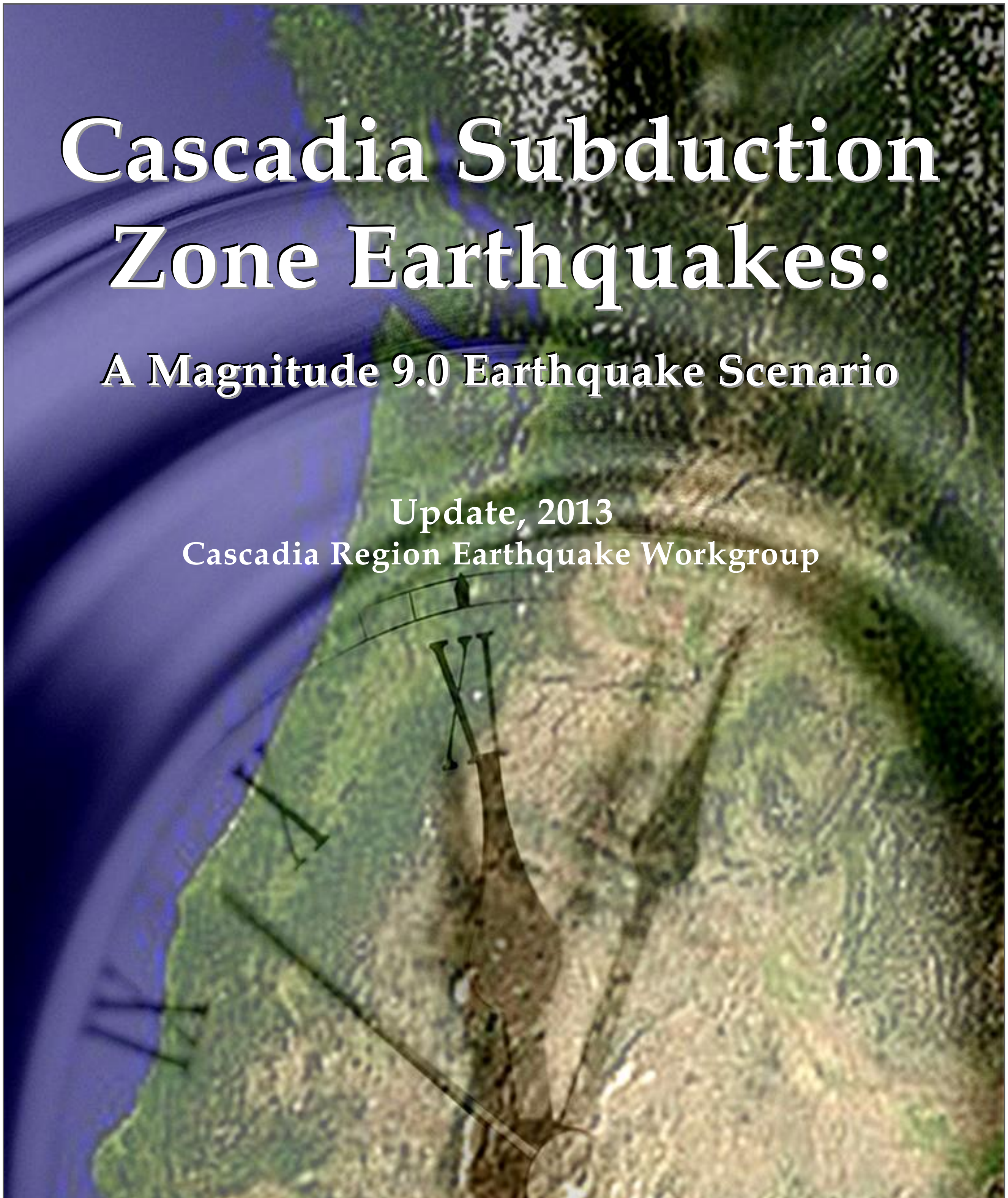
Cascadia Subduction Zone Earthquakes:

A Magnitude 9.0 Earthquake Scenario

Update, 2013

Cascadia Region Earthquake Workgroup



CASCADIA REGION EARTHQUAKE WORKGROUP
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Also available as Washington Division of Geology and Earth Resources Information Circular 116, Oregon Department of Geology and Mineral Industries Open-File Report 0-13-22, and British Columbia Geological Survey Information Circular 2013-3

Cascadia Region Earthquake Workgroup (CREW)

CREW is a non-profit coalition of business people, emergency managers, scientists, engineers, civic leaders, and government officials who are working together to reduce the effects of earthquakes in the Pacific Northwest.

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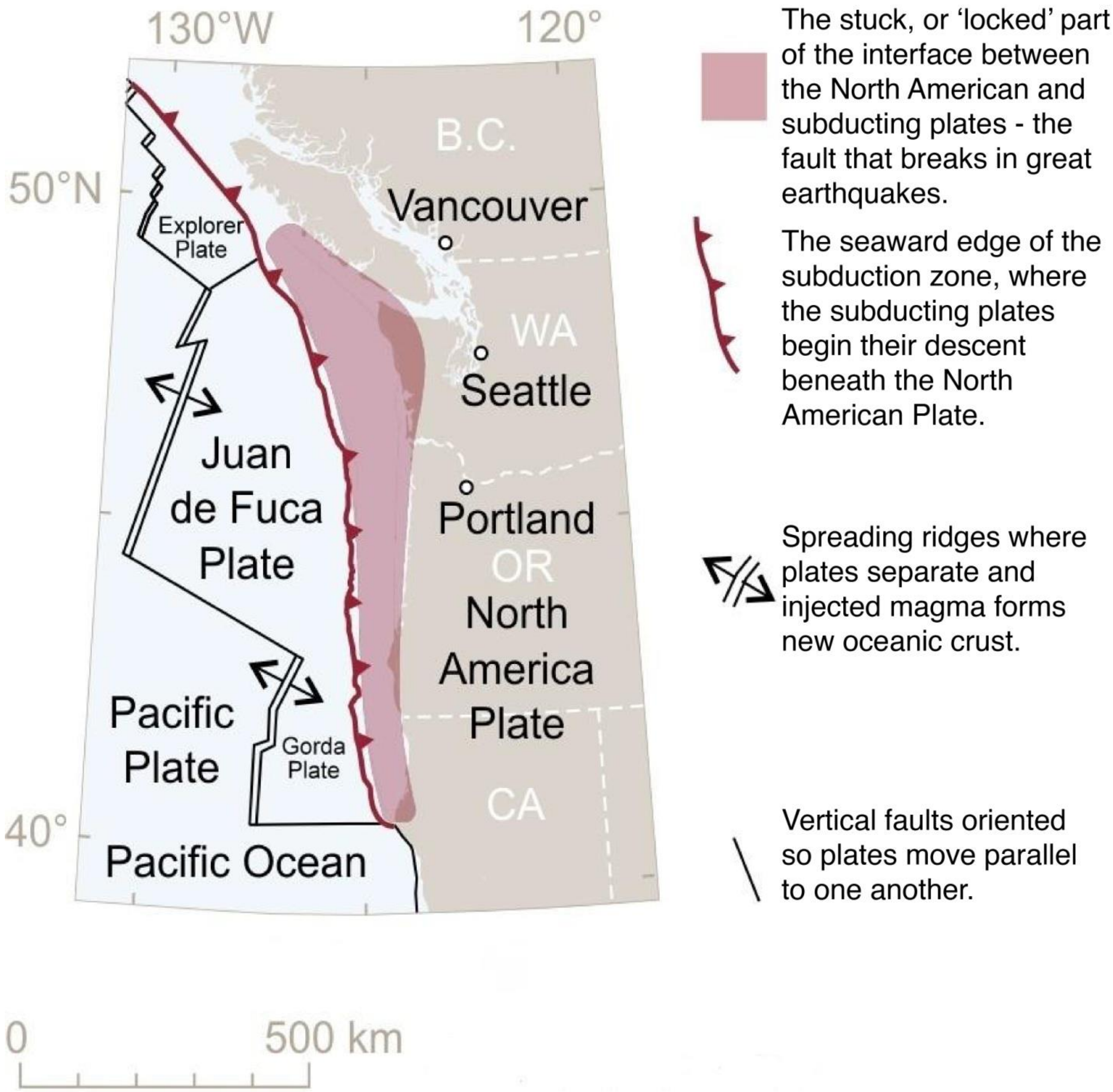


The Cascadia Subduction Zone: **The geography of northern California, Oregon, Washington, and southern British Columbia is shaped by the Cascadia subduction zone, where the North American Plate collides with a number of smaller plates: the largest of these is the Juan de Fuca Plate, flanked by the Explorer Plate to the north and the Gorda plate to the south. These smaller plates "subduct" (descend) beneath the North American Plate as they converge along a 700-mile long (1,130 km) boundary. A large portion of the boundary between the subducting and overriding plates resists the convergent motion, until this part of the boundary breaks in a great earthquake.**

Above: Schematic view of the source area for the largest Cascadia earthquakes. **(Image adapted from U.S. Geological Survey Professional Paper 1707 (page 8), Atwater et al., http://pubs.usgs.gov/pp/pp1707/)**

ONE DAY IN CASCADIA

Photo by Writegeist

It's 8:16 on a chilly, wet morning in early spring. You've just arrived at work and are pouring a cup of coffee when you become aware of a low rumbling noise. Within seconds, the rumbling becomes a roar, the floor beneath you heaves, and the building begins to pitch and shake so violently that you're thrown to the floor. The roaring is joined by a cacophony of crashing as windows shatter and every unsecured object in the room—from the desk chair to the coffee pot—is sent flying. Shaken loose by the shuddering and jolting of the building, dust and ceiling particles drift down like snow. Then the lights flicker and go out. Remembering to "drop, cover, and hold," you crawl under the nearest table, hold on tight, and tell yourself that the shaking should last only a few seconds more . . . but it goes on and on.

This is it: the Big One. The Cascadia subduction zone has just unleashed a magnitude 9.0 earthquake.

Are you prepared?

IF YOU LIVE IN NORTHERN CALIFORNIA, WASHINGTON, OREGON, OR BRITISH COLUMBIA, YOU LIVE IN CASCADIA, a region remarkable for its stunning mountain ranges, rich farmlands and vineyards, beautiful beaches, great rivers, and green forests. It is a region of vibrant communities, busy international ports, and thriving businesses. Residents and visitors alike enjoy the cultural offerings of Cascadia's cities and the diversity of outdoor activities at its natural areas. But the geologic forces that shaped the Northwest are still active: Cascadia is a region of earthquakes.

The Cascadia subduction zone is one of the principal sources of concern. Lying mostly offshore, this plate interface is a giant fault—approximately 700 miles long (1,130 km). Here, the set of tectonic plates to our west is sliding (subducting) beneath the North American Plate. The movement of these plates is neither constant nor smooth: the plates are stuck, and the stress will build up until the fault suddenly breaks. This last happened in 1700: the result was an earthquake on the order of magnitude 9.0, followed within minutes by a large tsunami—much like the earthquake and tsunami that struck Japan on March 11, 2011. Stresses have now been building along the Cascadia subduction zone for more than 300 years, and the communities of Cascadia can be certain that another great quake will again shake the region.

Because understanding the hazard is an essential step in preparing for it, the Cascadia Region Earthquake Workgroup (CREW) first published *Cascadia Subduction Zone Earthquakes* in 2005. Since then, scientists have further developed their understanding of the subduction zone, engineers have learned to build more resilient structures, emergency planners have made extensive use of earthquake and tsunami modeling tools to prepare more effectively, and the entire earthquake and emergency response community has learned volumes from recent subduction zone earthquakes and tsunamis in the Indian Ocean, Chile, and Japan. This second edition of *Cascadia Subduction Zone Earthquakes* incorporates these new developments and lessons, while also noting the progress that has been made since 2005 to prepare communities throughout the region for Cascadia's next big subduction zone earthquake.

DISCOVERING OUR REGION'S EARTHQUAKE PROFILE

The Pacific Northwest is prone to earthquakes. This has been demonstrated repeatedly by events as recent as the Nisqually earthquake in 2001 and the magnitude 7.7 earthquake off the coast of British Columbia in 2012. But what does this really mean in geologic and in human terms, and what is the risk to those who live here?

Tectonic Collision Zone

The Pacific Northwest has earthquakes because it lies within a tectonic collision zone. British Columbia, Washington, Oregon, and most of California sit on the edge of a slab of the earth's crust known as the North American Plate. This plate is being pushed slowly but inexorably against the system of plates beneath the Pacific Ocean just to the west of us: the Juan de Fuca Plate off the coasts of Washington and Oregon, the Explorer Plate off British Columbia, and the Gorda Plate off northern California. The Juan de Fuca, Explorer, and Gorda plates contain denser rock than the North American Plate and are driven beneath it in a process known as subduction. While the average rate of movement may seem slow—about 1.6 inches (4 cm) per year—the plates are massive in size. The slow insistent movement that forces them together causes tremendous strain to build up as the plates stick against each other. The sudden release of this strain produces an earthquake.

THE CASCADIA SUBDUCTION ZONE IN CROSS-SECTION:

New crust forms at spreading ridges between the Pacific Plate and the Juan de Fuca, Gorda, and Explorer plates. As these three plates are pushed east-ward, they are forced to subduct beneath the North American Plate. Strain builds up where they have become stuck (locked) and will be released one day in a great earthquake.

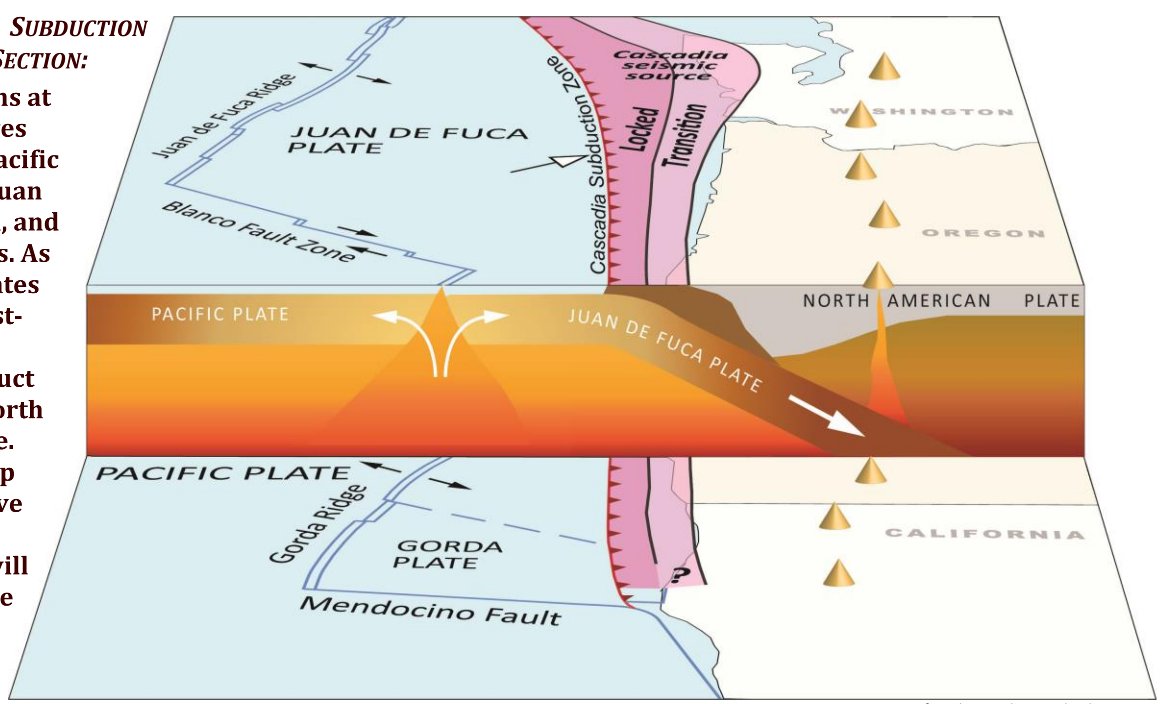


Image Source: Oregon Department of Geology and Mineral Industries

The collision of the tectonic plates along the Cascadia subduction zone and the geometry and geology of the plates produce several types of earthquakes, the intensity and effects of which can differ in significant ways:

Photo Source: USGS

Washington's capitol building was seriously damaged during the deep M6.8 Nisqually earthquake in 2001.

Deep Earthquakes—The magnitude 6.8 Nisqually earthquake in 2001 was a deep earthquake. This type originates in the descending slab—the part that has already slipped beneath the edge of the North American Plate—at a depth of 30–37 miles (48–60 km). Deep quakes can be felt over a very large area, but typically do less damage than a shallow quake of comparable size. This is because the quake originates farther below ground and is thus more distant from buildings on the surface. Deep quakes typically produce few aftershocks large enough to be felt.

Shallow or Crustal Earthquakes—Shallow quakes occur within the North American Plate along fractures created as a result of the collision process and jostling of blocks of continental crust. The Northwest is laced with such faults, and some even run under metropolitan areas. When a shallow fault breaks, the resulting earthquake affects a smaller area than would a deep earthquake of the same magnitude, but the shaking is usually more intense, and numerous aftershocks are likely. The two magnitude 6.0 earthquakes that struck Klamath Falls, Oregon, in 1993 are examples of this type of quake. They were followed immediately by many small aftershocks and, some three months later, by a magnitude 5.4 aftershock. A shallow earthquake may also generate a local tsunami if the rupture lies under a body of water. For example, scientists have discovered that a past earthquake greater than magnitude 7.0 on Washington's Seattle fault zone created a tsunami in Puget Sound.

Subduction Zone Earthquakes—The convergent boundary along which the Explorer, Juan de Fuca, and Gorda plates are sinking beneath the North American Plate is a long megathrust fault capable of producing very large earthquakes. The most recent event associated with this zone was the Cape Mendocino (Petrolia) earthquake in 1992. This magnitude 7.1 quake appears to have been the result of

Examples of Recent Earthquakes in the Pacific Northwest

Location	Date	Magnitude	Type/Origin
British Columbia: Haida Gwaii (Queen Charlotte Islands)	1949	8.1	Strike-slip at plate boundary—similar to California's San Andreas fault (interplate)
	2012	7.7	Thrust (interplate)
British Columbia: Vancouver Island	1946	7.3	Shallow/crustal (intraplate)
Washington: Nisqually	2001	6.8	Deep (intraplate)
Oregon: Klamath Falls (2 earthquakes)	1993	6.0	Shallow/crustal (intraplate)
Oregon: Scott Mills	1993	5.6	Shallow/crustal (intraplate)
Northern California: Cape Mendocino/Petrolia	1992	7.1	Subduction zone (interplate)
Cascadia: Pacific Northwest	1700	9.0	Subduction zone—full rupture (interplate)

(Note: *Interplate* refers to an event that occurs where two tectonic plates meet; *intraplate* refers to an event that occurs within a single plate.)

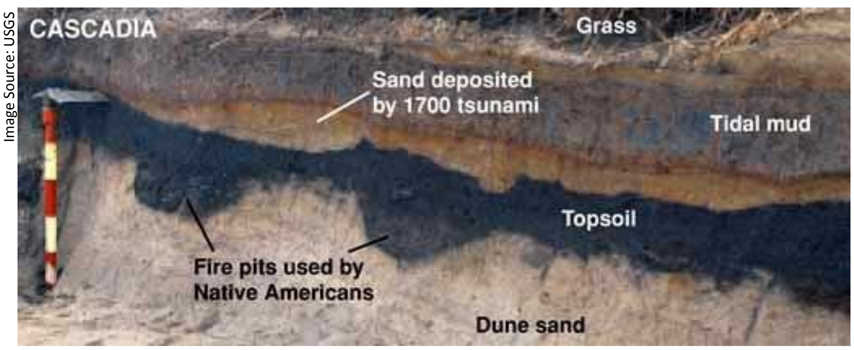
a small rupture at the southern end of the zone. It caused some fifteen miles of coastline to be permanently uplifted and produced a small tsunami, which reached Eureka, California, a mere twenty minutes later. In addition to generating tsunamis, subduction zone earthquakes are followed by significant aftershocks. The Cape Mendocino earthquake, for example, was followed by aftershocks as large as M6.5 and 6.7 the day after the main quake.

On the Trail of the Biggest Quake of All

While Cascadia is now one of the most closely studied and monitored subduction zones in the world, our present understanding of how it works and what to expect from it is relatively recent. It was not until the early 1980s that researchers began to recognize the zone's potential to produce great earthquakes, and it took years of geologic detective work to uncover the evidence.

The Cascadia subduction zone has not produced a great megathrust earthquake for several centuries, and Northwest history offers no written eye-witness accounts, although a few Native American and First Nations oral stories do relate some of the effects. Scientists instead found the record of Cascadia's past activity in the landscape itself, which was altered suddenly and in characteristic ways by these great earthquakes and the tsunamis they triggered (as seen in the photo at left). Once the scientists realized what to look for, they found the evidence up and down the coastline, on land and on the seafloor, from British Columbia to California.

Image Source: USGS



Evidence for at least 13 great earthquakes on the Cascadia subduction zone was discovered on top of a 6,600-year-old volcanic ash deposit from Crater Lake in Oregon. The most recent of these earthquakes is estimated to have been between magnitude 8.7 and 9.2 and occurred on the evening of January 26, 1700. We can date it precisely because the giant tsunami that Cascadia triggered flooded coastal villages in Japan and was recorded by officials there. In the 300 years since this event, the strain along the Cascadia subduction zone has been reloading—building up for the next great earthquake.

***What Are Great Earthquakes?* The world's largest quakes occur along subduction zones. Dubbed *great* earthquakes, the magnitude of these events ranges from 8.0 to 9.0+ (the largest recorded was a magnitude 9.5 quake off the coast of Chile in 1960). Their characteristics include prolonged ground shaking, large tsunamis, and numerous aftershocks. Because the magnitude scale is logarithmic, each increase of one unit signifies that the waves radiated by the earthquake are 10-times larger and 32-times more energetic: This means that a M9.0 quake releases 1,995 times more energy than a M6.8.**

Right: Onagawa, Ishinomaki, after the M9.0 Tohoku earthquake and tsunami in 2011.

Photo Source: NOAA/NGDC, Shunichi Koshimura

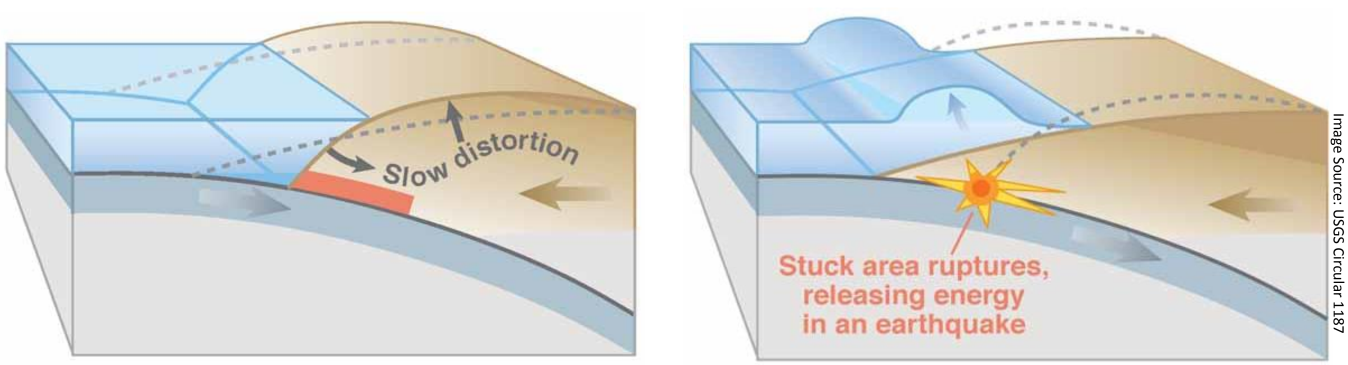
EXAMPLES OF GREAT SUBDUCTION ZONE (INTERPLATE) EARTHQUAKES					
Location	**Date**	**Size**	**Duration Shaking Was Felt**	**Tsunami**	**Aftershocks (M6.0 or Greater)**
Cascadia subduction zone, Pacific Northwest (northern CA to B.C.)	Jan. 26, 1700	M9.0 (approx.)	Unknown	Yes	Suspected (details unknown)
Prince William Sound, Alaska	March 27, 1964	M9.2	3–4 minutes	Yes	11 within the first day
Aceh-Andaman, Sumatra	Dec. 26, 2004	M9.1	3–4 minutes	Yes	13 within the first four days
Maule, Chile	Feb. 27, 2010	M8.8	2–3 minutes	Yes	21 within the first two months
Tohoku, Japan	March 11, 2011	M9.0	3–6 minutes	Yes	59 within the first three months
Compare Washington's recent Nisqually earthquake, an example of a deep (intraplate) quake.	Feb. 28, 2001	M6.8	Up to 40 seconds	No	Few aftershocks felt (the largest measured M4.3)

ANATOMY OF A CASCADIA SUBDUCTION ZONE EARTHQUAKE

To prepare effectively, we need to understand the hazard. Fortunately, scientists have been able to show not only what the Cascadia subduction zone has done in the past, but what is likely to happen when it makes its next move.

The Locked Zone Breaks

The Cascadia subduction zone stretches from Cape Mendocino in northern California to Brooks Peninsula on Vancouver Island in British Columbia, a distance of about 700 miles (1,130 km). All along this zone, which begins beneath the seafloor to the west and extends inland towards the Cascade and Coastal mountains, the subducting plates are forced beneath the North American Plate. At a relatively shallow depth (less than about 20 miles/30 km down), the plates have become stuck. Below this locked zone, warmer temperatures make the plates more pliable, allowing them to move more readily past each other. This freer movement deeper down causes strain to accumulate along the locked zone. Once that strain is great enough to overcome the friction that keeps the plates locked, the fault will rupture: the edge of the North American Plate will lurch suddenly upwards and southwestwards as the subducting plates slip under and northeastwards. With this movement, the deformed western edge of the North American Plate will flex, causing the land along large sections of Cascadia's coastline to drop as much as 6.6 feet (2 m) in elevation—an effect known as co-seismic subsidence.



DYNAMICS OF THE SUBDUCTION ZONE: **The subducting tectonic plate (solid gray) is currently stuck against the over-riding North American Plate (brown) along the locked zone (marked in red on the first image). This has caused the edge of the North American plate to warp and elevate the land. When the pressure finally causes the fault to rupture, the North American Plate will flex and drop, producing a major earthquake and tsunami. (The dotted lines in the left image mark the level of the land when not warped by accumulated strain; on the right, the dotted lines mark the elevation of the distorted plate just before the fault ruptured.)**

The Earthquake Hits

Although it is possible that the Cascadia subduction zone will rupture section by section in a series of large earthquakes (each measuring magnitude 8.0 to 8.5) over a period of years, the earthquake that many scientists and emergency planners anticipate is modeled on the zone's last major quake: the entire fault zone ruptures from end to end, causing one great earthquake measuring magnitude 9.0. The shaking that results from this abrupt shifting of the earth's crust will be felt throughout the Pacific Northwest—and the ground is expected to go on shaking for four to six minutes.

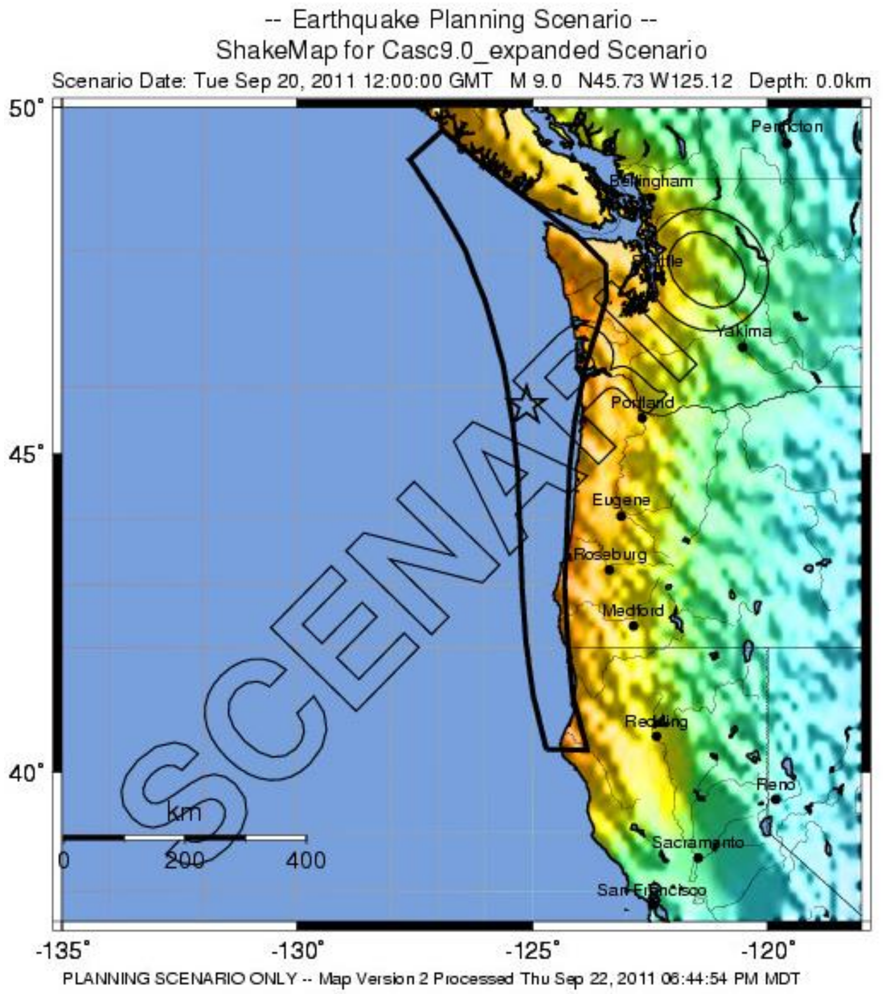
In general, the intensity and destructiveness of the shaking will be greater the closer one is to the plate interface, with coastal areas experiencing the highest intensities and the level of shaking diminishing the farther inland one goes. Distance, however, is not the only factor: local geologic conditions, including soil type, can increase or decrease the intensity of the shaking and produce a range of secondary effects, including landslides and liquefaction (the latter occurs when certain types of soil lose cohesion and behave like a liquid). As a result, shaking intensities will vary throughout the Pacific Northwest, and some areas will suffer more damage than others. The initial quake will likely be followed by aftershocks, which may begin within hours of the main shock and will continue to occur for months afterwards.

How Intense is the Shaking?

Magnitude is a measure of an earthquake's size: it tells how much energy was released when the fault ruptured. For the people and structures experiencing the earthquake, the intensity of the shaking is what really matters.

How much the ground shakes depends on your location. Proximity is a major factor (the closer you are to the rupture, the more intense the shaking tends to be), but the shape and consistency of the ground makes a big difference. In the 2001 Nisqually earthquake, for example, the greatest shaking intensities were not nearest the rupture, but in areas where the soft soils of river valleys and artificial fill amplified seismic waves, such as on Harbor Island in Seattle.

This map was created by the U.S. Geological Survey to show the shaking intensities that have been estimated for a scenario Cascadia earthquake measuring M9.0. The extent of the fault rupture is outlined in black. Areas colored red and orange will likely experience the strongest shaking (see the key at right for details).

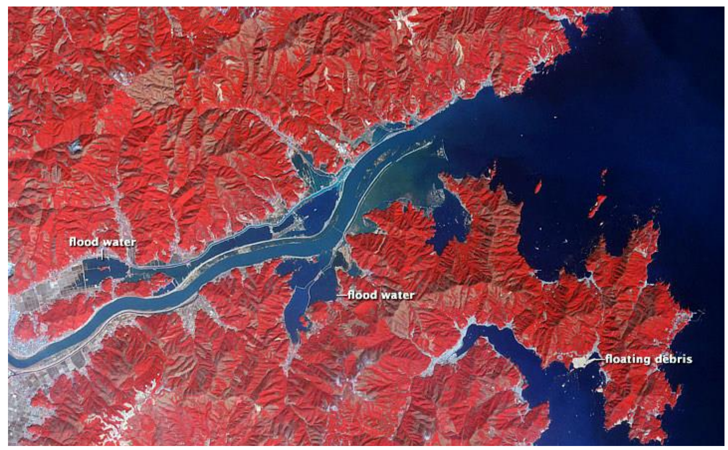


PERCEIVED SHAKING	Not felt	Weak	Light	Moderate	Strong	Very strong	Severe	Violent	Extreme
POTENTIAL DAMAGE	none	none	none	Very light	Light	Moderate	Moderate/Heavy	Heavy	Very Heavy
PEAK ACC.(%g)	<.17	.17-1.4	1.4-3.9	3.9-9.2	9.2-18	18-34	34-65	65-124	>124
PEAK VEL.(cm/s)	<0.1	0.1-1.1	1.1-3.4	3.4-8.1	8.1-16	16-31	31-60	60-116	>116
INSTRUMENTAL INTENSITY	I	II-III	IV	V	VI	VII	VIII	IX	X+

A Tsunami is Born

When the Cascadia subduction zone ruptures, it causes part of the seafloor to move abruptly upwards. This displaces the column of water above the rupture, and the result is a tsunami: a series of waves that travel outwards in all directions from the place where the uplift occurred. Unlike wind-generated waves that travel along the surface, tsunami waves move through the entire body of water from seafloor to surface. Tsunami waves have extremely long wave lengths and contain a much greater volume of water than surface waves: this means that they look and act less like an ordinary wave and more like a vast, moving plateau of water.

Image Source: NASA Earth Observatory



The top photo shows the Kitakami River in Japan before the Tohoku earthquake on March 11, 2011. The tsunami that followed traveled far up the river; large areas were still underwater when the bottom photo was taken on March 14. ***(Photos are false-color composites of infrared images in which healthy vegetation appears bright red.)***

A tsunami can travel across the deep ocean at nearly 500 miles (800 km) per hour. In deep water, the amplitude or height of the tsunami is low relative to its length, so the slope of the waves is very low, and they may pass unnoticed under ships. Upon entering shallower water, however, they slow down and gain in height as water piles up behind the wave front. Once it hits shore, a single tsunami wave can take as much as an hour to finish flowing in. The height of the wave and how far inland it travels will vary with location: In places along Cascadia's coast, the tsunami may be as high as 30–40 feet (9–12 m). Much depends on the local topography—the lay of the land—both underwater and along the shore. In general, the inundation will be greater where the land is low or the topography focuses the waves, such as at bays and river mouths. Other key factors are subsidence and tides: When the fault ruptures, the land in many coastal areas will drop in elevation, increasing the run-up of the subsequent tsunami; and if the quake occurs during high tide, the tsunami will travel farther inland than it would at low tide.

Because the Cascadia subduction zone is close to shore, the first wave will reach land soon after the earthquake—within 20 to 30 minutes in some locations (perhaps as little as 15 minutes along parts of the northern Californian coast). We can then expect multiple waves over a period of hours. In Japan, for example, the tsunami caused by the M9.0 Tohoku earthquake in 2011 produced as many as five large waves in some places, the last arriving more than two hours after the earthquake. The tsunami that struck Chile after the M8.8 Maule earthquake in 2010 consisted of three to four waves—the last tended to be the largest and reached shore as many as four hours after the earthquake. In addition, because parts of our coastline will have dropped (subsided) during the earthquake, some areas may remain flooded, or will continue to flood during high tide, even after the tsunami retreats.

Slow Earthquakes: **In 2003, scientists in Canada detected the occurrence of regular, slow earthquakes along the Cascadia subduction zone. Called *episodic tremor and slip*, these events are believed to originate along the plate interface at depths below the locked zone. About 15–28 miles (25–45 km) down, warmer temperatures make the plates pliable enough to permit some movement. This occurs about every 14–15 months in northern Washington and slightly more or less frequently elsewhere: The periods of deep slip last for several weeks and produce tremors that are too small to be felt (in other words, low-level seismic wave chattering).**

Unfortunately, such movement increases, rather than releases, the pressure on Cascadia's locked zone. Slow stick-slip cycles are now closely monitored, and they are providing clues that may help scientists predict when and where the locked zone itself is likely to break. Maps of slow-slip episodes can also reveal where the plate interface is locked, defining previously unknown boundaries of future ruptures.

What Are the Odds?

The evidence for past earthquakes of magnitude 9.0 suggests that they recur on average every 500 years, but the actual intervals between events are far from predictable—such earthquakes have been separated by as many as 1,000 years and as few as 200. The estimates of the sizes of pre-1700 earthquakes are also uncertain. Cascadia has now been building up strain for over 300 years, so the next great earthquake could happen at any time. Reduced to simple odds, the chances that an earthquake as large as magnitude 9.0 will occur along the zone within the next 50 years are about one in ten.

While the timing cannot be forecast very precisely, great subduction zone earthquakes are inevitable—they are a fundamental consequence of plate tectonics. Whether this type of earthquake is considered alone or in combination with other earthquake sources, the odds that a large, damaging earthquake will occur in the near future are very high. The more steps our communities take now to prepare, the more resilient we will be.

PREDICTING THE EFFECTS OF THE NEXT BIG EARTHQUAKE

No one can predict the exact date of the next Cascadia earthquake, but it is possible to anticipate the likely impacts on the region's communities, infrastructure, and economy. Due to the number of variables, earthquake simulations do not provide precise forecasts of every effect in every location, but they can provide useful insights. The results may help individuals, organizations, businesses, and communities define their risks, pinpoint their chief vulnerabilities, and make informed decisions as they develop emergency and continuity plans and invest in seismic mitigation strategies. The earthquake itself cannot be averted, but, with awareness and planning, many of the damaging impacts can.

If the Earthquake Happens Tomorrow....

The Cascadia subduction zone could produce an earthquake as large as the magnitude 9.0 event that devastated the east coast of Japan in 2011. Fortunately, Cascadia's earthquake is not expected to cause as many deaths or destroy as much infrastructure. In large part, this is because fewer people live along the coast of the Pacific Northwest, and it has far less infrastructure. Moreover, the majority of the fatalities in recent subduction zone earthquakes elsewhere were caused by tsunami waves. Potential fatalities along Cascadia's coast can be reduced if people in the tsunami zone are educated about the hazard and prepared to evacuate to higher ground.

This is not to say the Northwest would suffer only minor losses. Should the earthquake and tsunami happen tomorrow, the number of deaths could exceed 10,000. More than 30,000 people could be injured. The economic impacts would also be significant: for Washington, Oregon, and California, the losses have been estimated at upwards of $70 billion. While this is not as high as Japan's staggering $309 billion in estimated losses, the potential consequences of a great Cascadia quake are sobering.

Economic Impacts of a Cascadia Subduction Zone Earthquake			
Earthquake Scenario:	Cascadia M9.0: **Washington only** *(FEMA, 2011)*	Cascadia M9.0: **Oregon only** *(Oregon Resilience Plan, 2013)*	Post-earthquake loss estimate for the Nisqually M6.8 earthquake in 2001
Estimated Impact:	$49 billion	$32 billion	$2–4 billion

Estimating Losses: **Earthquake modeling seeks to anticipate the earthquake's effects, including economic impacts (both direct and indirect). This table shows two estimates based on a Cascadia M9.0 earthquake scenario; for comparison, the estimated economic losses for the Nisqually earthquake are also included. Loss estimates may vary as a result of differences between the models and assumptions that were used to calculate them. While the numbers are necessarily inexact, such estimates provide useful insights to those seeking to assess risk and find cost-effective ways to mitigate it.**

Aftershocks

The Cascadia earthquake is likely to be followed by aftershocks, which will occur throughout the region and vary in size: After a main shock as large as magnitude 9.0, a few aftershocks are likely to exceed magnitude 7.0. During the first month after the Maule earthquake in 2010, Chile experienced 19 aftershocks larger than magnitude 6.0 (the largest was magnitude 6.9). Japan's great Tohoku earthquake in 2011 was preceded by a magnitude 7.5 foreshock and followed by multiple aftershocks, the largest of which measured magnitude 7.9. Some of these aftershocks occurred on the west side of Honshu, demonstrating that such quakes may be triggered some distance from the main shock.

Aftershocks that follow hard on the heels of the main shock can bring down already weakened buildings. While the size and frequency of aftershocks will diminish over time, a few may cause additional damage long after the initial quake. This occurred in New Zealand, where the magnitude 7.0 Darfield earthquake in September of 2010 was followed over five months later by a magnitude 6.1 aftershock, which caused far more damage to the city of Christchurch than the main shock.

The following pages describe possible impacts based on modeling of a magnitude 9.0 main quake; large aftershocks would be likely to produce additional damage along the same lines.

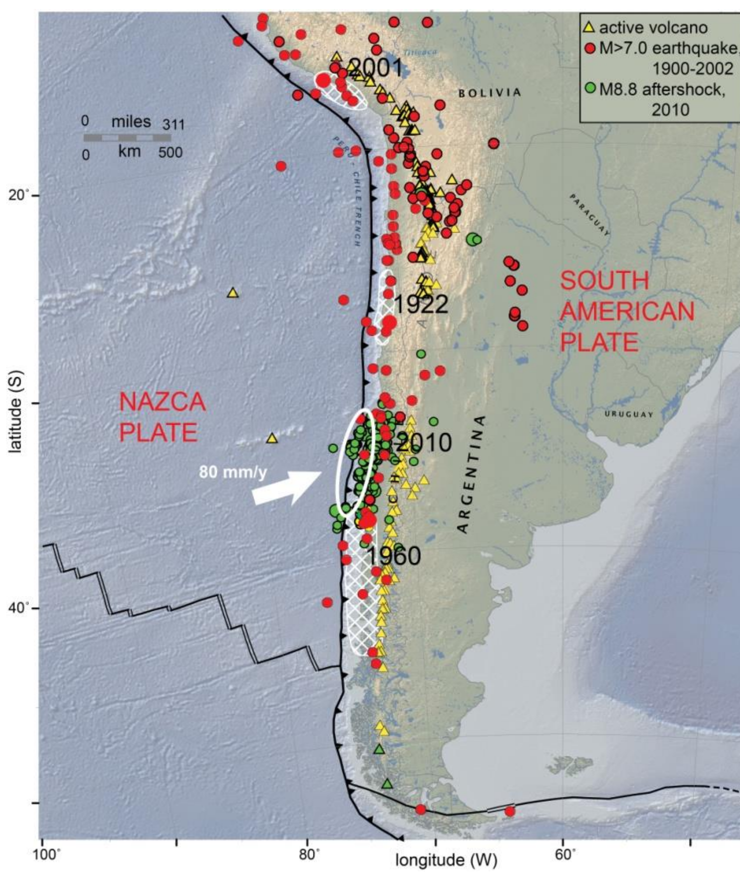


Image Source: USGS

Multitude of Aftershocks: **Chile's M8.8 Maule earthquake in 2010 occurred on a subduction zone similar to Cascadia. On this map, green dots mark aftershocks that followed the Maule quake; red dots mark past earthquakes greater than M7.0 (1900 to 2002). Earthquakes larger than M7.0 are rarer in Cascadia than in Chile, but a great quake on the Cascadia subduction zone is expected to trigger multiple aftershocks—including some far from the faulted area of the main shock. (On the map, a solid white line encircles the section of the plate interface that broke in the Maule quake; white cross-hatching marks past ruptures.)**

How Will Essential Infrastructure Perform?

Because Cascadia's earthquake potential has only come to light over the last few decades, most of our communities and much of the infrastructure that supports them were built without taking this seismic hazard into account. This means that unless structures are newly built or have been retrofitted (or, in particular cases, relocated), they are likely to be vulnerable. We have only just begun to take steps to rectify this, so if the earthquake happens tomorrow, many of the impacts could be severe. The good news is that earthquake modeling is helping to focus efforts to create a better outcome. The following description offers a snapshot of a few of the anticipated impacts.

Transportation Networks: Bridges, Roads, and Rail Lines

As the ground goes on shaking for several minutes, numerous roads and bridges will suffer damage, especially along the coast (for example, U.S. Highway 101) and routes connecting the coast to areas farther inland. This vulnerability is in part due to the age of many bridges: For example, noting that the majority of bridges along Interstate 5 in Oregon were constructed before the development of modern seismic design standards, the Oregon Department of Transportation (ODOT) has estimated that 19 of the bridges on this route are likely to be heavily damaged during a great subduction zone earthquake, and five are likely to collapse. Of the 135 bridges carrying U.S. 101 on the Oregon coast, ODOT estimates that 56 may collapse and 42 may be heavily damaged.

Terrain is another key factor. Many roads, bridges, and rail lines were built across old landslides that are likely to be set in motion by the earthquake. Bridges, by necessity, are often built across rivers, and their foundations are set in alluvial soils that may lose stability as the ground shakes. During the Maule earthquake in Chile, all of the bridges spanning the Bio-Bio River sustained damage when the ground they were built on liquefied and spread laterally.

Little redundancy has been built into the transportation system, in part because of the Pacific Northwest's steep mountain ranges and inland waterways (notably, the Columbia River, Puget Sound, and straits around Vancouver Island). It may therefore be hard to find detours around many of the damaged sections. Coastal communities are likely to be cut off from each other and from inland areas. Even some inland areas may become isolated, such as the island communities in and around Seattle that depend on bridges

Photo Source: Geotechnical Extreme Events Reconnaissance (GEER)

When Soil Acts Like a Liquid:

Liquefaction is one of the most damaging effects of ground shaking. Certain soils, such as water-saturated silt and sand, can become dangerously unstable during an earthquake. The shaking increases water pressure, forcing the water to move in between the individual grains of soil; as the grains lose contact with each other, the soil begins to act like a liquid. Overlying layers of sediment can slump and spread laterally. Structures built on such soils may shift position or sink, while buried pipes and tanks become buoyant and float to the surface. Liquefaction-prone soils are common in river valleys, along waterfronts, and in places covered with artificial fill. Unfortunately, these sites are often prime locations for important structures, including bridges, ports, airports, and industrial facilities.

Above: Damage due to liquefaction and lateral spreading at the Port of Coronel in Chile after the M8.8 Maule quake.

and ferries. In British Columbia, Highway 99 between Vancouver and communities to the south may become impassable in places. Rail service, such as that along the Interstate 5 corridor, is expected to be disrupted by landslides and damage to rail bridges that pass through Portland, Olympia, and Seattle.

Ports and Shipping Channels

While many coastal ports will be flooded by the tsunami, the large ports at Portland, Seattle, Tacoma, and Vancouver (B.C.) are, fortunately, not in the tsunami inundation zone. However, these and other ports are likely to experience severe currents, which can damage ships and piers within harbors. The tsunami triggered by Chile's Maule earthquake in 2010 caused currents that inflicted more than $1 million in damage to Crescent City, California. Moreover, the Northwest's inland ports may be damaged by the Cascadia quake itself: Ports tend to be vulnerable to earthquakes because the ground around and beneath natural waterways often consists of water-saturated soils that become unstable when shaken. In the Maule earthquake, the inland ports of Valparaíso and Concepción were damaged by strong ground shaking and liquefaction, rather than by the tsunami that followed the quake.

Shipping channels may also be disrupted by a Cascadia earthquake. Sections of the Columbia and lower Willamette rivers, for instance, are likely to be closed to shipping due to underwater landslides and the presence of debris where ground failures have caused parts of structures, such as bridges and electrical transmission towers and lines, to topple into the river.

Airports

The runways and facilities of airports along the coast may be damaged extensively or completely by liquefaction-induced deformation and heaving, ground settlement, and tsunami impacts. The runways of these airports are likely to be unusable by fixed-wing aircraft after the earthquake, although helicopters may still be able to use some of the airfields to support relief efforts. Farther inland, airports along the I-5 corridor (including Seattle/Tacoma International Airport and Portland International Airport) are expected to experience only slight to moderate damage. These airports may, however, experience fuel shortages due to disruption of the jet fuel that is delivered by pipeline.

Electricity, Natural Gas, and Liquid Fuel

Widespread power outages are expected throughout the Pacific Northwest, with partial blackouts in every city located within 100 miles of the coast in Washington and Oregon and in parts of northwestern California. Natural gas pipelines and compressor stations are also likely to sustain damage, leaving customers in western parts of Washington and Oregon without service. Restoration times for electricity and natural gas will depend on location—it may be a matter of days in some inland areas, but a matter of weeks or months nearer the coast.

Many of the region's refined fuel terminals and numerous pump stations along the pipeline system in Washington and Oregon are expected to suffer damage; and ground displacement may cause numerous breaks and leaks in both crude- and refined-product pipelines that run north-south in the western

Long lines at gas stations were a familiar sight in New York and New Jersey after damage caused by Hurricane Sandy led to power outages, fuel shortages, and rationing.

Photo by Jim Henderson

zones of these states. Because of damage to shipping channels, it may not be possible to transport petroleum by boat from the refineries in Puget Sound to Portland and other points along the Columbia and Snake rivers. Without the ability to store and distribute liquid fuels locally, shortages are likely, affecting not only the use of vehicles and aircraft, but also critical facilities and key industries.

As with other structures, the vulnerability of the region's energy infrastructure is variable. For example, Oregon's critical energy infrastructure hub is in the Willamette River valley in an area where the ground consists of layers of river sediments and man-made fill. Until the older structures are retrofitted or rebuilt and the ground beneath them is treated, this hub is judged to be very vulnerable and may incur extensive damage during a Cascadia earthquake.

Water Systems

Modeling shows that the supply of drinking water is very likely to be interrupted as a result of earthquake damage. As with other utilities, the time it takes to restore some level of functionality will depend on location: Estimates range from three weeks to seven months, and perhaps much longer in areas near the coast. Complete restoration of some damaged systems could take several years. Disruption of water systems is especially problematic because broken natural gas connections and fallen power lines frequently start fires in the aftermath of big earthquakes. In the 1989 Loma Prieta earthquake, for instance, fire broke out in San Francisco's Marina District after liquefaction caused underground gas lines to fail. Typically, the same water system that supplies drinking water is used by firefighters to put out fires, so quake damage to the system will seriously hamper their efforts.

Communications

Earthquake damage often impairs communication systems just when they are most needed. In Chile's Maule earthquake in 2010, landline and wireless services were disrupted for as much as a week by equipment failures, structural damage to key facilities, and power outages. Jamming is another typical problem, as demonstrated in two recent earthquakes in California: after a magnitude 5.5. quake in Chino Hills (2008) and a magnitude 7.2 event in Baja (2010), landline and cell communications were overwhelmed by the number of people trying to use them at the same time. In a great Cascadia earthquake, millions of customers could lose service as a result of broken cables and equipment failures at telecommunications centers. The earthquake may damage cell towers, throw antennae out of alignment, and break fiber connecting cables, thereby disrupting service to many cellular customers as well. It is likely that the earthquake will sever major undersea transpacific cables, disrupting service

Photo Source: National Archives and Records Administration, H.D. Chadwick

FIRE: **Damaging earthquakes often start fires, as was famously illustrated by the great San Francisco earthquake and fire in 1906 (left). Typical causes of fire are downed electrical lines and broken natural gas pipelines. Mitigation, such as fitting natural gas pipelines with automatic or remote shut-off valves and installing flexible connections, can substantially reduce the risk.**

The City of Vancouver in British Columbia has also prepared for this hazard by installing a dedicated fire protection system. Completed in 2003, this quake-resistant system allows firefighters to pump water from False Creek and Coal Harbour.

not only to East Asia, but also cutting Alaska off from the rest of the United States. It could take two to three months to restore these important connections.

Interdependence and Recovery of Infrastructure

Many parts of the region's infrastructure connect to and depend on others. Landslides and damaged bridges, for example, can prevent repair crews from reaching downed power lines or damaged sections of the water system. If the electricity is out for an extended period, communications systems that are functioning on back-up power will begin to fail, as will operations at water-treatment plants and hospitals that are relying on generators. Even with a functioning transportation system, it may be hard to refuel generators and vehicles if damaged pipelines and terminals lead to fuel shortages. By identifying vulnerabilities and critical interconnections, states and communities can prioritize mitigation and plan more effectively.

What Will Happen to Buildings?

As with other types of structures, a building's performance during the earthquake will depend on when it was built, where it is located, what it is made of, and how long the ground shakes. For tall buildings, large-magnitude earthquakes pose a particular challenge: High-rises and other tall structures vibrate at a lower frequency than shorter buildings. Because the frequency of a large earthquake's seismic waves is also low, some tall structures may resonate with the waves. This will amplify the intensity of the shaking and may increase the damage.

Some buildings should hold up fairly well. Structures that were designed and built to meet current seismic codes may sustain damage, but should not collapse and may be usable after the earthquake, although they may lack utilities. Many houses in the Northwest are wood-frame structures. This type of building is lightweight, flexible, and unlikely to collapse during the quake, although it may shift off of its foundation if not bolted to it (this is a major concern for houses built prior to 1976). Connections to utilities may also break, and fallen chimneys are quite common, as was seen during the Nisqually earthquake in 2001.

Other buildings will perform very badly indeed. Unreinforced masonry buildings (URMs), for example, predate seismic codes. Built of brick or concrete without steel reinforcement, they are prone to collapse during strong earthquakes, particularly when the shaking lasts for several minutes. URMs are often the cause of earthquake-related fatalities. Because of the danger such buildings pose, some governments are taking steps to eliminate

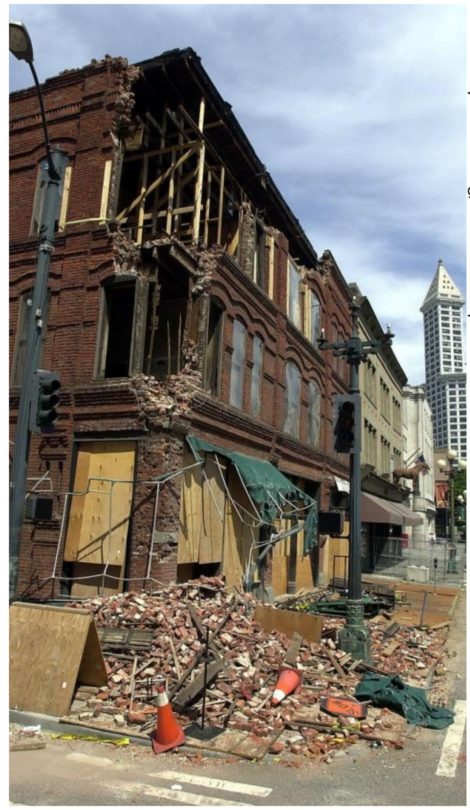


Photo by Eric Stahung, Seattle Municipal Archives

Dangerous Buildings: **Unreinforced masonry buildings (URMs) are notoriously dangerous in earthquakes. They can be found throughout the Northwest and include schools, courthouses, city halls, and apartment buildings; many are considered historic. The M6.8 Nisqually earthquake in 2001 lasted for under a minute, but caused serious damage to URMs; it even cracked the dome of Washington's capitol building and damaged its supporting columns.**

California has had legislation in place since 1986 that requires jurisdictions in seismic zones to adopt programs aimed at accelerating the retrofitting or demolition of URMs. The City of Eureka, for instance, has had such a program in place since 1989: The majority of the URMs identified as hazardous under Eureka's program have now been retrofitted. Similar programs are being contemplated in other states.

Above: The front of the historic Cadillac Hotel building in Seattle partially collapsed during the 2001 Nisqually earthquake.

or strengthen URMs. California state law requires local governments in seismic hazard zones to inventory URMs and adopt mitigation programs aimed at reducing the risk of collapse. Complete inventories have been done only in California, but URMs are common throughout the Northwest: Oregon has an estimated 5,000 to 10,000 statewide, with about 1,800 in the city of Portland alone. Seattle, which has about 1,000 URMs and has experienced three damaging earthquakes in the last 64 years, is considering adoption of a mandatory retrofit program similar to California's.


Photo by Ross Becker, CERA photo gallery

Many businesses lost inventory in the M6.1 quake that struck Christchurch, New Zealand in February of 2011.

Nonstructural Damage

A Cascadia earthquake may cause nonstructural damage even in buildings that were built or retrofitted to meet a higher structural seismic standard. Strong shaking can knock fittings and equipment loose and move anything that is not securely bolted down. Suspended ceilings, fire sprinkler systems, elevators, partition walls, air handling units, and hot water tanks are just a few of the vulnerable components. Non-structural damage was widespread in Chile's magnitude 8.8 quake in 2010 and affected every type of building. Damage to medical, mechanical, and electrical equipment can put even structurally sound healthcare facilities out of service: In Chile, some 83 percent of hospitals were rendered partially or totally non-functional as a result of this type of damage. Nonstructural damage also caused losses at industrial facilities in Chile and increased their downtime. People can prevent a lot of this damage by taking steps to secure furnishings, inventory, and equipment and by retrofitting nonstructural components.

Are Critical Facilities Ready? **Making sure critical facilities are able to survive the quake and function afterwards is a top priority. For example, many older fire stations must be retrofitted to make sure quake damage does not prevent firefighters from getting the engines out. Healthcare facilities also need to be built to current standards or retrofitted, but as Chile's M8.8 earthquake in 2010 showed, preparations must go beyond reinforcing the building's structure: Hospitals in Chile had emergency generators and supplies of water, but lacked backups for communication systems. This made it difficult for them to coordinate aid.**

Photo by Joe Mabel

Modeling of a Cascadia M9.0 quake predicts widespread damage to critical facilities in coastal zones and many western areas. Timeframes for restoration range from months to years where shaking intensities are high; it may be three years or more for parts of the coast.

Many of Seattle's fire stations were built between 1918 and 1974, so the city has begun a program of seismic up-grading and replacement. Station 10 (left) is a new building and was designed to meet seismic standards.

Onagawa, Ishinomaki (right), is one of many coastal communities in Japan devastated by the near-source tsunami that was triggered by the M9.0 Tohoku earthquake on March 11, 2011.

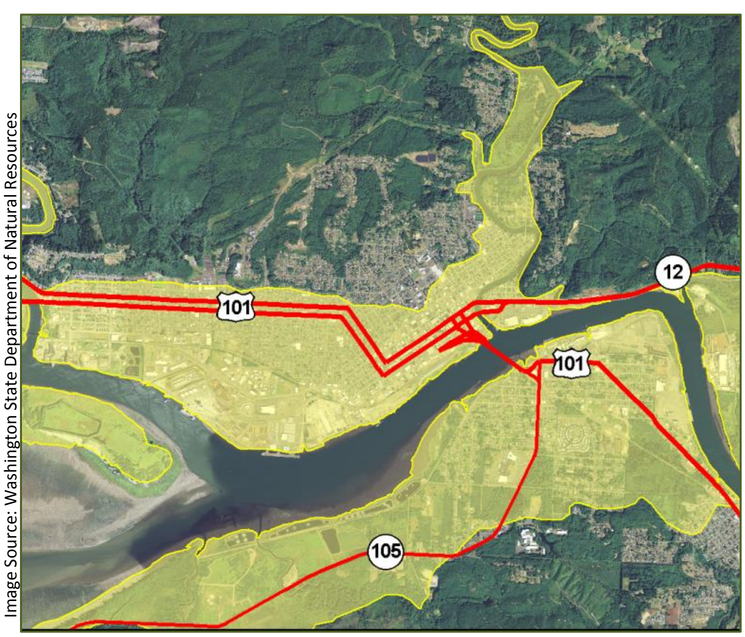
(Photo Source: NOAA/ NGDC, Shunichi Koshimura)

What Will Happen to Communities on the Coast?

After enduring several minutes of strong shaking, many of the Northwest's coastal communities will face a near-source tsunami. Communities most at risk are those along the outer Pacific Coast and Strait of Juan de Fuca. Everyone in the tsunami inundation zone must evacuate immediately in order to reach higher ground before the first wave reaches the shore, which in some areas could be 20 minutes or less. While the coast is not heavily developed or densely populated, over 71,000 people are estimated to live in the tsunami inundation zones of Washington, Oregon, and northern California (Del Norte, Humboldt, and Mendocino counties). This number does not include the people who work in thousands of businesses in the zone, or the many thousands of visitors who rent houses, stay in hotels, or camp there. During peak seasons, the number of visitors far exceeds the number of residents.

Evacuation is more challenging for some communities than others. In northern California and southern Oregon, where the subduction zone is closest to shore, the evacuation time may be as short as 15–20 minutes. The proportion of a community within the tsunami inundation zone and the distance to high ground are also critical factors. For example, in Washington, 70 percent of Aberdeen's population and 100 percent of the population of Ocean Shores live in the inundation zone. Most people in Aberdeen should be able to walk to high ground before the tsunami reaches shore, but the majority of Ocean Shores' residents may be too far from high ground to reach it in the time available. Given limited routes away from the coast and expected damage to roads and bridges, attempts to evacuate by car are likely to result in gridlock.

Image Source: Washington State Department of Natural Resources



Aerial view of the city of Aberdeen on the outer coast of Washington. The tsunami hazard zone is shaded in yellow. Highways are marked by solid red lines.

Because the shape of the seafloor and shoreline can focus and amplify the tsunami in some places, wave heights will vary: In parts of northern California, the height of the tsunami could exceed 26 feet (8 m). At Ocean Shores in Washington, modeled tsunami heights in one scenario reached 16–20 feet (5–6 m), while at Long Beach, they ranged between 23 and 26 feet (7–8 m). Wood-frame houses, although likely to survive the earthquake, are unlikely to withstand the impact of so much water, which will pick up large debris as it flows inland. These tsunami heights are also sufficient to flood the second and third stories of steel and reinforced concrete buildings. As the experience of Japan and Chile showed, even reinforced concrete buildings may be damaged by debris impact or scouring around their foundations. On the whole, however, reinforced concrete tends to hold up well and, if sufficiently tall, such buildings could serve as vertical evacuation refuges for those unable to reach high ground.

Cities and towns that are likely to be particularly hard hit by the tsunami include Eureka and Crescent City in California, Seaside and Warrenton in Oregon, coastal communities between Moclips and the Columbia River in Washington, and Port Alberni in British Columbia. Tsunami damage is also likely to be severe enough at the mouth of the Columbia River to impair navigation and prevent normal transport of goods, such as agricultural products, between inland areas and the coast. Cascadia's topography, however, makes the region as a whole far less vulnerable to tsunami than is the northeast coast of Japan. There, tsunami waves generated during the 2011 Tohoku earthquake ranged between 33 and 132.5 feet (10–40 m) in height and devastated that coast's many low-lying areas. Moreover, the Pacific Northwest's largest population centers and ports, including Portland (OR), Seattle and Tacoma (WA), and Vancouver (BC), are not expected to experience any significant tsunami impacts.

Earthquake and Tsunami Refugees

The great earthquake and tsunami that struck Japan in 2011 spotlighted the challenge of providing temporary shelter, services, and food to large numbers of displaced people. If, like the Tohoku event, the Cascadia earthquake happens during the winter or early spring, many people will need refuge from the cold, wet conditions, and generators, fuel, and other emergency supplies will be in high demand. If the earthquake occurs during the summer, the number of visitors that seasonally swell the population of seaside towns and campgrounds will increase the need for shelter and supplies in coastal areas.

Photo Source: FEMA, Walt Jennings

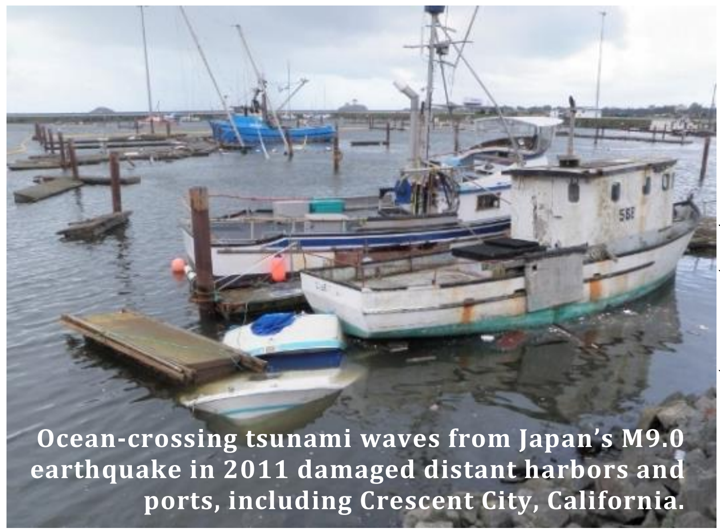
The American Red Cross delivered meals-on-wheels to those who could not reach a food source or were unable to cook, after Hurricane Sandy caused widespread damage along the northeast coast of the U.S. in the fall of 2012.

The need for shelter will be greatest near the tsunami hazard zones where evacuees are gathered, but earthquake damage is also likely to displace people farther inland. Ideally, people living in relatively undamaged buildings could shelter in place, but because many will be without electricity, running water, and other utilities, they will need supplies of water and access to portable facilities until their services are restored. If the earthquake occurs in winter, many will be without heat, and even those with portable generators may find it hard to obtain fuel. Among the most vulnerable are low-income individuals and families who may lack the resources to store emergency supplies, repair homes, replace belongings, or support themselves during a lengthy recovery.

Other Far-Reaching Impacts of a Cascadia Earthquake and Tsunami

Because the intensity of the shaking tends to diminish farther from the rupturing fault, eastern parts of British Columbia, Washington, Oregon, and northern California will be less affected than the coast and western river valleys and basins, although damage may still occur in places where layers of soft soil amplify the seismic waves. The earthquake could also produce a range hydrogeologic impacts, such as causing some wells to go dry or degrading the quality of well or surface water.

The more significant impacts in eastern regions will be indirect. Eastern cities and airports, such as Redmond, Oregon, and Spokane and Moses Lake, Washington, may become staging areas for emergency resources and personnel. Hospitals in western zones are likely to be damaged or overwhelmed by the number of injured, so patients may be evacuated to other hospitals as soon as transportation is available. Large companies and government agencies in the damage zone may also temporarily transfer administrative functions to backup facilities on the east side or elsewhere.



Ocean-crossing tsunami waves from Japan's M9.0 earthquake in 2011 damaged distant harbors and ports, including Crescent City, California.

Photo Source: NOAA/NGDC, Todd Williams, Cascadia GeoSciences

Eastern areas will also be affected economically by damage to western roads and bridges, ports, and the Columbia River navigation system, which will prevent the normal movement of goods, including the export of agricultural products. Disruption of the fuel distribution system may cause shortages in some inland areas, such as southeastern Washington. Because the region's economy is interconnected, less damaged eastern areas are also likely to be affected by economic changes on the west side, including the loss of numerous small businesses in quake-damaged areas, the possible exodus of some large businesses out of the region, and the decline in tourism, particularly along the coast.

Farther afield, the earthquake is expected to sever major undersea transpacific cables, which would substantially disrupt communications between the United States and East Asian countries. Rerouting communications traffic around the affected area may produce delays and disruption elsewhere in the United States, because the additional traffic could exceed the capacity of the network. Undersea cables also constitute Alaska's main communications link with the rest of the United States. Among other things, the loss of this link may disrupt normal banking activity in Alaska, preventing many people there from accessing funds and interrupting the direct deposit services of some out-of-state companies.

Another far-reaching impact will be the tsunami that travels across the Pacific, affecting coastal communities as far away as Japan. Fortunately, the Pacific Tsunami Warning Center in Hawaii and the West Coast/Alaska Tsunami Warning Center in Alaska are able to track ocean-crossing tsunamis and issue timely warnings. Thanks to such warnings, places as near as Alaska will have more than four hours to evacuate. Wave heights will be smaller farther from the subduction zone, but may still cause flooding and strong currents that can damage shorelines, ports, and property—much as the tsunami from the 2011 Tohoku earthquake sank several boats and damaged docks in Crescent City, California.

PREPARING FOR THE BIG ONE

As the foregoing description of possible impacts shows, the next big Cascadia earthquake is likely to have serious consequences, both within the region and beyond. Much still needs to be done to prepare the people and communities of the Pacific Northwest for this event. Nevertheless, progress has already been made toward identifying and lessening these potential impacts and improving the region's ability to withstand and recover from a great subduction zone earthquake.

Risk Assessment

Cascadia's earthquake hazard—its potential for earthquakes—is determined by the region's geology and the tectonic forces that continually shift and reshape the surface of the earth. Earthquakes may also trigger secondary hazards, such as liquefaction and landslides, tsunami waves, fires, and hazardous material spills. Identifying and analyzing the hazards makes it possible to assess the risk—the exposure and vulnerability of people, buildings, and infrastructure to the hazards.

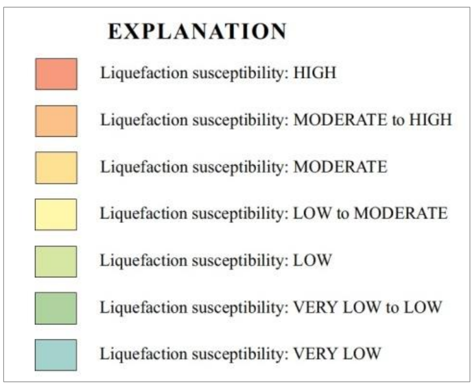


Image Source: Washington State Department of Natural Resources

This excerpt from a liquefaction susceptibility map of King County in Washington shows how such maps can help reveal the areas that are likely to experience greater damage during an earthquake.

Identification of the region's geologic hazards is progressing, and maps now exist that help reveal and define these features, including active faults, liquefiable soils, existing landslides, and tsunami inundation zones. As this work continues, hazard maps and associated data are refined and updated. Such maps are used to support earthquake modeling and risk assessment, which can help everyone from community and emergency planners to transportation officials and engineers pinpoint vulnerabilities and develop practical strategies to minimize risk. For example, FEMA's Hazus methodology and software is a modeling tool that uses data from hazard mapping and other sources to estimate potential losses from earthquakes and other natural disasters. This tool has been used to assess potential impacts from a Cascadia megathrust earthquake in Oregon, Washington, and California, and is now being used in parts of British Columbia as well.

Although scientists cannot predict earthquakes, they are using their growing understanding of how earthquakes work to hone their ability to estimate the probabilities: An earthquake relieves stored-up stresses, but it also perturbs the rocks and faults around it. This disturbance can trigger additional earthquakes (aftershocks being the most familiar). While an earthquake reduces the likelihood that another earthquake will occur on the fault that produced it, it actually raises the probability of earthquakes everywhere else. The probability of earthquakes smaller than the triggering earthquake can be significant (aftershocks). Even a small earthquake makes a subsequent big earthquake more likely, although the increase in probability is generally small. Fortunately, the effects of these perturbations decrease over time, as does the elevated probability. Scientists now understand this process well enough to consider estimating probabilities that change with time, particularly in California, where earthquake rates and experience are highest. In the coming years, these "time-dependent" forecasts will become routine following significant earthquakes nationwide.

Raising Awareness

The Cascadia Region Earthquake Workgroup (CREW) and emergency management and scientific agencies across Cascadia have been engaged for years in public education efforts aimed at raising awareness and encouraging individuals, families, and businesses to prepare for earthquakes and tsunamis. These efforts include coordinated "drop, cover, and hold" earthquake drills. Some coastal communities have also held tsunami evacuation drills, giving residents and visitors the opportunity to use evacuation maps and test-walk their routes to high ground. A number of national programs also exist. In the U.S., for example, FEMA maintains a website (www.ready.gov) as part of a campaign to educate the public and help people prepare for emergencies, including earthquakes. The National Weather Service's TsunamiReady™ program helps communities on the coast plan and prepare for potential tsunamis. Information about earthquake preparedness is also provided by the American Red Cross and by the U.S. Geological Survey's Earthquake Hazards Program, which monitors and reports earthquakes and assesses earthquake impacts and hazards.

Are You Prepared?

Individuals, families, and businesses can improve their own resilience by taking steps to prepare for earthquakes and other natural disasters:

- **Participate in drills: Drop, cover, and hold.**
- **Identify the hazards at your home and place of business.**
- **Develop a response plan.**
- **Maintain a disaster supply kit (sufficient to last 3–14 days).**

LEARN MORE AT CREW.ORG

Resilience Planning and Mitigation Strategies

The states of Washington and Oregon have completed resilient state plans. Inspired by San Francisco's Resilient City initiative, these efforts brought together experts and stakeholders to assess the current seismic vulnerability of a variety of key sectors, including critical and emergency services, transportation, utilities, communications, and finance and business. The initiatives identified state-level priorities and produced frameworks and recommendations for increasing each state's resilience over the next 50 years. While the initiatives focused on the earthquake hazard, many of the strategies and recommendations they produced would improve resilience in relation to other hazards as well.

A number of organizations and state agencies have also undertaken sector-specific assessment, planning, and mitigation. The Oregon Department of Transportation, for example, recently completed an assessment and prioritization of Oregon's lifeline corridors and produced recommendations for a strategic campaign to retrofit bridges and harden essential routes in seismic zones. The Washington State Department of Transportation began its retrofit program in 1991 and has retrofitted hundreds of bridges since then. British Columbia's Ministry of Transportation and Infrastructure is similarly engaged in building new and retrofitting old bridges to meet current seismic standards. Because of the great expense involved, programs such as these typically distribute the work over a period of many years, focusing first on priority routes in high-risk areas.

Photo Source: General Services Administration, Federal Judicial Center

Built in 1875, Pioneer Courthouse in Portland (OR) was rehabilitated in 2005. A seismic base isolation system was installed, which decouples the superstructure from the foundation during an earthquake: The foundation absorbs most of the shaking.

Engineering for Earthquakes

Just as bridges can be built or retrofitted to withstand the forces of an earthquake, new buildings can be designed to meet basic life-safety seismic standards or even remain sufficiently undamaged to be usable after the event. Seismic design and retrofitting is now well established and has been extensively tested in active seismic zones such as Japan, where international teams of engineers have been assessing how well seismically designed and retrofitted buildings performed during the strong, prolonged shaking of the Tohoku earthquake in 2011. This event tested engineering techniques on an unprecedented scale. For example, Japan has approximately 2,600 commercial buildings and 3,800 homes that were built or retrofitted using a technique known as seismic base isolation, which allows the foundation to absorb most of the earthquake's force. Many of these structures were shaken by the magnitude 9.0 Tohoku quake; engineers who inspected them afterwards found that they performed very well, exhibiting no structural damage and remaining fully functional. The U.S. currently has fewer than 100 base-isolated buildings. One of these is the newly-retrofitted Pioneer Courthouse in Portland, Oregon.

Base isolation is just one of many techniques that can now be used to improve the performance of buildings and other structures during an earthquake. While upgrading an older building to make it usable after an earthquake may be cost effective only in certain cases, upgrades that prevent collapse during an earthquake—such as stabilizing parapets, securing exterior walls to roof and floor joists, and installing diagonal steel bracing—are more affordable and can drastically improve safety. Because many schools in Cascadia's seismic zones occupy buildings that predate modern seismic codes, Oregon, Washington, California, and British Columbia have all—to varying degrees—sought to inventory school facilities and assess potential structural and nonstructural problems. Assessment, retrofitting, and replacement of these buildings proceeds as quickly as the available funding allows. For example, since 2001, British Columbia has allocated $2.2 billion (CAD) to seismic mitigation of school buildings.

The Limits of Building Codes: **Because Japan has a very long history of destructive earthquakes, it has had strict seismic standards in its building codes for a long time, and this effectively limited damage during the M9.0 Tohoku earthquake in 2011. By contrast, the development of seismic building standards in the Pacific Northwest is relatively recent and did not take the Cascadia subduction zone hazard into account until the early 1990s. This means that many older buildings were not designed or built to handle the ground shaking they are likely to experience during a large earthquake.**

Current standards for new buildings and major remodels in the region's seismic zones are intended to ensure that buildings will not collapse or injure people during an earthquake. This is a minimum standard and does not mean that a building will be undamaged and useable after the event. The ground on which a building stands is another factor affecting its performance in an earthquake. Although hazard mapping can indicate areas that are likely to liquefy or spread during an earthquake, and building sites can be evaluated for this potential, most of the Northwest is behind California in the development of grading ordinances.

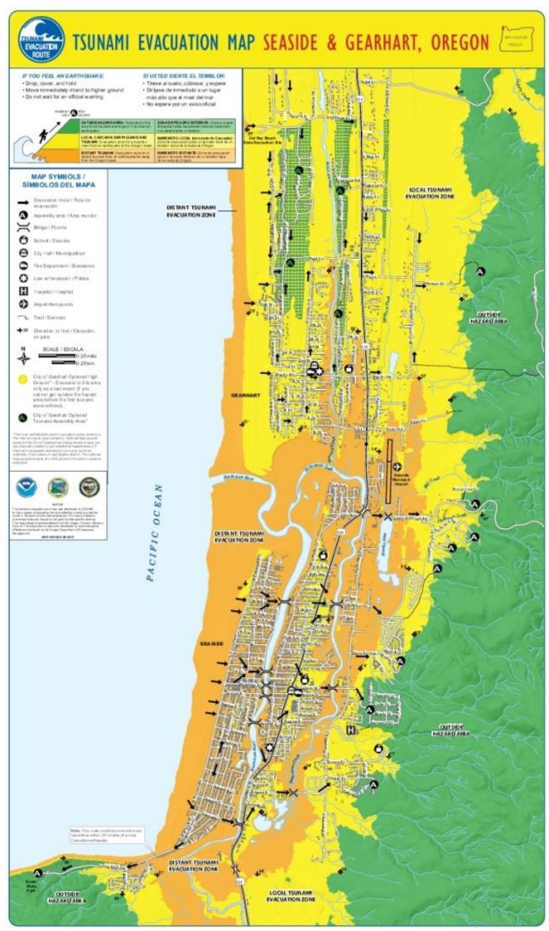
If the region's building stock is to become more resilient over time, all new buildings in Cascadia's seismic zones must be designed and built to meet the seismic standards in contemporary building codes. This will only happen if local jurisdictions adopt and enforce the most current seismic codes.

Earthquake Early Warning Systems

By detecting the smaller seismic waves that precede the earthquake's destructive waves, an early warning system might provide a few seconds to a few minutes of warning to cities (such as Portland, Seattle, and Vancouver) that are some distance from the Cascadia subduction zone. This would give people time to drop, cover, and hold, and it could be enough time to shut off gas mains, open fire station doors, slow freeway traffic, and clear cars away from potentially dangerous structures (such as bridges and viaducts). The University of Washington, Caltech, and University of California, Berkeley, with support from the U.S. Geological Survey and the Gordon and Betty Moore Foundation, have begun development of an earthquake early warning system. Japan has already implemented such a system and used it to provide some warning of the Tohoku earthquake on March 11, 2011. While Japan's experience suggests that early warning systems are promising, much still needs to be done to test the usefulness and appropriateness of such a system for the western coast of the United States.

British Columbia is likewise in the process of developing an earthquake early warning system through the cooperation of the Ministry of Transportation, Natural Resources Canada, University of British Columbia, and Ocean Networks Canada. The project will use offshore sensors in the northern Cascadia subduction zone and land-based instruments throughout the province to deliver earthquake warnings.

Preparing for Tsunamis



The devastation caused by the Tohoku tsunami in Japan might lead one to conclude that a tsunami is one feature of a subduction zone event that no amount of preparation can address—but such a conclusion is far from accurate.

Mapping the Tsunami Inundation Zones

From British Columbia to northern California, scientists and planners have been working to assess the tsunami hazard and identify the communities and infrastructure that are most at risk. For most of the coast, tsunami modeling and mapping began in the 1990s. The computer modeling takes into account not only a magnitude 9.1 earthquake and its effects (such as co-seismic subsidence), but also the shape of the undersea landscape and the topography of the coast. The modeling produces maps that show the parts of the coast that are likely to be in danger, as well as the zones that are likely to be beyond the tsunami's reach. While such modeling cannot portray the next Cascadia tsunami in precise detail, it does offer communities a useful tool to help inform local decisions about mitigation and future development, including the locations of schools and critical facilities. Emergency planners can use it to determine where to locate tsunami evacuation routes, assembly areas, and refuges.

Lessons from Abroad

Among the most important lessons to emerge from recent experience of tsunamis elsewhere is the importance of teaching people on the coast to evacuate as soon as the ground stops shaking. While official warning systems work well when the tsunami is generated by a distant earthquake, they proved far less effective during the recent near-shore events in Japan and Chile. Given the limited time for evacuation, the uncertainty of initial tsunami data, and the real possibility that local warning systems may suffer damage or lose power during the earthquake, many tsunami education materials now emphasize that people should treat the earthquake itself as the signal to evacuate to higher ground. Having evacuated, they should then stay out of the inundation zone until local officials announce that it is safe to return.

Evacuation Routes and Signs

Emergency management and natural resource agencies in Cascadia have designated evacuation routes for inundation zones and produced evacuation maps and brochures to help inform local planning agencies and the public. The National Tsunami Hazard Mitigation Program published guidelines to help communities develop the maps and to encourage consistency between communities and regions. Anyone can access these tsunami resources online. In addition, signs are now posted up and down the coast, informing people about the tsunami hazard and clearly marking tsunami evacuation routes.

Vertical Evacuation and Other Strategies

Attempts to evacuate the tsunami inundation zone by car are likely to result in gridlock, as traffic backs up and drivers encounter earthquake debris and damaged roads and bridges. People are therefore told to leave their cars and walk to high ground. Fortunately, for much of Cascadia's coast, high ground is not far away. As part of the ongoing effort to assess and mitigate the vulnerability of coastal communities, recent studies have estimated how long it would take pedestrians walking at various speeds to leave the inundation zones of many coastal communities in Cascadia. Emergency planners and communities can use such evacuation modeling to determine where vertical evacuation refuges might be needed and where less expensive strategies could help people reach safety before the tsunami reaches the shore.

For areas where high ground is too far away, vertical evacuation refuges may be an option. In Japan's tsunami in 2011, vertical evacuation structures saved thousands of lives. Such structures can take a variety of forms—buildings, elevated platforms, or even artificial berms—but should be constructed in accordance with FEMA's *Guidelines for Design of Structures for Vertical Evacuation from Tsunamis* (FEMA P646, Second Edition, 2012). Project Safe Haven in Washington is an example of a community-driven vertical evacuation development effort aimed at identifying potential locations for vertical evacuation refuges and selecting designs and strategies that best suit the needs of the community.

Other studies and mitigation efforts address the vulnerability of key transportation routes: The Oregon Department of Transportation, for example, has initiated a research program aimed at developing tsunami design criteria for bridges along U.S. Highway 101.

Outreach and Education

The tsunami that hit the coast of Chile after the Maule earthquake in 2010 demonstrated that a high level of tsunami awareness before the event will save lives. Most coastal residents knew that the earthquake was the natural warning to evacuate to high ground, and the number of people who died in this tsunami was greatly reduced as a result. Tsunami preparedness and education are well underway in Cascadia. In Washington, for instance, such efforts have been ongoing for more than a decade and include community education sessions, tsunami warning siren tests, and evacuation drills, in addition to the brochures, factsheets, videos, and other informational materials that are posted on the websites of emergency management and geological resource agencies throughout the Pacific Northwest. These education campaigns have been effective at raising awareness among the residents of coastal communities, although much remains to be done to increase their level of preparedness.

Visitors are often among the most vulnerable during a tsunami, because they are less likely to know how to respond and where to go. In the tsunami that followed the Maule earthquake, campers accounted for a large proportion of the fatalities. While some of these were on an island that lacked high ground and could only be accessed by boat, others simply did not know what to do.

LIVING IN CASCADIA

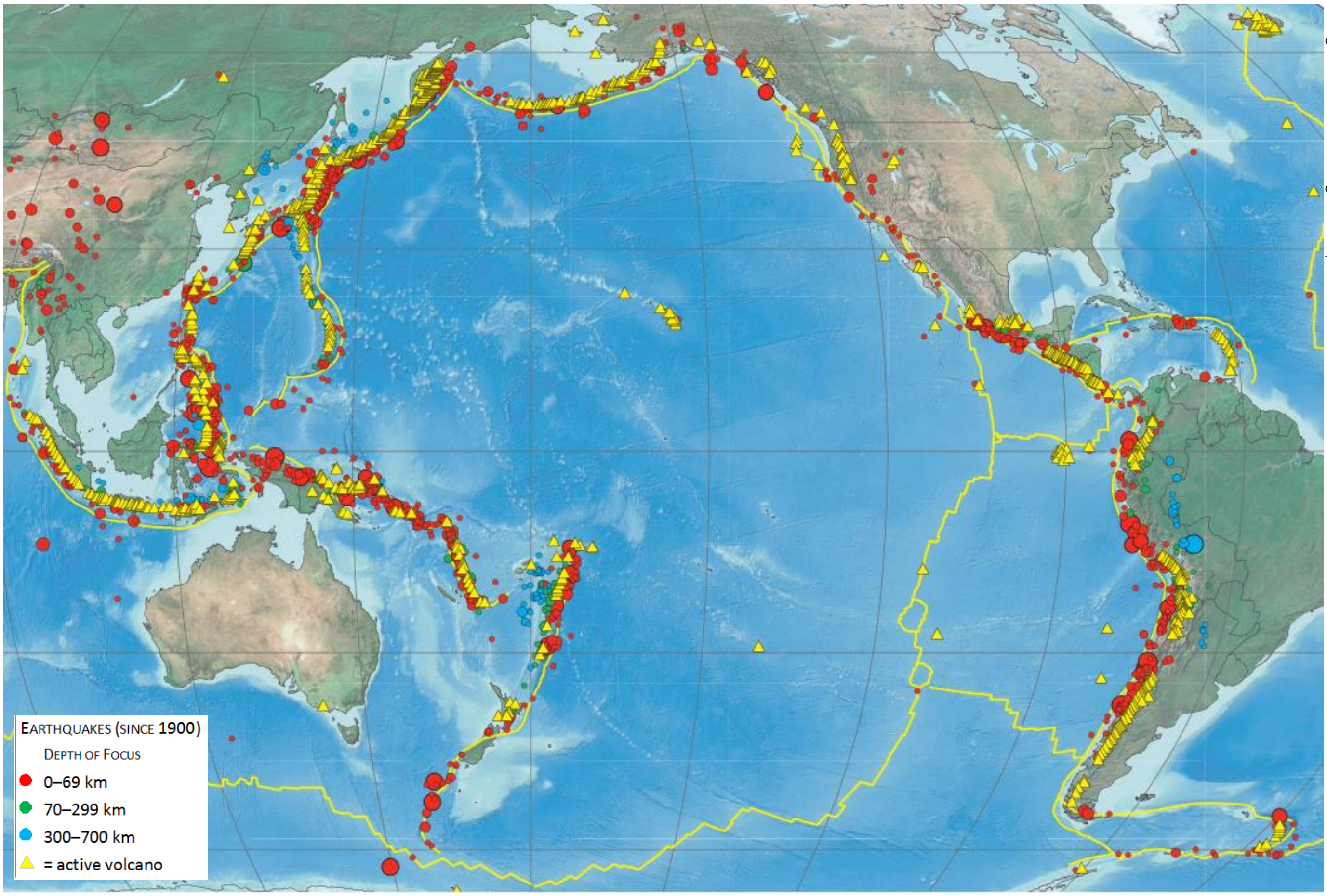
If a magnitude 9.0 Cascadia earthquake and tsunami strike tomorrow, the impacts to the region are likely to be severe and the recovery lengthy. Cascadia's communities will be transformed, but they will recover and rebuild. Every investment we now make in assessment, planning, and mitigation will pay dividends in the long run by shortening our recovery time, reducing our losses, and helping ensure that our communities emerge from the event just as vibrant—but more resilient—than they were before.

Image Source: OSU Active Tectonics and Seafloor Mapping Lab

Next Steps Forward

By implementing the recommendations that have already resulted from state and regional resilience planning and lifeline assessments, policy makers and community leaders can address many of the existing vulnerabilities of Cascadia's critical infrastructure. Local jurisdictions can also ensure that the region's building stock becomes more earthquake resistant over time by adopting the most recent building codes. Continued investment in earthquake research, including loss estimation, engineering, and social science, is also needed. Meanwhile, individuals, families, and businesses can raise their own level of preparedness and contribute to the resilience of their communities by learning more about the hazard, developing response plans, maintaining emergency supply kits, and taking steps to reduce risks at their homes and places of business.

For a list of resources and to learn more about how to prepare, visit CREW.ORG



The Pacific Ring of Fire: **The Cascadia subduction zone along the northwest coast of the United States and the southern coast of British Columbia in Canada is part of a much larger ring of active earthquake zones and volcanoes that exist around the edges of colliding tectonic plates (outlined on the map by yellow lines).**

For more information about the earthquake hazard in British Columbia, Washington, Oregon, and northern California, visit CREW's website (crew.org) or contact the following organizations:

Emergency Management BC
(www.embc.gov.bc.ca)

Natural Resources Canada
(www.nrcan.gc.ca)

Emergency Preparedness for Industry & Commerce
(www.epicc.org)

Washington Emergency Management Division
(www.emd.wa.gov)

Washington State Seismic Safety Committee
(www.emd.wa.gov/about/SeismicSafetyCommittee.shtml)

Washington Department of Natural Resources, Geology & Earth Resources Division *(www.dnr.wa.gov/geology)*

Oregon Office of Emergency Management
(www.oregon.gov)

Oregon Seismic Safety Policy Advisory Commission
(www.oregon.gov/omd/oem/pages/osspac/osspac.aspx)

Oregon Department of Geology and Mineral Industries
(www.oregongeology.org)

California Governor's Office of Emergency Services
(www.calema.ca.gov)

California Seismic Safety Commission
(www.seismic.ca.gov)

State of California Department of Conservation, California Geological Survey *(www.conservation.ca.gov)*

Federal Emergency Management Agency (FEMA)
(www.fema.gov)

National Oceanic and Atmospheric Administration
(tsunami.noaa.gov)

National Earthquake Hazards Reduction Program
(www.nehrp.gov)

United States Geological Survey
(usgs.gov)