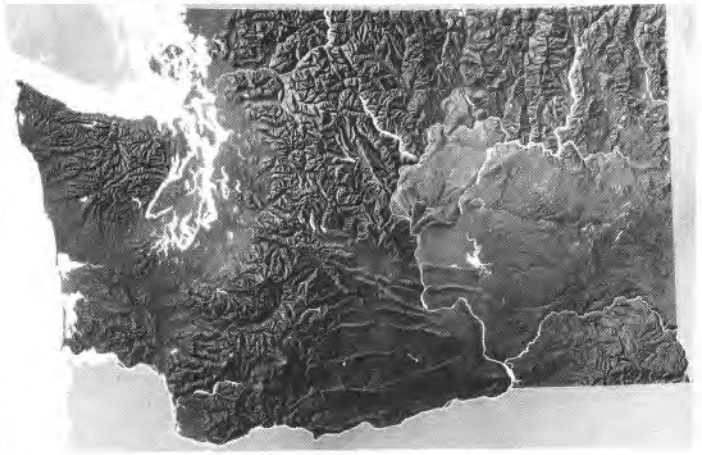

WASHINGTON GEOLOGIC NEWSLETTER

Volume 15 Number 2 May 1987

Washington State Department of Natural Resources

Division of Geology and Earth Resources

Portable seismometer measuring site response of State Capitol grounds to a remote blast. (See article, p. 11.) (USGS photo)

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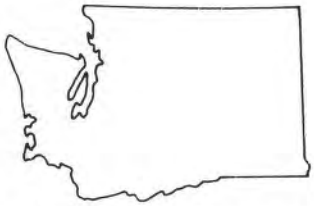

WASHINGTON GEOLOGIC NEWSLETTER

The Washington Geologic Newsletter is published quarterly by the Division of Geology and Earth Resources, Department of Natural Resources. The newsletter is free upon request. The Division also publishes bulletins, information circulars, reports of investigations, and geologic maps. A list of these publications will be sent upon request.

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EARTHQUAKE RESEARCH IN WASHINGTON--EVOLVING PROGRAMS

by
Raymond Lasmanis, State Geologist

Once again, as it does every year at this time, the Governor's proclamation of Earthquake Awareness Week brings briefly to the public consciousness the fact that we Washingtonians live in earthquake country. Yes, Washington has experienced damaging earthquakes, most recently in 1965. Scientists agree that similar earthquakes will occur from time to time in the future, and some believe we could experience much stronger earthquakes, akin to the 1964 Alaska earthquake. Our whole state is at moderate risk of earthquake damage, and the Puget Sound area is ranked among the most likely places in the country to experience damaging earthquakes.

The citizens of this state are fortunate in having all of the appropriate resources of the U.S. Geological Survey being directed at western Washington to unravel the mysteries of earthquakes caused by subduction. Research is accelerating in the state, and some of these projects are described in this newsletter. Other major efforts are in the conceptual stage. By the end of Phase I of the federal program (in 1989) and expenditure of $7 million, we will be in a much better position to determine:

- Convergence rate of the subducting Juan de Fuca plate with the continent
- Crustal geometry of the Juan de Fuca plate

(continued on p. 27)

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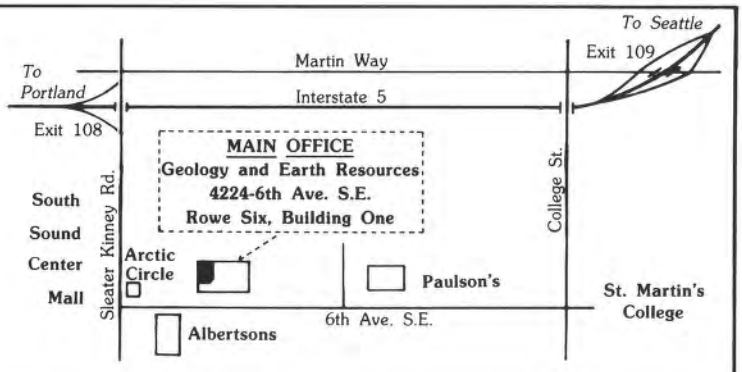

The State of Washington

Proclamation

WHEREAS, earthquakes are among the most devastating of natural disasters; and

WHEREAS, earthquakes have caused death and damage in Washington state in the past, and may do so again; and

WHEREAS, a damaging earthquake could occur anywhere in the state without warning; and

WHEREAS, the citizens of Washington State must be made aware of the potential threat of earthquakes and of those measures that can be done before, during and after a quake to save lives, protect property and mitigate damages and injuries;

NOW, THEREFORE, I, Booth Gardner, Governor of the State of Washington, do hereby proclaim the week of April 12 - 18, 1987, as

EARTHQUAKE AWARENESS WEEK

in the State of Washington, and I urge all citizens to take advantage of opportunities to learn about this natural hazard.

Signed, this 20th day of March, 1987.

Booth Gardner

Governor Booth Gardner

WASHINGTON STATE SEISMIC SAFETY COMMISSION RECOMMENDATIONS

Scientists generally agree that the region including Puget Sound and the Mount St. Helens area and extending as far south as Portland, Oregon, is at risk from earthquakes. Since 1840, most of the large and damaging earthquakes have been felt in this region; Richter magnitudes as great at 7.1 have been recorded. Current studies suggest that even larger earthquakes are possible. Subduction, the movement of oceanic crust downward below the continent, off the west coast of Washington could produce a magnitude 8.0 or greater, shallow earthquake. Further, studies near and at Mount St. Helens have revealed the presence of a seismic zone, possibly a strike-slip fault, that trends northwest through the volcano area toward Elk Lake.

The potential for damage by earthquakes produced by subduction- or volcano-related activity is two-fold (Fig. 1). First are the

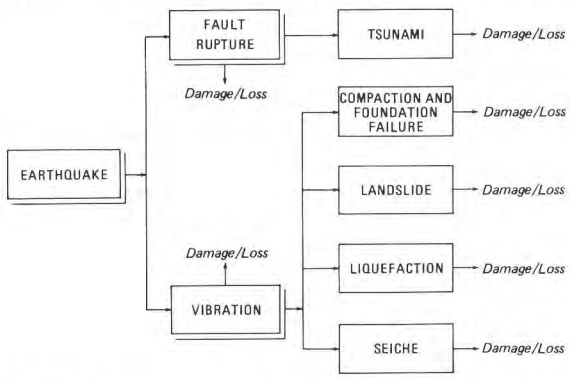

Figure 1.--Physical effects that can occur in an earthquake. The magnitude of the damage/loss effect is influenced by the distance from the earthquake hypocenter and the soil-structure interaction (modified from Hays and Gori, 1986)

secondary effects of ground shaking, such as landslides in areas of unstable soil or slopes, other types of ground failure, and tsunamis (sea waves). Second is the reaction of man-made structures to earthquakes. The two most recent (1949 and 1965) earthquakes in the Seattle area resulted in 15 deaths and caused more than $200 million damage (1984 dollars), and these were not unusually large earthquakes. As Thorsen (1986) points out, the potential for property damage and loss of life has increased with increasing population density. The amount of potential damage is also closely linked to building practices. And fires, chemical spills, and disruption of essential services are among the factors that must be included in earthquake hazard assessment for populated areas such as the Puget Lowland.

Given the geologic potential for earthquakes and the strong acknowledgment among scientists that earthquakes and consequent damage are inevitable, state officials are examining methods of reducing potential losses, in order to save lives and lessen both the cost and time required for recovery. Legislators are also looking into the state's responsibility for public safety so as to reduce its liability for deaths and damage caused by earthquakes.

The state has in past years generally assigned a low priority to seismic safety. However, retrofitting the state's Legislative, Insurance, and Old Capitol Buildings has brought the structures into compliance with the state building code and made them safer for employees working there, in the event of an earthquake. Development of a state seismic safety policy is, however, constrained by several factors, among them:

--a lack of technical information about soils and bedrock

--limited jurisdiction over local activities toward compliance with building codes

--concerns about the substantial cost of making public buildings safe in earthquakes, and

--concern about the complex legal issue of liability.

The central policy issue is: what will the state do, and encourage others to do, in reducing seismic risks?

One approach to addressing earthquake risks was the creation of the Washington State Seismic Safety Council. The State Geologist and State Seismologist were members of this council. In September 1986 the council issued a report, "Washington State Seismic Safety Council Policy Recommendation." The council recommended a seismic risk reduction program with several elements:

(1) Making school officials and students, the engineering and financial community, and industry aware of seismic risk and measures that can be taken to deal with such risk.

(2) Collecting and disseminating scientific information, a task to be shared among federal, state and academic investigations.

(3) Ensuring the safety of public buildings, including schools, buildings that house fire, police, and medical services, and communications facilities, and the integrity of power sources, pipelines and powerlines, and railroads, highways and bridges; and

(4) Working toward improving the incentives to take risk-reduction action, by encouraging inventorying and correcting deficiencies in a timely manner. Some legal incentives to take action might also be devised.

The Seismic Safety Council, which served until it completed the report, noted "Seismic hazards are serious threats to people and property in this state, for which even limited state and legislative action can be critical to reducing future losses..." (May and Noson, 1986).

"Much of the work in establishing an earthquake risk reduction program can be undertaken under existing authorities," they continued. Some of these agencies are the State Building Council, the Department of Natural Resources, and the State Board of Education. May and Noson also wrote, "The direction for the program can be established by the Legislature with a few key actions." Among those they listed are:

(1) Passage of a resolution recognizing the potential for loss of life and property damage in a large earthquake and expressing commitment to work on and fund risk reduction, in keeping with the goals of the National Earthquake Hazards Reduction Program.

(2) Review and revision of the State Building Code and implementation of earthquake resistance standards; and

(3) Enactment of legislation to mandate a study of school buildings and a plan for dealing with structures that are vulnerable.

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FEDERAL EARTHQUAKE RISK REDUCTION PROGRAM FOR THE PUGET SOUND AREA

An integrated, interagency plan to define research guidelines and general responsibilities for earthquake hazard studies from 1987 through 1989 has recently been devised by the U.S. Geological Survey, the Federal Emergency Management Agency, the Washington Department of Natural Resources, the Washington Office of Emergency Services, and other agencies. The plan is an outgrowth of (1) experience with studies in the Los Angeles, California, and Wasatch Mountains, Utah, areas and (2) a 1982 meeting concerning updating the U.S. Geological Survey's National Earthquake Hazards Reduction Program. One part of that program is regional earthquake hazard assessment.

An area from Puget Sound south to Portland, Oregon, has been ranked as highest priority (following the pattern of earlier studies, above) for such regional study. (See Washington Geologic Newsletter, April 1987, p. 2, and article by Tarr and King, this issue.) Research needs are being studied, and this research will take advantage of

accumulated data and the abilities of regional and local agencies. Assessment program components that serve as guidelines are:

(1) Organizing an information system. Identified needs are developing a computerized bibliography, standardizing of base maps and data storage, establishing a locus for information, and making it available to planners, scientists, and the public.

(2) Synthesis of geologic and geophysical data. The objectives of this component are (a) development of reports and maps that detail the geologic and tectonic setting, the tectonic history of the region for the past million years, and (b) characterization and periodicity of ground failures, as well as (c) generation of information for hazard reduction activities.

(3) Ground motion modeling. Priorities in this component are installation of instruments to detect ground motion and preparation of a report of available data on such motion. Figure 1 and Table 1 show locations of accelerometers in Washington. Data from past and current studies will help to estimate potential losses and casualties and form the basis for preparing maps of zones of ground shaking response and (or) intensity maps. Seismic reflection studies will help determine areas of high ground-motion risk. Synthesis of all this information will contribute to probabilistic hazard maps.

Figure 1.--USGS-monitored accelerometers in Washington; these are triggered by ground motion (modified from Hays and Gori, 1986)

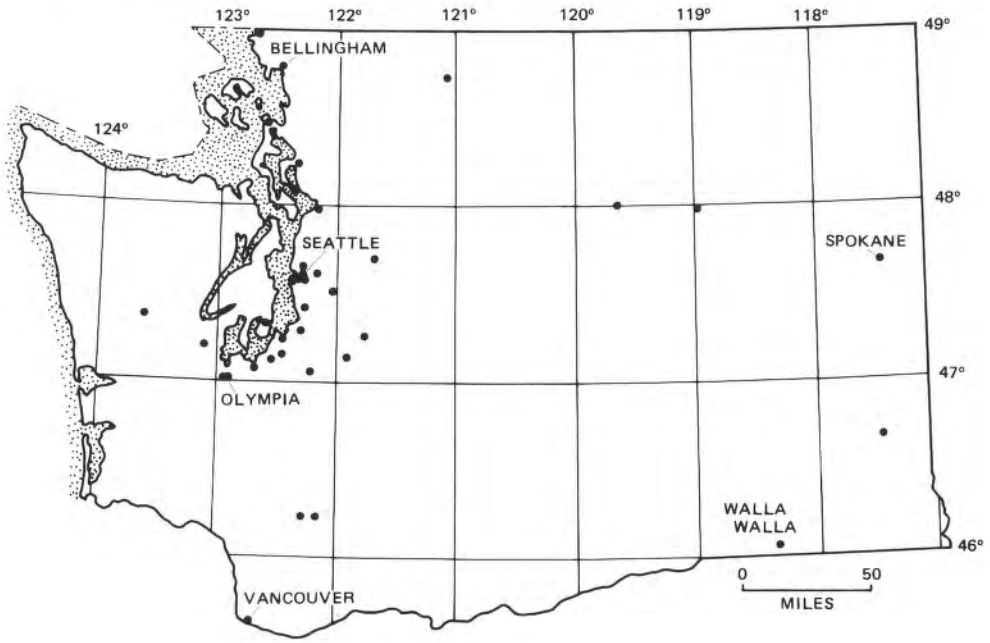


Table 1.--Accelerometer locations (modified from Hays and Gori, 1986)

Location	Instrument	Coordinates	Owner*	Comments
Anacortes	SMA-3910	48.47°N	USGS	Ground level
Bellevue				
I-90/136th Place SE		47.62°N	WSDOT/	Extensively
Highway overcrossing		122.19°W	USGS	instrumented
Structure array				structure
Recorder building				15 channels

Table 1, continued

Location	Instrument	Coordinates	Owner	Comments
Bellingham				
I-5/Bakerview Road		48.580°N	WSDOT/	Extensively
Highway overcrossing		122.484°W	USGS	instrumented
Structure array	CRA-129			structure
Recorder building	SMA-3346			15 channels
Blaine				
City Maintenance Yard	SMA-167	48.996°N	USGS	Ground level
		122.742°W		
Chief Joseph Dam				
Downstream	SMA-1253	48.00°N	COE	Moderate
Lower gallery	SMA-1249	119.63°W		instrumentation
Crest	SMA-1252			
Everett				
Courthouse	SMA-305	47.98°N	USGS	Ground level
		122.21°W		
Grand Coulee Dam				
Lower gallery	SMA-1899	47.96°N	USBR	Minimal
Upper gallery	SMA-1899	118.96°W		instrumentation
Gig Harbor				
Fire Station	SMA-125	47.333°N	USGS	Ground level
		122.602°W		
Howard A. Hanson Dam				
Crest	SMA-3348	47.282°N	COE	Moderate
Left Abutment	SMA-3345	121.791°W		instrumentation
Toe	SMA-3349			
Issaquah				
I-90/Sunset Way		47.532°N	WSDOT/	Extensively
Highway overcrossing		122.021°W	USGS	instrumented
Structure array	CRA-100			structure
Recorder house	SMA-1222			15 channels
Lower Granite Dam				
Center Crest	SMA-500	46.666°N	COE	Moderate
Right Crest	SMA-3112	117.431°W		instrumentation
Left Abutment	SMA-3111			
Lower gallery	SMA-2714			
Downstream	SMA-622			
McCord Air Force Base				
Passenger Terminal	SMA-639	47.15°N	USGS	Ground level
		122.48°W		
Mount St. Helens				
Spirit Lake				
Downhole system	CRA-283	46.27°N	USGS	Downhole sensors
Rock site	SMA-5121	122.16°W		acceleration &
				pore pressure
				15 channels

Table 1, continued

Location	Instrument	Coordinates	Owner	Comments
Castle Creek Downhole system	CRA-282	46.28°N 122.30°W	USGS	Downhole sensors accelaration & pore pressure 12 channels
Mud Mountain Dam Crest Right abutment Toe	SMA-1234 SMA-1251 SMA-1248	47.14°N 121.93°W	COE	Moderate instrumentation
Nisqually Wildlife Refuge Office Building	SMA-300	48.083°N 122.717°W	USGS	Ground level
Olympia Highway Test Lab	SMA-136	47.03°N 122.90°W	USGS	Ground level
Orting Pierce County Rock Quarry	SMA-642	47.07°N 122.21°W	USGS	Ground level
Ross Dam Upper gallery Right abutment	SMA-3987 SMA-3986	48.73°N 121.07°W	SDL	Minimal instrumentation
Seattle Bulk Mail Facility	SMA-3931	47.29°N 122.32°W	USGS	Ground level
Seattle Federal Building	SMA-2718	47.60°N 122.33°W	USGS	Basement
Seattle Pier 20	SMA-1931	47.58°N 122.35°W	USGS	Ground
Seattle SeaTac Airport Concourse C	SMA-134	47.42°N 122.30°W	USGS	Basement
Seattle Ship Canal Bridge	SMA-2535	47.42°N 122.32°W	USGS	Ground level
Seattle West High School	RFT-512	47.58°N 122.39°W	USGS	Basement
Seattle V.A. Hospital	SMA-775	47.56°N 122.31°W	VA	Sub-basement

Table 1, continued

Location	Instrument	Coordinates	Owner	Comments
Spokane				
V.A. Hospital Building #3	SMA-772	47.70°N 117.48°W	VA	Ground level
Shelton				
Fire Station	SMA-301	44.218°N 123.108°W	USGS	Ground level
Stanwood				
Snohomish Co. Library	SMA-173	48.247°N 122.346°W	USGS	Ground level
Tacoma				
City-County Building	SMA-307	47.25°N 122.45°W	USGS	Basement
Tacoma				
V.A. Hospital Boiler room	SMA-777	47.130°N 122.570°W	VA	Ground level
Tolt River Dam				
Crest	SMA-5132	47.69°N	SDW	Moderate
Abutment	SMA-5133	121.69°W		instrumentation
Toe	SMA-5313			
Tumwater				
Seismograph station	SMA-640	47.015°N 122.908°W	USGS	Ground level
Vancouver				
V.A. Hospital Building #4	SMA-771	45.64°N 122.66°W	VA	Ground level
Walla Walla				
V.A. Hospital Building #109	SMA-776	46.06°N 118.36°W	VA	Ground Level
Wynoochee Dam				
Upper gallery	SMA-1236	47.39°N	COE	Moderate
Lower gallery	SMA-1250	123.60°W		instrumentation
Downstream	SMA-1235			

*BR Bureau of Reclamation
COE Corps of Engineers
SDL Seattle Dept. of Lighting
SDW Seattle Dept. of Water
USGS U.S. Geological Survey
VA Veterans Administration
WSDOT Washington State Dept. of Transportation

Definition of terms:

- Minimal instrumentation is 2 accelerographs per ground/structure system.
- Moderate instrumentation is 3 or more accelerographs per ground/structure system with at least one instrument outside of the structure at a ground site.
- Extensive instrumentation consists of 12 or more remotely placed sensors that allow a rigorous analysis of structural response during an earthquake.

Implementation Actions for Reduction Measures*

Reduction Measures	Target Group	Implementing Actions	Control
BUILDING CODE PROVISIONS	Future developers of buildings in seismic areas	Building identification, standards, enforcement, sanctions	Local officials
		Adherence to standards	Target group
HAZARDOUS BUILDING ABATEMENT PROVISIONS	Owners of existing building in seismic areas	Building identification standards, enforcement, sanctions	Local officials
		Compliance with retrofit	Target group
ZONING PROVISIONS	Developers of property in seismic areas	Identify seismic zones, zoning revisions, plan review, sanctions	Local officials
		Compliance with zoning	Target group
SPECIAL USE or CRITICAL FACILITY PERMITS	Operators/owners of designated lifelines	Requirements for each lifeline (negotiated), sanctions, enforcement	Local officials
		Compliance with standards	
LIFELINE LOCATION or DESIGN RESTRICTIONS	Operators/owners of designated lifelines	Requirements for each lifeline (negotiated), sanctions, enforcement	Local officials
		Compliance with standards	Target group
SEISMIC AREA IMPACT REVIEW	Developers of property in seismic areas	Requirements for review, sanctions, enforcement	Local officals
		Submission of review	Target group
		Act upon review (negotiate) seismic requirements)	Local officials target group
REAL ESTATE DISCLOSURE	Buyers of property in seismic areas	Designate seismic areas, disclosure requirements, sanctions, enforcement	Local officials (may be shared w/ Real Estate Board)
		Disclosure of information	Real Estate Agents
		Act upon information	Target group
PURCHASE OF DEVELOPMENT RIGHTS or TAX CREDITS	Property owners in seismic areas	Property identification, assessment, financing, negotiations with owners	Local officials (may require voter action)
		Volunteer for participation	Target group
		Future land use monitoring	Local officials
PROPERTY ACQUISITION	Property owners in seismic areas	Property identification, assessment, financing, negotiations with owners	Local officials (may require voter action)
		Volunteer for participation	Target group

*This table is based on research and analysis done for an NSF-funded project on Land Use Planning for Earthquake Mitigation, carried out by the University of Washington and Battelle Human Affairs Research Center. The project team included Patricia Bolton, Marjorie Greene, Susan Heikkala and Peter May. The Project Director was Myer Wolfe. (From U.S. Geological Survey Open-File Report 86-253.)

(4) Loss-estimation modeling. Central to this element will be an update of building inventories in Seattle and other urban areas in the selected region. From this, and from the ground motion maps, probable losses from earthquakes of magnitudes 6.5 through 8.0 can be computed.

(5) Implementation. Success of the federal program will depend on communicating interpreted scientific information to user groups. An example of informing the local community is the U.S. Geological Survey's Open-File Report 86-253, which is the proceedings of a workshop on earthquake hazards in the Puget Sound area. The workshop participants agreed that it was important to acquire more technical data, particularly about earthquake recurrence intervals and ground responses. The need for maps of seismogenic zones, engineering properties of rock and soils, susceptibility to liquefaction, and fill locations was stressed. Implementation of the program will also entail identifying both the users and products of seismic studies, as well as the cost of delivering information at appropriate levels of detail and scales and in a timely and usable manner. (See Table 2, pp. 10.) Success will be enhanced by continual evaluation of this program component--how well scientists communicate with planners and how the information is then used.

The role of state agencies, at least as initially seen by the federal government, will be to advise the U.S. Geological Survey about the programs that will foster implementing the program, to serve as technical advisors and reviewers, and to work within the program through federal grants.

A grant of $25,000 from the U.S. Geological Survey to the Division of Geology and Earth Resources will allow implementation of parts of component (1) above in 1987. The Division plans to use its extensive data base in conjunction with the University of Washington to develop an information system.

USGS BEGINS SEISMIC GROUND RESPONSE EXPERIMENTS IN WASHINGTON

by
Arthur C. Tarr and Kenneth W. King
United States Geological Survey
Golden, Colorado

Residents of a West Seattle neighborhood must have been puzzled one Saturday morning last December. Two men, were leaning against the wall of a house and rhythmically pushing against it, urged on by the shouts of another man standing on the roof (Fig. 1). A horizontal seismometer was fastened to the top of the roof with a wad of beeswax; a thin cable trailed from the seismometer over the roof edge across the lawn and into a van parked at the curb. A digital seismograph in the van was recording the minute vibrations that were produced by the two men pushing on the wall and that were detected by the seismometer. From those recordings, the men could determine the predominant frequency and damping characteristics of the house when it is forced to oscillate in a horizontal direction as, for example, in an earthquake.

The men were Denver-based U.S. Geological Survey (USGS) geophysicists working on the Urban Hazards Field Investigations project. On the previous day they had recorded two events on their seismographs--a distant nuclear explosion in Nevada and a blast at a mine near Centralia, Washington. On another day, they used seismic refraction equipment to locate the depth and seismic velocity of bedrock at several locations in West Seattle and in the Seward Park-Brighton district of southeast Seattle.

New Hazards Assessment Program

Shaking houses, recording explosions, and running seismic refraction lines are only three of the many experiments the USGS is conducting as part of a new "Regional Earthquake Hazards Assessment of the Puget

A

B

Figure 1.--(A) U.S. Geological Survey personnel setting single-family dwelling into forced oscillation. Minute vibrations are detected by the horizontal seismometer attached to the top of the roof (B) and recorded by a digital seismograph system (not shown). (Photo courtesy USGS)

Sound-Portland Area" program. The program is a 3-year partnership among federal, state, and local governmental agencies, universities, and private companies to study how the Northwest would be impacted if a large, potentially damaging earthquake were to occur in the region; the Washington Division of Geology and Earth Resources is one of the participants in the partnership. The residents of large urban areas such as Seattle, Tacoma, Olympia, and Portland should be particularly interested in the hazards assessment because of the large numbers of people and substantial value of property at risk.

According to plate tectonic theory, the Northwest is subject to earthquakes and volcanic eruptions because of the subduction of the Juan de Fuca plate. The oceanic Juan de Fuca plate underthrusts the North American plate at a shallow dip angle along the Cascadia subduction zone off the coast of Washington, Oregon, and northern California; eastward of the coastline, the plate plunges more steeply into the upper mantle (Fig. 2). The major urban centers of western Washington and western Oregon and the volcanic Cascade Range are located above the steeply descending Juan de Fuca plate, within which major earthquakes may occur. In addition, potentially large, shallow, subduction earthquakes are possible westward to the zone of convergence offshore, and large, crustal earthquakes are possible farther inland.

The study of large Northwest earthquakes and the associated hazard involves a large number of geologists, geophysicists, engineers, local officials, and urban planners, working on scores of projects. The program discussed here is subdivided into five interrelated components:

(1) Synthesis of geological and geophysical data
(2) Ground motion modeling
(3) Loss estimation models
(4) Information systems
(5) Implementation

The overall program objectives are to:

(1) Compile and synthesize earth science data needed to evaluate the earthquake hazards of ground-shaking, ground failure, surface fault rupture, and tectonic deformation

(2) Assess the risk in urban areas

(3) Foster an environment for implementation, creating partnerships, and providing high quality scientific information that can be used by state and local governments to devise and implement loss-reduction measures.

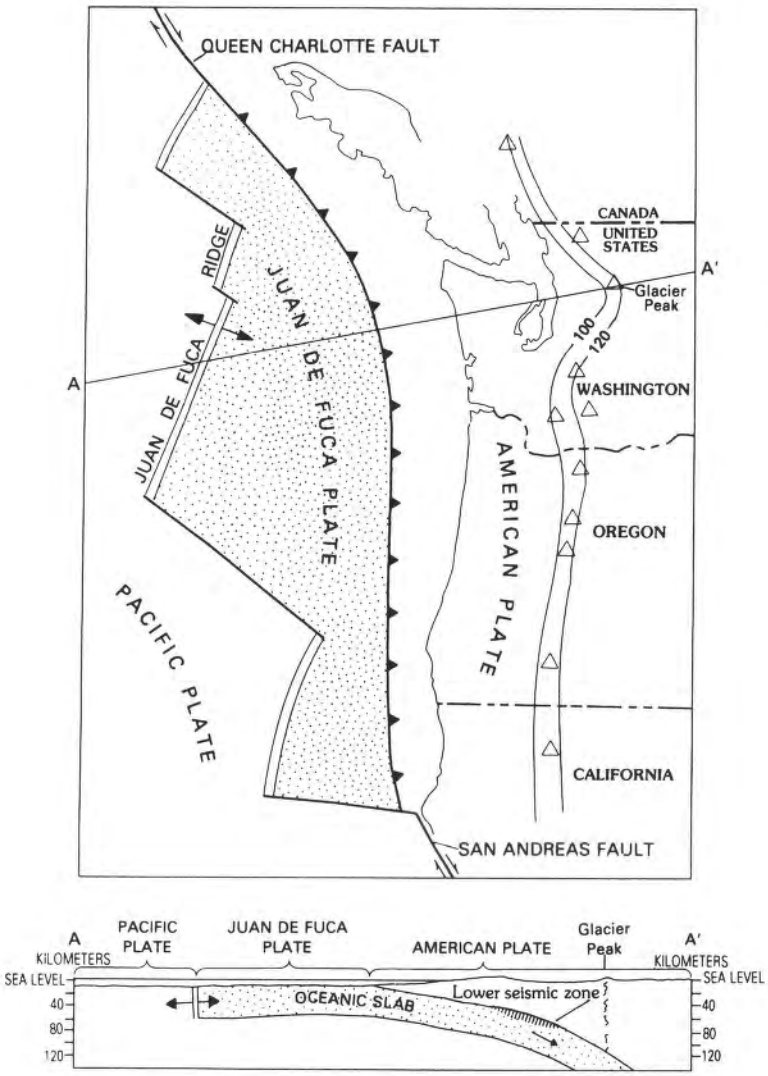


Figure 2.--Generalized subduction of oceanic lithosphere at the Cascadia subduction zone off the Northwest coast. Potentially large earthquakes may occur within the descending Juan de Fuca plate, within the zone of shallow underthrusting, and within the overthrusting continental lithosphere.

Predicting Ground Response

Most of the experiments performed by the Urban Hazards Field Investigations project are part of the ground motion modeling component. The objective of that component is to produce deterministic and probabilistic ground-motion models and to produce maps of ground-shaking hazard. Predicting how the ground will respond to strong vibratory motions when a large earthquake occurs is an important part of this component because once ground-motion models have been prepared, it is possible to predict how man-made structures of various classes and types will behave under conditions of strong vibratory motion. In addition, the ground-shaking hazards maps derived from these studies can be used to predict areas of ground failure (such as landsliding) and susceptibility of soils to liquefaction.

The first step in constructing a predictive ground response map is to measure vibratory motion from a variety of seismic sources at a large number of sites, including at least one site on hard rock (bedrock) that can be considered as a reference site. Naturally occurring earthquakes are one source of seismic energy that can be used for measurements of relative ground response; unfortunately, earthquakes are difficult to use because their occurrence is not predictable. Other sources of seismic energy are blasts at mines and quarries and distant nuclear explosions at the Nevada test site. The second step is to collect geological and engineering

data from sites near places where the seismic data were recorded. These data include thickness, type, and physical properties (such as density and seismic velocity) of soil and sediment layers under the site, depth to water table, and depth to bedrock. In some instances, these data are not available at a given site, so it is necessary to run geophysical experiments (such as seismic refraction and reflection lines) or to drill a borehole. The third step is to correlate these geotechnical data with the seismic data by clustering sites with similar geotechnical parameters; if the clusters have been chosen properly, that set of geotechnical parameters should correspond to some mean ground response. Finally, a map of predicted ground response can be compared with maps of intensity (or damage) data observed from actual earthquakes to check how accurate the predictions are.

Experiments in West Seattle and Olympia

West Seattle and Olympia were chosen as the first areas to be studied for ground response measurements because historically these areas had suffered significant damage due to earthquakes. Strong earthquakes in 1946, 1949, and 1965 caused deaths and widespread damage in the Puget Sound area, especially in Seattle, Tacoma, and Olympia. For example, the Modified Mercalli intensity (an indirect measure of ground motion) for the 1965 earthquake varied widely across Seattle, with intensity VIII effects occurring on Harbor Island and in parts of West Seattle; intensities in Olympia ranged from V to VII within a radius of just a few miles. The wide variation in intensity is probably due to several factors acting at both regional and local scales.

On a regional scale, complexities in the vicinity of the earthquake source (which may be as deep as 80 km below the surface) and in the intervening deep crust may account for some of the regional variation in intensity. On a local scale, complexity in the shallow crust and topographic relief may provide opportunities for focusing and amplification of seismic energy from earthquakes, especially in areas where large vertical and lateral changes in physical properties of crustal strata occur.

Seismic Amplification

Studies of earthquakes in California, Utah, Japan, and Mexico have shown amplification of seismic waves at sites where thick sequences of unconsolidated or semi-consolidated soils and sediments overlie more competent bedrock; such soft and weak sediments are usually characterized by low seismic shear-velocities. An excellent example of the soil amplification effect was experienced in the September 19, 1985, Mexico earthquake; localized areas of Mexico City, many hundreds of kilometers from the epicenter, were severely damaged because of amplification by 50-m-thick deposits of water-saturated lake deposits under the structures. Although Seattle, Tacoma, Olympia, and Portland are not located on such sediments, the effect of shallow geologic materials may still be considerable. In Seattle, large areas are covered with till (unconsolidated and semi-consolidated mixtures of clay, silt, sand, cobbles, and even boulders deposited during the glaciation of the region), fluvial deposits, and fill materials (such as sawdust and till washed from hillsides by high-powered hydraulic jets). The thickness of the sediments varies from 0 m at bedrock exposures to at least 1,000 m beneath downtown Seattle.

The extent and predominant frequencies of amplification depend, in part, on the thickness of the sediment and its physical properties. For example, the Los Angeles Basin is an area between the San Gabriel Mountains and the Santa Ana Mountains that is filled with sediments which are more than 10 km thick at the basin's deepest parts. The seismic response in the basin at low frequencies (0.1 to 0.3 Hz) was found to correlate with the sediment thickness--that is, higher response was found over thicker sequences in the basin (relative to hard-rock sites in the mountains) than over thinner sequences. At higher frequencies (0.5-5 Hz), the response also showed resonances which correspond with thin, very low shear-velocity surficial layers.

In Seattle and Olympia, scientists suspect that amplified seismic response (and higher intensity) occurs in places where the fill and glacial till cover bedrock. Bedrock is exposed at only a few places in Seattle, such as around Seward Park in the southeastern

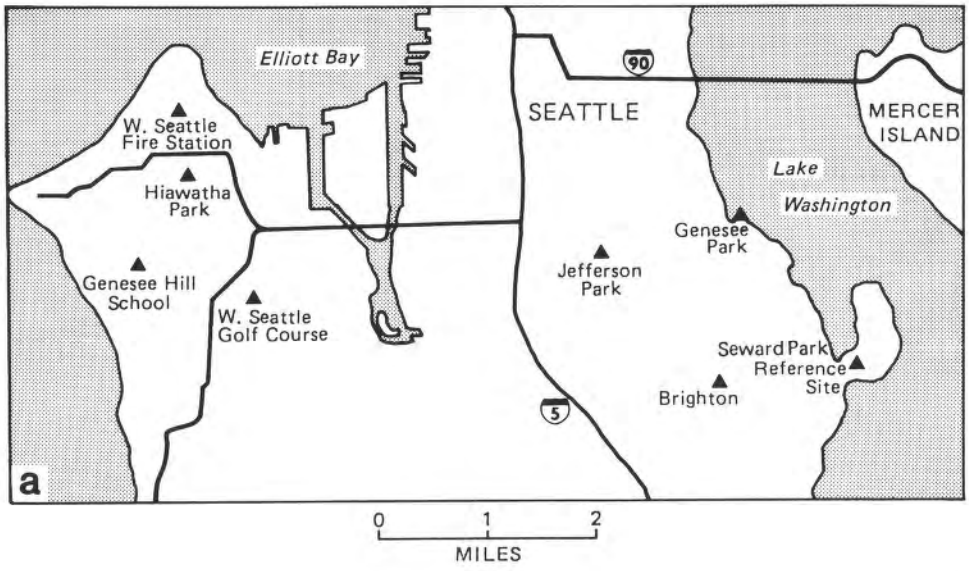
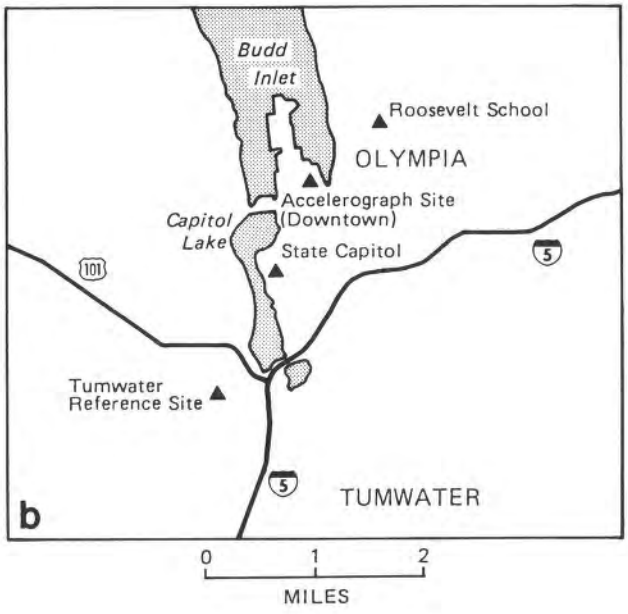


Figure 3.--Locations of seismograph stations for response studies in (a) Seattle and (b) Olympia.



part of the city (Fig. 3a). Thus, Seward Park is the location of the reference station for the network of USGS seismic ground response stations in Seattle. Observations of seismic waves at various sites are compared with the simultaneous observations at the reference station to determine relative ground response. Similarly, the Olympia reference station was located at a bedrock exposure in Tumwater (Fig. 3b). The surface (bedrock) velocity of compressional waves at the reference sites was determined by seismic refraction experiments to be in excess of 8,000 ft/sec (2,440 m/sec).

Results of First Experiments

This project has recorded all three types of seismic energy sources in Seattle with good results (one nuclear explosion at the Nevada test site, one mine blast at Centralia, and two local microearthquakes). Eight response sites, including the reference site at Seward Park, were selected in West Seattle and the Brighton district of Seattle (Fig. 3a). The depth to bedrock at the stations ranges from 0 m at Seward Park to about 100 m. Figure 4 shows examples of typical seismograms for the three types of seismic sources; Fourier amplitude spectra of the nuclear explosion signals are shown in Figure 5. The spectra at all response sites are amplified relative to the reference site at Seward Park.

In addition, three separate experiments were conducted to determine the character of ambient seismic background noise in Seattle. Digital seismograms were recorded at several times during the day, on successive days, and at various locations, including the bedrock sites. These data could be used to optimize conditions for later experiments (such as setting filters and parameters of the triggering algorithm in the digital recorders). The experiments showed, as expected, that noise from artificial sources decreases significantly at late night and early morning hours and on weekends. In addition, the ambient background noise at many sites seemed to peak in the 3- to 5-Hz range, in what seemed to be a systematic manner.

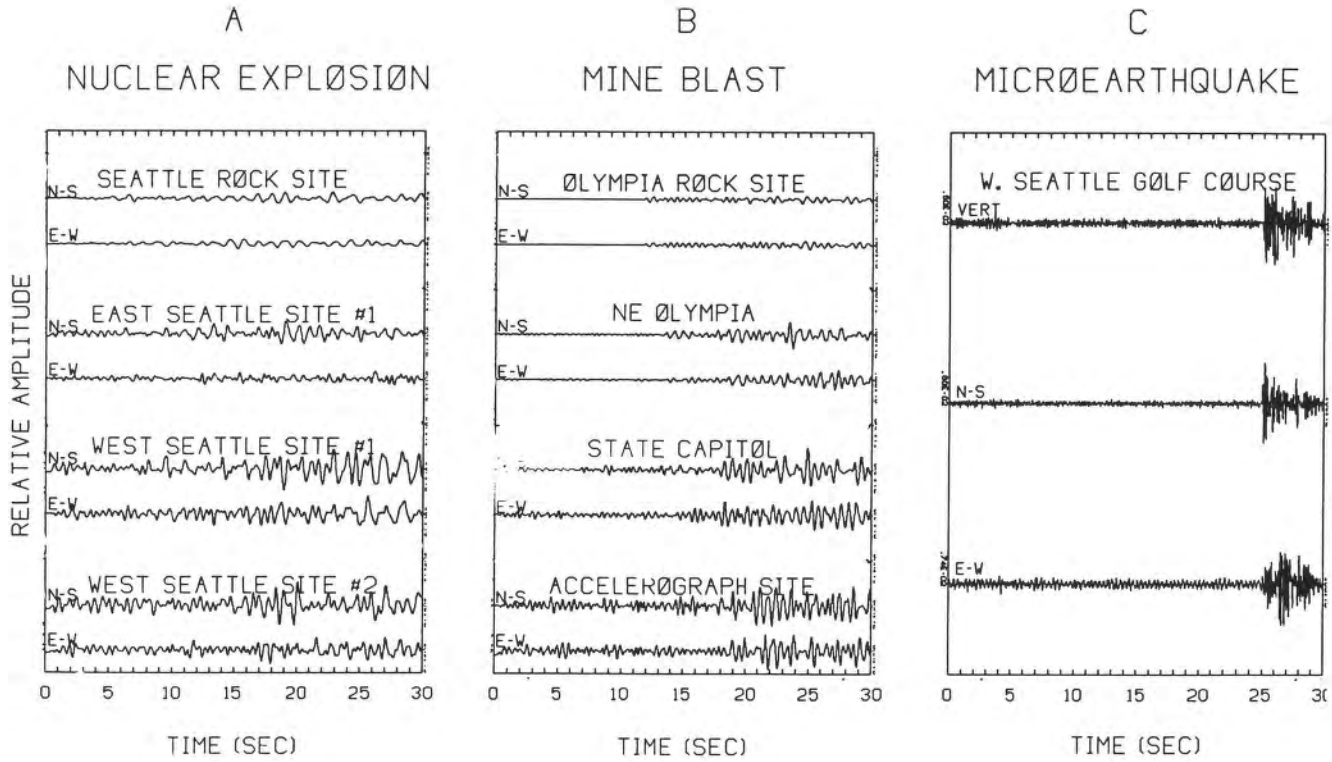


Figure 4.--Seismograms of three types of seismic sources recorded for relative ground motion response determinations. Horizontal seismometers oriented north-south and east-west are designated N-S and E-W, respectively. (A) Nuclear explosion at Nevada Test Site recorded at four sites in Seattle. (B) Mine blast recorded at four sites in or near Olympia. (C) Microearthquakes recorded at West Seattle Golf Course.

The nuclear explosion (Fig. 4) was observed adequately in Seattle at low and medium frequencies (up to about 2 Hz); however, above 2 Hz, ambient background noise masked the signal whose high frequency content had been attenuated by the Earth over the long path. Similarly, the signals from the mine blasts were masked at times by ambient noise. The microearthquake signal, on the other hand, was recorded quite well. The conclusion is that, although nuclear explosions and mine blasts will be used when possible, microearthquake signals may ultimately produce more usable data.

One mine blast was recorded at four sites in Olympia: the State Capitol (on alluvium); an accelerometer site of the National Strong Motion Network (on alluvium); a residential site in northeast Olympia (on glacial sediments); and a site in Tumwater (on bedrock; Fig. 6). The intensities of the 1965 shock reported at or near the first three sites were VII, VII and V, respectively; no intensity observations were made near the bedrock site. The amplification factor at the accelerometer site, relative to the residential site, was about 5 in the 0.5 to 4 Hz frequency band and 10 relative to the bedrock site in the same band. This result suggests that the variation in ground response could be mapped by observing seismic signals simultaneously at prospective ground response sites and at a reference site. The most reliable seismic source for ground response measurements in Olympia would seem to be mine blasts at Centralia.

Two microearthquakes were recorded by a digital station that had been allowed to operate in trigger mode. The signals contained usable information, even at frequencies above 10 Hz. We estimate that three or four microearthquakes per month ought to be recorded by the digital systems in trigger mode and thus provide usable high-frequency response data.

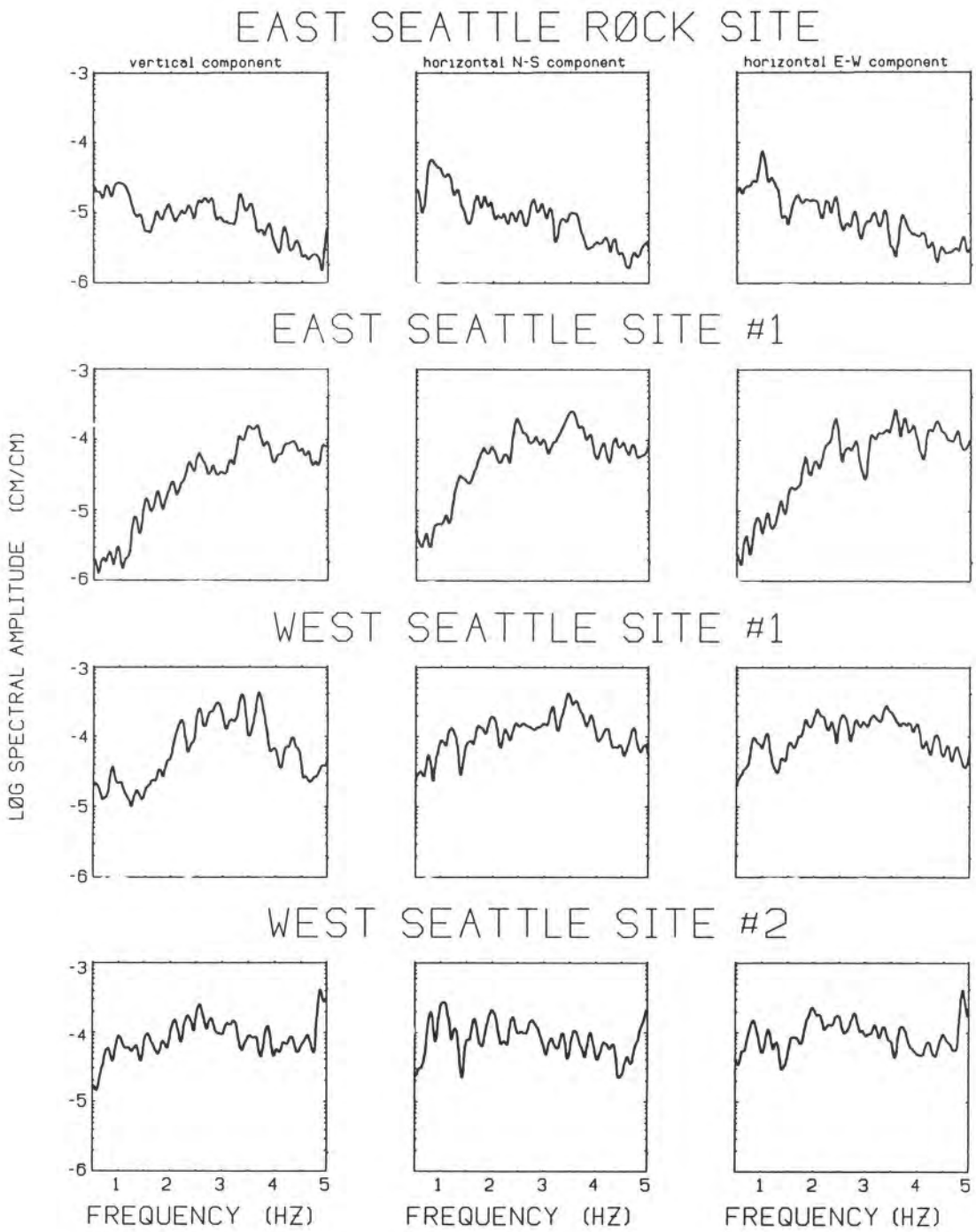


Figure 5.--Graphs showing Fourier amplitude spectra of three-component seismograms recorded at four sites in Seattle. Seismic source was a mine blast near Centralia, Washington. Note enhancement of high-frequency spectral amplitudes relative to the bedrock sites.

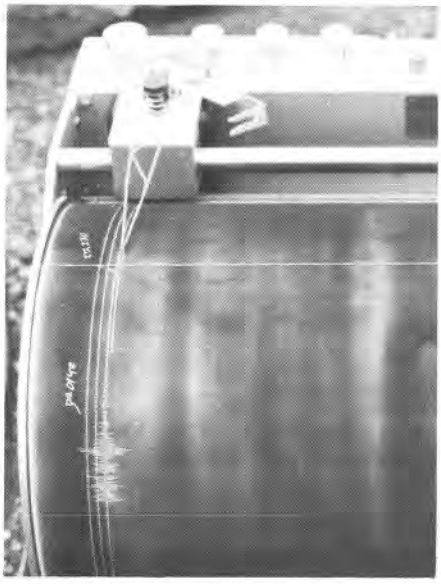


Figure 6.--Left: USGS portable digital seismic recorders and seismometer at the Tumwater bedrock reference site. Right: Trace of a blast at the coal mine in Centralia is shown in the close-up of the seismometer in the lower right corner of photo to left.

Plans for the Future

The 1986 experiments in Seattle and Olympia essentially set the stage for future work in these cities and later in Tacoma and Portland. Plans are to install a five-station network of digital seismographs at four seismic response sites and at one reference site in mid-1987; all stations will be triggered by one master station. Further plans are to occupy additional response sites in Seattle and Olympia during 1987, using such seismic sources as are available. High-resolution reflection profiles will be run at selected response sites to determine subsurface structure and to refine velocity models.

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1987 PNAGU MEETING ANNOUNCED

The Pacific Northwest American Geophysical Union will hold its 1987 meeting at the Evergreen State College in Olympia September 2 and 3. There will be a general session and a special session on accretionary tectonics. The meeting will include a field trip to the Washington coast to look at the Hoh melange. The deadline for abstracts is August 3. For further Information, write:

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GEOLOGIC EVIDENCE FOR LARGE EARTHQUAKES ALONG THE PACIFIC COAST ?

Western Washington is situated above the Cascadia subduction zone, in which the Juan de Fuca plate descends beneath the North American plate (Fig. 1). The proximity of the subduction zone to the coast and the fact that subduction zones are commonly the sites of earthquakes combine to make western Washington a promising area for seismic studies. Recent studies present evidence that the Cascadia subduction zone could produce great earthquakes, of magnitudes of 8 or larger.

T. H. Heaton and S. H. Hartzell of the U.S. Geological Survey (USGS) show that the subduction zone has many characteristics in common with others that have produced large quakes. They report (1987) that during the past 1 million years Juan de Fuca plate has been moving beneath the North American plate at an average rate of about 4 cm per year. (For a comparison of plate motion rates, see Table 1.) The subducting plate is sufficiently young, and thus buoyant, for "coupling" with the North American plate. Such coupling could result in large earthquakes. The fact that no earthquakes of magnitude 8 or greater have been noted in written records of the last 150 or more years suggests to these scientists that the two plates are locked together and that stress is building for release as a future quake (Heaton and Hartzell, 1987). An alternative interpretation is that that the two plates are not coupled but are slipping past one another without generating interplate earthquakes.

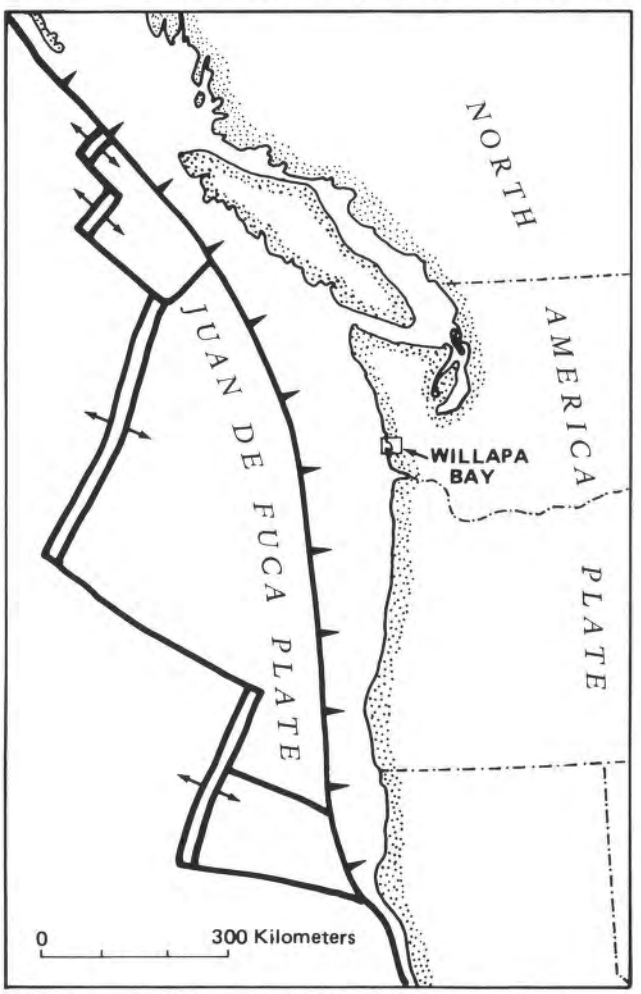

Figure 1.--Tectonic plates and coast of Washington.

During the past year, Brian Atwater, also of the USGS, has been testing the great-earthquake hypothesis by studying the Holocene stratigraphy of estuarine lowlands along Washington's outer coast (See Science, issue of May 22). He believes that deposits of these lowlands provide the first strong evidence that great earthquakes (magnitude about 8 or 9) have occurred during the last 7,000 years in the Pacific Northwest. The deposits record episodes of rapid subsidence during which marshy and wooded lowlands were transformed into sparsely vegetated tide flats (Fig. 2). Anomalous sheets of sand that lie on buried-lowland surfaces suggest to Atwater that each of the three or more episodes of subsidence may have coincided with a tsunami. He notes that this synchrony is typical of great subduction earthquakes and difficult to explain otherwise. For coastal lowland deposits of southwestern Washington, Atwater infers that at least six great earthquakes have occurred there in the past 7,000 years. He thinks that the likely source for such earthquakes is the shallow, chiefly offshore part of the Cascadia subduction zone.

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Table 1.--Comparison of characteristics of subduction zones along the west coast of North and South America and east of Japan. (Modified from Hays and Gori, 1986)

	Cascadia	Alaska	Nankai Trough (Japan)	Mexico (Rivera plate)	Columbia	Southern Chile
Age of subducted plate (m.y.)	10	40 to 50	18 to 24	10?	10 to 15	5 to 30
Convergence rate (cm/yr)	3.3 to 4.3	5.7	3.3 to 4.3	2.3	8	9
Character of trench	shallow, sediment filled	shallow, sediment filled	shallow, sediment filled	shallow, few sediments	shallow, sediment filled	shallow, sediment filled
Free-air gravity/ anomaly	small, 50 mgal	moderate, 100 mgal	moderate, 100 mgal	moderate, 100 mgal	small, 50 mgal	small, 50 mgal
Background seismicity	very low	moderate	low	moderate?	low	very low
Heat flow (HFU*)	high 1-2		high 1-2			high 1-2
Quaternary volcanism	yes	varies along the trench	no	yes	yes	yes
Inland sea or valley	yes	yes	yes	yes	no?	yes
Width of continental margin (km)	30-120	180	110	80	130	100
Largest historic earthquakes (M_W)	none in 150 yr	9.2 (1964)	8.1 (1944 1946); 8.5? (1707)	8.2 (1932)	8.8 (1906)	9.5 (1960)
Average repeat time (yr)	400	800?	180	50?	unknown	128

*Heat Flow Unit

Figure 2--Holocene deposits at minus tide along the Niawiakum River, Willapa Bay. Tide-flat mud abruptly overlies each of four peaty soils (arrows). Each of these soils represents a marshy or wooded lowland whose rapid change to a tide flat may signify earthquake-induced subsidence. (Photograph courtesy Brian Atwater, USGS)

STAFF NOTES

Staff members of the Division of Geology and Earth Resources are involved with numerous geologic issues. DGER activities described below are some of our current ways of providing information and services to Washington's residents.

Ray Lasmanis spoke to the Northwest Geology Society on April 21 in Seattle. His topic was the geological repository at Hanford and the unresolved problems, as well as the political situation regarding the nuclear waste site. Ray has served on the state's Nuclear Waste Board. He has also recently accepted a position on the Advisory Council for the Department of Geology at Portland State University.

A delegation of geologists from the Peoples' Republic of China visited the Division office in Olympia on April 30. The visitors were **Wang Shuxun**, Division Chief of the Bureau of Education of the Ministry of Geology and Mineral Resources in Beijing, **Zhao Pengda**, President of Wuhan College of Geology in Wuhan, **Zhai Yusheng**, President of the Beijing Education Center for Geology (Graduate School, National Geological University), **Ruan Tianjian, Head of the Department of Geochemistry at the Wuhan College of Geology, escorted by Maynard Miller**, Dean of the College of Mines at the University of Idaho. The Chinese geologists are part of a group from China's Ministry of Geology, and are in the United States on a geological exchange program. Ray Lasmanis was their host for a tour of the Division's facilities and a visit to the state capitol. The geologists met with Representative Dick Nelson, Governor Gardner spoke with them briefly. The scientists also visited the WIDCO coal mine in Centralia.

Weldon Rau gave an hour's lecture about the geologic history of the Washington coast to persons attending the Beachcombers Annual Fun Fair, held at Ocean Shores, WA, March 7 and 8.

SLAR REVEALS GEOLOGIC STRUCTURES IN THE PASCO BASIN

On March 17 William Brewer of the Washington Department of Ecology spoke to geologists of the Division of Geology and Earth Resources and guests about his interpretation of side-looking airborne radar (SLAR) imagery of the Ritzville, Walla Walla, and Pendleton 1:100,000-scale quadrangles. Brewer has combined SLAR data with geologic maps, satellite images, aeromagnetic and gravity data, as well as microearthquake epicenter data for the area. The result of this multidisciplinary approach is evidence that a rectangle about 5 by 6 kilometers that includes the Hanford proposed nuclear waste repository site is bounded by faults. Brewer noted, however, that it is not known if the faults are active or if they serve as conduits for ground water in the area of the proposed nuclear waste repository. Determination of these characteristics will require field studies.

The earliest radar images of eastern Washington were made by Westinghouse nearly 20 years ago. Over the years, the process has been refined. SLAR "looks" at a strip of the Earth's surface as much as 50 kilometers wide as the plane carrying the instruments travels at an altitude of 11,000 meters on a series of precise flight paths. An x-band (short) wavelength is used, to permit penetration of some surface vegetation. The technique takes seven images for each 100 meters of travel along the flight path; there is 60-percent overlap of these images. The multiple images are digitally recorded as pixels that represent an area 6 by 12 meters. This level of resolution is effectively increased by the overlap of the images, and surface features as small as 1 meter high or long can often be detected. Stereoscopic orthomosaics of the digital data resemble high-quality photographs, even though each is composed entirely of radar-generated pixels. The radar data can be computer enhanced to emphasize desired types of information.

The impetus for the SLAR work was the investigation of pathways for ground water in the Pasco basin, and the Hanford Reservation in particular: Is the ground water confined to individual basalt layers, or does it migrate vertically along structural breaks? Examination of ground water in the basin is the focus of a larger study by the Department of Ecology. That study will attempt to integrate water-level and water-quality information, as well as several kinds of well logging, from deep wells throughout the basin over at least one irrigation season. The results of this work may help define hydrologic boundaries in the basin--that is, whether there are several hydrologic subbasins and distinct aquifers or one basin-wide aquifer. The potential effect of nuclear waste storage on either one or several aquifers is an important consideration in the site selection process.

The groundwater studies may provide further information about the presence of natural gas in the Hanford area. Methane is present in well water, and gas has been reported in several wildcat wells. (See Lingley and Walsh, 1986.) Understanding the distribution and quantity of gas in the area is also critical to decisions regarding the use of Hanford as a nuclear waste repository; presence of natural gas resources may disqualify the site from further consideration.

Preliminary results of radar imagery studies by Richard Galster are in agreement with some of Brewer's work in showing several very large linear structures. Galster's work is concerned with dam safety in western Washington. For example, the images suggest that a major north-south fault, the Straight Creek fault, extends well into southern Washington and that a northeast-trending geologic fabric is present in the southwestern part of the state.

The U.S. Geological Survey funded the SLAR survey as part of a national program. Interpretation of the images will be done by the staff of the Office of Nuclear Waste Management, Washington Department of Ecology, with assistance from the Division of Geology and Earth Resources. Funding to the Department of Ecology for follow-up studies comes from the U.S. Department of Energy's high-level nuclear waste fund. All rate payers using nuclear power contribute money to this commercial nuclear waste fund.

Other geologic projects of the Department of Ecology include (1) re-examination of previous seismic refraction data and starting new refraction studies to be used in con-

junction with future SLAR flight data for the Hanford area; (2) documentation of all radioactive-contamination sites on the Hanford reservation (such as active waste burials, abandoned sites, and accidental spills) and effects of radiation exposure; and (3) involvement with the Department of Energy's geotechnical work related to the shaft that may be drilled at the proposed repository.

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EARTHQUAKE RESEARCH IN WASHINGTON

(continued from p. 2)

- Potential seismic sources
- Nature of interplate slippage
- Probability of a devastating earthquake in western Washington
- Maximum expected earthquake magnitude
- Recurrence interval
- Ground response in the Puget Lowland
- Level of risk in urban centers

To underscore the importance attached to Puget Sound, the National Earthquake Prediction Evaluation Council (NEPEC) held a three-day meeting at the University of Washington April 1-3. The theme of the field trip and meeting was "Subduction earthquakes in the Pacific Northwest". At the conclusion of the session, the council of national experts drafted a letter to the Director of the U.S. Geological Survey, Dallas Peck, confirming that Puget Sound is at risk and recommending research to obtain more definitive answers to questions about the magnitude of that risk.

In recent years we have occasionally found ourselves at odds with certain federal agencies. The current seismic studies program is one for which we have an opportunity to compliment a federal agency, namely the U.S. Geological Survey.

NEW PUBLICATION SUMMARIZES EXPLORATION DATA

Companies raising exploration funds through the facilities of the Vancouver Stock Exchange are required to submit a report, prepared by an independent and appropriately qualified engineer or geologist. These reports provide very useful information about the exploration potential of the property and the surrounding regions.

While these are in the public domain, it has previously been very difficult for exploration companies to make effective use of this source of information. The new publication USE-FILE (from MSS Ltd., 450 Shannon Way, Delta, B.C., Canada V4M 2W5) has solved this problem. Available reports are summarized and listed on a geographic basis for the benefit of the user. These data summaries are prepared by a former exploration manager for a large multinational mining company.

USE-FILE appears on a quarterly basis and provides a timely listing of active properties. The inaugural issue was published in March 1987 and contains summaries of 351 mineral properties. These are from as far afield as Brazil and Switzerland, with the majority being in Canada and the western USA. Copies of the full original text of the reports and the accompanying maps are also available from the publisher.

The publication contains a variety of other useful information including listings of directors, principal shareholers and option holders, showing their company affiliations and shareholdings. Summary information is also provided on underwritings in other business areas such as computer software and oil and gas companies.

Annual subscription is $350 for 4 issues; individual issues are available at $100 each.

(Text from of M.S.S. Ltd., 450 Shannon Way, Delta, B.C., Canada, V4M 2W5.)

SOURCES OF EARTHQUAKE INFORMATION BROCHURES

This list is based on information provided by Washington Department of Community Development, Division of Emergency Management.

1. County or local emergency management or service offices (These brochures are available in varying amounts, and not all are available at each office)

"27 Things to Help You Survive an Earthquake"
"Family Earthquake Drill"
"Coping with Children's Reactions to Earthquakes and Other Disasters"
"Earthquake Safety Checklist"
"Safety Tips for Washington Earthquakes"
"Home Hazard Hunt"
"Learning to Live in Earthquake Country: Preparedness for People with Disabilities, and Preparedness in Apartments and Mobile Homes"

2. Washington State Division of Emergency Management
Department of Community Development
4220 E. Martin Way
Olympia, WA 98540

"Washington State Seismic Safety Council Report"

3. U.S. Geological Survey Public Inquiries Office
Room 678, U.S. Courthouse
West 920 Riverside Ave.
Spokane, WA 99201
(509) 456-2524

"The Interior of the Earth"
"Safety and Survival in an Earthquake"
"The Severity of an Earthquake"
"Earthquake"

4. American Red Cross
(Contact local chapter for earthquake presentations and:)

"Family Disaster Plan and Personal Survival Guide"

"27 Things to Help You Survive an Earthquake"
"Safety and Survival in an Earthquake"

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

"The Puget Lowland Earthquakes of 1949 and 1965; Reproductions of selected articles describing damage" (DGER Information Circular 81, $2.50 + $1 for postage and handling)

WASHINGTON STATE DEPARTMENT OF
Natural Resources

Division of Geology and Earth Resources
Mail Stop PY-12
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