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Lifelines and Earthquake Hazards along the Interstate 5 Urban Corridor: Woodburn, Oregon to Centralia, Washington

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The lifeline systems and geology shown on the accompanying map have been greatly simplified. Most systems are shown in a general way for graphical purposes and may not be accurate in detail. In several locations where one system overlies another, system elements have been adjusted so that they are more distinctly visible on the map. The surface geology has been greatly simplified for the purposes of providing regionally consistent geological characteristics throughout the entire study area (Cottage Grove, Oregon, to Vancouver, British Columbia). This map should not be used for any site-specific purpose. Any site-specific consideration requires more detailed geotechnical and geological data than are presented in this map.

INTRODUCTION

The Interstate 5 highway corridor, stretching from Mexico to Canada, is not only the economic artery of the Pacific Northwest, but is also home to the majority of Oregonians and Washingtonians. Accordingly, most regional utility and transportation systems, such as railroads and electrical transmission lines, have major components in the I-5 corridor. The section of I-5 from Cottage Grove, Oregon, to Blaine, Washington, is rapidly urbanizing, with population growth and economic development centered around the cities of Eugene, Salem, Portland, Olympia, Tacoma, Seattle, Everett, and Bellingham. For the purposes of this map, we refer to this area as the I-5 Urban Corridor.

Lifelines in Earthquake country

Economic success in this urban corridor heavily depends on essential utility and transportation systems, called lifeline systems, such as highways, railroads, pipelines, ports, airports, communications, and electrical power. Consequently, natural disasters that disrupt these lifeline systems can cause economic losses. For example, a major winter windstorm may disrupt an electrical system causing loss of power at smaller distribution substations and widespread power outages due to falling trees breaking power lines. As a result, hundreds of thousands of residents and businesses may be without power for a day or longer. Larger scale natural disasters, such as earthquakes, can present more complex challenges because they tend to affect and disable many lifeline systems at once. For example, failures in the highway system after an earthquake may make restoration of critical electrical power substations or sewer treatment plants more difficult. Subsequently, determining priorities and strategies for recovery becomes increasingly difficult due to the potential simultaneous failures of several systems.

As the 2001 Nisqually earthquake reminded us, the Puget Sound region is earthquake country. Large-magnitude, damaging earthquakes struck Olympia in 1949 and Seattle in 1965, and the 2001 Nisqually earthquake occurred very near the epicenter of the 1949 event. In addition to these large events, earthquakes are felt in the Puget Sound region about once a month. In contrast, the southern part of the I-5 Urban Corridor, the Eugene and Salem areas in particular, has experienced very few felt earthquakes this century. However, during the last decade earth scientists have uncovered convincing evidence suggesting that the entire Urban Corridor, from Eugene to Vancouver, B.C. is at risk from great off-shore subduction zone earthquakes, perhaps of magnitude 9.

The lifeline and earthquake hazard map

Understanding where major lifeline systems are located in relation to earthquake hazards and population centers is an important first step in developing mitigation strategies that can make the I-5 Urban Corridor more earthquake resistant and expedite economic recovery after an earthquake. Lifeline systems are complex webs that cross through many communities and areas of higher and lower earthquake hazards. The result of the geographic relationships between the lifelines and underlying geology is a complicated multi-layered network that can be difficult to visualize for planners, emergency response providers, elected officials, and other non-specialists.

To meet the need for a simple and integrated graphical representation of lifeline systems and earthquake hazards, the United States Geological Survey, in cooperation with public agencies and private companies, has been developing a series of maps for the I-5 Urban Corridor. We have divided the I-5 Urban Corridor into four regions from Cottage Grove, Oregon to southern British Columbia. This map covers the area from Woodburn, Oregon (from about I-5 milepost 274) to Chehalis, Washington (about milepost 71) . The intent is to provide an overview of the lifeline systems and the corresponding earthquake hazards for the citizens, engineers, planners, and decision-makers who live and work in this region. Please note that the map does not provide site-specific information for engineering or environmental purposes.

The base of the I-5 Corridor maps is a shaded-relief background that provides a quick, qualitative depiction of slopes and river valleys. The regional geology is generalized and categorized as probably less hazardous ground (green) or probably more hazardous ground (beige) in the event of an earthquake. Simplified lifeline system elements superimposed on the geological base are shown for major electric power transmission lines, water supply pipelines, major sewer pipelines and treatment plants, liquid fuel pipelines, natural gas pipelines, and major ports and airports. Each map also shows recent earthquakes of magnitude 2.0 and larger, and historically important earthquakes estimated to be larger than magnitude 5. On this map from Woodburn, Oregon, to Chehalis, Washington, crustal earthquakes greater than magnitude 5 are known at Mount St. Helens, along the St. Helens seismic zone and near Portland.

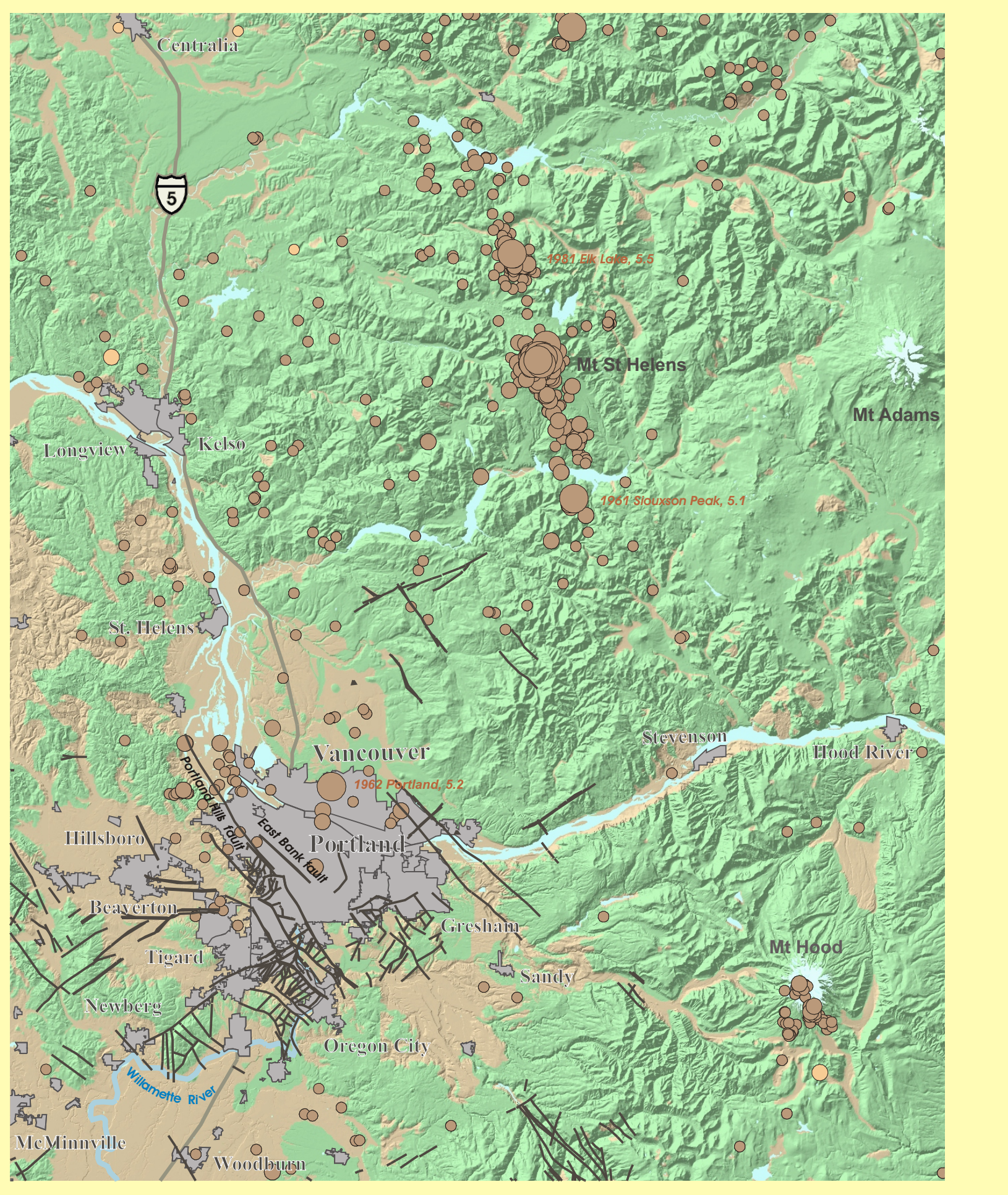

Figure 2. Faults and earthquakes in the Willamette Valley and vicinity. Solid lines show crustal faults identified by Yeats and others (1996). Smallest circles represent events between magnitude 2.0 and 3.4, medium circles events between 3.5 and 4.9, and largest circle size is over 5.0. Light symbols are intraplate events, dark symbols crustal earthquakes. (After Blakely and others, 2000)

LIFELINE SYSTEMS ON THE MAP

One purpose of the map series is to show schematically how the major regional lifeline systems connect with population centers. Representing highways, railroads, electrical transmission lines, and petroleum and natural gas pipelines is relatively straightforward since these systems are regional. However, representing local water and wastewater systems is more difficult because there are many local systems in the map area. With the assistance of local agencies, we selected and schematically show major water and wastewater systems for the four counties surrounding Portland: Washington, Clackamas, Multnomah, and Clark. The four counties have a combined population of just under 1.8 million (Table 2), which is heavily concentrated in several cities (Table 1) and in suburban centers in these counties. In all cases, the service area for water and wastewater utilities extends outside the city boundaries so that these five systems serve an estimated 80% of the population in the map area.

State	County	2000 Population
Oregon	Yamhill	84922
Oregon	Washington	445342
Oregon	Clackamas	338391
Oregon	Multnomah	660486
Oregon	Columbia	43560
Washington	Clark	345238
Washington	Cowlitz	92948

***Table 1**: Population of cities with 2000 population greater than 40,000 shown on map.*

State	City	2000 Population
Oregon	Beaverton	76,129
Oregon	Gresham	90,205
Oregon	Hillsboro	70,189
Oregon	Portland	526,986
Oregon	Tigard	41,223
Washington	Vancouver	143,560

***Table 2**: Population of counties shown on map. The Portland metropolitan area includes Washington, Clackamas, Multnomah, and Clark counties with a combined Population of 1,789,457.*

Water

The Portland Water Bureau serves almost 25% of the entire population of Oregon and over 40% of the people living in the map area. It relies on water from the Bull Run system in the Cascade foothills and well fields along the Columbia River near Portland. The transmission system connects with suburban users. The Tualatin Valley Water District provides water from the Portland system and surface water sources in the Coast Range to over 170,000 people living in Washington County. In Washington, the City of Vancouver operates the fourth largest water utility in the state, supplying over 140,000 residents from groundwater sources.

Where digital data are available, the map shows the rivers and reservoirs where surface water enters the pipeline transmission systems, generally selected by pipe diameter, and shows the transmission systems to their terminal reservoirs or major distribution branches.

Wastewater

There are four large wastewater systems serving the four urban counties surrounding Portland. The City of Portland Environmental Services operates two treatment plants that serve 660,000 people. Clean Water Services in Washington County handles wastewater for over 450,000 people. In Clackamas County the largest wastewater system is the Water Environmental Services with 150,000 customers. The wastewater treatment plants for these major systems in Oregon discharge into the Willamette River. The City of Vancouver system operates a system for 140,000 people in Clark County that discharges into the Columbia River. Major sewer lines, generally selected by pipe diameter, and selected treatment facilities are shown on the map.

Electrical Power

The major electric power provider in the Pacific Northwest is the Bonneville Power Administration, which transmits the region's electricity from hydroelectric plants along the Columbia and Snake rivers to the I-5 Urban Corridor. BPA sells power to the major distributors in the region. Portland General Electric (PGE) is Oregon's largest utility and serves over 1,500,000 people in the greater Portland area. PGE has extensive energy generation facilities. Other larger electrical utilities include Pacific Power serving a portion of Multnomah County, Clark County Public Utilities District (PUD) and Cowlitz County PUD. Each of these distributors has some generation capacity. Much of the power transmitted by BPA moves through 500 kV transmission lines shown on the map. The 230 kV and 115 kV grid shown on the map provides additional transmission capability.

Natural Gas

Williams Natural Gas Pipeline Company supplies natural gas to the Portland area. Pipelines generally run parallel to I-5 north to Seattle and east along the Columbia River. Pipelines continue south of Portland to supply natural gas to the Willamette Valley.

Liquid Fuel

The Portland area is served by the BP-Amoco pipeline that transports liquid fuel in a pair of pipelines (16-inch and 20-inch) from refineries in northwestern Washington south to Renton near Seattle. One line continues from Renton to serve Portland. The BP-Amoco pipeline connects to a steel, 8-inch diameter liquid fuel line operated by Kinder Morgan Energy Partners that provides liquid fuel to the southern Willamette Valley.

Highways

Large volumes of traffic generally flow along the I-5 Urban Corridor with between 80,000 vehicles per day near Cottage Grove south of Eugene and over 150,000 per day in southern Portland. Traffic across the Interstate Bridge over the Columbia River is 120,000 vehicles per day, including about 10,600 trucks (Oregon Dept of Transportation, 2002). Volumes on I-5 decrease to about 50,000 vehicles per day north of Vancouver. Downtown Portland sees another 100,000 vehicles per day on I-405. East of Portland, traffic counts vary from about 88,000 to over 150,000 per day, with 132,000 vehicles counted at the Columbia River. Oregon route 217 west of Portland sees over 100,000 vehicles per day between the junctions with I-5 and U.S. 26. An important non-freeway connection west of Portland, Oregon route 8 serves over 40,000 vehicles per day.

Several major east-west highways serve Portland. The main link is I-84, with as many as 180,000 vehicles per day in the downtown Portland area. Further east, near the map edge, counts on I-84 drop to about 20,000 vehicles per day. Along the Columbia River west of Portland, traffic counts range from about 48,000 vehicles per day in the city to less than 10,000 near the map edge. On U.S. 26, traffic volumes decrease from 60,000 vehicles per day in Portland at I-5 to about 12,000 to the east. At the intersection with I-405 in Portland, U.S. 26 counts are 140,000 vehicles per day, and decrease below 10,000 in the Coast Range.

Washington traffic counts along State Route 4, connecting Kelso to coast are about 28,000 vehicles per day at I-5 decreasing to less than 2000 at the western edge of the area. At the north edge of the map, about 6000 vehicles use U.S. 12 daily. Finally, State Route 14 has some 50,000 vehicles per day near the junction with I-5 and decreasing to about 5000 vehicles to the east.

Truck traffic on I-5 is extremely important to the regional economy. In a study of 17 western states, including heavily populated Texas and California, the Seattle-to-Portland section of I-5 ranks first in truck tonnage. In addition, the Portland-to-Eugene section of I-5 ranked second in tonnage and ranked fourth in total numbers (Oregon Dept of Transportation, 2000).

Railroads

The Union Pacific and Burlington Northern Santa Fe (BNSF) are the two mainline railroads operating in the greater Portland area. They provide north-south freight service to Portland, and tracks on both sides of the Columbia River connect the urban corridor with eastern markets. The rail lines through the Columbia River Gorge are by far the most heavily used tracks in the Pacific Northwest (Oregon Dept of Transportation, 2001). Major railroad bridges cross the Columbia and Willamette Rivers. The Columbia River bridge has 70 freight and 10 passenger trains cross every day. The Portland area is home to intermodal terminals that handle large volumes of freight. In 1999, the BNSF terminal in north Portland generated 1000 truck movements every day (Oregon Dept of Transportation, 2001).

The Port of Tillamook Bay (POTB) and the Pacific and Western (P & W) are the two main short line railroads that service the map area. The POTB lines run west from Portland to Tillamook Bay, whereas the P & W lines run south to the Willamette Valley and northwest to connect Portland to Astoria. Six daily passenger trains operate from Portland south and ten passenger trains connect north to Seattle. An expanding light rail system operates in the Portland urban area.

Airports

Portland International Airport is the second largest commercial airport in Oregon and Washington and the 30th largest in the United States. The airport serves over 12,000,000 passengers and handles 250,000 tons of air cargo. The largest general aviation airport in the area is Hillsboro, east of Portland.

Ports

The Port of Portland, located along the Columbia and Willamette rivers, is the eighth largest United States port in terms of total tonnage and the fourteenth largest in terms of container cargo. The port is the second largest exporter of wheat in the country and is the nation's largest importer of automobiles. Other key port facilities are located in Vancouver, Kalama, and Longview.

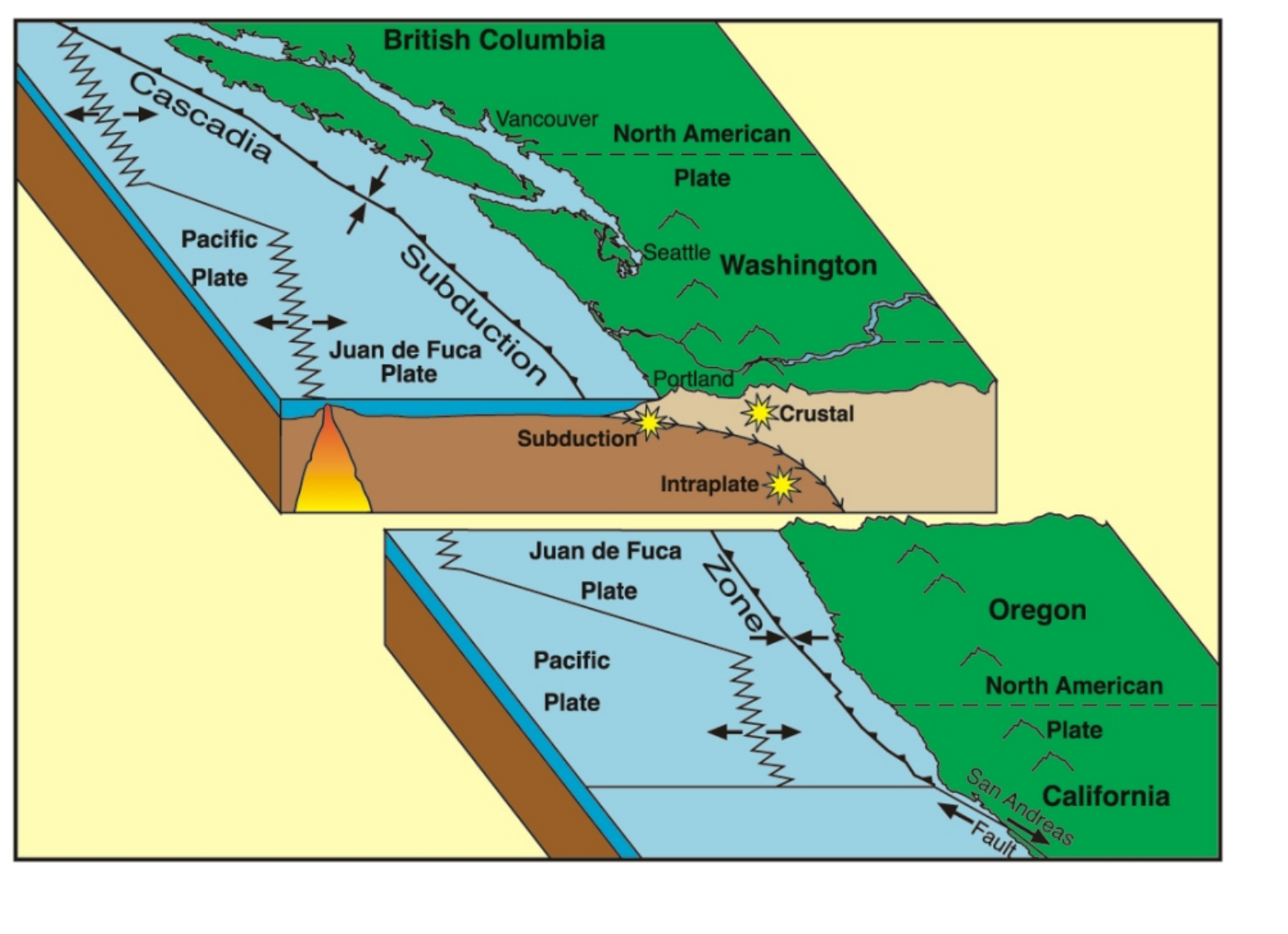

Figure 1. Schematic diagram showing the regional plate tectonic setting of the Pacific Northwest. Oregon is sliced to show the location of the three seismic source zones: subduction, intraplate, and crustal. (Modified from Black and others, 2000)

GEOLOGY AND EARTHQUAKE HAZARDS

Despite the lack of recent, large, damaging earthquakes, earth scientists now understand that earthquake hazards in the Willamette Valley are greater than previously known. This may seem at odds with the experience of long-time residents who can recall only the large earthquakes further north in Olympia in 1949 and Seattle in 1965 versus the relative quiet in Oregon. The recent Nisqually earthquake on February 28, 2001, only seems to further highlight the Puget Sound area as the region more exposed to earthquake hazards. However, two fault zones have drawn the attention of earth scientists with respect to Oregon. In the early 1990s, scientists reached a broad consensus that geologic evidence supports the history of great subduction zone earthquakes, of magnitude 8 to 9, repeatedly striking along the Oregon coast and shaking the western interior of the state. Consequently, the understanding that these great earthquakes occur on average every 500-600 years is one reason that the awareness of earthquake hazards in the western Oregon has increased. In addition, earth scientists are beginning to probe shallow faults near the earth's surface that may further influence earthquake hazard assessments for this part of the I-5 Urban Corridor. A number of major crustal faults are mapped in the Portland area, but how active these faults may be is still unknown.

Geologic Setting

Pacific Northwest earthquakes occur in three source zones: along the Cascadia subduction zone forming the interface between the oceanic and continental plates, within the subducting plate (called the intraplate or Benioff zone), and within the crust of the overlying North American plate. Earthquakes from all three zones threaten the greater Portland/Vancouver area.

SUBDUCTION ZONE

The forces responsible for producing earthquakes in western Oregon and southwest Washington are generated by the Juan de Fuca oceanic plate moving northeastward with respect to the North American continental plate at an average rate of about 4 centimeters (1.5 inches) per year along the Pacific Northwest coast (indicated by the arrow in Figure 1). At the region of contact between the two plates, the Juan de Fuca plate slides (or subducts) beneath the North American continent and sinks slowly into the earth's mantle, producing the Cascade volcanoes and earthquakes. The zone of the shallow, east-dipping subducting plate is called the Cascadia megathrust fault. During subduction, the eastward motion of the Juan de Fuca plate is absorbed by compression of the overriding North American plate, generally resulting in little slip on the Cascadia fault. However, geological evidence provided by buried soil layers, dead trees, and deep-sea deposits indicates to geologists that the upper portion of the shallowly dipping Cascadia fault ruptures offshore and releases this compression in great earthquakes of magnitude 8 to 9 about every 500-600 years. The last such earthquake occurred on January 26, 1700.

When the Cascadia subduction zone ruptures, it will likely cause:

1) Severe ground motions along the coast, with shaking in excess of 0.6 to 0.8 g peak horizontal acceleration in many locations. (The unit 1g is the acceleration of gravity and is used as a measurement of the severity of earthquake ground motion). The central Willamette Valley can expect ground motions of about 0.2g in the areas of less hazardous geology (green regions on map). Shaking levels will be greater westward toward the coast;

2) Strong shaking that may last for two to four minutes as the earthquake propagates along the fault and may include long-period seismic waves that can affect very tall structures and high bridges;

3) Tsunamis generated by sudden uplift of the sea floor above the Cascadia fault. Geologists infer the history of earthquakes in the subduction zone by observing effects of past tsunamis such as marine sediments deposited inland and ancient drowned forests;

4) Shaking effects that may significantly damage the regional lifelines in all of Cascadia's major population centers, from Vancouver, B.C., to Eugene, Oregon.

INTRAPLATE ZONE

As the Juan de Fuca oceanic plate subducts beneath North America, it becomes denser than the surrounding mantle rocks and breaks apart under its own weight, creating earthquakes within the Juan de Fuca plate. Beneath Puget Sound, the Juan de Fuca plate reaches a depth of 40-60 km and begins to bend even more steeply downward, forming a "knee" (see cross-section in Figure 1). The knee is the location where the largest intraplate zone earthquakes occur, such as the 1949 and 2001 events beneath Olympia and the 1965 event beneath the Seattle-Tacoma International Airport.

The lack of significant historic intraplate seismicity beneath western Oregon makes it difficult to assess the potential hazards from this source. The same mechanisms that cause the deep earthquakes beneath the Puget Sound may be active in Oregon. However, although there have been a few intraplate earthquakes beneath the Coast Range and Willamette Valley, there is only one notable event. In 1962 a magnitude 4.5 intraplate earthquake occurred northwest of Corvallis to the south of the map area. This is the most southerly known intraplate event of this size in Oregon.

We do know that intraplate earthquakes have several distinctive characteristics. Because intraplate earthquakes large enough to cause damage occur at depths of 35 kilometers or more, high frequency ground-motion energy attenuates before it reaches the earth's surface. On rock, peak ground accelerations are expected to be about 0.2g to 0.3g for even the very largest events. We note that 0.2g shaking levels can cause substantial damage to poorly built structures and the shaking can be amplified in shallow, soft soils. Furthermore, intraplate earthquakes tend to be felt over much broader areas than crustal zone earthquakes of comparable magnitude. Finally, based on experience in the Puget Sound region, significant after-shocks are not expected for intraplate earthquakes beneath western Oregon.

CRUSTAL ZONE

The third earthquake source zone is the crust of the North American plate. Crustal zone earthquakes, typically of small magnitudes and usually not felt, are the most common earthquakes in western Oregon and southwestern Washington. At magnitude 5.5, the 1981 Elk Lake earthquake (Map and Figure 2) is the largest known North American plate earthquake in the mapped area (the magnitude 5.7 1993 Scotts Mills earthquake occurred just to the south of the mapped area). There are two other events greater than magnitude 5 on the map. The 1961 magnitude 5.1 event at Siouxon Peak is on the southern extension of the St. Helens seismic zone and the 1962 magnitude 5.2 Portland earthquake is located just north of the Columbia River in Clark County. Most of the larger events plotted in Figure 2 are concentrated along the St. Helens seismic zone directly beneath Mount St. Helens and are related to volcanic processes.

There are many mapped faults in the northern Willamette Valley and Greater Portland/Vancouver areas, as shown in Figure 2. For most of these faults, not enough is known to estimate how often the faults might rupture and what magnitude earthquakes could result. Consequently, the hazards from shallow crustal earthquakes are poorly understood. Yeats and others (1996) noted that most of the mapped faults typically consist of short segments striking either northwest or northeast. For most faults, not enough data exist to estimate reliably how often the fault might rupture and what magnitude earthquake would result. Several faults near Portland may pose significant hazards for the city. Two examples are the Portland Hills fault that cuts through the downtown core at the northeast edge of the Portland Hills, and the East Bank fault that strikes parallel to the Willamette river on the east side of Portland (See Figure 2). Based on aeromagnetic data, Blakely and others (2000) suggested that these faults may connect with faults to the south. The length of this suggested zone could be associated with an earthquake of magnitude 7.

Earthquake scenarios for events as large as magnitude 6.8 on the Portland Hills fault predict very significant damage in Portland (Wong and others, 2000), however the frequency of these events remains unknown. Field investigations have found evidence of Holocene faulting in the Portland Hills fault zone, but much more scientific study needs to be done before the geologic understanding allows improvements to earthquake hazard assessments. Likewise, detailed geologic investigations are needed in Clark County and along the St. Helens zone. Although further from major population centers, the St. Helens zone is one of the most active seismic zones in Washington and has a length capable of producing a magnitude 7 earthquake.

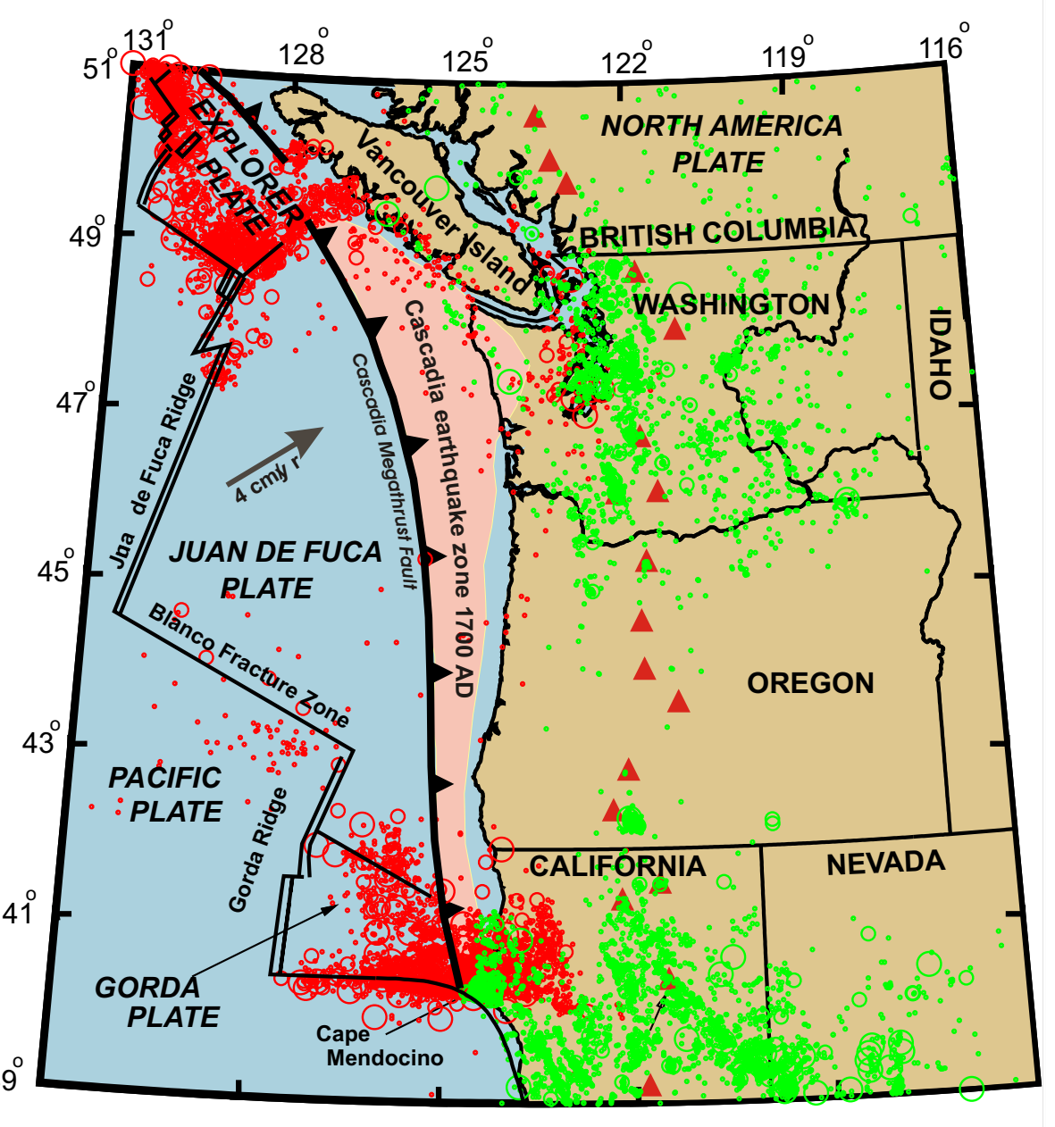

Figure 3. Earthquakes in Cascadia. Known earthquakes greater than magnitude 6 since about 1870, magnitude 5 since 1950, and earthquakes of magnitude 2 and greater located by the modern seismographic networks and catalogued by the University of Washington (www.ess.washington.edu). Smallest circles are magnitude 2, intermediate circles are between magnitude 5 and 6, and the largest circles are greater than magnitude 6. Earthquakes are grouped into two broad zones: red earthquakes occur in the intraplate zone, along with events that occurred within the shallow portion of the Juan de Fuca plate, and shallow crustal events are the green earthquakes. The 1700 AD Cascadia earthquake zone is shown in pink. The red triangles are the Cascade volcanoes.

Earthquake Distribution

Since the Cascadia subduction region stretches the length of the Pacific Northwest coastline, it is useful to consider the distribution of earthquakes across the entire plate boundary system and examine the regional picture formed by integrating all three source zones. In Figure 3, we show known earthquakes greater than magnitude 6 since about 1870, magnitude 5 since 1950, and earthquakes of magnitude 2 and greater located by the modern seismographic networks. The red earthquakes occur in the intraplate zone and within the shallow portion of the Juan de Fuca plate. Shallow crustal events are plotted in green.

Compared with earthquakes in the intraplate zone, crustal events are much more widespread, occurring over much of northwestern California and most of Washington. However, with the exception of the Klamath region in the south and the northern Oregon Cascade Range, Figure 3 shows that there are relatively few earthquakes in much of Oregon and that the Willamette Valley is particularly quiet. In spite of the fact that scientists know from field studies that subduction events are possible, there are no recent Cascadia zone earthquakes that have been located in Oregon. Thus, in the absence of recent significant seismic data, Figure 3 illustrates the importance of conducting more geological field studies and examining evidence of historical earthquakes in order to link recent earthquakes to faults and create a more complete understanding of the potential for future significant earthquake occurrences in the greater Portland/Vancouver region.

Probabilistic Ground Motion Map

A useful representation of earthquake shaking hazards is a probabilistic ground-motion hazard map, which the USGS has developed for the entire country (Frankel and others, 1996, http://geohazards.cr.usgs.gov/eq/index.html). These maps underpin seismic building codes and many highway construction standards. The probabilistic hazard map (Figure 4) shows the expected peak horizontal ground motions on a rock site with a 2% probability of being exceeded within a time frame of 50 years. Figure 4 includes all three potential earthquake sources for the Northwest: subduction zone, intraplate zone, and crustal faults. These maps rely on local geological and seismological data. Note that along the coast the contour lines strike north. Here the hazard is dominated by the subduction zone source, which also runs north-south. Moving eastward into the Greater Portland/Vancouver area, the inland contours broaden. This change reflects increased rates of seismicity in the northern Oregon Cascade Range (Figure 3) and along the St. Helens seismic zone (Figures 2 and 3). Further north, the eastward bulge of higher expected ground motions in the Seattle area reflects the high rate of large-magnitude intraplate earthquakes in this region.

The east-west oval contour of relatively higher hazard in central Puget Sound reflects current scientific understanding of the Seattle fault and illustrates how increasing the detailed geologic knowledge of an individual fault may change hazard assessment. For example, an area of higher hazard around the Seattle fault was included in some recent maps because field and seismic studies demonstrated that large (M 7.0) earthquakes have occurred on the Seattle fault in the past. Geologic studies examining faults are in progress in western Oregon to fine-tune the regional hazard assessments.

Earthquake Hazards

When an earthquake occurs, some of the most important earthquake hazards, with respect to the lifelines, are shown on the map: ground shaking, liquefaction, and earthquake-induced landslides. We note that even though there is considerable uncertainty as to how often earthquakes may hit the greater Portland/Vancouver area, it is possible to evaluate and improve estimates of potential earthquake damage.

Ground shaking occurs in a wide area following an earthquake. Because of the complexity of the three source zones, the probabilistic hazard map (see Figure 4) can be used as an initial guide to identify areas of strong shaking. However, engineers know from experience that unconsolidated young deposits often amplify low to moderate ground motions, sometimes by a factor of two or more. Poorly consolidated soils are typically found in river and stream valleys and areas of artificial fill. The detailed maps prepared by DOGAMI discuss key factors affecting amplification (see for instance Madin and Wang, 2000). Areas of unconsolidated deposits shown on the map in beige should be viewed with caution as ground motions in these areas will likely be more intense than those predicted for rock sites. Significant sections of the lifelines in the Willamette Valley and southwestern Washington cross areas of unconsolidated materials that may amplify ground motions.

Liquefaction is another hazard in areas of unconsolidated young deposits. Strong shaking may cause the pore pressure within water-saturated sandy soil to dramatically increase causing the soil to lose its shear strength and its ability to support large loads, such as buildings and roads. For areas adjacent to a riverbank, or on a gentle slope, ground can move laterally, carrying with it buried pipelines and foundations. Generally, many of the same areas subject to amplified ground shaking are also susceptible to liquefaction; thus the beige-shaded areas on the map carry additional hazard significance.

Steep slopes may produce landslides during earthquakes. An important lesson for the greater Portland/Vancouver area from the large earthquakes in Puget Sound is that not all landslides occur in the first few minutes following an earthquake, but can occur days later. In 1949, a large landslide near Tacoma slipped 3 days after the earthquake. Steep slopes along the edges of the Willamette Valley and southern Washington, often near saturated conditions because of high rainfall, are candidates for earthquake-induced failure, though we have not delineated these areas.

As earth scientists improve their estimates of crustal fault behavior in the Greater Portland/Vancouver area, it is possible that surface rupture may become a concern. In the Seattle area, recent discovery of young faults breaking to the surface has enabled the identification of a zone in central Puget Sound where surface rupture may occur. Although for any given earthquake the chances of surface rupture may be small, it may be appropriate for lifeline system engineers to consider such a possibility.

LIFELINE VULNERABILITY TO EARTHQUAKES

The vulnerability of a lifeline to earthquakes depends on the type and condition of lifeline structures and on the severity of the specific earthquake hazard. Lifeline building structures can be vulnerable to earthquake shaking, just as are some residential and commercial building structures. There are many special types of lifeline structures and components such as substation equipment, transmission towers, or pipelines. Damage to one of these system elements may disrupt the capacity of the system to function as a whole.

Pipelines: Water, Wastewater, Liquid Fuel, and Natural Gas

Buried pipelines carrying water, wastewater, natural gas, and liquid fuel can be vulnerable to surface faulting, strong shaking, liquefaction and lateral spreading, and landslides. Pipelines constructed of brittle materials are the most vulnerable because they are not able to bend and flex. Water and older gas distribution (low pressure) systems often have significant amounts of brittle cast iron pipe. Asbestos cement pipe found in many water systems is also brittle. Pipelines constructed of relatively ductile materials such as steel and ductile iron are more resistant to earthquake-induced failure. If liquefaction occurs, joint restraint is also important to prevent ruptures. Modern welded joints used on gas and liquid fuel lines, and "restrained" joints used for some water pipelines are preferred in areas subject to liquefaction. Pipelines buried in liquefiable soils can be susceptible to damage rates an order of magnitude larger than those in stable soils.

Natural gas and liquid fuel pipelines constructed of steel with modern welded joints have performed well except in the most extreme conditions of large permanent ground displacements. Pipeline joints welded with older techniques are in some cases more brittle, and have failed.

During an earthquake, it is common for many water pipelines on soft soils to fail, which can quickly drain the water system. Furthermore, after such failures, water is not available for fire suppression. This scenario occurred following the 1995 Kobe (Japan), 1994 Northridge (California), 1989 Loma Prieta (California), 1923 Tokyo (Japan) and 1906 San Francisco (California) earthquakes. In the worst earthquakes, such as Kobe, the water service was not fully restored for more than two months.

Sewer pipelines are vulnerable to flotation if the ground around them liquefies. As these are often gravity-operated systems, a change in grade can impair system operation. In the 1965 Seattle earthquake, a 108-inch diameter sewer was damaged when it floated upwards approximately two feet. Many sewers floated in the 1989 Loma Prieta earthquake, particularly in Santa Cruz, and in the 1995 Kobe Earthquake.

The Nisqually earthquake caused approximately 25 water pipeline failures, fewer than 10 natural gas distribution line failures, one sewer failure, and no natural gas transmission or liquid fuel line failures.

Tanks and Reservoirs

Earthquakes can cause liquids, such as water and liquid fuels, to slosh in tanks and reservoirs. Sudden ground motion and subsequent movement of the base of a tank can load a tank wall beyond capacity. An unanchored tank may rock resulting in connecting piping to break. As sloshing continues, rocking may cause the tank to buckle or burst. Sloshing can also damage tank roofs and immersed components such as baffles and sludge rakes. In the Nisqually earthquake approximately 15 water tanks were damaged, none catastrophically (Figure 5). Tanks containing liquid fuel have been damaged, and their contents burned. Earthen reservoirs and dams can also be vulnerable to liquefaction and embankment failure. For example, the Lower Van Norman Dam was damaged by liquefaction in the 1971 San Fernando (California) earthquake although no catastrophic water release occurred.

Electrical Power Facilities

Regional power systems went out of service following the 1995 Kobe, 1994 Northridge, and 1989 Loma Prieta earthquakes. Such power losses are often due to self-protecting features engineered into the system, and can often be restored within 24 to 72 hours. Many of the power losses in the Seattle area from the 2001 Nisqually earthquake were of this type.

The most vulnerable components of electrical power systems typically are high-voltage porcelain insulators. The higher the voltage, the larger and more vulnerable the insulator is to strong shaking. As a result, high-voltage substations, particularly 230 kV and above, can be vulnerable to moderate to strong earthquake ground shaking. Live tank circuit breakers, commonly used in industry, have not performed well in earthquakes. Rigid busses connecting substation equipment can transfer dynamic loads from other equipment, and exacerbate insulator failures. If well anchored, lower voltage equipment functions well. Ground motions from the Nisqually earthquake were not strong enough to produce significant damage at most substations.

Power poles and towers have performed well, except when they are founded on unstable soils where landslides or liquefaction can occur. In the 1993 Landers (California) earthquake, a fault ruptured through the base of a four-legged transmission tower. The tower was distorted, but it did not collapse. Ground shaking can cause low-voltage power lines to slap together causing short circuits. Higher voltage lines have greater separation, and thus are less prone to short circuits.

Highways

Bridges are usually the most vulnerable components of highway systems. More robust bridge designs were developed in the 1970s and 1980s. Older bridges, built to lower design standards, may be more prone to failure. Bridge decks can slide off their seats if the seats are too narrow or the seats are not adequately restrained. Supporting columns can buckle if they are over-loaded and not designed with adequate ductility. Single-span bridges supported on abutments perform better. Bridge foundations in liquefiable soils can move, allowing the spans they support to slide off.

The Nisqually earthquake caused significant damage to about a dozen bridges and highway structures (Figure 6), but none collapsed. A major intersection at the junction of Interstate 5 and Interstate 90 in downtown Seattle was closed for several weeks while inspections and repairs were made. Bridge damage caused closure of northbound lanes of Interstate 5 for 12 hours in Chehalis, and the Alaska Way viaduct in Seattle was closed intermittently for weeks to assess and repair earthquake damage. The Deschutes Parkway was closed for weeks in Olympia due to lateral spreading (Figure 7). Landslides caused closure of highways 101, 202 and 302 (Figure 8).

Railways

Railway bridges in general performed well as a result of the very large loads they are designed to carry. Earthquakes in the U.S. and Japan have not tested the resistance of railroad bridges to liquefaction or lateral spreading but either mode of ground failure could cause loss of bridge approaches. In addition, a variety of hazards such as failed overpasses, building debris, and ground failures could affect railroad right of ways.

Airports

Airport runways may be vulnerable to liquefaction. In the 1989 Loma Prieta Earthquake, 3000 feet at the end of the main runway of the Oakland Airport were taken out of service when liquefied sand erupted through runway joints. The Nisqually earthquake caused a similar failure at Boeing Field where most of the largest liquefaction zones correlated with old river channels. Airport control tower glass is vulnerable, as many tower structures are not adequately designed to transfer the roof load to the structure. Control towers at both the Seattle-Tacoma airport (Figure 9) and Boeing Field were damaged during the Nisqually earthquake.

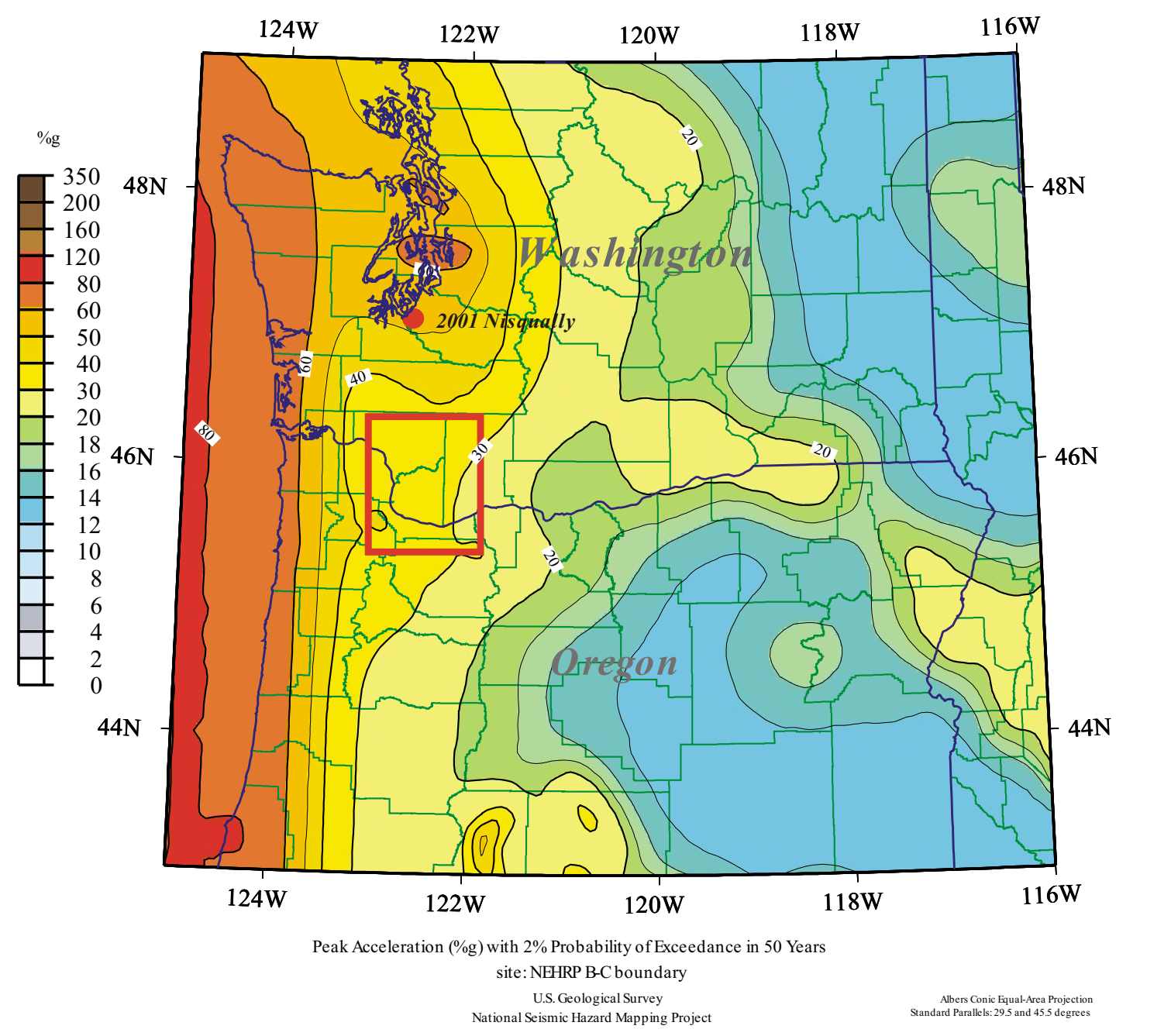

Figure 4. Probabilistic hazard map for portions of Oregon and Washington. The map shows the ground motions with a 2% probability of being exceeded in 50 years. Darker colors represent higher hazards; details are given in Frankel and others (1996) and at www.geohazards.cr.usgs.gov/eq/. The location of the 2001 Nisqually earthquake is shown by the red filled circle. The red box shows the location of the Cottage Grove to Woodburn, Oregon, I-5 Urban Corridor map.

ABOUT THE MAP

The base map is from standard USGS 30-meter digital elevation models (DEM's). Shorelines and streams are from USGS digital line graphs (DLG's) derived from standard 1:100,000-scale maps (see http://edc.usgs.gov/geodata/). This map is based on material originally published in U.S. Geological Survey Open-File Report 99-387.

Earthquakes and geologic units on the map

On the map, we have plotted located earthquakes from the University of Washington earthquake catalog ranging in magnitude from 2.0 to 5.5. Nearly all located earthquakes are shallow and occurred in the crust of the North American plate. Most of the events are located in the northeastern portion of the map and are along the St. Helens seismic zone or beneath Mount St. Helens. These later events reflect volcanic processes at Mount St. Helens. To the north, the 1981 Elk Lake earthquake, of magnitude 5.5, is the largest event on the map. Two other notable earthquakes on the map are the 1961 Siouxon Peak earthquake along the St. Helens seismic zone and a magnitude 5.2 earthquake in 1962 near Portland. The St. Helens seismic zone is the most active crustal earthquake area in Washington.

The geologic units shown on the map have been simplified into two basic units represented by the map colors of beige and green. The beige colors represent unconsolidated surface deposits, which are susceptible to liquefaction, ground amplification, and/or landslides triggered by a seismic event. Surface rocks and deposits considered to be seismically less subject to liquefaction, amplification, or landslides than the young deposits are shown in green. These units consist of bedrock and older well-consolidated deposits. Geologists working on this project reached a consensus on which mapped geologic units should be placed into each category. One way to refer to these units is to consider the beige areas as probably more hazardous relative to the green areas in terms of possible earthquake hazards. The geological information varies across the map area as a result of compiling several data sources reflecting different mapping scales from local to regional studies. The different geologic sources occasionally result in abrupt artificial boundaries due to data source boundaries. Please refer to references and the legend inset map for more details.

The lowest resolution data are based on a statewide building code soils map developed at a scale of 1:500,000 by Walker and McLeod (1991) and a preliminary version of the Washington NEHRP map (Palmer and others, 2003). Wang and others (1998) divided the very near surface geologic units into six types, of which types A-C fall into the green category, and D-F into the beige category. These data primarily cover the western and eastern edges of the lifeline map. The intermediate resolution data are taken from the 1:100,000 map of Quaternary time deposits in the Willamette Valley mapped by O'Connor and others (2001). Generally, hilly areas adjacent to the floor of the valley have been categorized as seismically less hazardous, green, whereas areas on the valley floor are all covered by less-consolidated deposits and are categorized as probably more hazardous ground, beige. The beige and green categories from both the 1:500,000 and 1:100,000 maps are determined solely on descriptive geologic information and do not incorporate engineering analyses.

The highest resolution data are from 1:24,000 scale hazard maps produced by DOGAMI for many Oregon communities and by the Washington Department of Natural Resources for the Vancouver area. The Portland Metro area has been complied as an IMS map at a scale of 1:62,500 from underlying hazard maps at a scale of 1:24,000. These IMS and GMS series maps plot relative earthquake hazards in four zones ranging from A, highest hazard to D, lowest hazard. Areas in zones A to C are beige on our map and zone D is green.

Communities with completed relative earthquake hazard maps are listed in Table 3.

City or Urban Area	DOGAMI Publication or Washington DNR Number	Year
McMinnville-Davton-Lafayette	IMS-7	1999
Newberg-Dundee	IMS-7	1999
Portland Metro	IMS-1	1997
Sandy	IMS-7	1999
St. Helens-Columbia City-Scapoose	IMS-7	1999
Vancouver, Washington	GM-42	1994
Woodburn-Hubbard	IMS-8	1999

***Table 3**: Communities on this map with completed relative earthquake hazard maps. The DOGAMI publication is repeated in the full citation in the reference section.*

MORE INFORMATION

There are many good sources for more information concerning earthquakes and the effects of earthquakes in the Willamette Valley. The Oregon Department of Geology and Mineral Industries has considerable expertise in evaluating and explaining earthquake issues (www.sarvis.dogami.state.or.us) and Oregon Emergency Management has information available regarding earthquake response and mitigation (www.osp.state.or.us/oem/). Both of these sites have many links to other resources. Current earthquake activity is available at www.ess.washington.edu. Complete details for national hazard maps can be found at the following USGS site: www.geohazards.cr.usgs.gov/eq/. A detailed study of the effects of various scenario earthquakes from each of the three source zones is available at www.eqe.com/impact. The Federal Emergency Management Agency maintains a long list of materials related to earthquake preparedness, mitigation, and response planning (www.fema.gov). The American Red Cross has details on personal preparedness (www.redcross.org). The Cascadia Regional Earthquake Workgroup (www.crew.org) is regional private-public partnership dedicated to increasing earthquake mitigation efforts in the Pacific Northwest.

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Figure 5. Water tank anchor damage in the Nisqually earthquake. The anchor is about 6" in length. (Ballantyne photo).

Figure 6. Short-column damage at Holgate overcrossing of Interstate 5 in Seattle caused by Nisqually earthquake. (Photo courtesy of Mark Eberhard, University of Washington,

Figure 7. Road failure at Capital Lake in Olympia caused by lateral spreading. This roadway also failed in the 1949 and 1965 earthquakes. (Photo courtesy Steve Kramer, University of Washington, www.maximus.ce.washington.edu).

Figure 8. Road failure on Washington highway 302 caused by landsliding during the Nisqually earthquake (Ballantyne photo).

Figure 9. Control tower failures at Seattle-Tacoma International Airport during the Nisqually earthquake. No one was seriously injured by the debris. (photo courtesy Carl Nelman, Boeing Company, www.maximus.ce.washington.edu).