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WASHINGTON AND OREGON EARTHQUAKE HISTORY AND HAZARDS

by

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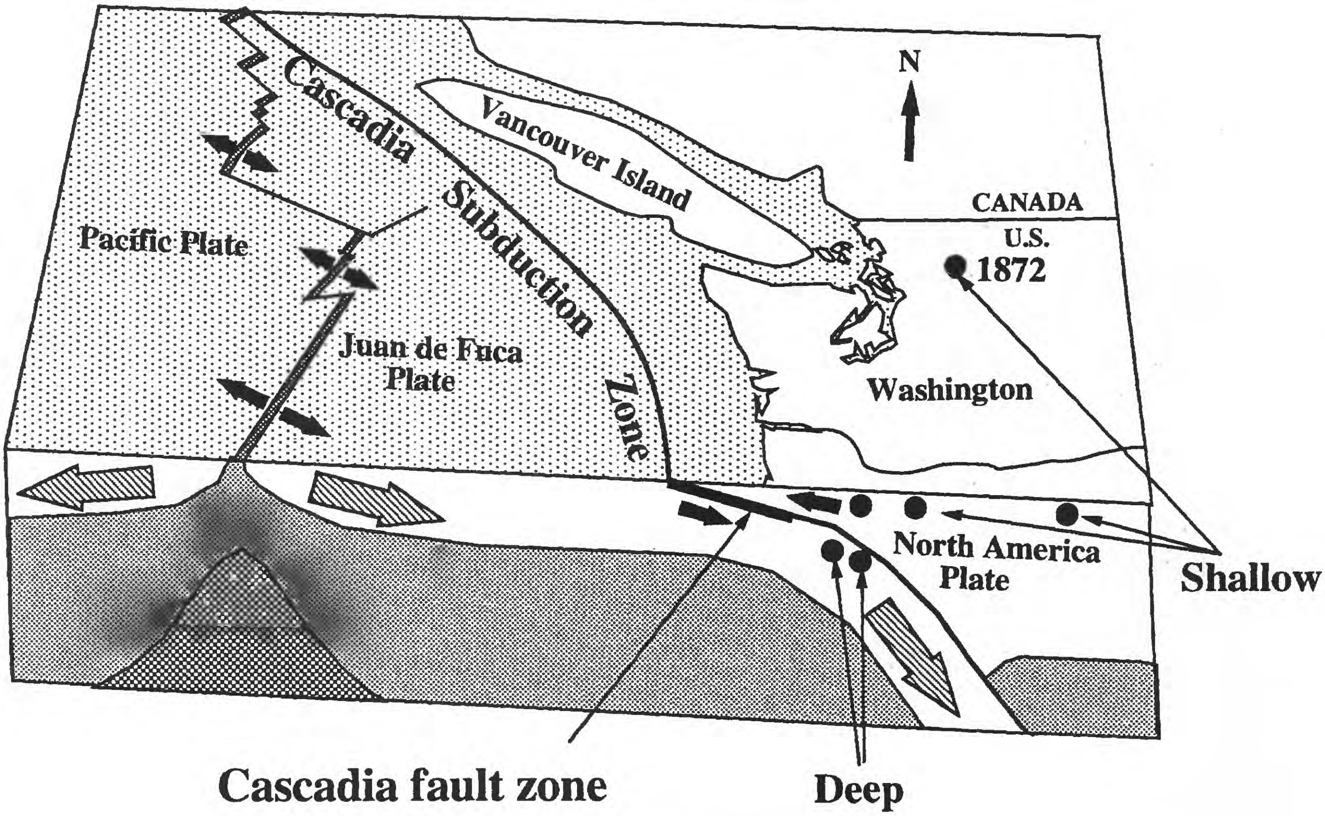

Open-File Report 94-226B

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Cover Illustration: A diagrammatic portrayal of the subduction of the Juan de Fuca plate beneath the North America plate. The three kinds of earthquake sources that threaten the region are portrayed: 1) subduction zone earthquakes that occur on the Cascadia fault zone, the gently dipping zone of contact between the Juan de Fuca and North America plates; 2) deep or Benioff zone earthquakes that occur within the subducted Juan de Fuca plate and 3) shallow earthquakes that occur within the North America plate. Oppositely directed arrows on either side of the Cascadia fault indicate the direction of relative motion that occurs during subduction earthquakes (*diagram courtesy of A. Qamar, University of Washington (UW) Geophysics Program*).

TABLE 1

No.	Earthquake†	Magnitude
1.	North Cascades, December 15, 1872 *(12/14 local)*	7.4
2.	Southwest Oregon, November 23, 1873	6.8
3.	Portland earthquake, October 12, 1877	5.3
4.	Central Vancouver Island, December 6, 1918	7.2
5.	Milton-Freewater, July 16, 1936 *(7/15 local)*	6.1‡
6.	Central Puget Sound, November 13, 1939 *(11/12 local)*	5.8
7.	Northern Idaho, November 1, 1942	5.5
8.	Central Puget Sound, February 15, 1946 *(2/14 local)*	6.1‡
9.	Olympia, Washington, April 13, 1949	7.1
10.	Portland, Oregon, November 6, 1962 *(11/5 local)*	5.2
11.	Seattle-Tacoma, April 29, 1965	6.5
12.	Elk Lake (SW Washington), February 14, 1981 *(2/13 local)*	5.5
13.	Scotts Mills, Oregon, March 25, 1993	5.6
14.	Klamath Falls, Oregon, September 21, 1993 (double event) *(9/20 local)*	5.9, 6.0
15.	Over 800 earthquakes with magnitudes 2.5 to 5.0 associated with the 1980 eruptions of Mount St. Helens	
16.	Central Vancouver Island, June 23, 1946	7.2

† Dates are Universal (Greenwich) Time (Pacific Standard Time + 8 hours) Where the local date differs from the Greenwich date, the local date is noted in parentheses.

‡ Published and unpublished estimates for the magnitudes of these earthquakes range from 5.8 to 6.4. The values listed here are in the middle of this range.

ACKNOWLEDGMENT

The earthquake locations in Figures 1a,b and c were compiled by Steve Malone of the UW Geophysics Program. The bulk of these locations were determined using data from the Washington Regional Seismograph Network operated by the UW under a cooperative agreement with the USGS, with Malone, R. Crosson and A. Qamar as principal investigators. The remaining locations were obtained using data from seismograph networks in adjacent regions. Open-File Report 226A has a complete list of contributors to the location data set.

ORDERING INFORMATION

U.S. Geological Survey Open File Report 94-226A, Earthquakes of Washington and Oregon, 1872-1993, is available through:

U.S. Geological Survey
National Earthquake Information Center
Box 25046, Mail Stop 967
Denver Federal Center
Denver, CO 80225

Plain paper copy - $12.00; laminated copy - $22.00. Prices include shipping and handling inside the U.S. Add $6.00 for shipping outside the U.S. Send check or money order payable to: DOI - USGS.

Note to the reader: References to original research consulted in writing this report are indicated by numbers in square brackets, e.g., [1], keyed to the bibliographic citation list at the report's end. Major earthquakes discussed in the text are assigned numbers and cited in this manner: (#1).

This report discusses the history and geographic distribution of earthquakes in Washington and Oregon. Epicenters of these earthquakes are shown on the 1:1,000,000 scale color, shaded-topographic relief map of the Pacific Northwest, that is published as U. S. Geological Survey Open-File Report 94-226A, Earthquakes of Washington and Oregon, 1872-1993 (hereafter referred to as "the poster"). A reduced-scale black and white version of the poster is reproduced here as Figure 1a so that this report can stand by itself. The reader may still want to acquire the poster; its larger scale provides more detail, both in the way of geographic landmarks and in the spatial distribution of earthquakes. Ordering information for OFR 94-226A is on page 1 of this report.

To frame our discussion of earthquakes, we begin with a brief description of the theory of plate tectonics, and of the three kinds of earthquakes in the region. Other sections cover the compilation of earthquake data, major historical earthquakes and the detailed spatial distribution of smaller earthquakes in the region. We conclude with a summary of known earthquake hazards, including a brief discussion of geologic evidence for earthquakes that occurred before the beginning of the region's written historical record.

PLATE TECTONICS AND HOW IT AFFECTS WASHINGTON AND OREGON

About twenty-five years ago earth scientists realized that the outermost 100 kilometers (60 miles) or so of the earth is divided into eight major pieces (or plates) and many minor plates. A variety of observations indicate that these plates are moving relative to one another, in some instances at rates up to 10 centimeters (4 inches) per year. Worldwide, most earthquakes occur on or close to plate boundaries and are ultimately caused by the relative motion between plates. The basic kinds of relative plate motion are: transverse motion (where two plates slide horizontally past each other), convergent or divergent motion (when plates move either directly toward or directly away from each other) and lastly, a combination of transverse and either convergent or divergent motion. Perhaps the best known plate boundary fault is central California's San Andreas fault, which is a dominantly transverse boundary, marking the edges of the North America and Pacific plates.

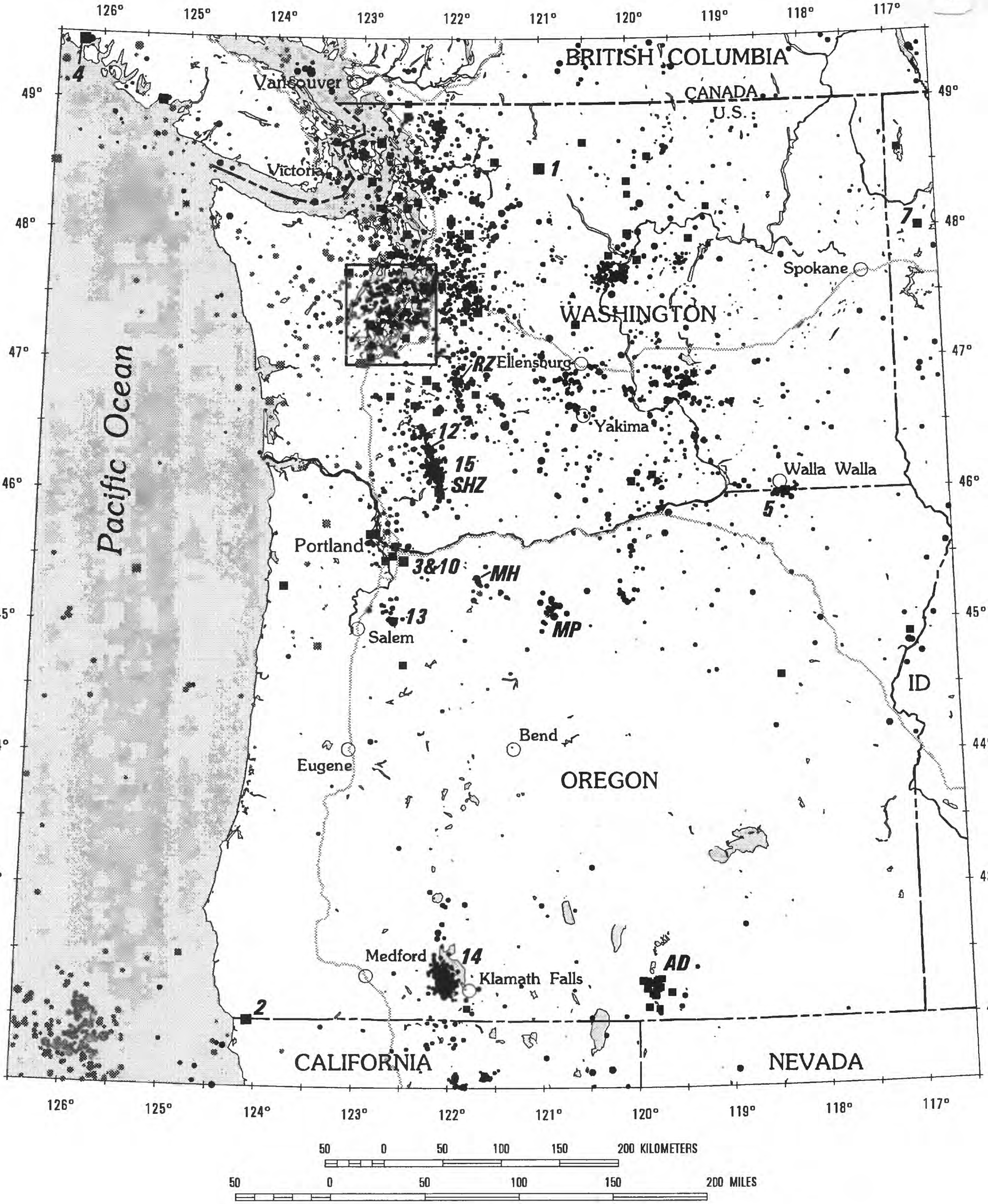
The most important plate boundary to citizens of Washington and Oregon is between the Juan de Fuca and North America plates (see Figure 2). This boundary is commonly called the Cascadia subduction zone. It is a convergent boundary, and the shallow, dipping zone of contact between the plates is the Cascadia fault zone (see cover). The Juan de Fuca plate moves northeastward with respect to the North America plate at a rate of about 4 centimeters (1.5 inches) per year, as indicated by the arrow in Figure 2. As it collides with North America, the Juan de Fuca plate slides (or *subducts*) beneath the continent and sinks slowly into the earth's mantle (the 3,000 kilometer (km) thick rocky shell between the outermost crust and the molten outer core of the earth). The collision of these plates produces three kinds of earthquakes.

THREE KINDS OF EARTHQUAKES

The kinds of earthquakes that threaten the region are: 1) earthquakes that occur on the Cascadia subduction fault, as a direct result of the convergence of the Juan de Fuca and North America plates, 2) deep earthquakes that occur within the Juan de Fuca plate as it sinks into the mantle and 3) shallow earthquakes occurring within the North America plate. We discuss each kind in turn.

The subduction of the Juan de Fuca plate beneath North America does not proceed as a smooth, continuous process. Rather, it happens in fits and starts. The two plates lock together and strain builds up in the rock on either side of the Cascadia subduction fault. When the rock can be deformed no further, the strain is released catastrophically in a *subduction earthquake*, and centuries of deferred motion at the plate boundary occurs in just a few minutes.

Two earthquakes that caused the most damage in western Washington in the twentieth-century, the 1949 Olympia and 1965 Seattle-Tacoma earthquakes represent the second kind of earthquake: "deep" or "Benioff zone" earthquakes. This class of earthquake occurs within the subducting Juan de



EXPLANATION

Figure 1a

	1872–1969	1970–1993
Juan de Fuca Plate	▩	●
North America Plate	■	●

Magnitude
- 3
- 5
- 7

Selected limited-access highways

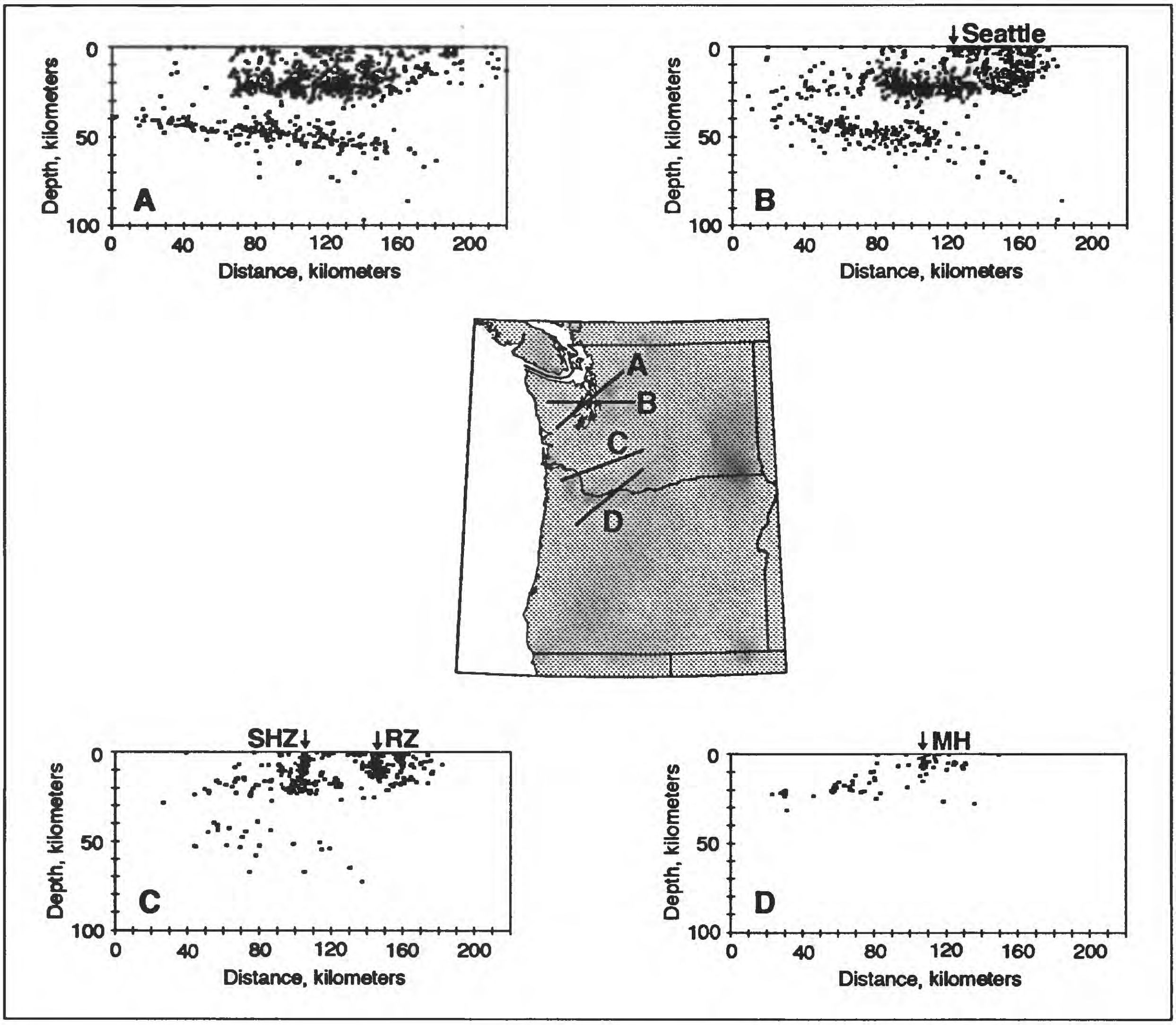


Figure 1c

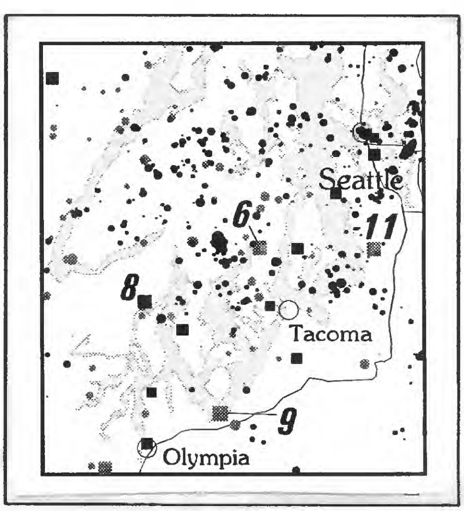


Figure 1b

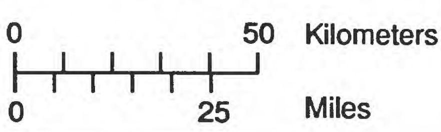


Figure 1a (on page 3): Map of earthquake locations for the years 1872-1993. Numbers denote earthquakes of particular interest noted in the text and listed in Table 1. "MH", "MP", "AD" and "SHZ" are groups of earthquakes referred to in the text. The box enclosing the southern Puget Sound region is the area shown in the inset map, Figure 1b. See text for detailed commentary on the distribution of earthquakes.

Figure 1b: Inset map showing earthquake locations in southern Puget Sound region. See caption for Figure 1a and text for further explanation.

Figure 1c: Four cross sections (vertical slices down through the earth) showing the depth distribution earthquakes. Only those earthquakes in Figure 1a with the best depth estimates are included in the sections, which are all to the same scale. The sections are labeled A - D and the index map (at a smaller scale than the sections) shows the location of each section line. In every section, the westernmost end is on the left.

Fuca plate as a result of stresses produced in that plate as it sinks into the earth's mantle (see the cover illustration and cross section A of Figure 1c). The depths of these earthquakes depend upon their distance from the region on the sea floor where the Juan de Fuca plate begins its descent beneath North America (the curved line labeled "Deformation Front" in Figure 2). Benioff zone earthquakes are deeper to the east (see Figure 1c, section A and the cover illustration). Beneath the Washington coast they are as shallow as 30 km; they occur at depths of 50-70 km beneath the Puget lowlands and beneath the Cascade foothills there are a few at depths of 80 to 90 km [1, 2]. Benioff zone earthquakes do not occur east of the Cascade Range.

It is important to understand the distinction between Benioff zone events, which occur *within* the subducting Juan de Fuca plate and subduction earthquakes which occur on the surface of contact *between* the North America and Juan de Fuca plates (see the cover for a graphical portrayal of this distinction). Few Benioff zone earthquakes have been recorded and located in southwestern Washington and western Oregon and it is not clear what this means regarding the likelihood of large, deep earthquakes in these areas.

Shallow earthquakes (with depths of 30 km or less) that occur within the North America plate are the third kind of earthquake in the region. Historically, these earthquakes have occurred throughout Washington and northern Oregon, from the coast to the eastern interior, and in the central part of southern Oregon (Figure 1a). The possibility of such earthquakes in the central third of Oregon cannot be dismissed. Most earthquakes that occur in the region are the shallow kind. The 1872 North Cascades earthquake, the 1918 and 1946 Vancouver Island earthquakes and the 1936 Milton-Freewater earthquake (see Figure 2 and Table 1 on page 1) were almost certainly members of this class. More recently, the 1993 Scotts Mills and Klamath Falls earthquakes in Oregon were North America plate events. Stress is probably transmitted from the Cascadia subduction fault into the interior of the North America plate, causing shallow earthquakes on secondary faults in the Puget-Willamette lowlands and the western Cascade Mountains, in addition to large earthquakes on the subduction zone. The causes of earthquakes east of the Cascade crest are more obscure. Some important characteristics of the three kinds of earthquakes are summarized in Table 2 on page 11.

COMPILATION OF THE EARTHQUAKE DATA BASE

The catalog of past earthquakes used to prepare the poster and Figure 1a is naturally divided into three parts. The first part is *historical* seismicity, spanning the time from 1872 through 1969. The second part includes earthquakes since 1970. We refer to these events as *instrumental* earthquakes because enough modern seismograph stations had been installed in Washington and Oregon by 1970 so that the earthquakes could be reliably located. We know about earthquakes before the 1800's only if they are recorded in the geologic record. We call such earthquakes *paleoseismic* events. Only instrumental and historic earthquakes are plotted in Figure 1a and on the poster, but paleoseismic events are very important in understanding earthquake hazards and are discussed later.

Seismologists have recorded and located approximately 15,600 earthquakes in Washington and Oregon with magnitudes between 1.0 and 6.0 from 1970 through 1993. This number excludes the thousands of earthquakes associated with the eruptions of Mount St. Helens. About 430 of these 15,600 earthquakes had magnitudes between 3.0 and 3.9 (in both states most events with magnitudes greater than 3.0 are felt by at least a few people). Fifty-two earthquakes had magnitudes between 4.0 and 4.9 and nine had magnitudes between 5.0 and 6.0. Earthquake epicenters shown on the poster and in Figure 1a include selected historical events (plotted in faint colors on the poster) and instrumental earthquakes with magnitudes of 1.5 or larger (plotted in bolder colors on the poster). North America plate events are plotted in red and Juan de Fuca plate events are plotted in purple on the poster. The corresponding symbols used in Figure 1a are explained on that figure. For most areas all magnitude 2.5 or larger earthquakes since 1970 are plotted on the poster and Figure 1a. In some areas there may have been some events with magnitudes less than 2.5 that were not recorded and are therefore absent from these maps.

Location errors for pre-1970 events may be 20 km or more in some cases. Most locations from 1970 on have horizontal errors less than 4 km (and in many cases probably less than 2 km). Depths of

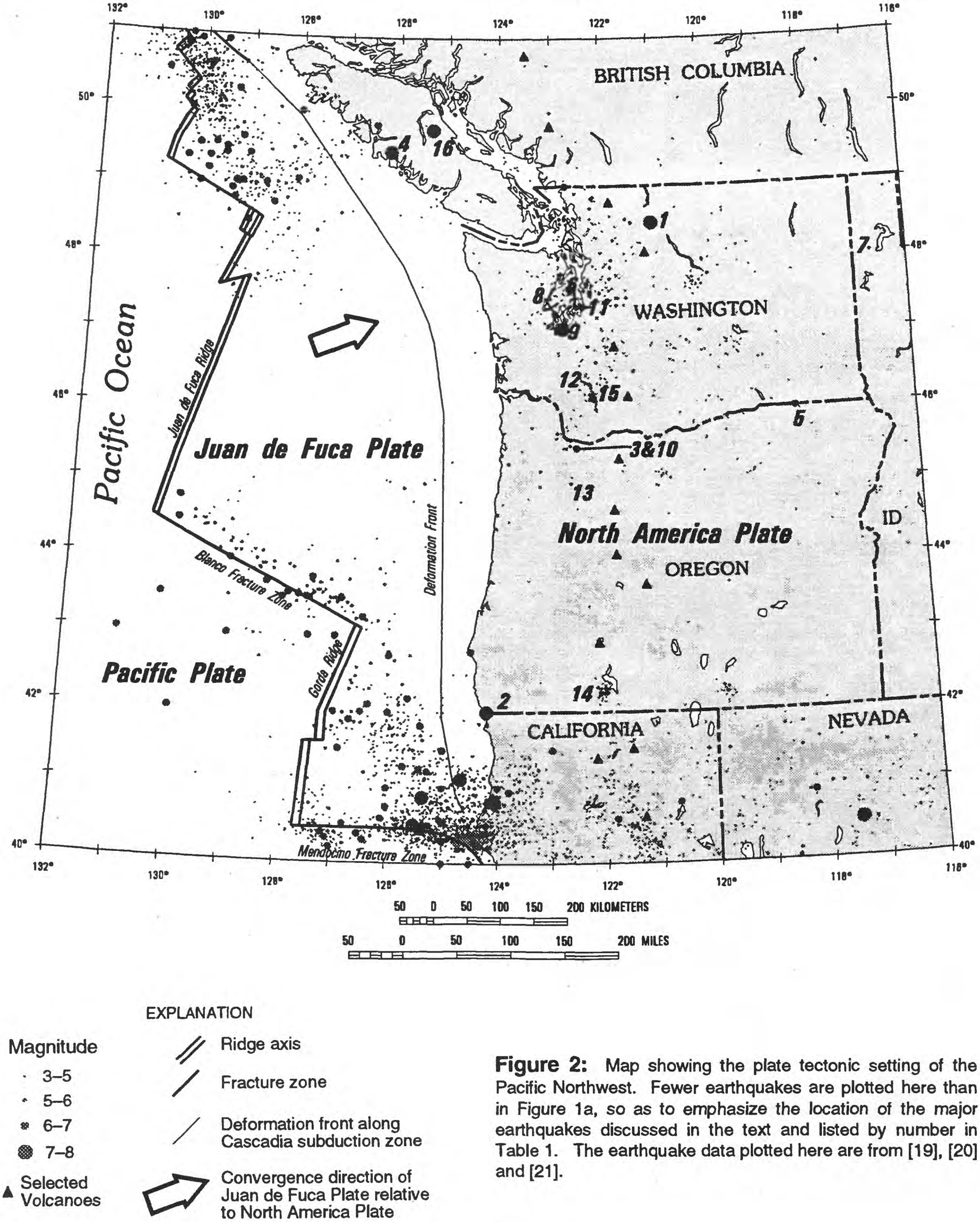


Figure 2: Map showing the plate tectonic setting of the Pacific Northwest. Fewer earthquakes are plotted here than in Figure 1a, so as to emphasize the location of the major earthquakes discussed in the text and listed by number in Table 1. The earthquake data plotted here are from [19], [20] and [21].

most pre-1970 earthquakes are not well determined, so in general there is uncertainty in deciding in which plate a pre-1970 earthquake occurred. In a few instances, there are good depth estimates available for pre-1970 events (for example earthquakes #9 and #11, that are discussed below).

MAJOR EARTHQUAKES IN WASHINGTON, OREGON AND SOUTHERN BRITISH COLUMBIA: 1872-1993

Major earthquakes have been assigned numbers that are listed in Table 1 and used in Figures 1a, 1b and 2. The locations of these earthquakes are best seen on Figure 2. The 1872 earthquake in the Cascade Mountains of northern Washington (#1) was probably the largest recorded earthquake in historical time. Its magnitude is estimated to have been about 7.4 [3], based on reported effects over the whole region. The second largest earthquake in Washington since 1872 was the 1949 magnitude 7.1 (M7.1) earthquake near Olympia, Washington (#9). This earthquake caused eight deaths and damage of approximately $150 million (in 1984 dollars) [4]. In 1965, a M6.5 earthquake (#11) approximately halfway between Seattle and Tacoma caused seven fatalities and about $50 million in damage (1984 dollars) [4]. Other earthquakes which caused lesser but still significant damage occurred in the central Puget lowlands near Seattle in 1939 (#6) and 1946 (#8).

Southernmost Oregon experienced an estimated M6.8 earthquake (#2) on 23 November 1873 [5]. This region has been seismically quiet since that time. In northeastern Oregon, the town of Milton-Freewater experienced a M6.1 earthquake in 1936 (#5). More recently, the 25 March 1993 M5.6 Scotts Mills, Oregon earthquake (#13) caused approximately $28 million in damage to public and private facilities, with no loss of life [6]. Six months later, on 21 September 1993 (20 September local date), M5.9 and M6.0 earthquakes (#14) occurred a little more than two hours apart about 25 km northwest of Klamath Falls, Oregon. Two persons died in these earthquakes, which also caused approximately $7.6 million in damage [7].

Central Vancouver Island has experienced two magnitude seven earthquakes since 1872: the 1918 M7.0 (#4) and the 1946 M7.2 (#16) events. The 1918 epicenter is shown on both Figures 1a and 2, while the 1946 epicenter is outside the boundaries of the poster and Figure 1a but is plotted in Figure 2. Both earthquakes occurred in sparsely populated areas and consequently caused little damage.

COMMENTS ON THE SPATIAL DISTRIBUTION OF EARTHQUAKES

The most striking feature in Figure 1a is the general decrease of seismic activity south of 45° north latitude. At this time there is no generally accepted explanation for this observation. Another notable feature is the contrast between the distribution of earthquakes in northwest Washington (where earthquakes are spread out over a large area), with the distribution in southwest Washington (where earthquakes tend to be distributed more in narrow, linear zones). This is discussed in more detail below.

Washington

The greatest concentration of earthquakes in Washington occurs in the Puget lowlands and the western Cascade Range, between longitudes 121.5° and 123.0°, and from about Olympia to the Canadian border (latitudes 47.0° to 49.0°). Earthquake epicenters are scattered throughout this area and at the scale of Figure 1a it is difficult to see any lineations or other patterns in the spatial distribution of earthquakes. Even at the scale of the poster there are simply no visible lineations of earthquakes to suggest the presence of long, vertical, seismically active faults like the San Andreas fault. This is not to say that large North America plate earthquakes never happen in northwest Washington; as we will discuss later, there is evidence for the prehistoric occurrence of just such an earthquake near Seattle.

Cross section A of Figure 1c shows selected post-1969 earthquake locations projected onto a northeast trending vertical plane cutting through the lowlands just west of Seattle. Only earthquakes with the most reliable depth estimates are plotted in this section. Locations of Benioff zone earthquakes are marked by the gently dipping band of symbols in the depth range 35 to 100 km. Above this band is a cloud of symbols representing earthquakes in the overlying North America plate. Section B of Figure 1c is a projection of the same selected set of earthquakes onto an east-west vertical plane centered just west of Seattle. This section more clearly shows that most North America plate earthquakes in the lowlands west of Seattle are in the 15 to 30 km range. East of Seattle the number of earthquakes in the upper 15 km increases dramatically, while activity also continues in the 15 to 30 km depth range. Why earthquakes are distributed in depth in this manner is being studied by many earth scientists; an understanding of this distribution may be important for the assessment of earthquake hazards in northwest Washington.

In contrast to the distribution in the Puget lowlands, earthquakes in the southern Washington Cascades tend to occur in linear zones. The most prominent of these zones is the 90 km long Saint Helens seismic zone (SHZ for short), a north-northwest trending zone of earthquakes labeled in Figure 1a [8]. A magnitude 5.5 earthquake (#12) occurred in the middle of the SHZ in 1981 [9], and two earthquakes (M4.8 and M5.1) occurred at its southern end in 1961 [10]. Mount St. Helens and the earthquakes associated with its eruptions (#15) lie in the middle of the southern half of the SHZ. A second less prominent zone of activity lies west of Mount Rainier, labeled "RZ" in Figure 1a. Through 1993 the largest earthquake on this zone had a magnitude of 4.1.

The depth distribution of earthquakes in southwest Washington is similar to the distribution in the Puget Sound region, as can be seen by comparing sections C and B in Figure 1c (section C, like sections A and B, includes only those earthquakes with reliable depth estimates). In the western part of section C, southwest of the SHZ, the few North America plate earthquakes that have occurred are in the 15 to 25 km depth range. Along the SHZ and to its northeast, North America plate earthquakes occur at focal depths of a few kilometers all the way down to 25 km, similar to the distribution of earthquakes east of Seattle.

Eastern Washington earthquakes concentrate most heavily in the western half of the Columbia basin and along the eastern flank of the Cascade Range (approximately between longitudes 119.0° and 121.0° and latitudes 46.0° and 47.0°, see Figure 1a). Ninety percent of the earthquakes occur at depths of 8 km or less [11]. Seismic activity is greatest in the northern half of this area; earthquakes with magnitudes in the 3.0 to 4.4 range are associated with several of the spectacular east-west trending ridges jutting out of the Cascade Range between Yakima and Ellensburg [11].

Outside the Columbia basin, the greatest concentration of earthquakes in eastern Washington lies 70 km north-northeast of Ellensburg. Sparse activity exists farther north, in the highlands of north-central Washington. Since 1970 earthquakes as large as M4.3 have occurred in southeastern Washington and northeastern Oregon, near Walla Walla. These events are close to the source of the 1936 earthquake (#5).

Oregon

Earthquakes larger than magnitude 1.5 in Oregon have been recorded only in the northern and southern parts of the state (Figure 1a); this does not rule out the possibility of future earthquakes in the middle third of the state. In this century, Oregon has lagged far behind Washington in total number of earthquakes, but the two most recent damaging earthquakes in the Pacific Northwest have been in Oregon. Oregonians should not be complacent about earthquake hazards.

Portland has been shaken by earthquakes as large as magnitude 5.2 in the twentieth century (#10) and bursts of smaller magnitude activity in the 1960's, in the late 1980's and early 1990's. The 1993 M5.6 Scotts Mills earthquake (#13) was the largest earthquake this century in Oregon west of the Cascade Range. Cross section D of Figure 1c shows the depth distribution of earthquakes in northwest Oregon (once again, only those events with the best depth estimates are included in the section). Earthquakes at Scotts Mills and near Portland are in the 15-20 km depth range, while earthquakes farther to the east (near Mount Hood) occur mostly in the upper 10 km of the earth's crust. Earthquakes near Mount Hood include a M4.0 event in 1974. These earthquakes are labeled "MH" in Figures 1a and 1c. Another group of earthquakes (labeled "MP" in Figure 1a) includes a M4.8 event just east of Maupin in 1976 [12]. Farther into northeastern Oregon, the activity decreases until you reach the vicinity of Walla Walla.

Activity in most of central and southern Oregon has been quite low since the early 1960's. In the 1960's a magnitude 4.0 earthquake anywhere in central and southern Oregon would most likely have been recorded by seismographs in Washington, California and Nevada and a location estimate would have been made. With the exceptions noted below, there were no such earthquakes so we can confidently state that most of central and southern Oregon has been seismically quiet at the magnitude 4.0 or larger level since the early 1960's. More extensive monitoring in these areas began in the late 1970's and was expanded in the late 1980's. There are two exceptions to the general lack of seismicity in southern Oregon. The first is the swarm of earthquakes (labeled "AD" in Figure 1a) near Adel in 1968, including a M5.1, a M5.0 and eleven earthquakes with M=4.2-4.7 [13]. The seismic quiescence of southern Oregon was shattered again in September of 1993 by the M5.9 and M6.0 Klamath Falls earthquakes (#14 in Figures 1a and 2). These earthquakes had over 2500 recorded and located aftershocks.

SUMMARY OF KNOWN EARTHQUAKE HAZARDS IN THE REGION

Figure 1a and the poster are visual presentations of what the historical record and modern seismologic instrumentation have told us about the occurrence of earthquakes in Washington and Oregon. The history and distribution of earthquakes, in combination with the geologic setting of a region are the cornerstones of earthquake hazard assessments for any region. In California, the historical record of earthquakes, the instrumental record, and the geologic record all lead to the same conclusion regarding earthquake hazards. Because of this, Californians have had a high level of awareness of earthquake hazards for many years.

Historical and instrumental seismic records tell only part of the story in Oregon and Washington. Because large earthquakes occur less frequently in the Pacific Northwest than they do in California, we must rely more heavily on geologic studies and their potential for peering further back into the earthquake history of the region. Since 1987 many studies have been published presenting evidence of sudden land level changes at many times in the past 5000 years and at many sites along the Vancouver Island, Washington, Oregon and extreme northern California coasts ([14], [15], [16] and [17] is a partial list of these studies). At several sites geologists have also found buried sand layers that were probably deposited by tsunamis (seismically generated sea waves), and soil liquefaction features that are evidence for strong ground shaking. Geologists generally believe that all these observations are best explained by a series of Cascadia subduction zone earthquakes. Before the gathering and publication of this evidence, subduction zone earthquakes were not considered in hazard assessments because none had been recorded in the written history of the region. Today we know that the Pacific coast from northernmost California (latitude 42.5°) to at least central Vancouver Island (latitude 50°) is at risk from great subduction earthquakes (Figure 2). These events could be very large, perhaps as large as that which struck Anchorage, Alaska in 1964 (magnitude 9.2). The large displacements of the ocean floor caused by subduction events would almost certainly produce a tsunami along the Pacific Northwest coast; waves would wash over the coast in tens of minutes or less after the ground began to shake (the time available to evacuate Pacific Northwest coastal regions is much less for Cascadia tsunamis than for tsunamis generated by earthquakes in southern Alaska, the Aleutian Islands or the northwestern Pacific). In the worst case strong shaking is expected in the I-5 corridor from Vancouver, British Columbia to Medford, Oregon; perhaps the greatest unknown is the effect of several minutes of strong shaking on critical structures.

A repeat of a Benioff zone (deep) earthquake like that in 1949 or 1965 will locally cause strong ground shaking for 20 to 30 seconds. This is similar to the duration of strong motion experienced by residents of the San Francisco Bay Area due to the 1989 Loma Prieta earthquake, or more recently, the 1994 Northridge earthquake in southern California. The upper limit on magnitude for deep events in western Washington is believed to be about 7.5 [11]. Ground motions will generally be smaller for a deep earthquake than for a shallower event of equal magnitude (simply because the earthquake source is farther from the earth's surface), but history shows that deep earthquakes can still cause significant damage. Unfortunately, building codes in western Oregon and southwestern Washington have only recently changed to match those in the Puget Sound region, so damage from a deep event may be substantial in those areas.

Finally, earth scientists are just now beginning to understand how severe shallow crustal earthquakes can be. In the Seattle area, geologic studies have shown that about 1100 years ago a very large earthquake occurred essentially beneath what is now the center of Seattle [18]; however, as of yet it is uncertain how frequently such events occur. In downtown Portland, geologists have uncovered evidence for a shallow crustal fault, but so far there is no evidence that the fault has broken in a large earthquake in recent geologic time (the last 10,000 years).

Despite many uncertainties in the geologic and seismologic records, earth scientists and engineers agree that Oregon and Washington have significant earthquake hazards. There is now widespread agreement that the historical and instrumental seismic records do not adequately represent the seismic hazards. Nevertheless, by incorporating the geologic findings in our assessments of hazards, and improving building codes in western Oregon and southwestern Washington, the region has begun the long process of becoming better prepared for the next large earthquake.

We thank R. Ludwin and W. Steele for helpful suggestions that improved this report.

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WASHINGTON AND OREGON EARTHQUAKE SUMMARY

SOURCE ZONE	HOW BIG?	WHERE?	RATE OF OCCURRENCE? / NEXT EVENT?	WHY DO THEY OCCUR?	PRECURSORS / AFTERSHOCKS	SHAKING EFFECTS
Intraplate or Benioff Zone "Deep"	7.1 largest known 1949 Olympia	At depths of 45-60 km in the Juan de Fuca & Gorda Plates	2 magnitude 7 events in 130 yr. 5 events > mag. 6 since 1909	Gravitational stress & phase changes within subducting plates	None expected	15-30 secs. strong shaking
	7.5 largest expected		?		None recorded after 1949, 1965 None expected	Accelerations of 0.20-0.35 g
Interface of Subduction Zone	1992 Petrolia mag. 7.1 may be on interface	From offshore deformation front to western Coast Range & Olympic Mts.	Every 300-500 yrs. Last event about 300 yrs. ago	Convergence at locked interface between Juan de Fuca & North America plates	Probable	Mag. 8, 1-3 min. of strong shaking Acc. of 0.5 g in urban areas
	8.0-9.0 expected		?		Many expected magnitude to 7.5+	Mag. 9, duration, acc. effects need study
Crustal (North America plate)	1872 N. Cascades largest known, approx. mag. 7.5	Known on Vancouver Is., N. Cascades, Seattle fault	Uncertain, 4 known in last 1000 yrs. from Vancouver Is. to Seattle	Uncertain	Unclear	Acc. > 0.5g but not studied
	Largest expected <8.0	Other areas are possible—SHZ, Portland fault	?		Many expected magnitude to 6.5+	Durations not studied, but 20-60 sec likely?

SOURCES OF FURTHER INFORMATION

Earth Science
Popular

Washington State Earthquake Hazards, available for $1.00 from the address in citation [4]. This booklet contains a wealth of information, including a good discussion of plate tectonics, detailed descriptions of damage from past earthquakes and discussion of public policy issues.

"Earthquakes", by Bruce A. Bolt, W.H. Freeman and Co., 1992. - an excellent general introduction to seismology for the lay reader.

Check your library for other titles on earthquakes and plate tectonics.

Earthquake Preparedness
Red Cross - preparedness literature and classes - call your local office.

Sunset Magazine - Two-part article on preparing homes for earthquakes, 10/90 and 11/90 issues. Reprints available for $2.00 from the magazine at 80 Willow Rd., Menlo Park, CA 94025.

Introduction to Earthquake Retrofitting, Owner Building Center, Berkeley, CA., $9.95, (510)848-6860, 1992. "...The information provided in this manual is designed to provide general consumer education to homeowners, not to substitute for professional engineering or guide work performed on a specific home." - from the Introduction.

The Federal Emergency Management Agency (FEMA) has many publications on this topic. They are all free and available from FEMA. P.O. Box 70274, Washington D.C. 20024. A partial list follows; a complete list may be obtained by writing to the address above.

Earthquake Preparedness Information for People with Disabilities, Publication No. FEMA70

Reducing the Risks of Nonstructural Earthquake Damage: A Practical Guide, FEMA74

Guidelines for Local Businesses, FEMA87

Preparedness in Apartments and Homes, L-143

Seismic Considerations Elementary and Secondary Schools, FEMA149

Videos

"Earthquake Home Safe Home", 1990, 30 min., available from KCSM, 1700 W. Hillsdale Blvd., San Mateo, CA 94402 (415)574-6586.

"Surviving the Big One", 58 minutes, KCTS, Seattle, 1-800-937-5287