referenced. Though the Nisqually earthquake is not the worst case earthquake Seattle may experience or even the design level earthquake, this earthquake indicates what is likely at the lower end of property damage costs associated with a significant earthquake. The EERI scenario was referenced for the costs associated with the loss of income due to businesses' inability to operate and costs associated with casualties. In terms of 2007 dollars, the estimated financial impact to Seattle ranged from $53 to $91 million.

For upgrade and retrofit costs, the Federal Emergency Management Agency's (FEMA) 157 and 276 documents were referenced, along with costs associated with improving URM buildings to FEMA's Life Safety performance level. At this performance level, the building sustains damage to those portions that were resisting a design level earthquake, but the gravity system and emergency egress routes remain intact and falling hazards are minimized. In terms of 2007 dollars, the resulting structural-only upgrade cost estimates ranged from $358 to $431 million. In terms of total project cost, considering architectural/nonstructural costs and excluding the variable historic preservation and disabled access upgrade costs, the estimated total project upgrade costs ranged from $900 million to $1.1 billion.

5.6 Other Cities in High Seismic Areas

Cities such as Oakland and Berkeley, California, have seen significant upgrades to their URM buildings since 1990. The upgrades have been funded through private funds and typically occurred after the URM building had been sold. These cities have ordinances that indicate the level to which the building's lateral system is expected to perform. Hence, the combination of significant economic reinvestment in the URM buildings from private owners wanting to be in areas experiencing redevelopment and city ordinances regarding upgrading of potentially hazardous URM buildings has resulted in this significant upgrade rate.

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Limitations

The professional services described in this report were performed based on available as-built information and limited visual observation of the structure. No destructive testing was performed to qualify as-built conditions and to verify the quality of materials and workmanship. No other warranty is made as to the professional advice included in this report. This report provides an overview of the City's unreinforced masonry buildings and does not address individual building's status. This report has been prepared for the exclusive use of the City of Seattle's Department of Planning and Development and is not intended for use by other parties, nor may it contain sufficient information for purposes of other parties or their uses.

The professional services described in this report are based on limited visual observations only. No testing was performed to qualify as-built conditions and to verify the quality of materials and workmanship. No calculations have been made to determine the adequacy of the structural system or its compliance with accepted building code requirements.

This report does not address portions of the structure other than those areas mentioned, nor does it provide warranty, either expressed or implied, for portion of the existing structure.

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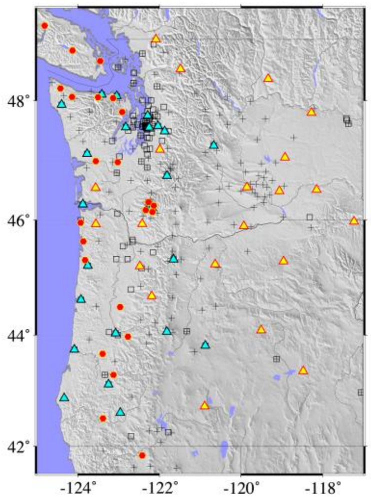

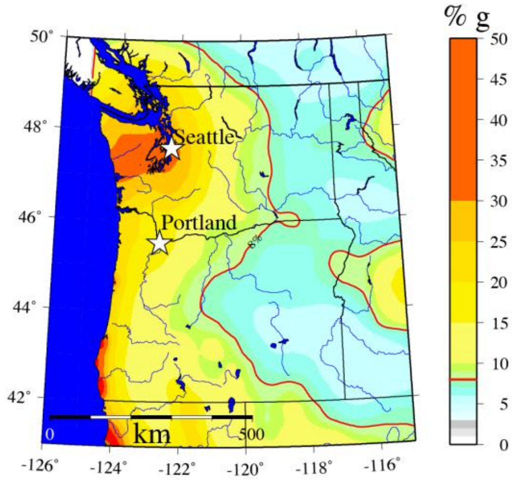

Earthquake Hazard Background:

The state of Washington is exposed to the second highest seismic risk of any state. Together, Washington and Oregon expect average annualized earthquake losses exceeding $570M (FEMA, 2006). Washington has experienced at least 20 damaging earthquakes during the past 125 years. Large earthquakes in 1946, 1949, and 1965 killed 15 people and caused more than $200 million (1984 dollars) in property damage. Most of these earthquakes were in western Washington, but several, including the largest historic earthquake in Washington (1872), occurred east of the Cascade crest. The M6.8 2001 Nisqually event was the most recent and expensive – "The damage caused by the quake is estimated at more than $3.5 billion, yet only some $350 million of the loss was insured" (www.crew.org), with the impact of the event mitigated by its location more than 30 miles deep.

The next M9 Cascadia-subduction-zone earthquake, which has average recurrence intervals of 300-500 years, will not only expose millions to strong shaking, but many coastal communities to possible inundation from tsunami. A large Seattle fault earthquake would severely shake the heart of metropolitan Seattle. Washington also host volcanoes of the highest-risk category.

Roles of the PNSN:

The Pacific Northwest Seismic Network (PNSN) at the University of Washington was established to monitor earthquakes that reflect the seismic and volcanic hazards in the states of Washington and Oregon. We envision a society armed with the information, tools, and knowledge to protect itself from earthquake damage. Our mission is to provide rapid and accurate technical information about seismic ground motions and hazards in the region.

In Washington State, the PNSN works in concert with the Washington Department of Natural Resources (DNR) to inform the Emergency Management Division (EMD) and other agencies (e.g., WSDOT, county and municipal emergency managers, building code planners) for disaster response and long-term seismic hazard mitigation.

Before earthquakes we supply background information and tools for planners, the public, educators, and researchers to understand likely events and consequence of future earthquakes. **During earthquakes** we record ground motions, and report this information as rapidly as possible to our regional and national partners and the public. **After earthquakes** we inform disaster responders and planners about their possible consequences and effects, and interpret the technical data for local officials and the public.

The PNSN collects data from hundreds of seismometers to issue alarms and notifications in near real-time: larger earthquakes (M>3) are reviewed by a seismologist and announced within 10 minutes. A series of products such as ShakeMaps are generated for serious earthquakes, and the seismograms are sent swiftly to a permanent Internet-available data archive for the use of scientists and engineers.

Current Advances:

Recently, increased support from Washington State has enabled PNSN to increase staffing. With the assistance and support of the United States Geological Survey (USGS) Advanced National Seismic System (ANSS), this staffing will increase the reliability, automation, and speed, of producing earthquake products for our state regional and national partners, and assuring that we can provide public safety information during very damaging earthquakes.

We have replaced much ageing and failing hardware, and have added fail-over servers in the event of unforeseen problems with our central processing computer. We have instituted an upgrade plan for remote data acquisition systems to increase reliability and data quality. We purchased, and have deployed several times, a flexible component of field stations to respond to swarms and aftershock sequences in sparsely-instrumented parts of the region and to perform targeted experiments needing denser data coverage than provided by the permanent network. We completed the production of High-Resolution ShakeMaps for Seattle/King County, which gives a more detailed picture of the exposure in the highly urbanized area to strong shaking. We have coordinated closely with state and local officials to try to meet their information needs.

We are undertaking 2 major network upgrades during the next year that will further modernize and standardize our backbone network operations. The first is the incorporation of 21 state-of-the-art seismic monitoring stations, purchased from the National Science Foundation's EarthScope experiment with the help of a generous grant from the J. P. Murdock Foundation. The second is an upgrade to a new database-driven data acquisition developed by our national ANSS partners. This new system will increase our network's reliability and response time with more rapid processing and more automation of routine network operations. And we are continually working to upgrade our data telemetry paths with the goal of making them more secure, robust, and easier to maintain.

Possible Future Enhancements:

Four enhancements that will be key to accomplishing our mission will require further resources to accomplish. Leveraging with Federal agencies makes these options possible, and each would cost roughly $200k/yr for the State of Washington. These include:

1. GPS

To permit more rapid and accurate assessment of strong earthquakes in Washington for the Emergency Management Division, we hope to integrate existing realtime high-sample-rate GPS from about a hundred locations into PNSN earthquake monitoring. Central Washington University is the collection point for Washington GPS data, so this effort would be collaborative.

Key goals are:

- Stream realtime, processed, high-sample-rate GPS data from CWU into the PNSN to use in earthquake analysis.
- Develop near-real-time analysis tools to exploit the GPS positioning data and integrate them with seismic data processing.
- Extend the use of GPS to monitoring of key infrastructure (See item #3 below).

2. NetQuakes

A complementary way to densify seismic network coverage that concentrates on urban regions has been proposed by the US Geological Survey, and is known as NetQuakes. NetQuakes provides a dense array of 500 extra seismic stations to be relatively easily and cheaply deployed.

A 500 station deployment of NetQuakes, shown in the map, would meet Washington State's need for rapid situational awareness to guide the immediate post-earthquake response, with the benefit of strengthening earthquake early warning in the future. This dense array would include critical highway and railway bridges, public schools, hospitals, and other key buildings and structures, currently unmonitored. The densest deployment is in the Tacoma-Seattle-Everett urban corridor, with the array becoming less dense northward to the Canadian border and west of Puget Sound. A ring of stations is included from the mouth of the Columbia River to Port Angeles to greatly improve the immediate assessment of a Cascadia earthquake.

3. Structural Instrumentation

In the immediate aftermath of a damaging, or potentially damaging, earthquake rapidly and accurately assessing the state of health of critical infrastructure is a priority. Public safety threat reduction while permitting the swiftest possible return to normal operations would be facilitated by recording the motion of critical structures. Given engineering expertise, these data could be interpreted to assess the likelihood of structural damage.

GPS plus seismic observations work three ways.

(1) Sensors report in real time the measured levels of shaking and drift, and derived from that, estimates of probability of damage at instrumented sites. (2) Recordings of smaller earthquakes would provide site characterization for more accurate forecasts of likelihood of strong shaking in future strong earthquakes. (3) Recordings of structural response to ambient noise can provide clues when structural integrity has degraded.

4. NEWS (Network Early Warning System)

NEWS detects a major earthquake with the goal of providing warning *before* the strong shaking arrives. Earthquake early warning is likely to play an important role in earthquake mitigation in the PacNW, as it does now in Japan. In Cascadia, the best possible case would give the city of Seattle perhaps 300 seconds of advance warning before the strongest shaking from an M9 subduction earthquake starting in the south of the Oregon. An earthquake starting closer, say on the Seattle fault, would give a few to 20 seconds of warning. Early warning systems rely on dense station coverage, reliable and robust telemetry, and accurate and fast data processing techniques. Thus, the use of GPS (#1 above) and QuakeNet (#2) are essential for an effective NEWS. Uses include moving emergency vehicles out of underground garages, shutting down critical computing systems gracefully, moving elevators to the nearest floors, moving trains out of tunnels, providing public notice, etc.

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Cascadia Deep Earthquakes

2008

CREW
AHEAD OF THE WAVE

Cascadia Region Earthquake Workgroup
Sharing Information to Promote Mitigation

Also published as Open File Report 2008-1 by the Washington Division of Geology and Earth Resources

Deep earthquakes

Deep earthquakes pose a serious risk to Cascadia. In Puget Sound, for example, there is an 84% chance of a magnitude 6.5 or greater deep earthquake striking within 50 years. Beneath northwestern California, northwestern Oregon and southwestern British Columbia the probability of a similar sized earthquake over 50 years is somewhat lower, but still a major component of the earthquake hazard in each area.

The most recent deep event was a M6.8 earthquake on February 28, 2001, centered under the Nisqually delta. Building walls crumbled, bridge supports cracked, and the cost ultimately tallied at $4 billion. The number of injuries exceeded 400, but resulted in only one death.

The Nisqually earthquake was 'deep', because the fault slipped almost 30 miles (50 kilometers) underground. Deep earthquakes are particularly important because of their frequency. Preparing for a deep earthquake will help prepare you for other types of earthquakes that put the region at risk.

Deep earthquakes characteristics in Cascadia

- They occur generally below depths of 18 miles (30 kilometers) on fractures within the subducting seafloor plate. Northern California deep earthquakes may be shallower.
- They are usually less than M7.5.
- Damaging deep earthquakes occur every 10-30 years in the Puget Sound area.
- Because the faults break so deeply, the seismic wave energy they radiate spreads over a much larger area than in a shallow quake. A larger area experiences significant shaking, although much less so directly above the fault, than in a similar-sized shallow quake.
- Few, if any, aftershocks occur.
- No tsunami is expected, although landslides could trigger local tsunamis.

Potential hazards

Primary hazards include ground shaking (which can be increased locally by poor soils) and ground failure (including liquefaction and landslides). These can also produce secondary hazards, such as ruptured utility lines, hazardous spills, and fires. Damage to buildings and bridges is probably the most visible and dangerous. Unreinforced masonry (URM) and other types of buildings can fail, burying streets with rubble or trapping people inside. Other types of buildings are also at risk. Failed bridges can disrupt entire neighborhoods for months after an earthquake.

Recent earthquakes

Recent deep earthquakes in the Puget Sound area show similar general patterns of damage, though the details of each was different, depending on the size of the event, the epicenter, and the affected built environment.

Deep earthquakes have also occurred under Pender Island, British Columbia; Corvallis, Oregon; and northwestern California.

Potential future earthquakes

Four enclosed maps show potential peak ground accelerations (pga) for deep earthquakes centered beneath several Cascadia locations. PGA is one measure of shaking, which can help forecast areas of damage. Local soil conditions and building vulnerability also influence the amount of damage.

Pender Island, British Columbia
The heaviest damage is likely to be concentrated on Vancouver Island and along the Strait of Georgia.

Everett, Washington
Much of the Puget Sound area would be at risk.

Beaverton, Oregon
This earthquake could destroy many URMs in the greater Portland-Vancouver (Washington) area.

Northwestern California
Deep earthquakes here contribute a significant hazard between Cape Mendocino and southernmost Oregon.

Lessons for the future

The Nisqually earthquake showed that mitigating hazards before an earthquake can pay off. Homeowners who reinforced their chimneys were spared having to repair or replace them. Companies in upgraded buildings and with effective contingency plans were able to continue their operations. Post-disaster recovery starts before the earthquake hits, with preparation and mitigation plans. Steps for earthquake planning:

- Take care of people first. Prepare a family plan. Businesses and governments must help their employees stay safe and know their families are safe.
- Learn about your local earthquake hazard.
- Have a response plan and practice it.
- Assume that utilities and transportation lines may not be available immediately after the shaking.
- Know where the most vulnerable buildings and other structures are and work with others to develop and implement plans to strengthen them.

Why deep earthquakes matter

If you live in Cascadia, you'll probably experience a serious, damaging earthquake in your lifetime. Scientists estimate that within 50 years, there's an 84% chance of a magnitude (M)6.5 or higher deep earthquake occurring in the Puget Sound region. The odds are less for Oregon and northern California, but still significant.

This means every person, every business, and every organization in the region is nearly guaranteed to face the consequences of a deep, damaging earthquake. Such earthquakes strike, on average, every 30 years, with the latest in 2001, 1965 and 1949. Several of them are reviewed later in this paper.

On February 28, 2001, Puget Sound was rocked by an M6.8 deep earthquake centered about 30 miles (50 km) beneath the surface. It was felt from British Columbia to Utah, though the property damage was largely confined to western Washington. Building walls crumbled, bridge supports cracked, and the cost ultimately reached $4 billion. More than 400 injuries resulted, but fortunately, only one death.

While not the largest earthquakes expected in Cascadia, the frequency of deep earthquakes makes them particularly important. If you live west of the Cascade Range, preparing for a deep earthquake will minimize the effects on you and the region when all types of earthquakes occur.

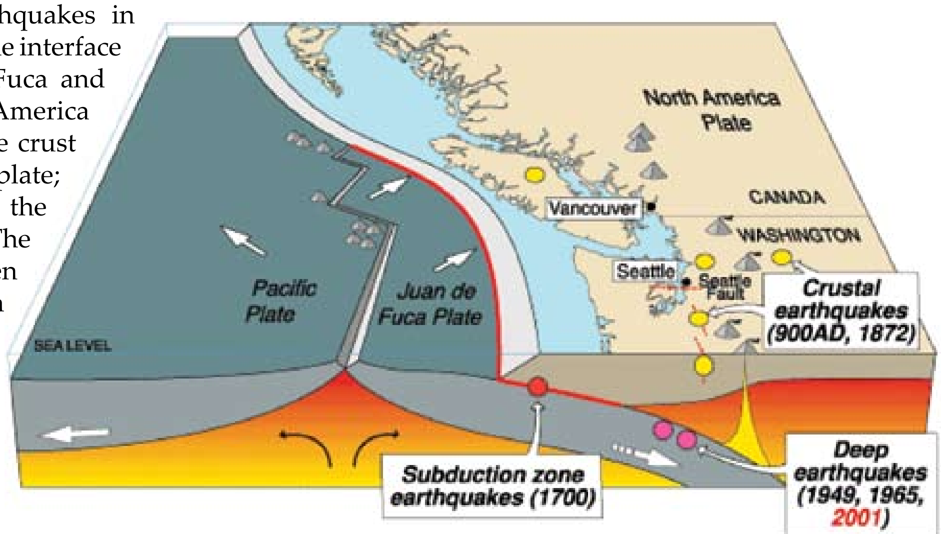
The Cascadia subduction zone stretches 800 miles (1,300 km) from the Brooks Peninsula, Vancouver Island to Cape Mendocino, California. As the Juan de Fuca and Gorda plates descend beneath the North America plate (red hachured line), active geologic processes affect the entire overlying region. Map: Oregon Department of Geology and Mineral Industries (DOGAMI)

Earthquake characteristics

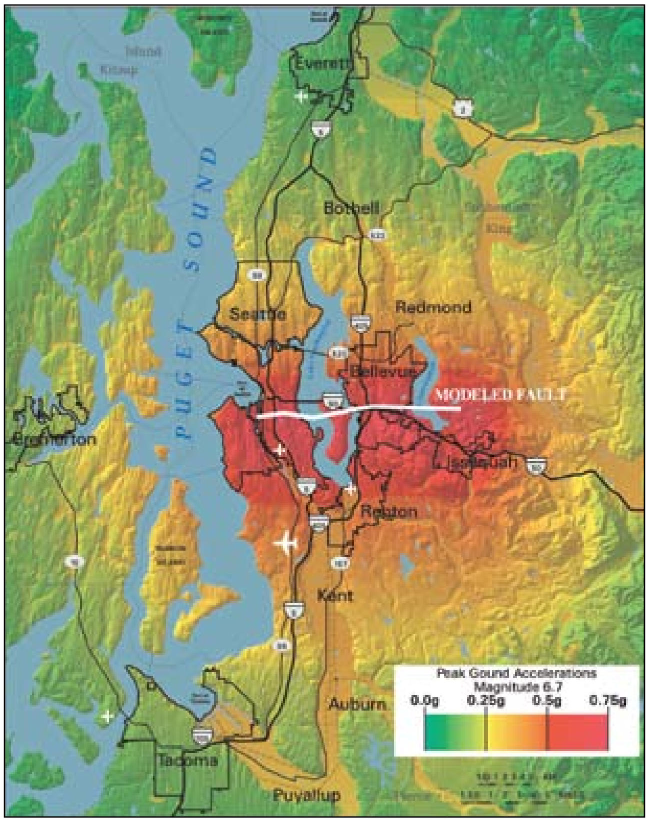
Three source zones produce earthquakes in Cascadia. Deep events start below the interface between the subducting Juan de Fuca and Gorda plates and overlying North America plate. A second zone lies within the crust of the overlying North America plate; this hosts shallow earthquakes like the 1994 Northridge, California event. The third zone is on the interface between the subducting plate and the North America plate. Because of its great extent, it can break over an enormous area, causing chaos across all of Cascadia. Each type exhibits a specific set of characteristics.

Deep earthquakes

Deep earthquakes take place within the oceanic plate as it descends, or subducts, beneath the North America plate. Several



Deep, shallow (or crustal), and subduction zone earthquakes each initiate in a different section of the Earth's interior, as shown above. The frequent occurrence and widespread effects of deep earthquakes means everyone should prepare for them. Map: United States Geological Survey (USGS)



In 2005, the Earthquake Engineering Research Institute and the Washington Military Department published a scenario for an M6.7 earthquake on the Seattle Fault (which would be a shallow event). The report was written by an interdisciplinary team of scientists, engineers, and emergency managers from throughout the region.

The map above shows the approximate location of the fault trace on the surface (white line), along with areas (in red) that would likely suffer the greatest damage. Peak ground accelerations (pga) of .10g to .20g could cause slight damage, with major damage occurring at higher pga values. Map: USGS

terms are used to describe these events, including slab, intraslab, intraplate, subcrustal, Wadati-Benioff zone, and Benioff zone earthquakes.

Deep earthquakes in Cascadia exhibit a specific set of characteristics:

- They occur on faults within the subducting Juan de Fuca plate. (Beneath northwestern California, deep earthquakes occur within the Gorda plate.) Beneath Puget Sound, deep earthquakes occur at depths of about 30 to 50 miles (80 to 45 km); beneath northwestern California the depths are somewhat shallower, on the order of 25 miles (40 km).
- They are usually less than M7.5.
- Damaging deep earthquakes occur every 10-30 years in Puget Sound, less frequently elsewhere.
- Because the faults that break during the earthquake are so deep, the seismic wave energy they radiate spreads over a much larger area than in a shallow quake. A larger area experiences significant shaking, although much less so directly above the fault, than in a similar-sized shallow quake.
- Few, if any, aftershocks occur.
- No tsunami is expected, although landslides could trigger local tsunamis.
- In the past 150 years, most damaging deep earthquakes have been in the Puget Sound area. Recent examples include the 2001 Nisqually (M6.8), the 1965 Seattle (M6.5), and the 1949 Olympia (originally measured M7.1, now revised to M6.8) earthquakes in Washington.

Shallow earthquakes

- They occur within the continental crust of the overlying North America plate, generally at depths of less than 20 miles (35 kilometers).
- They are expected to be less than M7.5.
- Because of the abundance of shallow faults, small earthquakes are recorded every day in Cascadia. The presence of these faults directly under the surface, sometimes in populated areas, means that damaging shallow earthquakes occur every few decades. Any specific fault may produce an earthquake every few hundred years or every few thousand years.
- Strong shaking generally lasts a few seconds to a minute or so, although it could be longer in localized areas.
- Aftershocks are common and may cause further disruption.
- Tsunamis are unlikely, though there could be a local tsunami from landslides, or from shallow earthquakes occurring under Puget Sound, the Strait of Georgia, or large lakes and rivers.

- Several significant Cascadia earthquakes were shallow, including the 1946 Vancouver Island, British Columbia (M7.3), 1993 Scotts Mills, Oregon (M5.6), and 1954 Eureka, California (M6.5) events.

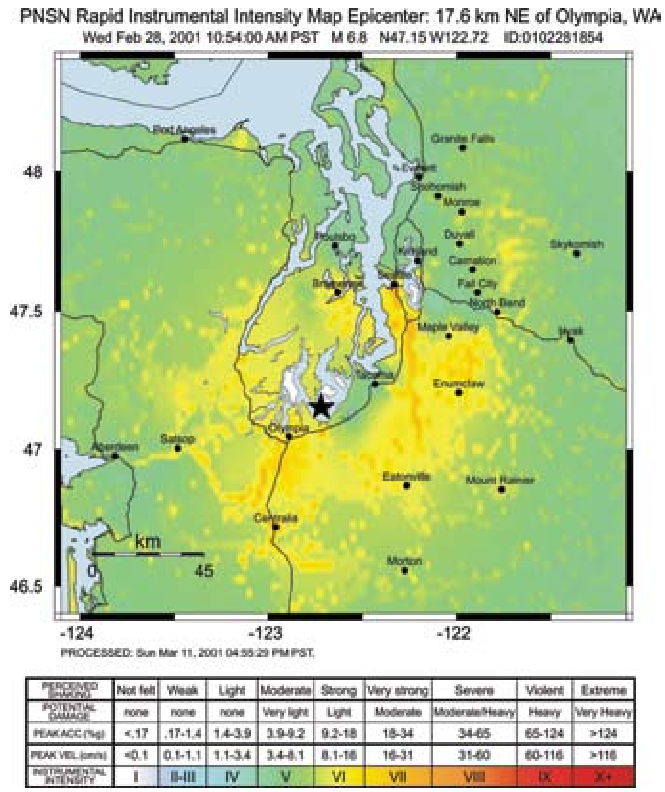
Subduction earthquakes

- The Juan de Fuca and Gorda plates (offshore northern California) descend, or subduct, beneath the North America plate. Large areas of the interface between the two plates act as if stuck, causing stresses to build. Eventually the stresses reach the breaking strength and the two plates slip rapidly, releasing the stresses. Huge areas may slip, generating very large earthquakes that radiate strong seismic waves throughout Cascadia.
- They can be as large as M9.
- Geological evidence suggests an average of 500 years between events.
- Depending on location, strong shaking might be felt for several minutes.
- Injuries and fatalities could number in the thousands, and hundreds of buildings could be destroyed.
- Many aftershocks will occur; some in the M7 range are possible, creating the potential for additional damage.
- A destructive tsunami will quickly hit the Cascadia coast, and travel across the Pacific Ocean toward Alaska, Hawaii, and Asia.
- The last Cascadia earthquake occurred on January 26, 1700. Previous quakes were in the years (approximately) 900, 750, and 400.

Similar magnitude, different outcomes

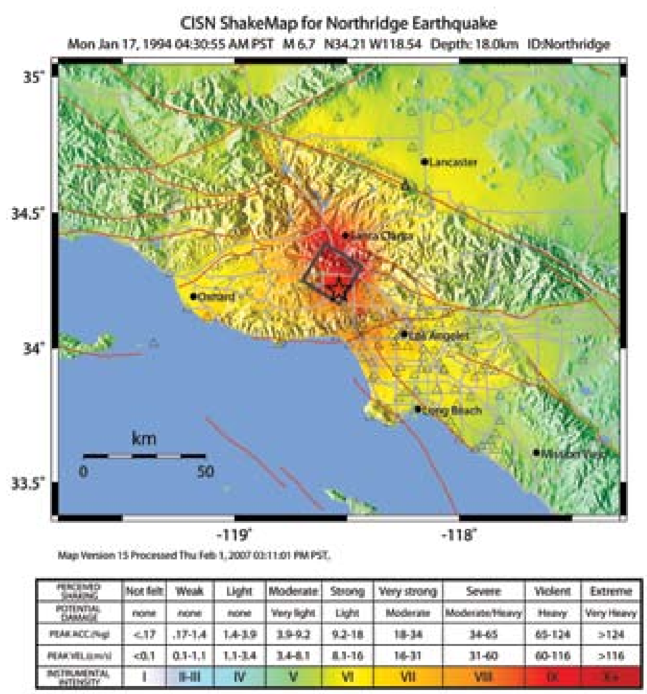
A comparison of the effects of the Nisqually earthquake and those of the 1994 event in Northridge, California (M6.7) illustrates the differences between deep and shallow earthquakes. The smaller, shallow (11 miles or 17 km deep) Northridge event caused 72 deaths and economic damage of more than $12 billion. The deep Nisqually earthquake produced only one death and losses of $4 billion. Although Northridge was a more developed area, part of the difference was due to the different source regions of the earthquakes.

The Nisqually earthquake occurred when a deep fault broke, radiating seismic waves as the two sides of the fault slipped several feet within a few seconds. Because the waves originated from such depth, they traveled farther to reach the surface, losing energy along the way, and spreading out laterally. As in all deep earthquakes, the area directly above the epicenter felt less severe shaking than from a shallow earthquake of the same magnitude, but the shaking affected a larger area overall.



These maps compare the intensity of shaking felt in the 2001 Nisqually earthquake (above) and the 1994 Northridge earthquake (below).

The distance and intensity scales of the maps are identical. The deep earthquake at Nisqually shows a wide area of potential damage, but Northridge shows a concentration of heavier damage near the epicenter.



This photo of a building in Olympia after the 2001 Nisqually earthquake shows typical damage from a deep earthquake. A major source of injury is falling parapets, such as those seen above. Photo: Josh (Robert) Logan, DGER

ShakeMaps, maps of shaking intensity generated nearly instantly, help emergency responders, and provide a basis for assessing region-wide damage, as well as providing public information in the aftermath of a large earthquake. ShakeMaps are automatically produced by computers receiving measurements of actual shaking levels from continuously operating monitoring instruments.

Comparing the maps on page 3 from the M6.8 Nisqually and M6.7 Northridge events shows the difference between deep and shallow events. The ShakeMaps have identical distance and intensity scales. Intensity measures the effects of an earthquakes, which can be estimated from the ground motions recorded by monitoring instruments in the region. It is different than magnitude, which directly measures the size of the earthquake; that is, it measures a characteristic of the earthquake itself, not its effects.

Shallow earthquakes like Northridge cause destruction near the epicenter, evident in the larger, but concentrated red area on the Northridge ShakeMap. However, the yellow area, indicative of light damage, is more widespread on the Nisqually map than the Northridge map. Shallow earthquakes commonly have numerous aftershocks, which can cause more damage. Deep earthquakes have few, if any, aftershocks.

What kind of earthquake should you prepare for?

In the Puget Sound area, as mentioned above, the chances of a deep earthquake larger than M6.5 in the next 50 years is 84%. The chances are 15% for a shallow event, and 10-14% for a subduction earthquake. In your area, the exact percentages for each type of event may differ, but damage from a deep earthquake should be considered.

Preparations can reduce earthquake damage. Repairs to homes, offices, schools, and other buildings can be expensive. Earthquake insurance deductibles are typically high. After a large event, federal funds may be available, but they may be in the form of loans, or may not cover your entire loss. Many small businesses that close because of an earthquake never reopen.

Whatever measurers you take will also prepare you for the other two types of earthquakes. In addition to preparing your own home and having an emergency plan, earthquake hazard reduction calls for regional planning and preparation. Individuals and companies can be part of broader discussions about what needs to be done and how to do it.

Hazards in a deep earthquake

Ground shaking: Some soil types cause earthquake waves to amplify, causing increased shaking and damage. The risk of amplification increases on deep, soft soils, especially on valley bottoms and areas of artificial fill. These soils can be identified before an earthquake. Most areas at risk can be identified from soil studies done for land use planning and development, or on geologic maps.

Ground failure: Sandy soils saturated with water can liquefy — behave like a liquid — during an earthquake. Major earthquake destruction is often found on these soils, which are prevalent along rivers, streams, and lakes. Liquefaction can seriously damage buildings, bridges, pipelines, and roads by undermining their foundations and supports.

Earthquakes can also trigger landslides. These may happen immediately, or can occur days, even weeks, later. The more water there is in the soil, the more likely are landslides. Lateral spreading is a specific type of landslide that forms on very gentle slopes. It can, for example, cause roadways to break up.

After shaking and liquefaction, the ground must resettle. Differential settlement can cause structures to tilt, resulting in structural and nonstructural damage.

Tsunami: Deep earthquakes do not produce tsunamis because they do not significantly disrupt the ocean floor or inland waterways. Landslides could produce localized tsunamis, but they are rare in the history of Cascadia.

Secondary hazards

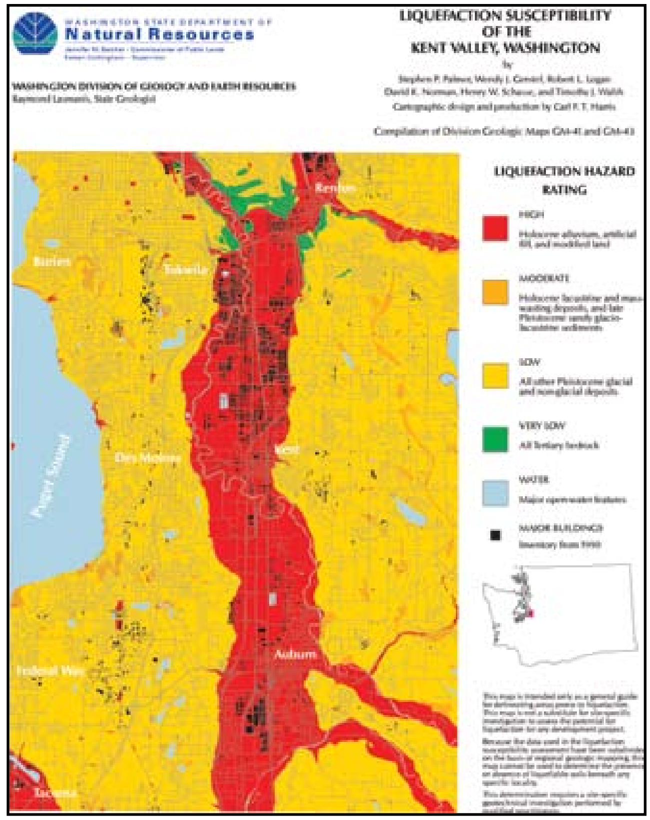
Fire: Fire often destroys property after an earthquake. Ruptured gas lines may provide fuel, and broken water lines hinder firefighters' efforts. Gas lines turned off to prevent fire may not be restored for days, causing other hardships.

Hazardous materials: Hazardous materials may be spilled from commercial or industrial sources, but they can also be released in households. Serious problems can happen if the contents of several containers mix — such as ammonia and chlorine bleach.

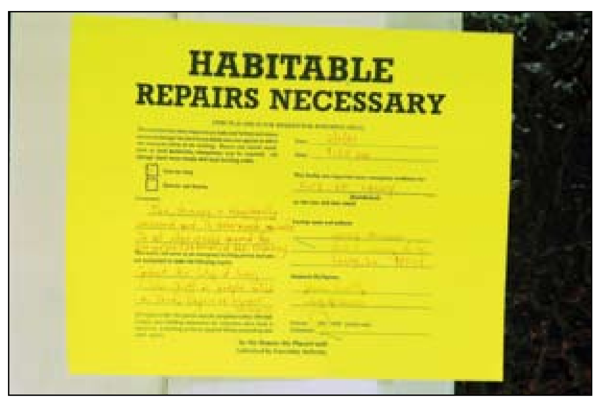
In addition, trucks carrying hazardous materials may be stuck on roadways if highways and bridges have to be closed.

Building vulnerabilities: Much damage and injury in earthquakes results from structural failures. However, we can reduce building vulnerability.

As we've learned more about the earthquake danger in Cascadia, building codes have been upgraded. The buildings most at risk in an earthquake include unreinforced masonry buildings (URMs) and nonductile



Many areas of potential liquefaction have been mapped. These are among the most likely places to have damage in an earthquake. The above map shows potential liquefaction sites in the Kent Valley, Washington, south of Seattle. Red shows the highest risk. Black areas are concentrations of major buildings. Map: Washington State Division of Geology and Earth Resources (DGER)



Many structures, utility lines, and transportation systems (road, air, rail, port) need to be inspected after a large earthquake. Structures can be given a yellow tag, like this one, meaning it can be used to some extent but repairs must be made. A red tag means the structure cannot be used until it is repaired. Photo: William S. Lingley, DGER

This house shifted off its foundation, breaking the utility lines and leaving it uninhabitable. Newer building codes require a house being tied to the foundation, but homeowners may need to retrofit older homes. Photo: USGS

Closed businesses and disrupted streets, like this one after the Nisqually earthquake, can be a problem for the economic health of communities. Photo: Robert J. Reid

concrete-frame buildings. URMs are generally built with brick walls and wood or concrete floors that are poorly connected to the walls. Nonductile concrete frames have very little steel reinforcement and are very brittle when subjected to earthquake motions.

Wood-frame homes generally fare well in earthquakes. But chimneys and brick facings can collapse and windows can break. If not securely fastened together, a house may separate from its foundation, disconnecting utility lines and making the house unlivable.

The design of a building, as well as construction material, also affects its vulnerability. The more square or rectangular a building shape, the more likely it can withstand shaking. Parts of individual structures or closely-spaced, adjacent buildings may pound against each other. Soft stories, such as parking levels, open retail space, and other floors with insufficient strength are more susceptible to collapse in earthquakes.

The most common type of damage is nonstructural. All buildings can suffer nonstructural damage, resulting in injuries and economic losses. Falling debris like bookshelves, light fixtures, and computers can be dangerous, even at home. Furniture moving across a floor, pipes breaking and spilling contents, and parapets falling from buildings are just a few examples that can be avoided by relatively inexpensive nonstructural strengthening before earthquakes occur.

Mitigating nonstructural hazards is usually less expensive than reinforcing or rebuilding existing structures. It also can be done in stages, as resources permit. The best time to address building structural and nonstructural deficiencies is in conjunction with other planned major renovations.

It's not over when the shaking stops

Damaged bridges, destroyed building walls, and impassable roads are examples of obvious and immediate earthquake damage. Some dangers may not be immediately apparent — as in landslides that occur days after the shaking.

Closed businesses are not just a problem for the owners, but for the employees who lose jobs and the overall economic health of the city, which loses tax revenue particularly needed to cover the extra expenses of earthquake repairs. Damaged roads, bridges, and other transportation lines can snarl traffic and delay the arrival of supplies needed for rebuilding.

Although fortunately rare where enforced building codes exist, deaths and serious injuries do occur, and take their own toll on a community.

It is easier and less expensive to take precautions before an earthquake than to experience and pay for the cleanup after one.

Recent deep earthquakes

The epicenters of several Cascadia deep earthquakes during the last hundred years were in the Puget Sound region. However, they can also be centered under British Columbia (an M5.6 earthquake in 1909 off Vancouver Island caused damage in British Columbia and Washington), Oregon, and California.

Their frequent occurrence, the high population density in the areas likely affected, and the damage pattern of these events, means all of Cascadia needs to be aware of deep earthquakes.

Looking at the past helps us understand what the next earthquake might look like, keeping in mind that deep earthquakes provide relatively gentle reminders of the inevitable, but less frequent, catastrophic subduction zone earthquakes that loom in Cascadia's future. The 2001 Nisqually earthquake, the most damaging recent event in Cascadia, is described in a separate section.

Chimney failures are a common problem for homeowners after an earthquake. The above chimney did not fall but remained a safety hazard until it was rebuilt. Photo: Michael Polenz, DGER

1949 Olympia

A deep earthquake at 11:55 AM on April 13, 1949 was centered between Olympia and Tacoma, along the southern edge of Puget Sound. The original magnitude of 7.1 has been revised to M6.8. It was felt from British Columbia to Montana to California.

Eight people were killed and dozens seriously injured. Two of the dead were children: one was crushed by falling brick while working as a crossing guard and one was the senior class president at Castle Rock High School.

Olympia, Seattle, and Tacoma incurred property damage estimated at $200 million (in 2006 dollars). The most severe damage was centered between Seattle and Chehalis, with 40% of Chehalis' business buildings and houses damaged. About 10,000 chimneys in Western Washington needed repair.

Thirty Washington schools, normally serving 10,000 students, were damaged in 1949. Ten of these schools were condemned and permanently closed Three Seattle schools were torn down and one rebuilt. Fortunately the 1949 and 1965 earthquakes occurred during spring vacation, sparing more school children from fatalities and injuries.

In Olympia, almost all large buildings were

The Long Beach, California school above shows how dangerous old, brick buildings can be. In the 1949 Olympia earthquake, the Senior Class President of Castle Rock High School was killed by falling bricks. The gable on the school collapsed, even though the structure was more than 50 miles (80 kilometers) from the epicenter. Photo: USGS

During the April 1949 earthquake, the owner of the Busy Bee Cafe barred the doors to keep panicking patrons from rushing outside. Seconds later, brick fell from the top of the Hotel Seattle, crushing several cars. Photo: Seattle Post-Intelligencer Collection, Museum of History & Industry; All Rights Reserved

Landslides are an often-overlooked danger of earthquakes. They are particularly likely during rainy, water-soaked winter months in Cascadia. Almost 40 miles (60 kilometers) from the epicenter, this section of the Union Pacific Railway was left dangling after the hillside fill beneath it slid away in the 1965 earthquake. A sewer main also broke. Photo: University of California, Berkeley

damaged to some extent, including eight structures on the Capitol grounds. Water and gas mains broke, and electric and telegraph services were interrupted.

In Tacoma, many chimneys were knocked to the ground and many buildings were damaged. The Tacoma Narrows bridge sustained damage. South of Tacoma, railroad bridges were thrown out of alignment.

In Seattle, houses on filled ground were demolished, many old brick buildings were damaged, and chimneys toppled. Because of old construction and unstable ground, most buildings in Pioneer Square received some damage.

Water spouted from cracks that formed in the ground at Centralia, Longview, and Seattle. One new spring developed on a farm at Forest.

1962 Corvallis

At 7:45 AM on September 1, 1962, an M4.5 deep event struck northwest of Corvallis. Because of the earthquake's small size, there was no damage. However, it does demonstrate that Oregon is at risk from deep earthquakes located inside its own borders, as well as from those centered in Washington and California.

1965 Seattle

At 7:28 AM on April 29, 1965, an M6.5 earthquake struck very near the 1949 epicenter. It killed seven and caused damage of $100 million (in 2006 dollars).

Falling debris killed three people: one on South King Street in Seattle's Pioneer Square and two at Fisher Flouring Mills on Seattle's Harbor Island. Four elderly women died from heart failure attributed to the earthquake.

In general, damage patterns repeated those from the 1949 shock. Some buildings damaged in 1949 sustained additional damage in 1965. One example is the Alki Beach section of West Seattle, where a majority of chimneys were knocked down in 1949, and again in 1965.

The greatest devastation in 1965 occurred in West Seattle, Harbor Island, the Duwamish River Industrial Area, and South Seattle. Numerous bridges were damaged along the Duwamish Waterway and River blocking boat traffic along the river. Failures affected virtually every building, pier, and facility at Harbor Island and along the Seattle waterfront.

In Tacoma, damage occurred mainly to cornices and chimneys of older structures built on soft ground in lowland areas and on firmer gravel in highland areas.

In Olympia, damage was primarily confined to the old part of the city and to areas of the port built on artificial fill. The State Capitol Building was temporarily closed and government departments moved to nearby motels while buildings were being repaired.

Eight Seattle schools normally serving 8,800 students were closed until safety inspections could be carried out.

In general the most vulnerable buildings were those having unreinforced masonry walls with sand-lime mortar. Wood-frame houses came through quite well, although a few had cracked plaster or chimney failures. Split-level homes fared worse because the two sections of the houses vibrated at different frequencies, concentrating stress along the junction between the sections.

1976 Pender Island

At 1:35 AM on May 16, 1976, an M5.3 earthquake, about 40 miles (70 km) deep woke the residents of Pender Island (to the east of Vancouver Island).

The earthquake jolted people awake and even knocked people out of their beds in White Rock. The Lower Mainland and southern Vancouver Island sustained slight damage. Banks alarms rang out, windows broke, and dishes rattled in Victoria. Electrical service was cut in Richmond, South Vancouver, and the Sechelt Peninsula.

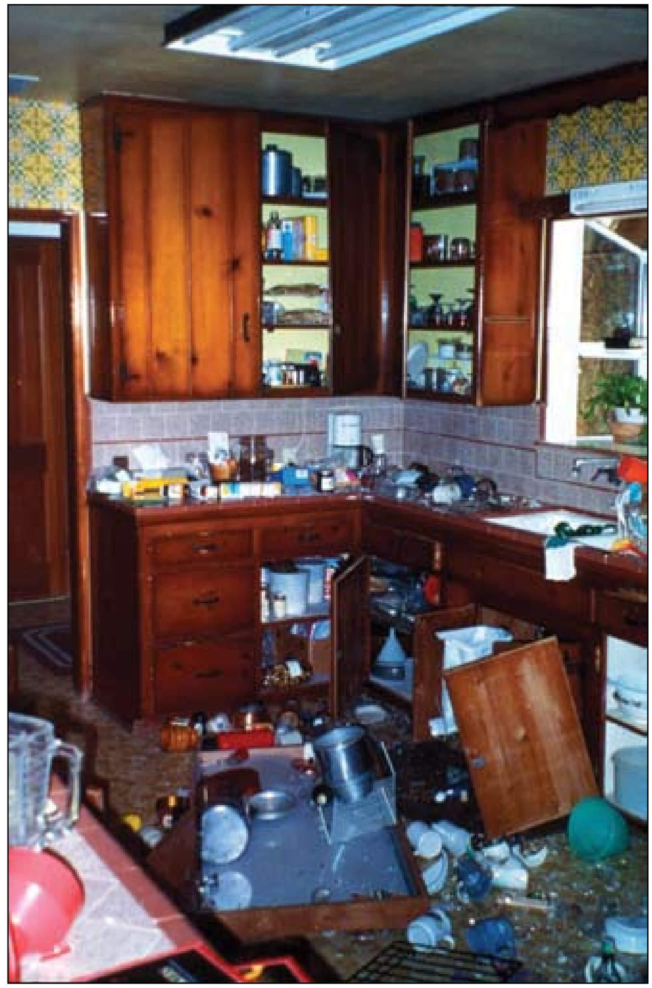
Although small and without significant consequence, this earthquake provides an important reminder of the risk that local deep earthquakes pose to British Columbia.

1999 Satsop

A M5.9 earthquake shook the Pacific Northwest on July 2, 1999, at 6:44 PM. It was centered beneath Satsop, just west of Olympia, and felt from British Columbia to Idaho to Oregon.

The most visible damage was to the Grays Harbor County Courthouse in Montesano, an unreinforced mansonry building from 1910. The cupola atop a clock tower was extensively damaged, and interior walls showed new cracks. Total damage to county buildings was estimated at $10 million.

The Montesano fire station, built around 1979, also suffered structural damage. A number of other fire stations in the county were damaged.



Falling walls are not necessary for injuries to occur. Kitchens can be a place of major nonstructural damage. Glassware, dishes, and food containers can fall from shelves. Cleaning supplies can fall off shelves and break. Mixing of some chemicals, like chlorine bleach and ammonia, can produce serious hazards. Photo: P. W. Weigand, California State University at Northridge

The historic Grays Harbor County Courthouse in Montesano, Washington suffered several million dollars' worth of damage in the 1999 earthquake. Photo: Grays Harbor County

Gas leaks, toppled chimneys, and power outages were reported all over Grays Harbor County after the earthquake. More than 300 homes needed repair.

Many of the brick and concrete buildings in Aberdeen were damaged. These included a furniture store built of unreinforced masonry, which suffered a roof and exterior wall collapse. The city lost power following the earthquake, but it was fully restored by the following morning. Several water main breaks were reported. There was a gas leak reported downtown and the Grays Harbor PUD shut off the natural gas supply for a day after the earthquake.

The Gorda plate: Off the northwestern California coast

Major Gorda earthquakes

Year	M	Location
1899	7.0	West of Eureka
1922	7.3	West of Eureka
1923	7.2	Cape Mendocino
1980	7.2	Gorda Plate
1991	7.1	West of Crescent City
1992	7.2	Cape Mendocino
1994	7.1	Off Coast
2005	7.2	Gorda Plate

Although often considered as a single subduction zone, Cascadia actually contains two subducting plates – the larger Juan de Fuca plate and the smaller Gorda plate off the northwestern California coast (see the map on page 1).

The Gorda, the North America and the Pacific plates meet at the Mendocino Triple Junction, located just seaward of Cape Mendocino.

Off northern California, there is a fourth earthquake source zone that contributes to the hazard and risk of the region. The flat-lying section of the Gorda plate immediately north and west of the triple junction is one of the most seismically active areas in North America. Since 1899, eight earthquakes greater than M7 have occurred here. One event, the 1992 Mendocino earthquake, occurred on the southern portion of the Cascadia subduction zone; the other events were further offshore.

2001 Nisqually

On February 28, 2001 at 10:54 AM, an earthquake measuring M6.8 was centered near the Nisqually delta north of Olympia. It shook Puget Sound and beyond. One person died from a stress-induced heart attack and there were 400 injuries, including 27 head injuries from falling brick. After the shaking stopped, 40,000 people applied for FEMA assistance. Damage was estimated at $4 billion. Only 10% of that was insured.

The earthquake caused evacuations from Victoria to Oregon (along the coast and in the mid-Willamette Valley), and was felt as far away as Salt Lake City, Utah.

The damage pattern showed the importance of local soil and geological conditions. Seattle and Olympia had numerous damaged buildings. Although Tacoma sits between these two cities and did suffer some damage, as detailed in sections below, it was substantially less affected than the other metropolitan regions. This is clearly shown on the intensity map on page 3.

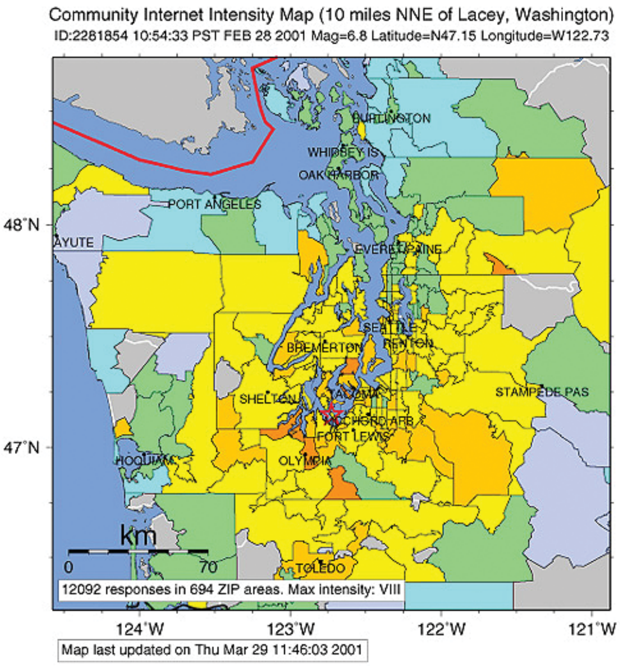
Damage to buildings

Most of the property damage occurred very near the epicenter in Olympia; in nonductile concrete or masonry (URM) buildings, such as those in the Pioneer Square and SODO neighborhoods of Seattle; and in areas of poor soils, such as near Sea-Tac Airport. Repairs to more than 350 historic buildings in Washington cost an estimated $50 million. Nonstructural damage was extensive, though generally not life-threatening.

Even in these areas, however, there were success stories. The SODO Center building, home of Starbucks, originally built in 1914 and expanded over the next few decades, sustained little structural damage. The building owner had retrofitted the structure to improve seismic performance and Starbucks had extensive contingency planning in place. Although operations had to be temporarily relocated, its business was able to sustain the interruption

The Capitol building in Olympia had to be closed for over three years because the dome shifted. It had previously been damaged in 1949 and 1965. Other buildings on the Capitol campus were also closed for repair. Damage forced Washington's Governor Gary Locke to move out of the Governor's Mansion, and he reported watching their television bounce off its shelf, nearly hitting his young son. In all, 27 buildings were closed in Olympia.

URMs in Olympia and Seattle were hit hard. Several buildings had wall collapses and more than a thousand



INTENSITY	I	II-III	IV	V	VI	VII	VIII	IX	X+
SHAKING	Not felt	Weak	Light	Moderate	Strong	Very strong	Severe	Violent	Extreme
DAMAGE	none	none	none	Very light	Light	Moderate	Moderate/Heavy	Heavy	Very Heavy

A Community Internet Intensity Map for the Nisqually earthquake was immediately generated online by the USGS. An Internet survey asked people to record whether they felt the earthquake and how strong it was. The results are displayed by zip code area. The earthquake was felt outside the area shown on this map, but this shows where it was most intense.

The red star shows the epicenter, and colored areas on the map indicate the intensity, as described in the key. Map: USGS

Earthquake retrofits and other preparations paid off at the SODO Center for Starbucks. They were able to sustain the interruption due to the earthquake. Photo: A. Sanli and M. Celebi, USGS; and S. Akkar, METU, Turkey

Successful preparation: Project Impact

The damage in Seattle could have been much worse without the seismic upgrades made just before the earthquake.

Project Impact, a now discontinued Federal Emergency Management Agency (FEMA) program, was intended to help communities reduce future damage from earthquakes. It worked quite well in Seattle.

"Seattle Emergency Management provided overall project coordination and fund management of its $1 million Project Impact grant, which was completed in 2001. City of Seattle has institutionalized Seattle Project Impact and we are committed to continuing these efforts well into the future, including managing additional grants and regional partnerships.

"Over the life of the Project Impact grant, approximately half of the money was spent on the Home Retrofit program, the overall goal of which is to encourage homeowners to structurally retrofit their homes. Seattle Public Schools received most of the remaining money for non-structural Schools Retrofit. The last component of the grant supported better Hazard Mapping."

From the Seattle City website. For more information, go to: http://www.seattle.gov/emergency/programs/projectimpact.

were red-tagged (too dangerous to remain open) or yellow-tagged (seriously damaged and only partially usable). The most common damage was cracking or partial collapse of walls and loose bricks from falling parapets and chimneys. More than 300,000 buildings were damaged. After one year there were still 17 red-tagged buildings and 204 yellow-tagged.

Wood-frame and more modern constructed buildings performed well. However, downtown Olympia and select neighborhoods around Seattle had heavy chimney damage, usually the most vulnerable part of wood houses. In west Seattle, areas suffering damage in the 1965 earthquake experienced a high rate of chimney damage. Damage was also concentrated along the Seattle fault zone.

In Seattle, 75 schools reported mostly light damage. The Seattle School District had focused on nonstructural upgrades that undoubtedly prevented injuries. Typical projects had secured items such as bookcases, library shelves, ceiling light fixtures, wall-mounted speakers, computers, and vending machines.

All hospitals in the area stayed open, though some had nonstructural damage. One Seattle hospital spent $3 million in repairs, having to replace 85 seismic joints. In Steilacoom, south of Tacoma, a building at Western State Hospital was red-tagged, so the staff had to transfer patients to another ward.

A fire station in Ashford, east of Tacoma, was red-tagged because of severe cracking.

New buildings built to updated building codes or to structures retrofitted to current standards fared well, although even they experienced nonstructural damage.

Minor damage was found as far away as Victoria, British Columbia, including broken pipes and windows, and small cracks in walls.

Shelter

The American Red Cross opened seven shelters on the day of the disaster. Four days later they were all closed. The scant need for shelter may be connected to the type of buildings damaged, most being commercial and governmental properties. Only about 200 homes and apartments were seriously damaged.

Small business losses

The Small Business Administration granted 6,253 low-interest loans, totaling $834 million. They approved 61% of applications to the program.

A University of Washington survey taken after the earthquake found that 75% of the business owners surveyed paid for damages out of their own pocket, without insurance or government loans.

Roads

Most damage to roads was because of liquefaction and landslides.

The northbound lanes of US 101 west of Olympia slid away during the earthquake and were closed until a detour was established.

Two lanes of I-405 in the Renton area buckled because the earthquake rerouted groundwater, which then pressed against the surface of the freeway.

The Deschutes Parkway in Olympia closed for more than a year. Liquefaction of fill under the Parkway caused part of the road to slide into Capitol Lake. Solid fill materials were added to the road's foundation to compensate for the high water table in the area, but it may not be a permanent solution. Repairs totaled $5 million.

A landslide caused significant damage to five houses, as well as the roadway, on Maplewild Avenue in Burien, which was built in the 1930s on a steep slope. Repair costs exceeded $7 million. Because Maplewild is a Federal Arterial, it was eligible for $6.6 million in federal aid.

On SR 202 near Snoqualmie Falls, the shoulder fell away about six inches and a 900-foot long crack developed in the road.

SR 302 east of Allyn had a quarter-mile stretch where the lanes dropped several inches and left significant cracks in the pavement. Repairs cost $1.4 million.

Bridges

Washington State Department of Transportation (WSDOT) inspected nearly a thousand bridges, finding damage, mostly light, at 40 of them. The City of Seattle reported mostly light damage to 22 other bridges, and other counties around the epicenter found similar damage. Very few bridges, mainly among those built before 1980, had to be closed for an extended time.

Undoubtedly this success reflects an extensive retrofit program, implemented during the

The South Park Bridge in Seattle suffered extensive damage. Above is one of 22 columns that cracked in the earthquake. Epoxy was injected to shore up the structure. Crews worked round the clock to repair this and other structures throughout the area. Photo: King County

Liquefaction, lateral spreading, and landslides damaged many roads throughout the area. Photo: William S. Lingley, DGER

Olympia's Fourth Avenue Bridge was closed after the earthquake because of severe damage (above). The rebuilt structure (below) is an asset to the community, not only because of its aesthetics, but because it was designed for pedestrians and bicyclists as well as automobiles. Above photo: Robert J. Reid; Below photo: Timothy J. Walsh, DGER

decade before the earthquake, that upgraded many bridges. Three in Seattle (the Ballard, Fremont, and University bridges), each more than 80 years old, were seismically retrofitted before the earthquake, and escaped damage.

Seattle

The Alaskan Way Viaduct along the waterfront was (and remains) a great concern after the earthquake. WSDOT made $3.5 million in immediate repairs to keep it functional and began semi-annual earthquake inspections to closely monitor cracks, structural movement and foundation integrity. A long-term plan for this structure is still being developed, with any replacement costs certain to be in the billions of dollars.

The Magnolia Bridge was closed for nearly four months. Immediate repairs cost $3 million, but the span is due to be replaced because of its age. Funding has not yet been identified, but Seattle is hoping to start construction in 2009.

The Holgate Street overpass over I-5 was closed a few days.

The SR 99 Spokane Street Viaduct was closed briefly due to minor damage to existing seismic retrofit features.

The 1st Avenue S. Drawbridge on SR 509 had minor damage that cost $500,000 to repair.

The eastbound on-ramp to Interstate 90 at 4th Avenue S. experienced minor cracks.

Olympia

The Fourth Avenue bridge, built in 1920 and retrofitted in 1949, was severely damaged and closed. Even before the earthquake it had been scheduled for replacement and upgrade to current seismic codes. It is now part of the 4th/5th Avenue Bridge and Corridor. The $37 million project included a wider bridge, with three vehicle lanes, plus sidewalks and bike lanes on both sides.

The I-5 Capitol Lake Bridge suffered minor damage.

The I-5 Capitol Way Bridge had damage to existing seismic retrofit features.

Tacoma

The Tacoma Narrows Bridge needed minor repairs. The bridge is undergoing a complete retrofit, to be completed in 2008.

The SR 509 bridge (11th Street) was unable to open for ships until repaired.

Other

Three days after the earthquake, 25 bridges in the area were still closed for repair or inspection. One was over I-5 near Chehalis, where the railroad overcrossing was seriously damaged and needed emergency repairs costing $550,000. Other bridges near Centralia, Morton, and Kalama were closed briefly to vehicles.

Airports

At Sea-Tac, the tower was damaged severely enough to reroute air traffic to Portland and Spokane for several hours. By the end of the day, 50% of traffic was restored to Sea-Tac. The tower itself sustained structural damage. There was also significant nonstructural damage.

Boeing Field is part of the King County Airport and is home to cargo carriers and civil aviation, as well as being a support facility for Boeing's final manufacturing operations. Liquefaction caused gaps in the runway, closing the airport for a week. Boeing sent 90,000 workers home the day of the quake.

The tower at Sea-Tac sustained both structural and nonstructural damage. Even so, the airport was able to reopen after a few hours. Photo: Washington State Department of Transportation

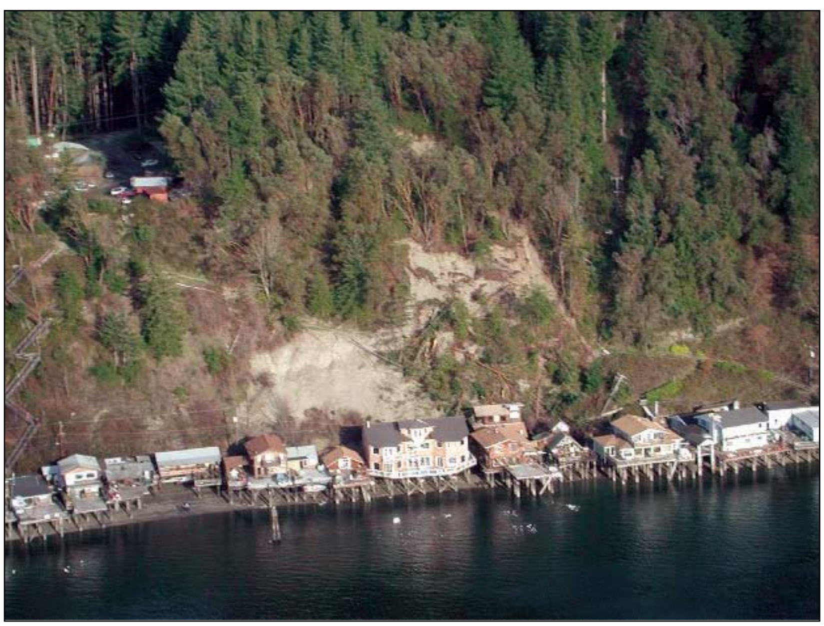
Railroads

The earthquake disrupted Amtrak's train service between Portland and Seattle, and on another line between Seattle and Los Angeles.

Ports

Seattle is the fifth largest US container port, so any disruption is potentially serious. Cargo handling was briefly suspended until inspections were completed and showed no damage. As expected in areas with soft soils, there were sand boils, lateral spreading, and water line breaks, but none of them interrupted service.

Liquefaction and landslides can break utility lines as well as damage roads and property. With widespread damage, repairs may take longer than expected. Photo: Robert J. Reid



Salmon Beach, near Tacoma, was the site of a landslide three days after the 2001 earthquake. The same hillside slid after the 1949 event. Photo: Dave Sherrod, USGS

Tacoma is the sixth largest container port. The Port of Tacoma had some buckled pavement and structural damage to three buildings, largely because of liquefaction.

Power

Immediately after the earthquake, 200,000 customers in South King, Pierce, and Thurston counties lost power. Within six hours, only 8,000 customers remained without power. No damage was reported to the electrical power generation and distribution systems.

Water, sewer, and gas lines

Although there were several water main breaks throughout the area, water supplies were not disrupted.

In Victoria, a broken water main in south Oak Bay flooded six homes.

One gas line and several water lines were ruptured in Tumwater's Mobile Estate Park.

At the Cedar Creek Correctional Center near Olympia, an explosion on a natural gas line injured two workers.

On Harbor Island in King County, there was a 1,300 gallon spill of diesel and gasoline.

Fire is often a major concern after an earthquake because of broken gas lines and the difficulty of fire fighting with broken water mains. However, only one fire was reported, a building in Seattle.

Communications

Telephone lines — both landlines and cell phones — were jammed immediately after the earthquake. According to US West, 60 million calls were initiated in Western Washington on the day of the quake. The overall number of calls for the 24-hour period was at least six times normal. In the first 24 hours after the earthquake, AT&T rejected seven million calls from outside the area.

On the afternoon of the earthquake, MSN reported five million more emails than normal.

In general, the 800 MHz public safety radio system worked well, but not all jurisdictions had it. The system was overwhelmed in King County and was only partly functional the day of the earthquake.

Dams

Washington state engineers inspected almost 300 dams and only five were damaged. All five had previously been identified as potential problems. Inspectors from the Federal Energy Regulatory Commission, the Bureau of Reclamation, and the US Army Corps of Engineers found no damage to the dams they regulate.

Landslides

Damage from earthquake-induced landslides was estimated at approximately $34 million. Hundreds of landslides occurred, though not all with damage. Landslides were mapped from British Columbia to Portland, Oregon, but were concentrated in the Puget Sound area. The large events described below were not included in the road damage or other sections above.

A landslide dammed the Cedar River, resulting in flooding that damaged two houses. Photo: King County

Salmon Beach (near Tacoma)

Repair costs were estimated at $1.5 million. The slide demolished two houses at the base of the slope; eight other houses were red-tagged because of danger from slide material still above them. The slide occurred three days after the earthquake, as the result of the cliff being weakened from shaking.

Salmon Beach was also the site of an enormous landslide after the 1949 landslide. Damage then included smashed boats, dock areas, and a wooden boardwalk.

Deschutes Parkway (Olympia)

Besides the road damage to the Deschutes Parkway described above, several lateral-spread landslides around the margins of Capitol Lake created a significantly larger problem. Water and sewer lines crossing the area broke in places. The cost to repair landslide damage to Capitol Lake, Marathon Park, and Deschutes Parkway was estimated at approximately $22 million.

Cedar River (near Renton)

Landslides caused damage costing nearly $2 million to fix. One slide blocked the Cedar River and created a reservoir until the debris could be moved. Part of a flood-erosion control facility was destroyed. Two houses and considerable land were flooded upstream of the temporary dam.

A second landslide just upstream of the dam slammed into a house. A woman ran out of her home and barely avoided being buried by the debris that filled her kitchen.

Future Deep Earthquakes

Not the Big One, but big enough to matter

Reading the maps

1. What is acceleration?

Acceleration is how much velocity changes over time.

Consider a car increasing in speed from 0 to 60 mph (see metric units below). 60 mph is 88 feet per second (s). If the acceleration is constant, then the car reaches a velocity of 88 ft/s in 8 seconds. The velocity changes by 11 ft/s every second, so the acceleration is 11 ft/s/s.

In metric units, consider a car increasing in speed from 0 to 97 kph. 97 kph is 27 meters per second (s). If the acceleration is constant, then the car reaches a velocity of 27 m/s in 8 seconds. The velocity changes by 3.4 m/s every second, so the acceleration is 3.4 m/s/s.

If the acceleration were not uniform, but started small then increased, the highest value of acceleration would be the "peak acceleration".

2. What is peak acceleration as a measure of earthquake ground motion?

All particles comprising the Earth and objects sitting on its surface move back and forth irregularly as earthquake waves pass through them. The rate at which this movement changes can be described by its acceleration. Peak acceleration is the maximum reached during the passage of the earthquake waves.

3. What is percent of gravity (%g)?

We experience acceleration as a force (as in a moving car). The force we are most experienced with is due to gravity. The units of acceleration on the map are measure in terms of g, the acceleration due to gravity. This factor 'g' has a value of 32 ft/s/s (9.8 m/s/s).

For the car example above, an acceleration of 11 ft/s/s (3.4 m/s/s), divided by g, is 34%g or 0.34g.

Modified from the USGS Earthquakes Hazards Programs definitions. For more information on pga and how it affects buildings, see http://earthquake.usgs.gov/research/hazmaps/haz101/faq/faq.php.

What follows are four maps that show how deep earthquakes could affect various parts of Cascadia. Four epicenters are discussed: Everett (north of Seattle), Washington; Pender Island (off southeastern Vancouver Island), British Columbia; Beaverton (west of Portland), Oregon; and northwestern California.

For each area, the map shows the extent of expected ground shaking. This will help local authorities understand how a large, deep earthquake could affect their communities. (Note: Earthquakes centered under other locations are also possible.)

Ground shaking strength is measured in terms of peak ground acceleration (pga). Higher pga generally results in more damage. The effect of any earthquake will depend on the distance to the epicenter, how deep it is, soil types, and building types. PGA is used because building codes prescribe how much horizontal force, or acceleration, a building should be able to withstand during an earthquake. The force we are most experienced with is due to gravity, so pga is expressed as a percent of gravity.

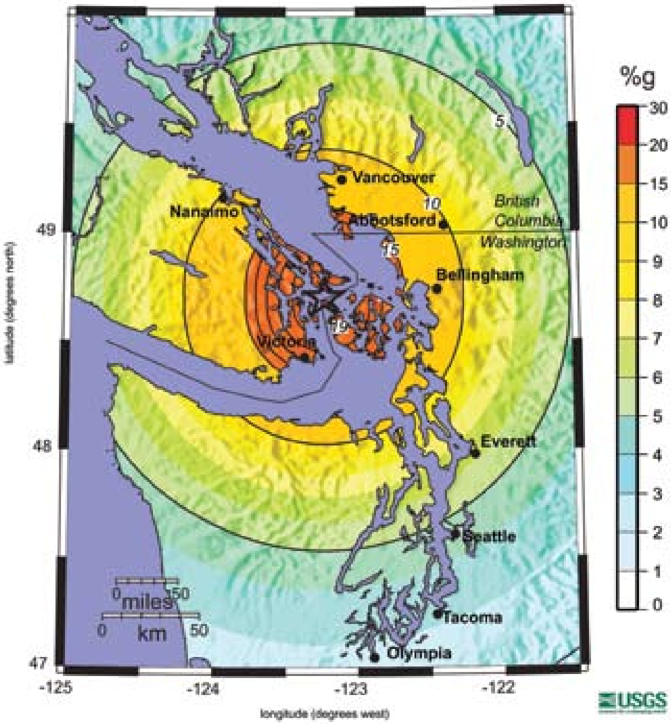
These maps are broad generalizations of the expected shaking patterns, and do not include the effects of variations in local soil types. In many areas, the pga will be higher than indicated. A pga of approximately .10 to .20 can cause damage in unreinforced masonry buildings (URMs) on soft soils. A .20 pga can trigger landslides on steep slopes with saturated soils.

URMs are old brick or masonry buildings that have not been upgraded to current earthquake codes. Though these are among the most dangerous places to be in an earthquake, they can be retrofitted for greater safety.

These maps can be used as inputs in HAZUS, a model developed by the Department of Homeland Security Federal Emergency Management Agency (FEMA) to forecast earthquake damage and losses. Maps of forecasted pga are input to HAZUS, which produces estimates of potential damage to buildings, utilities and roadways, and more, as well as forecasts for injuries at various times of day. HAZUS can be used as a starting point for earthquake preparation and response planning.

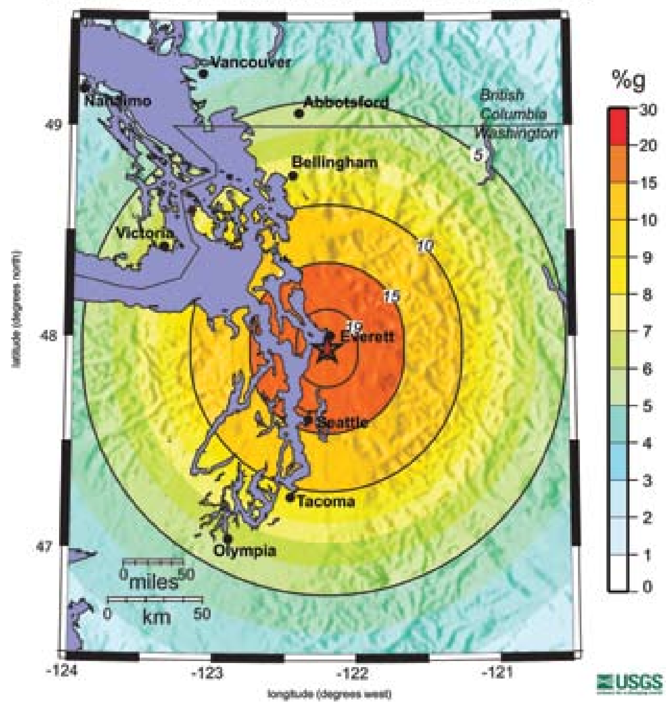
Some previous deep earthquakes are recapped earlier, starting on page 7. These give you an idea of the kind of damage and losses that can be expected in future deep earthquakes.

M6.8 'Pender Island' Earthquake, Depth 34 mi (55 km)

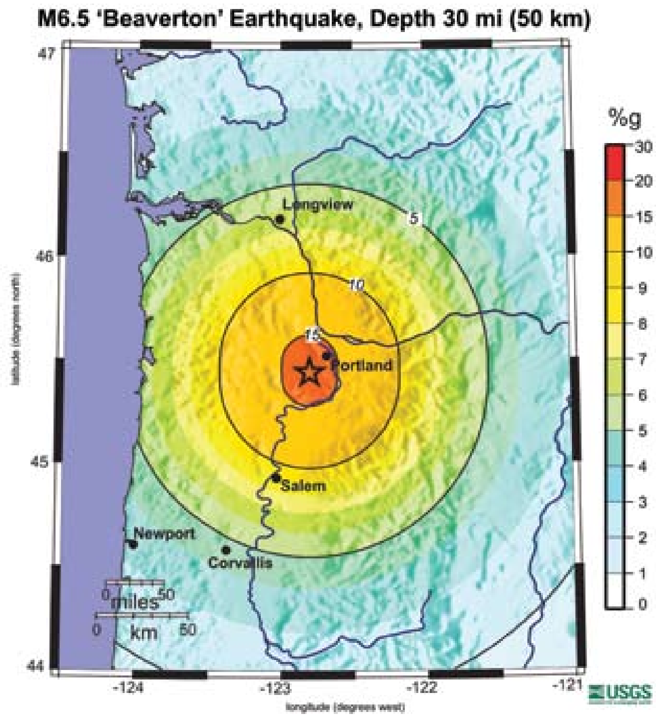


The above map shows potential pga for an M6.8 deep earthquake under Pender Island, British Columbia. This map does not include the variations in soil types, topography, and subsurface geologic structure that may increase or decrease shaking and damage locally. The heaviest damage is likely to be concentrated on Vancouver Island and along the Strait of Georgia. The shaking itself will be felt beyond the edges of this map. Map: Art Frankel, USGS

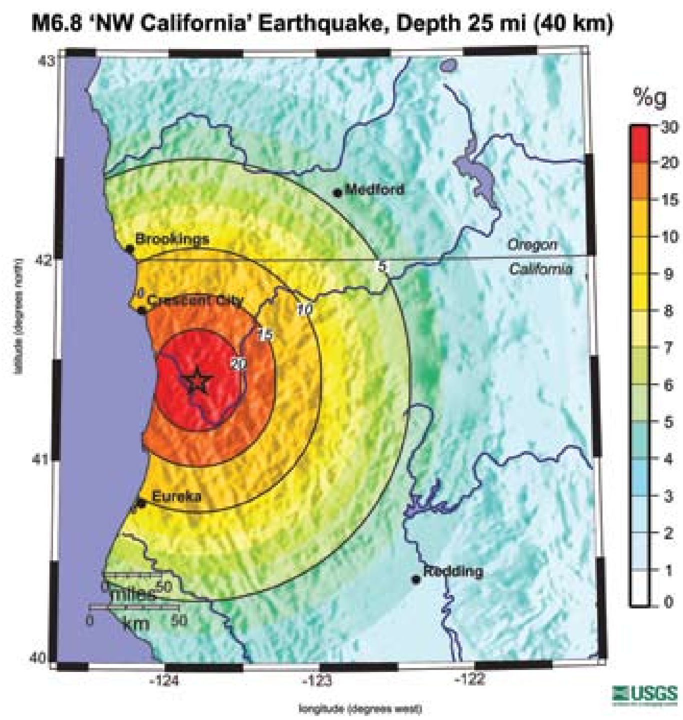
M6.8 'Everett' Earthquake, Depth 34 mi (55 km)



The above map shows potential pga for an M6.8 deep earthquake under Everett, Washington. This map does not include the variations in soil types, topography, and subsurface geologic structure that may increase or decrease shaking and damage locally. Much of the Puget Sound area would be at risk for damage. Because the epicenter is under a more developed area than the Nisqually earthquake was, the damage is likely to be worse. The shaking itself will be felt beyond the edges of this map. Map: Art Frankel, USGS



The above map shows potential pga for an M6.5 deep earthquake under Beaverton, Oregon. This map does not include the variations in soil types, topography, and sub-surface geologic structure that may increase or decrease shaking and damage locally. This earthquake could pose a significant risk to many URMs in the greater Portland area. The shaking itself will be felt beyond the edges of this map. Map: Art Frankel, USGS



The above map shows potential pga for an M6.8 deep earthquake under northwestern California. This map does not include the variations in soil types, topography, and subsurface geologic structure that may increase or decrease shaking and damage locally. The shaking itself is likely to be felt beyond the edges of this map. Deep earthquakes beneath northwestern California contribute significant hazard to the coast between Cape Mendocino and southernmost Oregon. Map: Art Frankel, USGS

Lessons for the future

Preparation dramatically reduces injuries, deaths, and property loss from earthquakes. What are the most important preparations we can make before the next earthquake?

Individuals and families can take basic steps like assembling emergency kits, making their homes earthquake resistant, and having a family communication plan. Governments, utilities, and businesses must also make plans to protect and support their staffs. In addition, they will need to have preparedness plans and have implemented mitigation measures.

Extensive work has been done on how to prepare for future earthquakes. You can take advantage of this knowledge as you plan to reduce future damage in your own community. The websites on page 22 are a good place to start your research.

Start with people

Whether you're responsible for a family or a multinational corporation, your preparedness plans and mitigation measures should start with protecting people. Employees cannot focus on the work you need them to do unless they are safe and they know their loved ones are safe.

- Family emergency plans are easy to put together. In general, they include where the family members should meet after an earthquake (driving may be difficult because of jammed roads) and how they can contact each other (a central phone number, preferably outside Cascadia). Many organizations have templates.
- Learn to drop, cover, and hold, and know the evacuation routes out of your homes, offices, or schools. Drills can be held periodically. Provisions should be made for those with disabilities.
- Whether you're responsible for a family, a school, a workplace, or an entire region, an emergency response plan is a must. It should be flexible enough to put into place with whoever is available during the earthquake, but detailed enough so that people know what is expected of them. It must be practiced.
- Three-day emergency kits can be stocked, kept current, and placed to be easily grabbed when evacuating.
- Know your earthquake hazard. Become educated about the earthquake hazard where you live, work, or go to school. Many local or state jurisdictions publish maps that show the hazard in their area. Some are even available online.

Never stand in a doorway during an earthquake. The safest course is to drop (beneath a desk or table), cover, and hold. The table surface will help protect you from falling debris. Some states mandate drills for their students, but not all adults know these simple steps. Photo: USGS

Nonstructural damage in homes and offices, like bookcases, computers, and dishes falling, can be dangerous and expensive. Photo: Ray Lasmanis, DGER

Buildings are important

Three things make a building dangerous: its type of construction, the soil it's built on, and how secure the nonstructural elements are. Most urban jurisdictions have soil maps that show more vulnerable areas. Information about buildings also is available. For example, the American Society of Civil Engineers published *ASCE 31-02, Seismic Evaluation of Existing Buildings*, to help assess building risk. The National Research Council of Canada published *NRCC-36941, Guidelines for the Seismic Evaluation of Existing Buildings.*

These or other methods can be used to make an inventory of the most potentially hazardous buildings in a community. This is particularly important for public facilities like fire/police stations and schools. Large apartments or commercial buildings might also be high risk. Since resources are always limited, it makes sense to start mitigation with the structures that may affect the most people.

- Securing nonstructural elements may prevent considerable injury and damage. This could mean providing stronger ties for overhead lights or better strapping for water heaters and piping, bracing for sprinkler lines, and fastening bookshelves to walls. In offices, low-cost effective improvements include using nonskid mats for computers and restraints for bookshelves.
- Simple measures can help. Reinforcing parapets and bolting houses to foundations lessen the danger of injury and property damage. A building does not need to be completely rebuilt to make a significant difference.
- Mitigation measures sometimes involves difficult choices, such as choosing a new building site in a safer location, either on harder ground or away from active faults.

Many resources exist to help with earthquake preparation. Here are just a few:

CREW
www.crew.org

Red Cross
www.redcross.org

Institute for Business & Home Safety
www.ibhs.com

Emergency Preparedness for Industry and Commerce Council
www.epicc.org/manuals.aspx

USGS and regional earthquake centers:
earthquake.usgs.gov
pnsn.org
seismo.berkeley.edu

British Columbia
earthquakescanada.ca
www.pep.bc.ca

Washington state
www.dnr.wa.gov/geology
emd.wa.gov

Oregon
www.oregongeology.com
http://www.oregon.gov/OMD/OEM

California
www.consrv.ca.gov/cgs
www.oes.ca.gov

Business lessons learned

Businesses with comprehensive contingency plans are much more likely to remain open after the earthquake, or reopen quickly. Experience has shown that many businesses that close after a natural disaster never reopen. Besides making provisions for their staffs, there are operational issues to consider.

A survey after Nisqually showed what business leaders learned from that earthquake.

- *Seismic restraints paid off:* Inexpensive earthquake straps and quake mats saved equipment and downtime. Seismic retrofits were proven in several companies.
- *Suspended ceiling grids and light fixtures need to be seismically restrained:* If they drop, people and sprinkler systems are endangered.
- *Shelving must be braced:* Freestanding shelving should be secured to the wall and/or floor. Tall shelving, like in warehouses and warehouse clubs, should be secured to the floor, and from the top, and/or be diagonally braced.
- *Don't get red-tagged needlessly:* Even without significant structural damage, buildings can be red-tagged because of nonstructural hazards that can be mitigated before an earthquake.
- *Simple disaster plans are the best:* A hospital supervisor said, "Our disaster script needs to be rewritten with the highlights on ONE page at the beginning of the plan."
- *Train employees:* People who immediately dropped under desks or tables (drop, cover, and hold) emerged uninjured and ready to help after the shaking stopped.
- *Emergency drills are important:* When a disaster hits, knowing where to go and what to do must be automatic. Fright and panic are reduced when employees know what to expect.
- *The telephone system was overwhelmed:* For the first 90 minutes (to accommodate emergency calls), don't use the phone unless you have an emergency. After the shaking stops, hang up any phones that may have shaken off the hook.
- *Employees need to contact their families:* People need to let their families know they are safe, though they should wait 90 minutes before calling. Encourage them to arrange an out-of-state contact for family members to call to coordinate messages. Employees will not be able to concentrate on work until they know their loved ones are safe.

A more general list of needs was put together by a group of Puget Sound business representatives invited by CREW to discuss potential post-earthquake con-

Successful response: The Boeing Company in Seattle

Within minutes after the Nisqually earthquake, Boeing activated eight Emergency Operations Centers and these centers were fully operational and staffed in 45 minutes. Emergency generators kicked in and within 42 seconds, the company's Computing Emergency Response Center transferred computing control to a backup center in Wichita, Kansas.

Though the facility was evacuated, some people stayed behind to ensure that the gas was shut off within minutes and water within the first half hour. One overhead crane operator remained at his post until the fin of a large commercial aircraft was no longer a hazard, saving lives and millions of dollars in product.

The Nisqually earthquake caused damage to the Boeing plant but product orders were not affected and no product delivery was delayed. Like Starbucks, if you were a customer and you hadn't read the press, you wouldn't know Boeing had damage.

From the CREW paper, "Did the Nisqually Earthquake Cause Change Within the Business Community?"

See http://www.crew.org/papers/businesslearn.html for more examples.

Nonprofit rebirth: The Seattle Compass Center

For 55 years, the Compass Center served as a homeless shelter, housed in a 5-story brick building in Seattle's Pioneer Square. Nisqually earthquake damage caused the building to be red-tagged, and many thought it was the end of the shelter and the other services it offered.

In fact, it took $16 million to rehabilitate the building, raised from public and private sources. But the Compass Center reopened in June 2005, complete with a new hygiene center, and is again serving some of Seattle's homeless residents.

cerns. This list can be used to help businesses focus on pre-earthquake mitigation activities.

Here are the post-earthquake issues identified by this group, listed in order of importance:

1. Personal concerns such as childcare, food, and shelter, including the effects on businesses because of injuries or deaths to employees and customers.
2. Loss of power during and immediately following the event. Specific effects vary by industry.
3. Loss of surface transportation — the ability to get employees and inventory to and from work, and access of emergency vehicles and repair equipment to damaged areas.
4. Questions of the ability of businesses to communicate with customers, from being open for business to the general loss of communication services during and after a disaster.
5. Physical loss and damage to business structures and facilities.
6. Questions of the capacity of hospitals and health care facilities to accommodate people injured by the earthquake, while continuing to provide care to people ailing from other causes.
7. Losses because of limited Just in-Time inventories.
8. Potential for permanent loss of businesses due to weeks or months of damaged infrastructure.

Merchandise spilled off shelves in the Nisqually earthquake. It creates a safety problem for business employees and customers, and also diminishes the amount of resources available for use after the earthquake. Grocery stores, among others, have the type of stock needed to respond to, and resupply after, an earthquake. Photo: Brian Sandwick

Government lessons

We expect governments to do some projects that are massive in scale or that cannot be done for profit. Examples include running the school or road systems. As employers and service providers, governments must take care of their staff, and can incorporate the business lessons outlined above. But they have additional responsibilities. Here are three examples of government mitigation activities.

Vulnerable public buildings

In 1933, an M6.2 earthquake struck Long Beach, California. Engineered buildings and reinforced concrete buildings sustained little or no structural damage in the earthquake. But brick buildings, including many schools, failed catastrophically. Even though the tremor was just before 6 PM, five children died in school gymnasiums. If the earthquake had struck during school hours, there would have been significant loss of life. Another 115 people died, mostly from collapsed houses and other buildings, or falling debris. As a result, the Field Act passed in California, mandating earthquake-resistant design and construction for public schools from kindergartens through community colleges. No Field Act school has ever failed in an earthquake.

In 2007, the State of Oregon completed a Statewide Seismic Needs Assessment of public school buildings, acute in-patient care facilities, fire stations, police stations, sheriffs' offices, and other law enforcement agency buildings. This is only the first step in a multi-part process that will eventually create a pool of state money that can be used to seismically retrofit eligible buildings.

The 1971 San Fernando earthquake substantially damaged these Juvenile Hall facilities. A portion of the two-story administration building collapsed completely into the first story. Photo: E.V. Leyendecker, USGS

Planning for the future

The City of Cannon Beach, Oregon was the pilot community for a study in post-disaster, long-term recovery planning.

Long-term recovery planning is a blueprint for how a community can be restored after a major disaster. It incorporates both long- and short-term strategies, including land use planning, business continuity planning, and other programs. Recovery planning is a shared responsibility between individuals, private businesses and industries, state and local governments, and the federal government.

The planning forum resulted in a number of recommendations for action. Here are just a few:

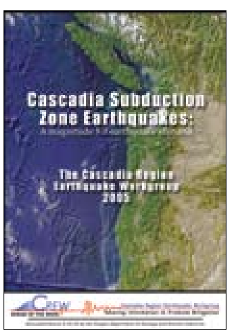
- Establish a Disaster Resilience Committee.
- Develop a Post-Disaster Recovery Ordinance.
- Develop a funding matrix that provides a list of potential funding mechanisms for disaster recovery and mitigation activities.
- Conduct a study to determine priorities for post-disaster utility restoration.
- Develop a proposal to relocate or retrofit important buildings that are critical to post-disaster recovery efforts.
- Assist businesses in developing business continuity plans.
- Create a list of qualified local and regional contractors to perform recovery work post-disaster.
- Prepare a City Continuity of Operations Plan.
- Create a post-disaster housing plan that includes a vacant home database.

For more information on how your community can develop a similar plan, go to www.crew.org, and click on *Post-Disaster Recovery Planning Forum.*

The mall in Scotia, California was destroyed by a fire after an earthquake. Before the fire, the mall consisted of a lumber yard, pharmacy, coffee shop, grocery store, and variety store. Long-term recovery planning gives communities a framework for post-disaster rebuilding. Photo: Lindie Brewer, USGS

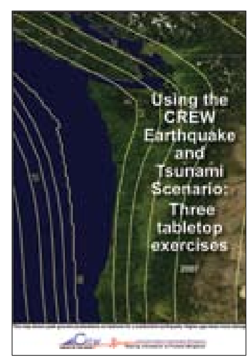
CREW

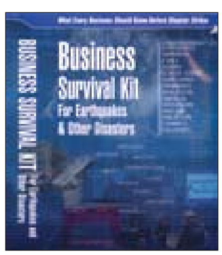
CREW (the Cascadia Region Earthquake Workgroup) is a partnership of the private and public sectors, created to help our area prepare for earthquakes. A variety of products about the region's earthquake threat and how to prepare for it are available as .pdf files on our website (http://crew.org).



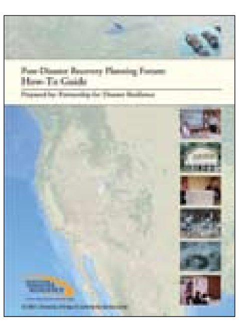
This 24-page report gives background information on earthquakes in Cascadia and presents a scenario of what a magnitude 9 earthquake might do to the region.

This 16-page report explains how other groups have used CREW scenarios and how you can use the lessons they learned to help your earthquake preparations.



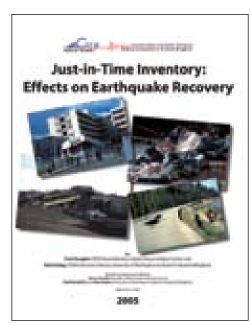


This 27-minute video documents what risk reduction measures worked to mitigate damage in the 2001 Nisqually earthquake.



This 32-page guide provides an approach for assisting communities in identifying issues they will face after a disaster.

This 12-page paper uses the Seattle area as a case study of how crucial it is to understand inventory and supply chain practices as part of earthquake preparation.



Earthquake Damage:
Why does it keep happening in the same places?

Tacoma Narrows, 1949

Deschutes Parkway, 1965

Pioneer Square, 1949

Tacoma Narrows, 2001

Deschutes Parkway, 2001

Pioneer Square, 2001

What You Should Know About Earthquakes and Related Geologic Hazards

Washington has the second largest population at-risk from earthquakes in the nation. It experiences numerous earthquakes that could be catastrophic without the proper geological, land-use, and emergency management planning.

Washington has suffered at least 20 damaging earthquakes during the past 125 years, the most recent of which caused billions of dollars in damage.

Earthquake damage is strongly influenced by near-surface geology.

Earthquake safety requires that geologists, geophysicists, seismologists, engineers, architects, and building officials work together to create a safe and robust built environment

Both the private and public sectors play a crucial role in maintaining communities that are resilient.

The Department of Natural Resources, Division of Geology and Earth Resources and its partners make Washington safer and more resistant to geologic hazards

WASHINGTON STATE DEPARTMENT OF
Natural Resources
Doug Sutherland - Commissioner of Public Lands

Division of Geology and Earth Resources
Ron Teissere - State Geologist

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