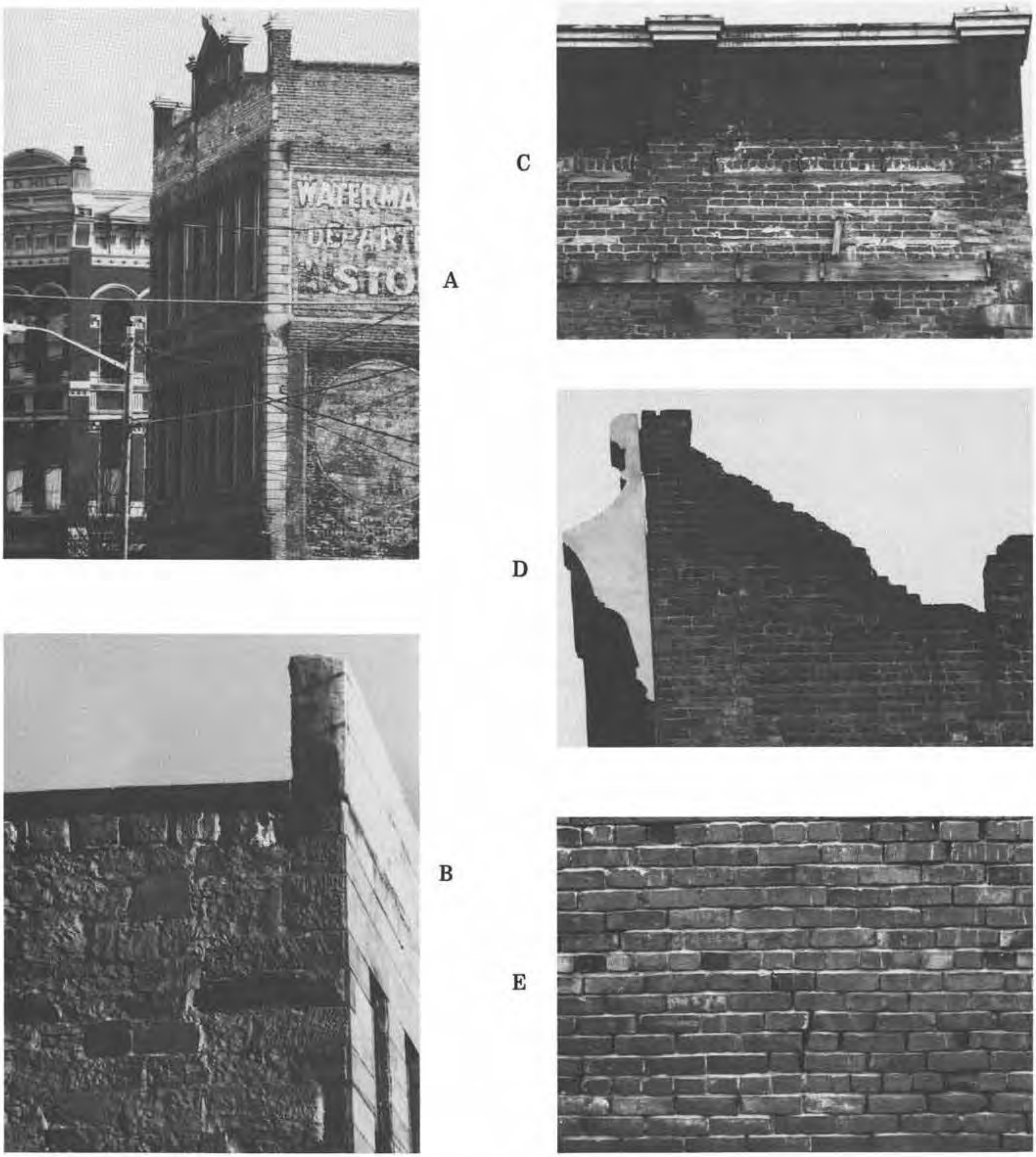


Figure 45. Examples of unreinforced masonry buildings in Port Townsend. A and B show unbraced parapet walls. C is a close-up of the parapet wall in A; note the lack of anchoring between parapet and wall below. D shows a loosely attached parapet face. E illustrates deteriorated mortar; this wall consists of brick only marginally held together. (Photos by G. W. Thorsen)

Earthquake Preparedness Programs

A major earthquake in Washington could occur tomorrow—or 25 years from now. Earthquake preparedness actions must be a part of routine safety and building maintenance procedures to insure protection when the next earthquake happens. Individuals must know what to do before, during, and after an earthquake where they live and work.

Before an earthquake occurs, homeowners and employers should obtain information on actions to take to protect life and property. Books and magazine articles are available that offer detailed information about what to do to reduce earthquake hazards, what emergency supplies should be on hand, and what steps to take during and after an earthquake to reduce loss of life (Yanev, 1974; Kimball, 1981; Sunset Magazine, 1982; Gere and Shah, 1984). The Federal Emergency Management Agency (FEMA), the Washington Division of Emergency Management (DEM), and the American Red Cross provide information on different aspects of earthquake preparedness, including identifying earthquake hazards, earthquake drills, emergency supplies, and shelter management. (FEMA, Region X, Bothell, WA; DEM, Lacey, WA, offer information; see list at end of this report's summary.) County and city emergency management offices also give assistance and information to the public about what to do in an earthquake.

Earthquake preparations that can be taken now are easy to identify. Learning and practicing what to do during an earthquake is an important first step toward earthquake preparedness. Preparations at home or work might initially include identifying areas that are safe from falling objects, practicing what to do during the shaking and when the shaking stops, and obtaining essential emergency supplies like a first aid kit. Some preparations, like securing water heaters and bookshelves, may require a longer time to complete (Fig. 46). Earthquake preparedness is an on-going activity, not something to do once and forget.

During an earthquake, individuals, no matter where they are, must be able to respond quickly to reduce loss of life and injury. Strong ground shaking often lasts only 30 to 60 seconds. One should expect considerable noise and confusion. Power failures may plunge a room into darkness. Sprinkler and alarm systems may be activated. One must immediately find a nearby protected place to take shelter until the shaking stops. The drop and cover position (Fig. 47) should be taken under a sturdy desk or table, inside a doorway, along a wall entirely inside a building, or within the inside corner of a room. Table 4 lists actions to take during an earthquake if one is inside a building, outside, or in a vehicle.

After a major earthquake, individuals must be able to perform a number of actions to prevent additional injury and loss of life (Table 5). Usually a building should be evacuated because of the possibility of further damage during aftershocks or secondary hazards like fire or gas leaks. All building occupants should be accounted for and given medical attention if needed. People may need to be self-sufficient for as long as 72 hours after an earthquake because emergency response personnel will likely be handicapped by impaired communications, damaged and blocked transportation routes, damaged equipment, and injured personnel.

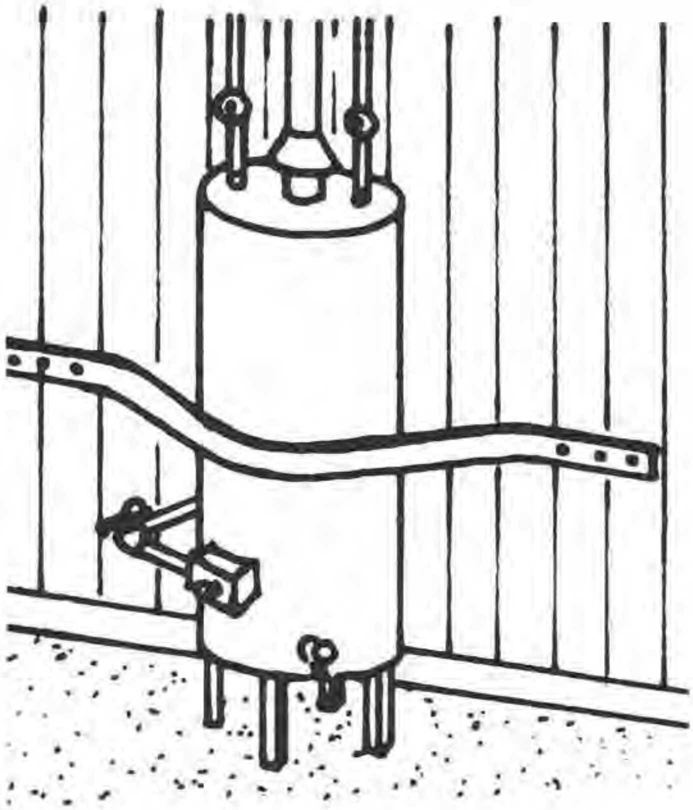


Figure 46. Water heater anchored with inexpensive plumbers' tape to prevent overturning during ground shaking. (From Federal Emergency Management Agency files)

Besides protecting personnel from injury, schools, hospitals, governments, and certain businesses need to be concerned about maintaining and continuing operations after an earthquake. Nearly two-thirds of all businesses fail following a major disaster for which they were unprepared (Bay Area Regional Earthquake Preparedness Project, 1986).

Figure 47. Child in drop and cover position. (Drawing by Kathy Sharpe, University of Washington)

In 1983, FEMA established a comprehensive Earthquake Education Program under the authority of the National Earthquake Hazards Reduction Act of 1977. The goals of this program include increasing public awareness of earthquake hazards and promoting public involvement in earthquake preparedness and hazard reduction. Three pilot projects of the Earthquake Education Program were funded to develop methods to provide information on earthquake safety to specific audiences, such as school personnel and hospital administrators, and to encourage the development of local earthquake safety programs. Strong response to these pilot projects indicates a keen interest in earthquake preparedness and a need for guidance to develop earthquake preparedness programs. Information developed by the pilot projects is available from the national FEMA office in Washington, D.C.

The following lists summarize some recommendations about additional earthquake preparedness actions for work, school, and the home that have been suggested in FEMA publications and by participants in the pilot projects:

Work:

- Post brief, clear instructions for actions to take during and after an earthquake
- Hold earthquake drills on site
- Instruct personnel to give instructions to customers during an earthquake and to direct evacuation of buildings
- Securely store hazardous materials
- Keep a flashlight at sales counters, in desk drawers, and other areas that would be difficult to evacuate or inspect in the dark
- Securely store files essential to business operations
- Maintain an inventory and location list of valuable items that may need to be moved to a temporary site following an earthquake
- Protect computer systems and personal computers against damage and loss of data as a result of ground shaking and power outage

School:

School district administrators should have the seismic safety of school buildings evaluated and take steps to improve the ability of school buildings to resist ground shaking without total or partial collapse. In addition, staff and students in each building should develop an earthquake safety program. (See McCabe, 1985) As part of such a program, schools should:

- Hold earthquake drills, including evacuation of the building
- Inform parents about plans to care for students during and after a major earthquake
- Encourage the training of school personnel in first aid, CPR, search and rescue, and building safety procedures (turning off utilities and the like)
- Develop an attendance system that will provide an accurate list of all students and staff on site, each day
- Include information on earthquakes and earthquake preparedness in the curriculum

Home:

Among the many things homeowners and families can do are:

- Have family earthquake drills
- Have a family plan for what family members should do during and after an earthquake
- Make sure children know what to do during an earthquake if they are at home alone, and where the family should leave messages if relocation is necessary

Risk Reduction Policy

Many of the actions necessary to reduce earthquake risks can be carried out by any interested individual. Often, however, risk reduction efforts require the cooperation of many people. The establishment of policies to guide earthquake loss reduction programs provides needed coordination and provides program standards. Preparation for future Washington earthquakes must be an on-going process, not a momentary effort inspired by events like the recent earthquake disasters in Mexico or California. Such tragedies may motivate the hasty development of earthquake safety programs, but that action does not substitute for thoughtful program development and implementation during less stressful and emotional times.

Table 4. What to do during an earthquake

Location	Action	Where	Hazards
Inside building	Drop and cover	Under sturdy desk Under sturdy table Along inside wall In doorway In corner	Window glass Overhead objects Objects on wheels Swinging doors Collapsing fireplace chimneys
Outside building	Drop and cover (if necessary)	Building entryway (inside, where not subject to material falling from outside walls); in clearing, away from wires and other overhead dangers	Building facades Overhead wires Trees Steep slopes
Outdoors in open	Stay in open areas	Away from falling objects	Rockfall, landslide
School bus or other vehicles	Bring bus to stop Hold on to seat Stay in bus	Side of road	Overpasses Underpasses Overhead wires
All locations	Protect oneself	Nearest place	Falling debris

Table 5. What to do after the shaking stops

Steps	Specific Actions	Concerns
Check for injuries	Administer emergency first aid	Move severely injured only if mandatory Be prepared for aftershocks
Evacuate	Leave cautiously	Put on shoes Avoid elevators Choose exits carefully Be prepared for aftershocks
Check for safety	Turn off utilities Use flashlight, not candles Account for building occupants Confine pets	Gas, water, electric lines may be broken Electric sparks or flame may ignite gas May need to do search and rescue Dog bites common after earthquakes
Get information	Use portable or car radio	Are there nearby secondary hazards, like chemical spills, fire? Avoid sightseeing, unnecessary travel, or spreading rumors
Care for and comfort others	Reassure children, ill, handicapped and elderly	Need physical and emotional care Avoid leaving them alone More physical and emotional trauma than other individuals
Make shelter	Use large plastic garbage bags Use blankets	Existing structures may be unsafe Prevent hypothermia Locate food and water

In 1985, the Governor of Washington instructed the Director of the Department of Emergency Management to form a Washington State Seismic Safety Council to make policy recommendations for dealing with Washington state earthquake risks. This action followed the Governor's veto of a bill that would have established a Washington State Seismic Safety Commission. Activities of the council, including the final report to the Governor, were funded by the Federal Emergency Management Agency out of the Washington State National Earthquake Hazard Reduction Program allocation for fiscal year 1986. Although the state legislature has made significant contributions to the modernization of building codes, the Seismic Safety Council identified several additional areas that require attention. The final report of the council to the Governor (Washington Seismic Safety Council, 1986) includes an assessment of the state role in reducing earthquake losses and suggests priorities for state action. The council concluded that the key policy issue for the state is definition of the state role in both fulfilling its responsibilities and inducing others to fulfill theirs. The council suggested that those two sets of obligations could be carried out through the following actions at a statewide level:

Education – calling attention to seismic risks

Information – supporting research on state earthquake hazards and disseminating information that is necessary to carry out state and local risk reduction programs

Building safety – ensuring the structural integrity of public facilities, hospitals, schools, prisons, and other essential facilities in the event of a major earthquake

Lifeline safety – ensuring the integrity of life lines (transportation, communication, etc.)

Regulation – establishing the necessary statutes or other authorities to facilitate actions by state and local governments, private industries, and individual citizens to avert earthquake losses

The long-term agenda for the state was outlined as an on-going seismic risk reduction program that fulfills the obligations listed above. The Council proposed the following legislative priorities:

(1) Enact a School Seismic Safety Act, like the 1933 Field Act in California, to assess the vulnerability of state school buildings;

(2) Revise the 1955 Earthquake Resistance Standards that apply to public facilities;

(3) Pass a joint resolution acknowledging the potential for loss of life and property in Washington in the aftermath of a major earthquake; and

(4) Participate in the National Earthquake Hazard Reduction Program by cooperating and working with federal agencies responsible for implementing that program.

Following the release of the council report in September of 1986, the House of Representatives passed a resolution in the 1987 session recognizing the potential for serious damage, loss of life, and injury in Washington from earthquakes. This was an important first step in developing public policy that will improve our ability to reduce the risk of earthquakes in Washington.

Meanwhile, individuals, both at home and in the work place, should not wait until earthquake safety actions become required by law. Rather, for their physical, emotional, and financial protection, earthquake preparedness should be included in routine training and building safety programs as soon as possible.

GLOSSARY

This glossary includes words commonly used to describe the nature of earthquakes, how they occur, and their effects, as well as a discussion of the instruments used to record earthquake motion. Each word or phrase that is in bold print in the text is explained in this glossary.

Accelerograph: A seismograph whose output is proportional to ground acceleration (in comparison to the usual seismograph whose output is proportional to ground velocity). Accelerographs are typically used as instruments designed to record very strong ground motion useful in engineering design; seismographs commonly record off scale in these circumstances. Normally, strong motion instruments do not record unless triggered by strong ground motion.

Aftershock: One of many earthquakes that often occur during the days to months after some larger earthquake (mainshock) has occurred. Aftershocks occur in the same general region as the mainshock and are believed to be the result of minor readjustments of stress at places in the fault zone.

Amplitude: The amplitude of a seismic wave is the amount the ground moves as the wave passes by. (As an illustration, the amplitude of an ocean wave is one-half the distance between the peak and trough of the wave. The amplitude of a seismic wave can be measured from the signal recorded on a seismogram.)

Aseismic creep: Movement along a fracture in the Earth that occurs without causing earthquakes. This movement is so slow that it is not recorded by ordinary seismographs.

Collision: A term sometimes applied to the convergence of two plates in which neither plate subducts. Instead, the edges of the plates crumple and are severely deformed.

Convection: The motion of a liquid driven by gravity and temperature differences in the material. In the Earth, where pressure and temperature are high, rocks can act like viscous fluids on a time scale of millions of years. Thus, scientists believe that convection is an important process in the rocks that make up the Earth.

Convergent boundary: The boundary between two plates that approach one another. The convergence may result in subduction if one plate yields by diving deep into the Earth, obduction if one plate is thrust over the other, or collision if the plates simply ram into each other and are deformed.

Core: The Earth's central region, believed to be composed mostly of iron. The core has a radius of 3,477 kilometers and is surrounded by the Earth's mantle. At the center of the molten outer core is a solid inner core with a radius of 1,213 kilometers. (See Fig. 9.)

Earthquake: The release of stored elastic energy caused by sudden fracture and movement of rocks inside the Earth. Part of the energy released produces seismic waves, like P, S, and surface waves, that travel outward in all directions from the point of initial rupture. These waves shake the ground as they pass by. An earthquake is felt if the shaking is strong enough to cause ground accelerations exceeding approximately 1.0 centimeter/second^2 (Richter, 1958).

Epicenter: The location on the surface of the Earth directly above the focus, or place where an earthquake originates. An earthquake caused by a fault that offsets features on the Earth's surface may have an epicenter that does not lie on the trace of that fault on the surface. This occurs if the fault plane is not vertical and the earthquake occurs below the Earth's surface. (See Fig. 1).

Fault: A break in the Earth along which movement occurs. Sudden movement along a fault produces earthquakes. Slow movement produces aseismic creep.

Fault plane solution: The calculation of the orientation, dip, and slip direction of a fault that produced the ground motion recorded at seismograph stations. Sometimes called a focal mechanism solution.

Focus: The place in the Earth where rock first breaks or slips at the time of an earthquake; also called the hypocenter. The focus is a single point on the surface of a ruptured fault. During a great earthquake, which might rupture a fault for hundreds of kilometers, one could be standing on the rupturing fault, yet be hundreds of kilometers from the focus.

Hypocenter: See focus.

Intensity: A measure of the severity of shaking at a particular site. It is usually estimated from descriptions of damage to buildings and terrain. The intensity is often greatest near the earthquake epicenter. Today, the Modified Mercalli Scale is commonly used to rank the intensity from I to XII according to the kind and amount of damage produced. Before 1931 earthquake intensities were often reported using the Rossi-Forel scale (Richter, 1958).

Kilometers and other metric units of measure: Conversion formulae:

Millimeters x 0.039 = inches

Centimeters x 0.394 = inches

Meters x 3.28 = feet

Kilometers x 0.621 = statute miles

Square kilometers x 0.386 = square miles

Cubic kilometers x 0.240 = cubic miles

Liquefaction: A process, in which, during ground shaking, some sandy, water-saturated soils can behave like liquids rather than solids.

Magnitude: A quantity characteristic of the total energy released by an earthquake, as contrasted with intensity, which describes its effects at a particular place. A number of earthquake magnitude scales exist, including local (or Richter) magnitude (M_L), body wave magnitude (m_b), surface wave magnitude (M_S), moment magnitude (M_w), and coda magnitude (M_c). As a general rule, an increase of one magnitude unit corresponds to ten times greater ground motion, an increase of two magnitude units corresponds to 100 times greater ground motion, and so on in a logarithmic series. Commonly, earthquakes are recorded with magnitudes from 0 to 8, although occasionally large ones (M = 9) and very small ones (M = -1 or -2) are also recorded. Nearby earthquakes with magnitudes as small as 2 to 3 are frequently felt. The actual ground motion for, say, a magnitude 5 earthquake is about 0.04 millimeters at a distance of 100 kilometers from the epicenter; it is 1.1 millimeters at a distance of 10 kilometers from the epicenter.

Mainshock: The largest in a series of earthquakes occurring closely in time and space. The mainshock may be preceded by foreshocks or followed by aftershocks.

Mantle: A rock layer, about 2,894 kilometers thick, between the Earth's crust and core. Like the crust, the upper part of the mantle is relatively brittle. Together, the upper brittle part of the mantle and the crust form tectonic plates.

Modified Mercalli Intensity Scale: A scale for measuring ground shaking at a site, and whose values range from I (not felt) to XII (extreme damage to buildings and land surfaces). (See intensity and Table 1.)

NEHRP: The federal National Earthquake Hazard Reduction Program, enacted in 1977, to reduce potential losses from earthquakes by funding research in earthquake prediction and hazards and to guide the implementation of earthquake loss-reduction programs.

Normal fault: A normal fault can result from vertical motion of two adjacent blocks under horizontal tension. (It also occurs in rocks under compression if stress is unequal in different directions. In this case, the minimum and maximum compressive stresses must be applied horizontally and vertically respectively.) In a normal fault, the upper of the two adjacent blocks of rock slips relatively downward. (See reverse (thrust) fault and Fig. 1.)

P (Primary) waves: Also called compressional or longitudinal waves, P waves are the fastest seismic waves produced by an earthquake. (See seismic waves and Fig. 2.) They oscillate the ground back and forth along the direction of wave travel, in much the same way as sound waves, which are also compressional, move the air back and forth as the waves travel from the sound source to a sound receiver.

Plates: Pieces of crust and brittle uppermost mantle, perhaps 100 kilometers thick and hundreds or thousands of kilometers wide, that cover the Earth's surface. The plates move very slowly over, or possibly with, a viscous layer in the mantle at rates of a few centimeters per year. (See Fig. 8.)

Plate boundaries: The edges of plates or the junction between plates. See also plates, convergent (both collision and subduction), spreading, and transform boundaries.

Plate tectonics: A widely accepted theory that relates most of the geologic features near the Earth's surface to the movement and interaction of relatively thin rock plates. The theory predicts that most earthquakes occur when plates move past each other. (See also mantle.)

Return times: Sometimes called the recurrence time or recurrence interval. The return time, or more properly the average return time, of an earthquake is the number of years between occurrences of an earthquake of a given magnitude in a particular area. For example, if the average time of an earthquake having magnitude greater than or equal to 7 is 100 years, then, on the average, such earthquakes will occur every 100 years. If such earthquakes occur randomly in time, there is always the chance that the actual time interval between the events will be less or greater than 100 years. Return time is best described in terms of probabilities. In the case of an earthquake having a 100-year average return time, there is about an 18 percent chance that such an earthquake will occur in the next 20 years and a 63 percent chance than it will occur in the next 100 years. On the other hand, there is a 14 percent chance that it will not occur in the next 200 years.

Reverse fault: A rupture that results from vertical motion of two adjacent blocks caused by horizontal compression. Sometimes called a thrust fault. In a reverse fault, the upper of the two adjacent blocks moves relatively upward. (See Fig. 1 and normal fault.)

Richter Magnitude scale: An earthquake magnitude scale, more properly called local magnitude scale, based on measurements of the amplitude of earthquake waves recorded on a standard Wood-Anderson type seismograph at a distance of less than 600 kilometers from the epicenter (Richter, 1958). (See magnitude and Fig. 6.)

S (Secondary or shear) waves: S waves oscillate the ground perpendicular to the direction of wave travel. They travel about 1.7 times slower than P waves. Because liquids will not sustain shear stresses, S waves will not travel through liquids like water, molten rock, or the Earth's outer core. (See seismic waves and Fig. 2.)

Seiche: A standing wave in a closed body of water such as a lake or bay. It can be characterized as the sloshing of water in the enclosing basin. Seiches can be produced by seismic waves from earthquakes. The permanent tilting of lake basins caused by nearby fault motions has produced very energetic seiches.

Seismic waves: A vibrational disturbance in the Earth that travels at speeds of several kilometers per second. There are three main types of seismic waves in the earth: P (fastest), S (slower), and Surface waves (slowest). Seismic waves are produced by earthquakes.

Seismogram: A graph showing the motion of the ground versus time. (See Fig. 5.)

Seismograph: A sensitive instrument that can detect, amplify, and record ground vibrations too small to be perceived by human beings. (See also accelerograph.)

Site response: Local vibratory response to seismic waves. Some sites experience more or less violent shaking than others, depending on factors such as the nature and thickness of unconsolidated sediments and/or the configuration of the underlying bedrock.

Strike-slip fault: Horizontal motion of one block relative to another along a fault plane. If one stands on one side of the fault and observes that an object on the other side moves to the right during an earthquake, the fault is called a right-lateral strike-slip fault (like California's San Andreas fault). If the object moves to the left, the fault is called a left-lateral strike-slip fault.

Subduction zone boundary: The region between converging plates, one of which dives beneath the other. The Cascadia subduction zone boundary (Fig. 12) is an example.

Subduction earthquake: A thrust-type earthquake caused by slip between converging plates in a subduction zone. Such earthquakes usually occur on the shallow part of the boundary and can exceed magnitude 8.

Surface waves: Seismic waves, slower than P or S waves, that propagate along the Earth's surface rather than through the deep interior. Two principal types of surface waves, Love and Rayleigh waves, are generated during an earthquake. Rayleigh waves cause both vertical and horizontal ground motion, and Love waves cause horizontal motion only. They both produce ground shaking at the Earth's surface but very little motion deep in the Earth. Because the amplitude of surface waves diminishes less rapidly with distance than the amplitude of P or S waves, surface waves are often the most important component of ground shaking far from the earthquake source. (See seismic waves.)

Thrust fault: See reverse fault and Figure 1.

Transform boundary: A boundary between plates where the relative motion is horizontal. The San Andreas fault is a transform boundary between the North America plate and the Pacific plate. The Blanco fracture zone (Fig. 12) is a transform boundary between the Juan de Fuca and the Pacific plates.

Tsunami: A tsunami is a series of very long wavelength ocean waves caused by the sudden displacement of water by earthquakes, landslides, or submarine slumps. Ordinarily, tsunamis are produced only by earthquakes exceeding magnitude 7.5. In the open ocean, tsunami waves travel at speeds of 600-800 kilometers/hour, but their wave heights are usually only a few centimeters. As they approach shallow water near a coast, tsunami waves travel more slowly, but their wave heights may increase to many meters, and thus they can become very destructive.

World-Wide Standard Seismograph Network (WWSSN): A network of about 110 similarly calibrated seismograph stations that are distributed throughout the world. The network was originally established in the early 1960s, and its operation is now coordinated by the U.S. Geological Survey. Each station has six seismometers that measure vertical and horizontal ground motion in two frequency ranges.

REFERENCES CITED

Adams, John, 1984, Active deformation of the Pacific Northwest continental margin: Tectonics, v. 3, no. 4, p. 449-472.

Algermissen, S. T., 1983, An introduction to the seismicity of the United States: Earthquake Engineering Research Institute [Berkeley, Calif.], 148 p.

Algermissen, S. T.; Harding, S. T., 1965, Preliminary seismological report. *In* U.S. Coast and Geodetic Survey, 1965, The Puget Sound, Washington earthquake of April 29, 1965: U.S. Coast and Geodetic Survey, p. 1-26. (Reproduced in Thorsen, 1986.)

Algermissen, S. T.; Perkins, D. M., 1976, A probabilistic estimate of maximum acceleration in rock in the contiguous United States: U.S. Geological Survey Open-File Report 76-416, 45 p., 2 plates.

Algermissen, S. T.; Perkins, D. M.; Thenhaus, P. C.; Hanson, S. L.; Bender, B. L., 1982, Probabilistic estimates of maximum acceleration and velocity in rock in the contiguous United States: U.S. Geological Survey Open-File Report 82-1033, 99 p., 6 plates.

Ando, M.; Balazs, E. I., 1979, Geodetic evidence for aseismic subduction of the Juan de Fuca plate: Journal of Geophysical Research, v. 84, no. B6, p. 3023-3028.

Armstrong, J. E., 1984, Environmental and engineering applications of the surficial geology of the Fraser Lowland, British Columbia: Canada Geological Survey Paper 83-23, 54 p., 1 plate.

Atwater, B. F., 1987, Evidence for great Holocene earthquakes along the outer coast of Washington State: Science, v. 236, no. 4804, p. 942-944.

Atwater, B. F., 1988, Geologic studies for seismic zonation of the Puget lowland. *In* National Earthquake Hazards Reduction Program, Summaries of Technical Reports, V. 25: U.S. Geological Survey Open-File Report 88-16, p. 120-133.

Atwater, B. F.; Grant, Wendy, 1987 Holocene subduction earthquakes in coastal Washington [abstract]: EOS (American Geophysical Union Transactions), v. 67, no. 44, p. 906.

Atwater, B. F.; Hull, A. G.; Bevis, K. A., 1987, Aperiodic Holocene recurrence of widespread, probably coseismic subsidence in southwestern Washington [abstract]: EOS (American Geophysical Union Transactions), v. 68, no. 44, p. 1468.

Baker, E. J., 1976, Toward an evaluation of policy alternatives governing hazard-zone land uses: University of Colorado Institute for Behavioral Sciences, Natural Hazard Research Working Paper 28, 73 p.

Baker, G. E.; Langston, C. A., 1987, Source parameters of the 1949 magnitude 7.1 south Puget Sound, Washington, earthquake as determined from long-period body waves and strong motions: Seismological Society of America Bulletin, v. 77, no. 5, p. 1530-1557.

Barksdale, J. D.; Coombs, H. A., 1946, The Puget Sound earthquake of February 14, 1946: Seismological Society of America Bulletin, v. 36, no. 4, p. 349-354.

Barnard, W. D., 1978, The Washington continental slope—Quaternary tectonics and sedimentation: Marine Geology, v. 27, no. 1-2, p. 79-114.

Bay Area Regional Earthquake Preparedness Project, 1985, Reducing the risks of nonstructural earthquake damage—A practical guide; 2nd ed.: Bay Area Regional Earthquake Preparedness Project [Oakland, Calif.] BAREPP 85-10, 86 p.

Bechtel, Inc., 1975, Appendix 2J, Investigation of the December 14, 1872 earthquake in the Pacific Northwest: Bechtel, Inc., 1 v.

Beget, J. E., 1983, Glacier Peak, Washington—A potentially hazardous Cascade volcano: Environmental Geology, v. 5, no. 2, p. 83-92.

Berg, J. W.; Baker, C. D., 1963, Oregon earthquakes, 1841 through 1958: Seismological Society of America Bulletin, v. 53, no. 1, p. 95-108.

Bodle, R. R.; Murphy, L. M., 1947, United States earthquakes 1941-1945: U.S. Department of Commerce and Coast and Geodetic Survey Serial No. 699, 38 p. [Re-issued by National Earthquake Information Center, Coast and Geodetic Survey, Rockville, MD, in 1969]

Bolt, B. A., 1988, Earthquakes: New York, W. H. Freeman and Co., 282 p.

Bradford, D. C.; Waters, A. C., 1934, The Tolt river earthquake and its bearing on the structure of the Cascade Range: Seismological Society of America Bulletin, v. 24, no. 1, p. 51-62.

Brown, B. H., 1937, The state-line earthquake at Milton and Walla Walla: Seismological Society of America Bulletin, v. 27, no. 3, p. 205-209.

Bulman, R. E., 1983, The Coalinga earthquake, Monday, May 2, 1983—A report on schools prepared for the San Bernardino Superintendent of Schools: Prepared for distribution by CAEER (Community Alliance of Earthquake Education Resources), a project of the Environmental Volunteers, Inc., and the Junior League of Palo Alto [CA], Inc., 9 p.

Campbell, N. P.; Bentley, R. D., 1981, Late Quaternary deformation of the Toppenish Ridge uplift in south-central Washington: Geology, v. 9, no. 11, p. 519-524.

Chase, R. L.; Tiffin, D. L.; Murray, J. W., 1975, The western Canadian continental margin. *In* Yorath, C. J.; Parker, E. R.; Glass, D. J., editors, 1975, Canada's continental margins and offshore petroleum exploration: Canadian Society of Petroleum Geologists Memoir 4, p. 701-721.

Coffman, J. L.; Von Hake, C. A.; Stover, C. W., editors, 1982, Earthquake history of the United States; revised edition: U.S. National Oceanic and Atmospheric Administration–U.S. Geological Survey Publication 41-1, 270 p. [Revised edition of an earlier report including a supplement for 1971-1980]

Coombs, H. A.; Barksdale, J. D., 1942, The Olympia earthquake of November 13, 1939: Seismological Society of America Bulletin, v. 32, no. 1, p. 1-6.

Couch, R. W.; Johnson, S. H.; Gallegher, J. N.; 1968, The Portland earthquake of May 13, 1968, and earthquake energy release in the Portland area: Ore Bin, v. 30, no. 10, p. 185-190.

Crandell, D. R., 1973, Map showing potential hazards from future eruptions of Mount Rainier, Washington: U.S. Geological Survey Miscellaneous Investigations Map I-836, 1 sheet, scale 1:250,000.

Crandell, D. R.; Mullineaux, D. R., 1967, Volcanic hazards at Mount Rainier Washington: U.S. Geological Survey Bulletin 1238, 26 p.

Crandell, D. R.; Mullineaux, D. R., 1978, Potential hazards from future eruptions of Mount St. Helens volcano, Washington: U.S. Geological Survey Bulletin 1383-C, 26 p.

Crosson, R. S., 1983, Review of seismicity in the Puget Sound region from 1970 through 1978. *In* Yount, J. C.; Crosson, R. S., editors, 1983, Proceedings of Conference XIV, Earthquake hazards of the Puget Sound region, Washington: U.S. Geological Survey Open-File Report 83-19, p. 6-18.

Crosson, R. S.; Frank, D. G., 1975, The Mt. Rainier earthquake of July 18, 1973, and its tectonic significance: Seismological Society of America Bulletin, v. 65, no. 2, p. 393-401.

Davies, J.; Sykes, L.; House, L.; Jacob, K., 1981, Shumagin seismic gap, Alaska Peninsula—History of great earthquakes, tectonic setting, and evidence for high seismic potential: Journal of Geophysical Research, v. 86, no. B5, p. 3821-3855.

Dehlinger, Peter; Berg, J. W., Jr., 1962, The Portland earthquake of November 5, 1962: The Ore Bin, v. 24, no. 11, p. 185-188.

Dehlinger, Peter; Bowen, R. G.; Chiburis, E. F.; Westphal, W. H., 1963, Investigations of the earthquake of November 5, 1962, north of Portland: The Ore Bin, v. 25, no. 4, p. 53-68.

Driedger, C. L.; Kennard, P. M., 1986, Ice volumes on Cascade volcanoes—Mount Rainier, Mount Hood, Three Sisters, and Mount Shasta: U.S. Geological Survey Professional Paper 1365, 28 p., 6 plates.

Edwards, H. H., 1950, Discussion of damage caused by the Pacific Northwest earthquake of April 13, 1949, and, Recommendations of measures to reduce property damage and public hazards due to future earthquakes: American Society of Civil Engineers, Seattle Section, 30 p.

Edwards, H. H., 1951, repr. 1986, Lessons in structural safety learned from the 1949 northwest earthquake; 1st, 2nd, [and] 3rd installments. *In* Thorsen, G. W., compiler, 1986, The Puget Lowland earthquakes of 1949 and 1965—Reproductions of selected articles describing damage: Washington Division of Geology and Earth Resources Information Circular 81, p. 3-14.

Evans, S. G., 1986, Landslide damming in the Cordillera of western Canada. *In* Schuster, R. L., editor, 1986, Landslide dams—Processes, risk and mitigation: American Society of Civil Engineers Geotechnical Special Publication 3, p. 111-130.

Gere, J. M.; Shah, H. C., 1984, Terra Non Firma—Understanding and Preparing for Earthquakes: W. H. Freeman and Co., 203 p.

Gonen, Behram; Hawkins, N. M., 1974, Building standards and the earthquake hazard for the Puget Sound basin: University of Washington Department of Civil Engineering Report SM 74-1, 146 p.

Gori, P. L., editor, 1984, Primer on improving the state of earthquake hazards mitigation and preparedness: U.S. Geological Survey Open-File Report 84-772, 219 p.

Gower, H. D.; Yount, J. C.; Crosson, R. S., 1985, Seismotectonic map of the Puget Sound region, Washington: U.S. Geological Survey Miscellaneous Investigations Series Map I-1613, 15 p., 1 plate, scale 1:250,000.

Grant, W. C.; Weaver, C. S.; Zollweg, J. E., 1984, The 14 February 1981 Elk Lake, WA, earthquake sequence: Seismological Society of America Bulletin, v. 74, no. 4, p. 1289-1309.

Grant, W. P., 1986, The potential for ground failures in the Puget Sound area. *In* Hays, W. W.; Gori, P. L., editors, 1986, Proceedings of conference XXXIII, "Earthquake hazards in the Puget Sound, Washington area": U.S. Geological Survey Open-File Report 86-253, p. 134-138.

Gutenberg, Beno; Richter, C. F., 1954, Seismicity of the earth and associated phenomena; 2nd ed.: Princeton University Press, 310 p.

Hansen, W. R., 1966, Effects of the earthquake of March 27, 1964, at Anchorage, Alaska: U.S. Geological Survey Professional Paper 542-A, 68 p., 2 pl.

Harp, E. L.; Wilson, R. C.; Wieczorek, G. F., 1981, Landslides from the February 4, 1976, Guatemala earthquake: U.S. Geological Survey Professional Paper 1204-A, 35 p., 2 pl.

Hartzell, S. H.; Heaton, T. H., 1984, Estimating the source parameters from a major subduction zone earthquake in the Pacific Northwest: Earthquake Notes, v. 55, no. 1, p. 15.

Hawkins, N. M.; Crosson, R. S., 1975, Causes, characteristics and effects of Puget Sound earthquakes: U.S. National Conference on Earthquake Engineering, 1975, Proceedings, p. 104-112.

Hays, W. W.; Gori, P. L., editors, 1986, Proceedings of conference XXXIII, "Earthquake hazards in the Puget Sound, Washington area": U.S. Geological Survey Open-File Report 86-253, 238 p. and 3 appendices.

Heaton, T. H.; Hartzell, S. H., 1986, Source characteristics of hypothetical subduction earthquakes in the northwestern United States: Seismological Society of America Bulletin, v. 76, no. 3, p. 675-703.

Heaton, T. H.; Hartzell, S. H., 1987, Earthquake hazards on the Cascadia subduction zone: Science, v. 236, no. 4798, p. 162-168.

Heaton, T. H.; Kanamori, Hiroo, 1984, Seismic potential associated with subduction in the northwestern United States: Seismological Society of America Bulletin, v. 74, no. 3, p. 933-941.

Hogan, D. W.; Whipple, W. W.; Lundy, C., 1964, Tsunami of 27 and 28 March 1964, State of Washington coastline: U.S. Army Corps of Engineers [Seattle, Wash.] unpublished file report, 29 p.

Howard, K. A.; Aaron, J. M.; Brabb, E. E.; Brock, M. R.; Gower, H. D.; Hunt, S. J.; Milton, D. J.; Muehlberger, W. R.; Nakata, J. K.; Plafker, G.; Prowell, D. C.; Wallace, R. E.; Witkind, I. J., compilers, 1978, Preliminary map of young faults in the United States as a guide to possible fault activity: U.S. Geological Survey Miscellaneous Field Studies Map MF-916, 2 sheets, scale 1:5,000,000.

Hull, A. G., 1987, Buried lowland soils from Willapa Bay, southwest Washington—Further evidence for recurrence of large earthquakes during the last 5000 years [abstract]: EOS (American Geophysical Union Transactions), v. 68, no. 44, p. 1468-1469.

Hyde, J. H.; Crandell, D. R., 1978, Postglacial volcanic deposits at Mount Baker, Washington, and potential hazards from future eruptions: U.S. Geological Survey Professional Paper 1022-C, 17 p., 1 plate.

Ihnen, S.; Hadley, D. M., 1986, Prediction of strong ground motion in the Puget Sound region—The 1965 Seattle earthquake: Seismological Society of America Bulletin, v. 76, no. 4, p. 905- 922.

International Conference of Building Officials, 1988, Uniform Building Code: Whittier, CA. [In press as of May 1988]

Keefer, D. K., 1983, Landslides, soil liquefaction, and related ground failures in Puget Sound earthquakes. *In* Yount, J. C.; Crosson, R. S., editors, 1983, Proceedings of Conference XIV, Earthquake hazards of the Puget Sound region, Washington: U.S. Geological Survey Open-File Report 83-19, p. 280-299.

Keefer, D. K., 1984, Landslides caused by earthquakes: Geological Society of America Bulletin, v. 95, no. 4, p. 406-421.

Kimball, Virginia, 1981, Earthquake Ready: Culver City, CA, Peace Press, 153 p.

Kowalik, Zygmunt; Murty, T. S., 1984, Computation of tsunami amplitudes resulting from a predicted major earthquake in the Shumagin seismic gap: Geophysical Research Letters, v. 11, no. 12, p. 1243-1246.

Langston, C. A., 1981, A study of Puget Sound strong ground motion: Seismological Society of America Bulletin, v. 71, no. 3, p. 883-903.

Langston, C. A.; Blum, D. E., 1977, The April 29, 1965, Puget Sound earthquake and the crustal and upper mantle structure of western Washington: Seismological Society of America Bulletin, v. 67, no. 3, p. 693-711.

Langston, C. A.; Lee, J.-J., 1983, Effect of structure geometry on strong ground motions—The Duwamish River Valley, Seattle, Washington: Seismological Society of America Bulletin, v. 73, no. 6, p. 1851-1863.

MacCabe, M. P., 1985, Guidebook for developing a school earthquake safety program: U.S. Federal Emergency Management Agency Publication 88, 1 v.

MacPherson, S. H., 1965, A report of the April 29, 1965 earthquake, Seattle, Washington: Seattle Fire Department, 21 p.

Malone, S. D.; Bor, S.-S., 1979, Attenuation patterns in the Pacific Northwest based on intensity data and the location of the 1872 north Cascades earthquake: Seismological Society of America Bulletin, v. 69, no. 2, p. 531-546.

Malone, S. D.; Boyko, Christina; Weaver, C. S., 1983, Seismic precursors to the Mount St. Helens eruptions in 1981 and 1982: Science, v. 221, no. 4618, p. 1376-1378.

Malone, S. D.; Rothe, G. H.; Smith, S. W., 1975, Details of microearthquake swarms in the Columbia Basin, Washington: Seismological Society of America Bulletin, v. 65, no. 4, p. 855-864.

Martens, C., 1984, Earthquake safety of school buildings—A discussion of the minimum seismic safety standards for the Seattle School District: Seattle Public Schools Department of Facilities Planning, 67 p.

McCulloch, D. S.; Bonilla, M. G., 1970, Effects of the earthquake of March 27, 1964, on the Alaska railroad: U.S. Geological Survey Professional Paper 545-D, 161 p.

McGarr, Arthur; Vorhis, R. C., 1968, Seismic seiches from the March 1964 Alaska earthquake: U.S. Geological Survey Professional Paper 544-E, 43 p.

McLucas, G. B., compiler, 1980, Preliminary fault map of Washington: Washington Division of Geology and Earth Resources Open-File Report 80-2, 5 p., 1 plate, scale 1:1,000,000.

Meyer, William; Sabol, M. A.; Schuster, R. L., 1986, Landslide dammed lakes at Mount St. Helens, Washington. *In* Schuster, R. L., editor, 1986, Landslide dams—Processes, risk and mitigation: American Society of Civil Engineers Geotechnical Special Publication 3, p. 21-41.

Milne, W. G., 1956, Seismic activity in Canada, west of the 113th meridian, 1841-1951: Canada Dominion Observatory Publication, v. 18, no. 7, p. 126-127.

Mullineaux, D. R.; Bonilla, M. G.; Schlocker, Julius, 1967, Relation of building damage to geology in Seattle, Washington, during the April 1965 earthquake: U.S. Geological Survey Professional Paper 575-D, p. 183-191.

Murphy, L. M.; Ulrich, F. P., 1951, United States earthquakes 1949: U.S. Coast and Geodetic Survey Serial 748, 64 p. (Pages 20-28 reproduced in Thorsen, 1986.)

National Research Council Committee on Earthquake Engineering, 1985, Liquefaction of soils during earthquakes: National Academy Press, 240 p.

Newmark, N. M.; Hall, W. J., 1982, Earthquake spectra and design: Earthquake Engineering Research Institute Monograph, v. 3, 103 p.

Nuttli, O. W., 1952, The western Washington earthquake of April 13, 1949: Seismological Society of America Bulletin, v. 42, no. 1, p. 21-28.

Page, Robert, 1968, Focal depths of aftershocks: Journal of Geophysical Research, v. 73, no. 12, p. 3897-3903.

Palm, Risa, 1981, Real estate agents and special studies zones disclosure—The response of California home buyers to earthquake hazards information: University of Colorado Institute of Behavioral Science, Program on Technology, Environment and Man Monograph 32, 147 p.

Plafker, George, 1969, Tectonics of the March 27, 1964, Alaska earthquake. [Chapter I of] The Alaska earthquake, March 27, 1964—Regional effects: U.S. Geological Survey Professional Paper 543-I, 74 p.

Plafker, George; Kachadoorian, Reuben; Eckel, E. B.; Mayo, L. R., 1969, The effects of the earthquake of March 27, 1964, on various communities. [Chapter G of] The Alaska earthquake, March 27, 1964—Effects on communities: U.S. Geological Survey Professional Paper 542-G, 50 p.

Preuss, Jane, 1986, Tsunami and flood hazard preparedness and mitigation program for Aberdeen. *In* Hays, W. W.; Gori, P. L., editors, 1986, Proceedings of conference XXXIII; A workshop on "Earthquake hazards in the Puget Sound, Washington area": U.S. Geological Survey Open-File Report 86-253, p. 139-156.

Qamar, Anthony; Rathbun, Anne; Ludwin, R. S.; Crosson, R. S.; Malone, S. D., 1986, Earthquake hypocenters in Washington and northern Oregon—1980: Washington Division of Geology and Earth Resources Information Circular 82, 64 p.

Rasmussen, N. H., 1967, Washington State earthquakes, 1840 through 1965: Seismological Society of America Bulletin, v. 57, no. 3, p. 463-476.

Rasmussen, N. H.; Millard, R. C.; Smith, S. W., 1974, Earthquake hazard evaluation of the Puget Sound region Washington State: University of Washington Geophysics Program, 99 p.

Reinhart, M. A.; Bourgeois, Joanne, 1987, Distribution of anomalous sand at Willapa Bay, Washington—Evidence for large-scale landward-directed processes [abstract]: EOS (American Geophysical Union Transactions), v. 68, no. 44, p. 1469.

Reitherman, Robert, 1986, How to prepare a hospital for an earthquake; Selected topics disaster management: Journal of Emergency Medicine, v. 4, p. 119-131.

Richins, W. D.; Pechmann, J. C.; Smith, R. B.; Langer, C. J.; Goter, S. K.; Zollweg, J. E.; King, J. J., 1987, The 1983 Borah Peak, Idaho, earthquake and its aftershocks: Bulletin of the Seismological Society of America, v. 77, no. 3, p. 697-723.

Richter, C. F., 1958, Elementary Seismology: San Francisco, W. H. Freeman and Co., 768 p.

Riddihough, R. P., 1984, Recent movements of the Juan de Fuca plate system: Journal of Geophysical Research, v. 89, no. B8, p. 6980-6994.

Rogers, G. C., 1983, Seismotectonics of British Columbia: University of British Columbia Doctor of Philosophy thesis, 247 p.

Rosenblueth, Emilio, 1986, The Mexican earthquake—A firsthand report: Civil Engineering/American Society of Civil Engineers, v. 56, no. 1, p. 38-40.

Rothe, G. H., 1978, Earthquake swarms in the Columbia River basalts: University of Washington Doctor of Philosophy thesis, 181 p.

Savage, J. C.; Lisowski, M.; Prescott, W. H., 1981, Geodetic strain measurements in Washington: Journal of Geophysical Research, v. 86, no. B6, p. 4929-4940.

Schnell, M. L.; Herd, D. G., editors, [1984], National Earthquake Hazards Reduction Program—Overview: U.S. Geological Survey Circular 918, 65 p.

Scott, Stanley, 1979, Policies for seismic safety; Elements of a state government program: Institute of Governmental Studies, University of California, Berkeley, 94 p.

Seattle Fire Department, [undated, 1965], A report on the Arpil 29, 1965 earthquake: 262 p. and 16 unnumbered pages. [Available for inspection in the Washington Division Geology and Earth Resources library, Olympia]

Shannon and Wilson, Inc., 1975, Geotechnical investigation for central plant facilities Pebble Springs site, Boardman nuclear project, Gillian County, Oregon; Appendix B—Earthquake and ground response analysis: Portland General Electric, p. 2.5-83 - 2.5-96.

Slemmons, D. B.; Carver, G. C.; Glass, C. E.; Trexler, D. T.; Tillson, D. D., 1981, Remote sensing analysis of fault activity and lineament pattern of the epicentral region of the 1872 Pacific Northwest earthquake. *In* O'Leary, D. W.; Earle, J. L., editors, 1981, Proceedings of the Third International Conference on Basement Tectonics: Denver, CO, Basement Tectonics Committee, Publication 3, p. 51-63.

Silver, E. A., 1971, Small plate tectonics in the northeastern Pacific: Geological Society of America Bulletin, v. 82, p. 3491-3496.

Smith, W. D., 1919, Earthquakes in Oregon: Seismological Society of America Bulletin, v. 9, no. 3, p. 59-71.

Spaeth, M. G.; Berkman, S. C., 1972, The tsunamis as recorded at tide stations and the seismic sea wave warning system. *In* The great Alaska earthquake of 1964—Oceanography and coastal engineering: National Academy of Sciences, p. 38-110.

Stein, R. S., and Bucknam, R. C., editors, 1985, Proceedings of Workshop 28 on the Borah Peak, Idaho earthquake, Volume A: U.S. Geological Survey Open-File Report 85-290-A, 686 p.

Steinbrugge, K. V., 1982, Earthquakes, volcanoes and tsunami—An anatomy of hazards: New York, NY, Skandia America Group, 392 p.

Steinbrugge, K. V.: Cloud, W. K., 1965, Preliminary engineering report. *In* The Puget Sound, Washington, earthquake of April 29, 1965: U.S. Department of Commerce, 51 p. (Reproduced in Thorsen, 1986.)

Stepp, J. C., 1973, Analysis of completeness of the earthquake sample in the Puget Sound area. *In* Harding, S. T., editor, 1973, Contributions to seismic zoning: U.S. National Oceanic and Atmospheric Administration Technical Report ERL 267-ESL 30, p. 16-28.

Stermitz, Frank, 1964, Effects of the Hebgen Lake earthquake on surface water. *In* U.S. Geological Survey, 1964, The Hebgen Lake, Montana, earthquake of August 17, 1959: U.S. Geological Survey Professional Paper 435, p. 139-150.

Stover, C. W., editor, 1985, United States earthquakes, 1981: U.S. Geological Survey Bulletin 1655, 141 p.

Stover, C. W., editor, 1987, United States earthquakes, 1983: U.S. Geological Survey Bulletin 1698, 196 p.

Subcommittee on Water and Sewerage Systems, 1973, Earthquake damage to water and sewerage systems. *In* Murphy, Leonard, [scientific coordinator], 1973, San Fernando, Calif., earthquake of Feb. 9, 1971: U.S. Department of Commerce, National Oceanic and Atmospheric Administration, Environmental Research Laboratories, v. 2, p. 75-193.

Sunset Magazine, 1982, Getting ready for a big quake: Sunset Magazine, March 1982, p. 104-111.

Taber, J. J., Jr.; Smith, S. W., 1985, Seismicity and focal mechanisms associated with the subduction of the Juan de Fuca plate beneath the Olympic Peninsula, Washington: Seismological Society of America Bulletin, v. 75, no. 1, p. 237-249.

Tabor, R. W.; Cady, W. M., 1978, Geologic map of the Olympic Peninsula, Washington: U.S. Geological Survey Miscellaneous Investigations Series Map I-994, 2 sheets, scale 1:125,000.

Tabor, R. W.; Frizzell, V. A., Jr.: Booth, D. B.; Whetten, J. T.; Waitt, R. B.; Zartman, R. E., 1982, Preliminary map of the Skykomish River 1:100,000 quadrangle, Washington: U.S. Geological Survey Open-File Report 82-747, 31 p., 1 plate, scale 1:100,000.

Thenhaus, P. C., 1978, A study of the October 12, 1877, Oregon earthquake: U.S. Geological Survey Open-File Report 78-234, 14 p.

Thorsen, G. W., compiler, 1986, The Puget Lowland earthquakes of 1949 and 1965—Reproductions of selected articles describing damage: Washington Division of Geology and Earth Resources Information Circular 81, 113 p.

Toppozada, T. R., 1975, Earthquake magnitude as a function of intensity data in California and western Nevada: Bulletin of the Seismological Society of America, v. 65, no. 5, p. 1223-1238.

Townley, S. D.; Allen, M. W., 1939, Descriptive catalogue of earthquakes of the Pacific coast of the United States 1769 to 1928: Seismological Society of America Bulletin, v. 29, no. 1, p. 1-297.

Tubbs, D. W., 1974, Landslides in Seattle: Washington Division of Mines and Geology Information Circular 52, 15 p.

U.S. Army Corps of Engineers, 1949, Report on damage resulting from eathquake of 13 April, 1949: Seattle District, 27 p.

U.S. Army Corps of Engineers, 1983, Earthquake analysis of Wynoochee Dam: U.S. Army Corps of Engineers [Seattle, Wash.] Design Memorandum Supplement 17, 1 v.

U.S. Coast and Geodetic Survey, 1961, Abstracts of earthquake reports for the Pacific Coast and the western mountain region: U.S. Department of Commerce, MSA-103 [July, Aug., Sept., 1959], p. 51-89.

U.S. Coast and Geodetic Survey, 1967, Abstracts of earthquake reports for the Pacific Coast and the western mountain region; April-June 1965: U.S. Coast and Geodetic Survey MSA-126, 1 v.

U.S. Geological Survey, 1963, The Hebgen Lake, Montana earthquake of August 17, 1959: U.S. Geological Survey Professional Paper 435, 241 p.

U.S. Geological Survey, 1975, A study of earthquake losses in the Puget Sound, Washington, area: U.S. Geological Survey Open-File Report 75-375, 298 p.

Vance, J. A.; Miller, R. B., 1983, Geologic constraints on the movement history of the Straight Creek fault. *In* Yount, J. C.; Crosson, R. S., editors, 1983, Proceedings of Conference XIV—Earthquake hazards of the Puget Sound region, Washington: U.S. Geological Survey Open-File Report 83-19, p. 302-306.

Walter, S. R., 1986, Intermediate-focus earthquakes associated with Gorda Plate subduction in northern California: Seismological Society of America Bulletin, v. 76, no. 2, p. 583-588.

Washington Public Power Supply System, 1977, Washington Public Power Supply System nuclear projects nos. 1 and 4, Preliminary Site Assessment Report, Amendment 23: Washington Public Power Supply System, 1 v.

Washington Seismic Safety Council, 1986, Washington Seismic Safety Council policy recommendations: Washington Seismic Safety Council, 2 v.

Washington Surveying and Rating Bureau, 1966, Seattle and vicinity, Washington—Earthquake map showing areas of filled or unstable ground: Seattle, 1 p., 1 pl., scale approx. 1:4,000. [Similar maps available for Tacoma, Everett, and Bellingham, at scales from approx. 1:4,500 to 1:2,300.]

Weaver, C. S.; Baker, G. E., 1988, Geometry of the Juan de Fuca Plate beneath Washington and northern Oregon from seismicity: Seismological Society of America Bulletin, v. 78, no. 1, p. 264-275.

Weaver, C. S.; Smith, S. W., 1983, Regional tectonic and earthquake hazard implications of a crustal fault zone in southwestern Washington: Journal of Geophysical Research, v. 88, no. B12, p. 10,371-10,383.

Wiegel, R. L., 1970, Tsunamis. *In* Wiegel, R. L., editor, 1970, Earthquake engineering: Prentice-Hall, Inc., p. 253-308.

Wilson, B. W.; Torum, A. F., 1972, Effects of the tsunamis—An engineering study. *In* National Research Council Committee on the Alaska Earthquake, 1972, The great Alaska earthquake of 1964—Oceanography and coastal engineering, p. 361-523.

Wilson, J. R.; Bartholomew, M. J.; Carson, R. J., 1979, Late Quaternary faults and their relationship to tectonism in the Olympic Peninsula, Washington: Geology, v. 7, no. 5, p. 235-239.

Wood, H. O.; Neumann, Frank, 1931, Modified Mercalli intensity scale of 1931: Seismological Society of America Bulletin, v. 21, no. 4, p. 277-283.

Woollard, G. P., 1968, A catalogue of earthquakes in the United States prior to 1925: Hawaii Institute of Geophysics Data Report 10, 1 v.

Yanev, Peter, 1974, Peace of mind in earthquake country—How to save your home and your life: San Fransisco, CA, Chronical Books, 304 p.

Yelin, T. S.; Crosson, R. S., 1982, A note on the south Puget Sound basin magnitude 4.6 earthquake of 11 March 1978 and its aftershocks: Seismological Society of America Bulletin, v. 72, no. 3, p. 1033-1038.

Yount, J. C., 1983, Geologic units that likely control seismic ground shaking in the greater Seattle area. *In* Yount, J.C.; Crosson, R. S., editors, 1983, Proceedings of Conference XIV—Earthquake hazards of the Puget Sound region, Washington: U.S. Geological Survey Open-File Report 83-19, p. 268-279.

SELECTED CATALOGS CONTAINING INFORMATION ABOUT EARTHQUAKES IN WASHINGTON AND ADJACENT AREAS

Report Series for the United States or Western States

The report series listed below will guide readers to technical data for earthquakes that have occurred in this century. The publishers of these series have changed periodically, as have the titles; this list highlights those changes. (For a history of earthquakes in the United States prior to 1925, see Woollard, 1968, listed in "References cited")

Abstracts of Earthquake Reports for the Pacific Coast and Western Mountain Region (Title changed in 1967 to "Abstracts of Earthquake Reports for the United States"; superseded in 1974 by the quarterly "Earthquakes in the United States". See below.)

Published quarterly; detailed accounts of observed earthquake effects. A condensed summary of this is published annually in "United States Earthquakes"; see below.

1937? - 1964: MSA 1-124
Department of Commerce
Coast and Geodetic Survey

1965 - 1966: MSA 125-132
Department of Commerce
Environmental Science Services Administration (ESSA, a consolidation of the Weather Service and the Coast and Geodetic Survey)

1967 - 1970 (title changed in 1967): MSA 133-148
Department of Commerce
ESSA/ National Oceanic and Atmospheric Administration (NOAA) (In October 1970, functions of ESSA transferred to NOAA, still as part of the Department of Commerce)

1967 - 1969: MSA 133-142
Issued by Coast and Geodetic Survey Seismological Survey in San Francisco, part of ESSA

1969 (3d quarter only): MSA 143-144
Issued by National Ocean Survey (part of ESSA)

1970: MSA 145-148
Issued by the Environmental Data Service, a new section of ESSA; in October 1970, functions of ESSA were transferred to NOAA, still Department of Commerce.

1971 - 1973: MSA 149-160
Issued by NOAA, Department of Commerce, and U.S. Geologial Survey (USGS), Department of the Interior; in 1973, operations of the National Earthquake Information Center (NEIC) and Seismological Field Survey (SFS) of NOAA's Environmental Research Laboratories were absorbed by the USGS. MSA 149-160 were produced cooperatively by NOAA and USGS groups as USGS Open-File Report 75-5.

1974: Series superseded by "Earthquakes in the United States"
Department of the Interior
USGS
(Other NOAA units continued to collect and publish earthquake data with the USGS in "United States Earthquakes" and "Earthquake History of the United States"; see below.)

Earthquake Data Reports

Contains raw phase data used in the computation of information published in "Preliminary Determinations of Epicenters" (listed below); useful to some seismologists; since 1985 published as USGS Open-File Report 86-551A-L.

Earthquake History of the United States

Contains a history of prominent earthquakes in the United States for historical time; maps, bibliography; periodically revised; the current edition is the most comprehensive.

1928 (Original edition)
Department of Commerce
U.S. Coast and Geodetic Survey (as a special publication)

Earthquake History of the United States (continued)

Revised editions:

1934: Special Pub. 191

1938-1947: Serial No. 609, Pt. 1

1929, 1941, 1951: Serial No. 609, Pt. II

1958, 1965: Publication No. 41-1, Pt. I

1961, 1966: Publication No. 41-1, Pt. II

Through 1970: Publication No. 41-1 released in 1973.

1971-1980: Supplement added to Publication No. 41-1, which was reprinted in 1982 (edited by J.L. Coffman, Carl Von Hake, and C.W. Stover; printed jointly by NOAA and USGS)

Earthquakes in the United States (continues "Abstracts of Earthquake Reports for the United States"; see above)

Published quarterly; contains detailed accounts of observed earthquake effects, preliminary isoseismal maps; final information summarized and condensed in "United States Earthquakes" in the USGS Circular series:

1974: Circulars 723A-D

1975: Circulars 749A-D

1976: Circulars 766A-D

1977: Circulars 788A-D

1978: Circulars 819A-D

1979: Circulars 836A-D

1980: Circulars 853A-D

1981: Circulars 871A-D

1982: Circulars 896A-D

(Discontinued in 1983)

Preliminary Determination of Epicenters (PDE)

Computer locations of earthquakes determined from data furnished by seismographic observatories worldwide; locations may be revised as new or more extensive network data are used and published elsewhere; lists latitude, longitude, region of occurrence, magnitude, depth, number of deaths, comments on damage. Published weekly with monthly cumulations that supersede weekly issues.

1937 - 1973: Department of Commerce
U.S. Coast and Geodetic Survey

1973 - 1988: Department of the Interior
USGS

Monthly Weather Review

Monthly summary; earthquakes described in this series are entered for the month in which they occurred. The series was published from 1915 through June 1924.

United States Earthquakes

Published annually. Preceded by "Seismological Report" (see below); condensed summary of the quarterly series "Abstracts of Earthquake Reports for the Pacific Coast and the Western Mountain Region" (see above), which was superseded in 1974 by "Earthquakes in the United States" (see above). Less information than quarterly reports, but more information than is included in "Earthquake History of the United States" (see above). Describes earthquakes in the United States, the Panama Canal Zone, Puerto Rico, and the Virgin Islands. Includes list and short descriptions of principal earthquakes of the world for the year. Older issues and new annual issues published by the USGS in either its open-file report or bulletin series.

1925 - 1927: Seismological Report Serial No. 328 (11 v.; published quarterly)
Department of Commerce
U.S. Coast and Geodetic Survey

1928 - 1965: Department of Commerce
U.S. Coast and Geodetic Survey

1966 - 1969: Department of Commerce
NEIC (absorbed in 1973 into Department of the Interior, USGS)

1970: Department of Commerce
NOAA, National Geophysical Data Center

1971 - 1972: Department of Commerce
NOAA, National Geophysical and Solar-Terrestrial Data Center (name change from National Geophysical Data Center)

1973: Department of Commerce, NOAA, and Department of the Interior, USGS

U.S. Earthquakes

Cumulated reprints.

1928-1935: Department of Commerce

1936-1940: ESSA

1941-1945: (ESSA), NEIC; originally published by the U.S. Government Printing Office, later by USGS in its open-file report series.

Earthquakes in the Pacific Northwest

The references listed here focus on Washington, Oregon, and western Canada. For additional information about earthquakes in eastern Washington, see also the annual technical reports (S. D. Malone, principal investigator) produced by the Geophysics Program, University of Washington.

Western United States

1769-1897:

Holden, E. S., 1898, A catalogue of earthquakes on the Pacific Coast 1769 to 1897: Smithsonian Miscellaneous Collections 37 (1087), 253 p.

1769-1928:

Townley, S. D.; Allen, M. W., 1939, Descriptive catalogue of earthquakes of the Pacific coast of the United States 1769 to 1928: Seismological Society of America Bulletin, v. 29, no. 1, p. 1-297.

1840-1965:

Rasmussen, N. H., 1967, Washington State earthquakes, 1840 through 1965: Seismological Society of America Bulletin, v. 57, no. 3, p. 463-476.

1841-1958:

Berg, J. W.; Baker, C. D., 1963, Oregon earthquakes, 1841 through 1958: Seismological Society of America Bulletin, v. 53, no. 1, p. 95-108.

1897-1906:

McAdie, A. G., 1907, Catalogue of earthquakes on the Pacific Coast, 1897-1906: Smithsonian Miscellaneous Collections 49, article 5, 64 p.

1846-1915:

Smith, W. D., 1919, Earthquakes in Oregon: Seismological Society of America Bulletin, v. 9, no. 3, p. 59-71.

1970-1972:

Crosson, R. S., 1974, Compilation of earthquake hypocenters in western Washington, July 1970-Dec. 1972: Washington Division of Geology and Earth Resources Information Circular 53, 25 p.

See also

Crosson, R. S., 1983, Review of seismicity in the Puget Sound region from 1970 through 1978. *In* Yount, J. C.; Crosson, R. S., editors, 1983, Proceedings of Conference XIV, Earthquake hazards of the Puget Sound region, Washington: U.S. Geological Survey Open-File Report 83-19, p. 6-18.

1974:

Crosson, R. S.; Millard, R. C., 1975, Compilation of earthquake hypocenters in western Washington, 1974: Washington Division of Geology and Earth Resources Information Circular 56, 14 p.

1975:

Crosson, R. S.; Noson, L. L., 1978a, Compilation of earthquake hypocenters in western Washington, 1975: Washington Division of Geology and Earth Resources Information Circular 64, 12 p.

1976:

Crosson, R. S.; Noson, L. L., 1978b, Compilation of earthquake hypocenters in western Washington, 1976: Washington Division of Geology and Earth Resources Information Circular 65, 13 p.

1977:

Crosson, R. S.; Noson, L. L., 1979, Compilation of earthquake hypocenters in western Washington, 1977: Washington Division of Geology and Earth Resources Information Circular 66, 12 p.

1978:

Noson, L. L.; Crosson, R. S., 1980, Compilation of earthquake hypocenters in western Washington, 1978: Washington Division of Geology and Earth Resources Information Circular 72, 17 p.

1979:

Noson, L. L.; Ludwin, R. S.; Crosson, R. S., 1985, Compilation of earthquake hypocenters in western Washington, 1979: Washington Division of Geology and Earth Resources Information Circular 79, 19 p.

1980:

Qamar, Anthony; Rathbun, Anne; Ludwin, R. S.; Crosson, R. S.; Malone, S. D., 1986, Earthquake hypocenters in Washington and northern Oregon—1980: Washington Division of Geology and Earth Resources Information Circular 82, 64 p.

1981:

Qamar, Anthony; Rathbun, Anne; Ludwin, R. S., Noson, L. L.; Crosson, R. S., Malone, S. D., 1987, Earthquake hypocenters in Washington and northern Oregon—1981: Washington Division of Geology and Earth Resources Information Circular 83, 50 p.

1982-1986:

Qamar, Anthony; Ludwin, R. S.; Crosson, R. S.; Malone, S. D., 1987, Earthquake hypocenters in Washington and northern Oregon—1982-1986: Washington Division of Geology and Earth Resources Information Circular 84, 78 p.

[The reports by Qamar and others contain chronological lists of earthquakes in Washington and northern Oregon, a short review of earthquake activity for the period covered, and a description of the University of Washington seismograph network. Earthquake compilations for eastern and western Washington for years prior to 1980 were published separately; see reports by S. D. Malone cited in these reports and unpublished annual technical reports for 1975-1987 by Malone, available from the Geophysics Program, University of Washington.]

Western Canada

1840-1975:

Milne, W. G.; Rogers, G. C.; Riddihough, R. P.; McMechan, G. A.; Hyndman, R. D., 1978, Seismicity of western Canada: Canadian Journal of Earth Sciences, v. 15, no. 7, p. 1170-1193.

See also

1841-1951:

Milne, W. G., 1956, Seismic activity in Canada, west of the 113th meridian, 1841-1951: Canada Dominion Observatory Publication, v. 18, no. 7, p. 126-127.

1951-1954:

Milne, W. G.; Lombardo, F., 1967, Canadian west coast earthquakes 1951-1954: Canada Department of Energy, Mines and Resources Observatories Branch, 54 p.

Includes:

Milne, W. G.; Lombardo F., 1953 (reprinted 1967), Canadian west coast earthquakes, 1952: Dominion Observatory Ottawa Publications, v. 16, no. 9, p. 313-325.

Milne, W. G., 1955 (reprinted 1967), Canadian west coast earthquakes, 1953: Dominion Observatory Ottawa Publications, v. 16, no. 13, p. 393-401.

Milne, W. G., 1955 (reprinted 1967), Canadian west coast earthquakes, 1954: Dominion Observatory Ottawa Publications, v. 18, p. 47-58.

1955-1959:

Milne, W. G.; Lucas, K. A., 1961, Seismic activity in western Canada, 1955 to 1959, inclusive: Dominion Observatory Ottawa Publications, v. 26, no. 1, 23 p.

General:

Rogers, G. C., 1982, Revised seismicity and revised fault plane solutions for the Queen Charlotte Islands region: Canada Department of Energy, Mines and Resources, Earth Physics Branch, Open File 82-23.

Rogers, G. C., 1983, Seismotectonics of British Columbia: University of British Columbia Doctor of Philosophy thesis, 247 p.

PUBLICATIONS OF THE FEDERAL EMERGENCY MANAGEMENT AGENCY (FEMA)

(Available free from FEMA, P.O. Box 70274, Washington, D.C. 20024)

Earthquake Public Information Materials: An Annotated Bibliography (Publication 67)

Earthquake Insurance (Publication 68)

Reducing the Risks of Nonstructural Earthquake Damage: A Practical Guide (Publication 74)

National Earthquake Hazards Reduction Program (NEHRP) Recommended Provisions for the Development of Seismic Regulations for New Buildings, Part II: Commentary (1985 edition) (Publication 96)

NEHRP Recommended Provisions for the Development of Seismic Regulations for New Buildings, Part III: Appendix (1985 edition) (Publication 97)

Guidelines for Preparing Code Changes Based on the NEHRP Recommended Provisions (Publication 98)

Improving Seismic Safety of New Buildings: A Nontechnical Explanation of NEHRP Provisions (Publication 99)

A Guide to Marketing Earthquake Preparedness: Community Campaigns that Get Results (Publication 111)

Marketing Earthquake Preparedness: Community Campaigns that Get Results (Publication 112)

Abatement of Seismic Hazards to Lifelines: Proceedings of a Workshop on Development of an Action Plan—Water and Sewer (Publication 135)

Abatement of Seismic Hazards to Lifelines: Proceedings of a Workshop on Development of an Action Plan—Transportation (Publication 136)

Abatement of Seismic Hazards to Lifelines: Proceedings of a Workshop on Development of an Action Plan—Communications (Publication 137)

Abatement of Seismic Hazards to Lifelines: Proceedings of a Workshop on Development of an Action Plan—Power (Publication 138)

Abatement of Seismic Hazards to Lifelines: Proceedings of a Workshop on Development of an Action Plan—Gas and Liquid Fuels (Publication 139)

Abatement of Seismic Hazards: An Action Plan (Publication 142)

Abatement of Seismic Hazards to Lifelines: Proceedings of a Workshop on Development of an Action Plan—Papers on Political, Economic, Social, Legal, and Regulatory Issues (Publication 143)

Comprehensive Earthquake Preparedness Planning Guidelines: Large City (Publication 146)

Seismic Considerations, Elementary and Secondary Schools (Publication 149)

Seismic Considerations, Health Care Facilities (Publication 150)

Seismic Considerations, Hotels and Motels (Publication 151)