

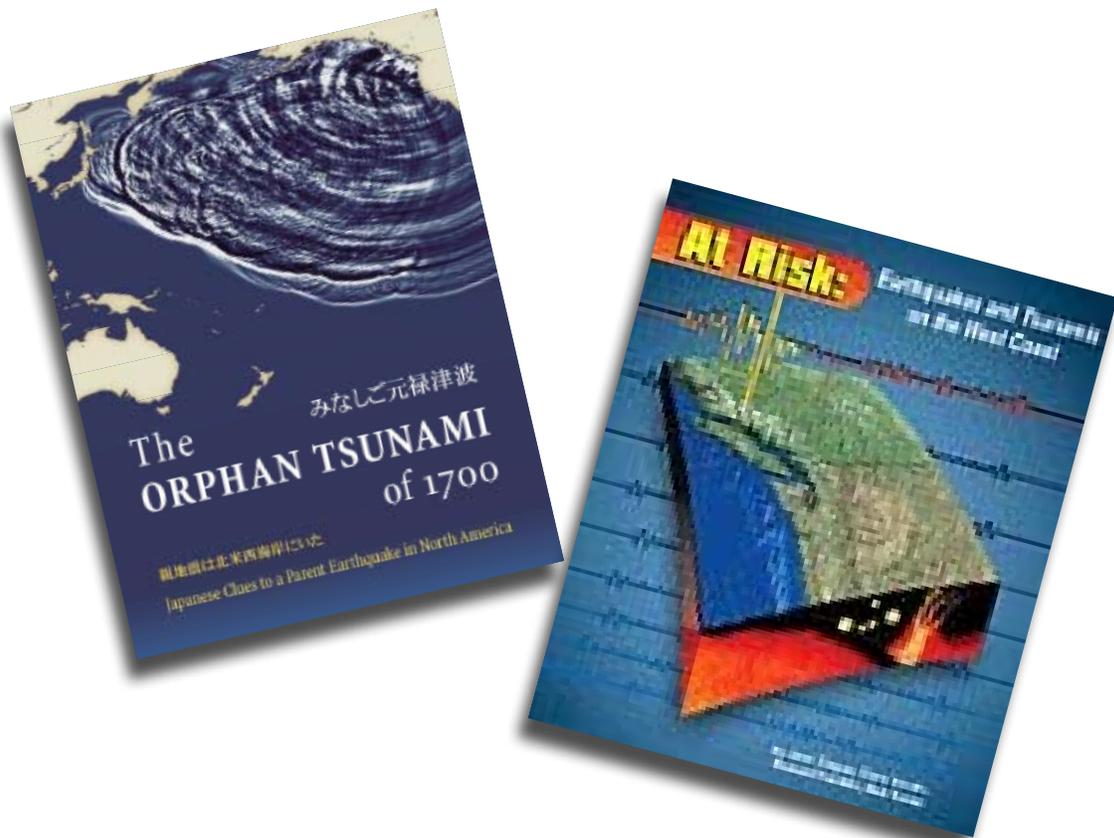
Generalized Geologic Setting of the Pacific Northwest

Part 1: Earthquakes

Part 2: Subduction-zone Volcanism

The Pacific Northwest comprises many diverse geologic settings. Here we focus mainly on the subduction zone (coast to Cascade Mountains) because that is where most of the earthquakes and volcanoes occur, and where tsunamis can be generated.

Material on the following pages was gathered from the Pacific Northwest Seismograph Network (www.pnsn.org/), the U.S. Geological Survey (www.usgs.gov/), and from two books: *Orphan Tsunami of 1700**, by Brian Awtater and others, and *At Risk: Earthquakes and Tsunamis on the West Coast**** by John Clague and others.



*Brian F. ATWATER, MUSUMI-ROKKAKU Satoko, SATAKE Kenji, TSUJI Yoshinobu, UEDA Kazue, and David K. YAMAGUCHI, 2005, *The Orphan Tsunami of 1700—Japanese Clues to a Parent Earthquake in North America*; University of Washington Press

**John Clague, Chris Yorath, Richard Franklin, and Bob Turner, 2006, *At Risk: Earthquakes and Tsunamis on the West Coast*; Tricouni Press

ANIMATION RESOURCES for the Pacific NW—Compare the PNW with Sumatra & more

Interactive Animations www.iris.edu/hq/programs/education_and_outreach/animations/interactive

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Part 1: Earthquakes in the Pacific Northwest

Cascadia Subduction Zone

The Cascadia Subduction Zone (figure 1) is a very long sloping fault stretching from mid-Vancouver Island to Northern California. This subduction zone is where the Juan de Fuca oceanic plate meets the continental part of the North American Plate in the Pacific Northwest. New ocean floor is being created offshore of Washington and Oregon at the Juan de Fuca Ridge where seafloor spreading occurs between the Pacific and Juan de Fuca plates. As the Juan de Fuca Ridge moves away from the ridge, material wells up along the spreading ridge creating new oceanic crust. A very different type of magma rises beneath the North America Plate forming the Cascade Range (See *Subduction Zone Volcanism* on page 11).

The width of the Cascadia Subduction Zone fault varies along its length (figure 2), depending on the angle at which the oceanic plate is subducting. At shallow depths along this fault, rocks are relatively cold and brittle so they can store up elastic energy until they rupture in an earthquake. This shallow part of the Cascadia Subduction Zone fault is often referred to as the “locked” zone because it generally stores up elastic energy for centuries and then ruptures to produce very large earthquakes. At increased depths along this fault, rocks become hotter and more plastic, although they can probably also rupture to release of elastic energy during great earthquakes. As a result of the compression between the Juan de Fuca and North American plates at the Cascadia subduction zone, the continent overlying the subduction zone is actively deforming.

Earthquakes in the Pacific Northwest are generally thought to occur in three different parts of the Cascadia subduction zone (figure 3):

1. Within the deforming part of the North American plate;
2. Along the subduction zone fault between the two plates, sometimes called the interplate thrust or megathrust fault; and
3. Within the down-going Juan de Fuca Plate beneath the North American Plate.

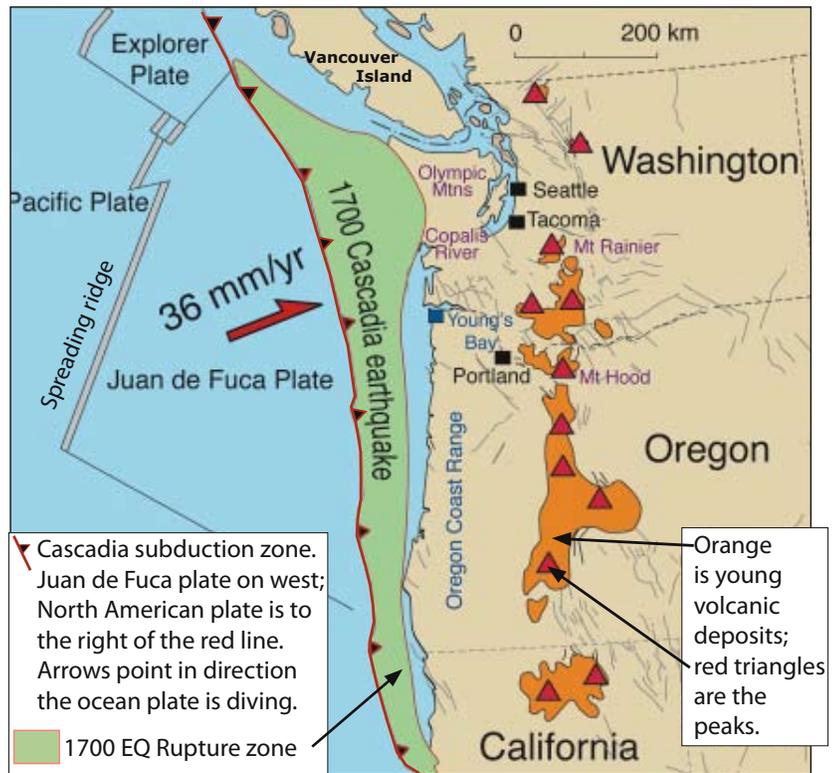
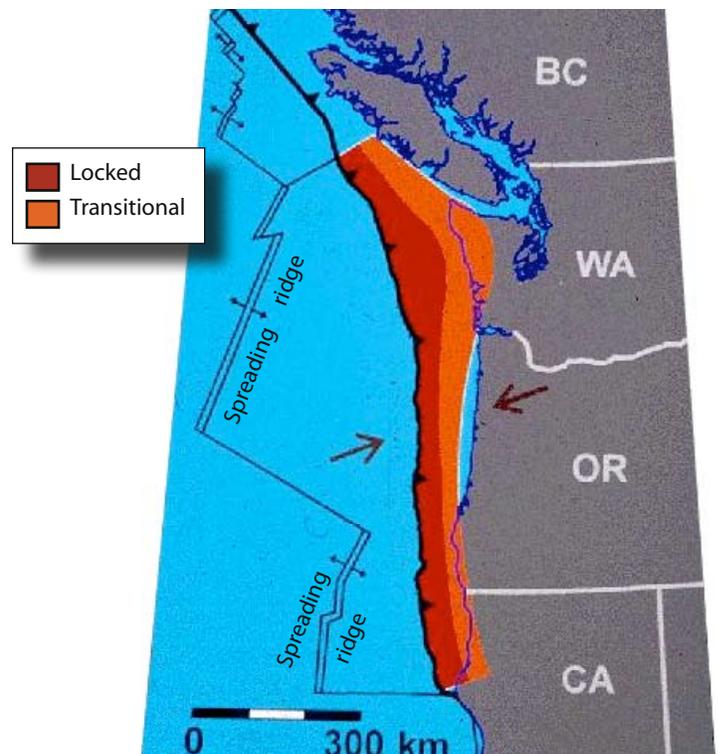


Figure 1 (above): USGS map of the Pacific Northwest geologic setting. Green area is the sloping subduction zone that ruptured during the great earthquake of 1700. The line of contact between the Juan de Fuca and North American plates on the surface is on the western edge of the green area. (See also Figure 6 to put earthquakes on this map.)

Figure 2 (below): USGS map from Hyndman and Wang, 1995, shows the shallow locked portion of the Cascadia Subduction Zone fault and the deeper transitional zone where small earthquake clusters sometimes occur.



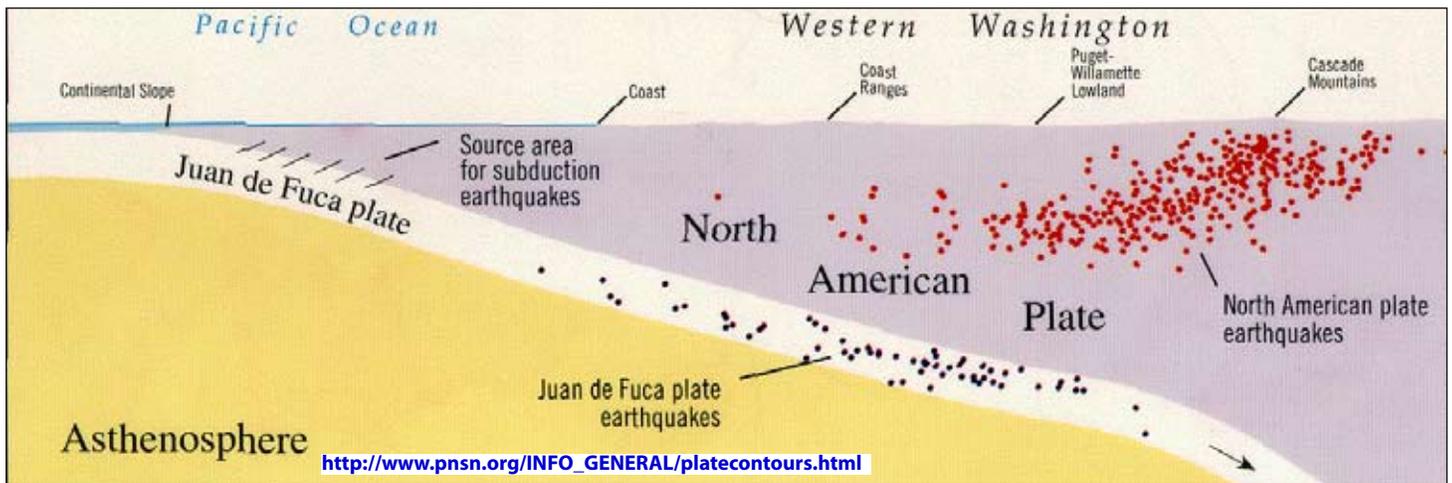


Figure 3: Cross section of seismicity in the continental North America Plate and in the subducting oceanic Juan de Fuca Plate

Figure 4: Descriptions of the Juan de Fuca Ridge and the Cascade Range. Water from the subducting oceanic plate causes melting of hot mantle rocks above the subducting plate. The resulting magma rises into the overlying North American continental crust. Some of this magma erupts as ash or lava from Cascade volcanoes. Modified from Lynn Topinka, USGS/CVO, 1999, which was modified from Brantley, 1994, *Volcanoes of the United States*

Juan de Fuca Ridge – Cascade Range

Juan de Fuca Ridge

The boundary between the Pacific and Juan de Fuca Plates is marked by a broad submarine mountain chain about 500 kilometers long (300 miles), known as the Juan de Fuca Ridge. Young volcanoes, lava flows, and hot springs were discovered in a broad valley less than 8 kilometers wide (5 miles) along the crest of the ridge in the 1970's. The ocean floor is spreading apart and forming new ocean crust along this valley or "rift" as hot magma from the Earth's interior is injected into the ridge and erupted at its top.

Cascade Range

In the Pacific Northwest, the Juan de Fuca Plate plunges beneath the North American Plate. As the denser plate of oceanic crust is forced deep into the Earth's interior beneath the continental plate, a process known as "subduction", it encounters high temperatures and pressures that partially melt solid rock. Some of this newly formed magma rises toward the Earth's surface to erupt, forming a chain of volcanoes above the subduction zone.

Topinka, USGS/CVO, 1999, Modified from: Brantley, 1994, Volcanoes of the United States, USGS General Interest Publication 376-846

Earthquakes in the Pacific Northwest

The Pacific Northwest (PNW) is an active seismic area with three distinct types of earthquakes and additional “slow-slip events” (figure 5). Subduction-zone earthquakes, which can be as large as magnitude 9.0 (M9.0), recur every few hundred years on the shallow part of the Cascadia Subduction Zone fault that lies off the coast of Washington and Oregon. Deep earthquakes of M6 to M7 recur every 30 years or so within the subducting Juan de Fuca Plate beneath western Washington. Earthquakes on faults within

the crust in the Pacific Northwest are a hazard to major urban centers like the Seattle and Portland metropolitan areas. Although recurrence times are poorly known, crustal earthquakes are possible across much of Washington and Oregon, including areas east of the Cascades. Small crustal earthquakes often precede volcanic activity and were used to forecast eruptions at Mount St. Helens in the 1980s. Each year, the Pacific Northwest Seismic Network records several dozen felt earthquakes and thousands of smaller earthquakes — ongoing reminders of the earthquake hazards in Washington and Oregon.

Figure 5. The circles on the cross-section diagram show positions of earthquakes relative to the Juan de Fuca and North American plates.

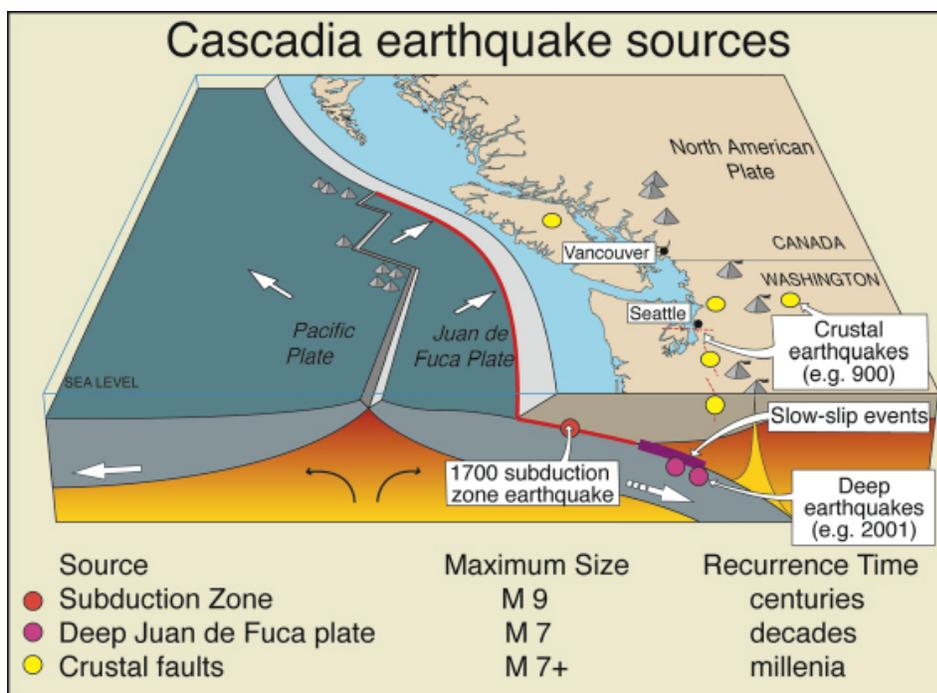
Types of earthquakes in the Pacific Northwest:

Crustal earthquakes — Shallow earthquakes (less than 15 miles deep) occur on faults within the North American continental crust. The Seattle fault produced a shallow magnitude 7+ earthquake 1,100 years ago. Other strong to major (M6 to M7) crustal earthquakes occurred in 1872, 1918, and 1946.

Subduction zone — (Red zone: Juan de Fuca–North America plate boundary) Huge earthquakes (>M8) occur when the boundary between the oceanic and continental plates ruptures to release large amounts of stored elastic energy. In 1700, the most recent great Cascadia Subduction Zone earthquake sent a tsunami across the Pacific Ocean to Japan. This subduction zone fault is similar to the fault that ruptured to produce the Sumatra - Andaman earthquake and the Indian Ocean tsunami that killed 250,000 people in December 2004. For the Pacific Northwest, a repeat of the 1700 great Cascadia Subduction Zone earthquake would definitely be “The Big One”.

Deep earthquakes — These strong to major earthquakes occur about 40 miles below the Earth’s surface within the subducting Juan de Fuca oceanic plate as it bends and dives beneath the North American continental plate. Deep earthquakes occurred in 1949 (M7.1), 1965 (M6.5), and 2001 (M6.8; Nisqually). The 1949 earthquake caused over \$100 million in damage, including damage to the Capitol Building in Olympia. The 1965 earthquake caused over \$50 million in damage. As population has increased in the Puget Sound area, the cost of damage from these earthquakes has increased dramatically. Damage from the 2001 Nisqually earthquake was about \$2.5 billion.

Slow-slip events — During slow-slip events that last for seven to ten days, the Juan de Fuca plate slips further into the mantle underlying the North American continental crust. Slow-slip events do not produce violent seismic waves like typical earthquakes. Instead they cause tremors of Earth’s surface like the vibration of a drumhead. These events occur about every 14 months, are sometimes called “Episodic Tremor and Slip”, and are the subject of EarthScope research (See green box at right).



Hot Recent PNW topic
“Episodic Tremor & Slip” (ETS)

An article published in **onSite**, an [EarthScope](#) quarterly, describes the process. To see just the article: **TOUCH HERE** to go to Page 11 of this document

How big are subduction-zone earthquakes?

Great subduction zone earthquakes are the largest earthquakes in the world and can exceed magnitude 9.0. Earthquake magnitude is proportional to the fault area that ruptures to produce the earthquake. The Cascadia Subduction Zone fault stretches from mid-Vancouver Island to Northern California. Because the fault area is very large, the Cascadia Subduction Zone can produce great earthquakes of magnitude 9.0 or higher, if rupture occurred over its entire area. The most famous subduction-zone earthquakes occurred in Alaska, Chile, and Sumatra.

How often do Cascadia subduction-zone quakes occur?

Geological evidence (see next page) indicates that great Cascadia Subduction Zone earthquakes have occurred at least seven times in the last 3,500 years with intervals between great earthquakes ranging from about 200 to almost 1000 years. The last great Cascadia earthquake occurred just over 300 years ago during the evening of January 26, 1700. Plus, GPS evidence shows the coastline along Vancouver Island, Washington, and to a slightly lesser extent, Oregon is being pushed to the northeast at a steady rate. This indicates that we should prepare ourselves for a large earthquake.

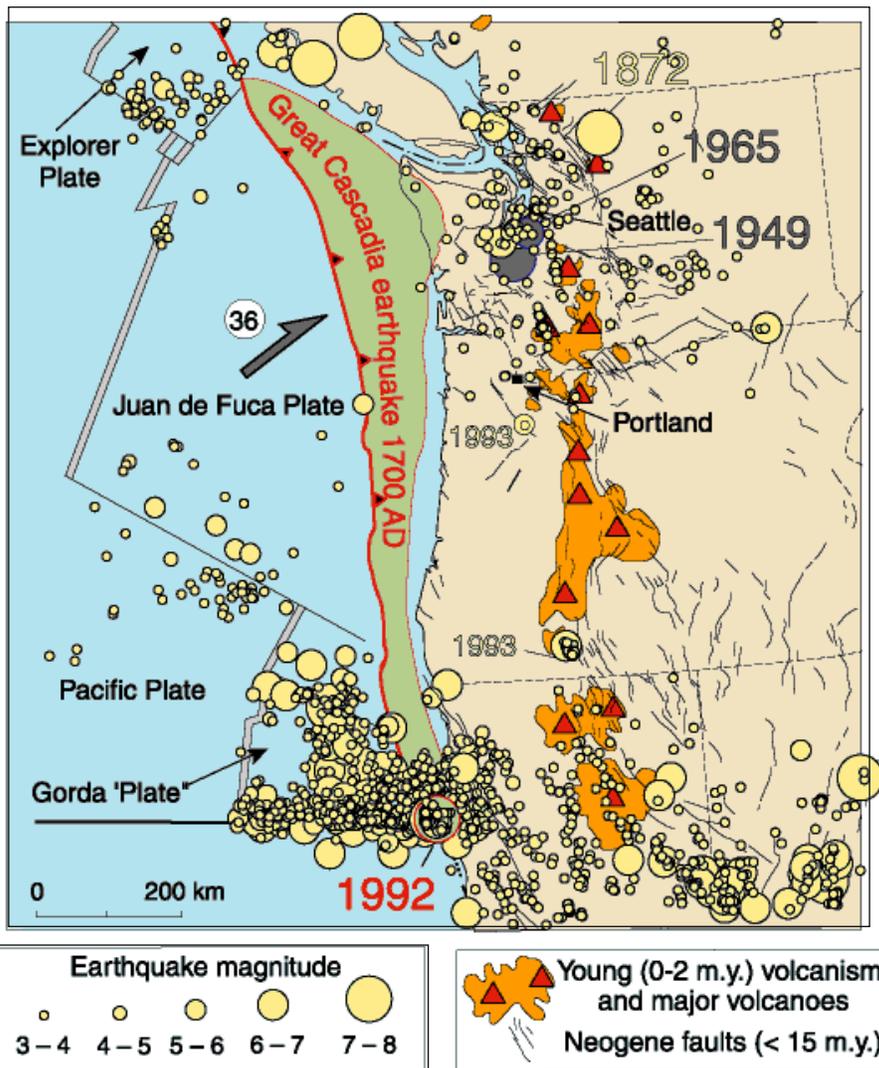


Figure 6. Active continental margin: Cascadian earthquakes, volcanic edifices and faults.

Unresolved questions being studied in the Pacific N.W.:

1. Because the Juan de Fuca plate is moving northeast toward North America, one would expect the orientation of compressional stress across the Pacific Northwest to be northeast – southwest. However, there are additional components of stress that change in strength and direction from place to place within the Pacific Northwest. These additional stresses are not well understood and are the subject of current research.
2. A very unusual aspect of the Cascadia subduction zone is that there have been few, if any, instrumentally-recorded earthquakes along the Cascadia megathrust

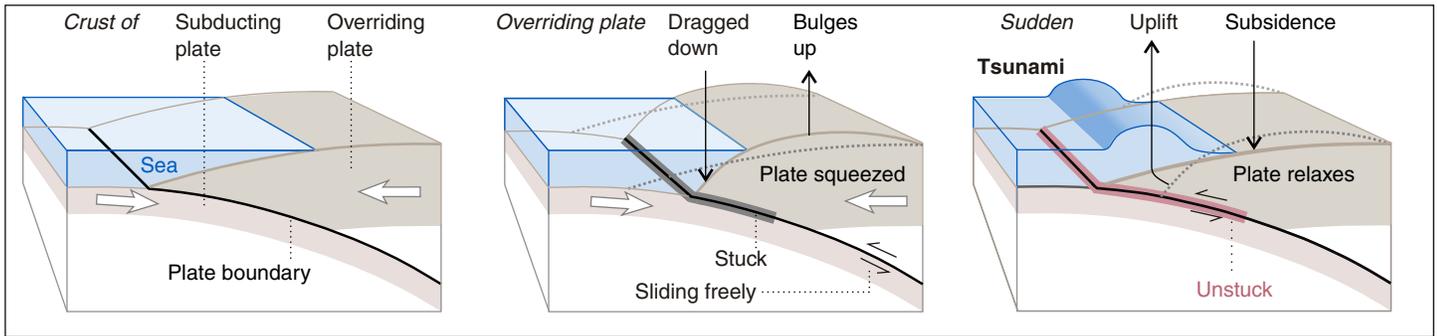
fault. In combination with the fact that the shallow part of the Cascadia megathrust is located offshore, the lack of recent earthquakes limits our understanding of the mechanics of this important fault. Can the observed stress field in the Pacific Northwest tell us anything about the fault itself? In light of the fact that earthquakes only infrequently occur along the Cascadia megathrust, how is this fault mechanically similar to or different from other major plate boundary faults around the world (e.g., the San Andreas fault)? Ongoing EarthScope research is helping to address these important questions.

January 26, 1700—Cascadia Subduction Zone earthquake and tsunami

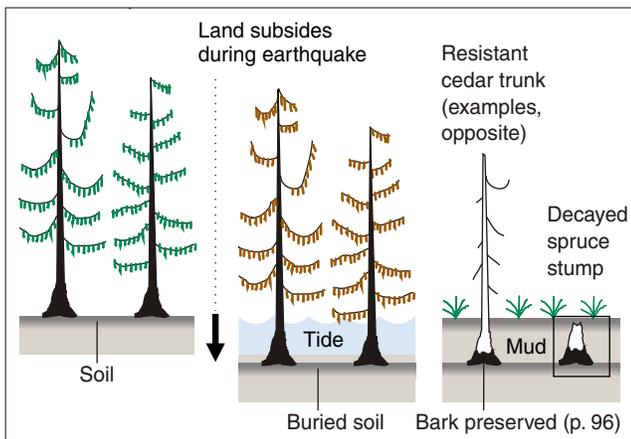
Between 9:00 PM and 10:00 PM, local time, on January 26th 1700, a great earthquake shook the Pacific Northwest. This quake, with magnitude estimated at 9.0, rocked the region with strong shaking for several long minutes while coastal Washington plummeted as much as 1.5 meters relative to coastal waters.

How is it possible to know that an event during pre-written history ever occurred on the Cascadia Subduction, let alone to place it within one hour of its occurrence 300 years ago? The evidence speaks for itself: Read steps 1–6 in the figures below:

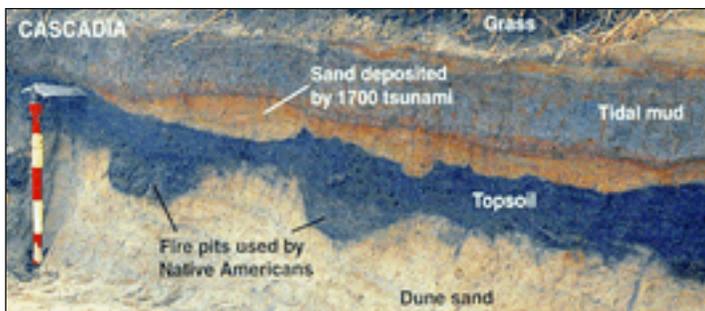
Figure 7A–F. Evidence of the Great Quake of 1700. Images from Brian Atwater’s *Orphan Tsunami*.



A. Land Levels—PNW geologic evidence (changes in land levels found during geologica mapping) shows that subduction zone earthquakes occur cyclically.



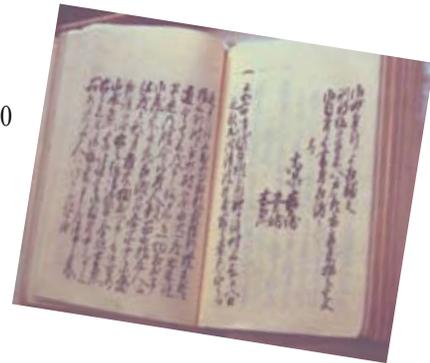
B. Tree Rings—Ancient trees, once submerged along PNW coastal beaches, put an accurate date on a likely seismic event occurring in the Pacific Northwest.



C. Tsunami Traces—Uncharacteristic sand deposits in coastal soil give evidence of local tsunamis.

D. Historic Records

Japanese government (Samurai) records from 1700 describe a large tsunami likely originating from the Pacific Northwest. It swept along the coast killing villagers.



E. Native Tales

Native American stories from the Pacific Northwest describe an event strikingly similar to a large Cascadia subduction zone quake where rocks rolled down the mountains and the ocean put the canoes in the trees.



F. Turbidite Record—Layers of sediment off the PNW coast show that widespread, simultaneous shaking of the region was very likely.

Read all about it!!

Orphan Tsunami, a 144-page (116Mb) book, details this story. You can download for free from: <http://pubs.usgs.gov/pp/pp1707/>

More Questions (& Answers) about Earthquakes in Washington and Oregon

These questions are from the **Pacific Northwest Seismograph Network** (with permission from Steve Malone).

- 1 Where are the major faults in the Pacific Northwest?
- 2 Are there faults near Seattle and Portland?
- 3 Why does the Pacific Northwest have earthquakes?
- 4 How often do earthquakes occur in the Pacific Northwest?
- 5 How many and what size of earthquakes occur near Seattle?
- 6 How many and what size of earthquakes occur near Portland?
- 7 Could a big earthquake in California, Alaska, or Japan cause earthquakes in Washington or Oregon?
- 8 Could bridges collapse due to seismic activity in the Pacific Northwest?
- 9 Should I buy earthquake insurance for my house?
- 10 Can earthquakes be predicted?
- 11 Is one Seattle area neighborhood safer from earthquakes than another?
- 12 What fault lines pass under Mount Saint Helens?
- 13 What is the best site for Volcano information?
- 14 There seems to be a lot of activity on the Webicorders, but there are not any events listed on the "Recent Events" list. What is going on?

Answers

1 Where are the major faults in the Pacific NW?

A: There are many faults in the Pacific Northwest that can produce damaging earthquakes, including hard-to-identify faults that exist entirely underground and have not been identified at the earth's surface. At the same time, some mapped faults have been located that have not generated earthquakes in recent geologic time. New faults continue to be discovered as more field observations and earthquake data are collected. There are three different sources for damaging earthquakes in the Pacific Northwest. The first of these is the "Cascadia Subduction Zone", a 1000 km long thrust fault which is the convergent boundary between the Juan de Fuca and North American plates and is the most extensive fault in the Pacific Northwest area. It surfaces about 50 miles offshore along the coasts of British Columbia, Washington, Oregon and northern California. No historic earthquakes have been directly recorded from this source zone. According to recent research, an earthquake estimated to be as large as 8.0 to 9.0 occurred in this zone in January of 1700. The second source for damaging earthquakes is the Benioff Zone. This zone is the continuation of the extensive faulting that results as the subducting plate is forced into the upper mantle. The Benioff Zone can probably produce earthquakes with magnitudes as large as 7.5. Benioff Zone earthquakes are deeper than 30km. The third source consists of shallow crustal earthquake activity (depths of 0 to 20 km) within the North

American continental plate where faulting is extensive. Past earthquakes have revealed many shallow fault structures, including the Western Rainier Seismic Zone and the Mt. St. Helens Seismic Zone. Our best known crustal fault, the Seattle Fault, runs east-west through Seattle from Issaquah to Bremerton. This fault generated a very large earthquake approximately 1100 years ago. Other crustal faults have been located in the Puget Basin region.

2 Are there faults near Seattle and Portland?

A: Yes. Some of these are well known from geologic or geophysical surveys. Examples include the Seattle Fault and the Portland Hills Fault. How often earthquakes occur on these faults is not well known, but they are believed to have the potential to produce damaging earthquakes.

3 Why does the Pacific Northwest have earthquakes?

A: We are located at a convergent continental boundary, where two tectonic plates are colliding. This boundary is called the Cascadia Subduction Zone. It lies offshore and runs from British Columbia to northern California. The two plates are converging at a rate of about 3-4 cm/year (1-2 inches/year), and the northeast-moving Juan de Fuca Plate is pushing into North America, causing stress to accumulate. Earthquakes are caused by the abrupt release of this slowly accumulated stress.

4 How often do earthquakes occur in the Pacific Northwest?

A: Typically, each year we locate over 1000 earthquakes with magnitude 1.0 or greater in Washington and Oregon. Of these, approximately two dozen are large enough to be felt. These felt events offer us a subtle reminder that the Pacific Northwest is an earthquake-prone region. As residents of the Pacific Northwest, we should be prepared for the consequences of larger earthquakes that could result in damage to the transportation systems and lifelines. There have been about 25 damaging earthquakes in Washington and Oregon since 1872. In the 20th century, about 17 people lost their lives due to earthquakes in the Pacific Northwest.

5 How many and what size of earthquakes occur near Seattle?

A: In the 20th century, there were eleven earthquakes of magnitude 5 or greater that have occurred near Puget Sound: in 1904 (M 5.3), 1909 (M 6.0), 1932 (M 5.2), 1939 (M 6.2), 1945 (M 5.9), 1946 (M 6.4), 1949 (M 7.0), 1965 (M 6.5), 1995 (M 5.0), 1996 (M 5.3), and 1999 (M 5.1). Most of the events are associated with deep Benioff zone earthquake activity that effects the Pacific Northwest Region. The 1995 and 1996 events were shallow crustal events.

6 How many and what size of earthquakes occur near Portland?

A: In this century there have been three significant earthquakes near Portland: in 1877 (M 5.3), 1962 (M 5.5), and 1993 (M 5.5). Additionally, Portland has been damaged by earthquakes that occurred in the Puget Sound region, such as the 1949 magnitude 7.1 event near Olympia, WA, and the 1965 magnitude 6.5 event located between Seattle and Tacoma.

7 Could a big earthquake in California, Alaska, or Japan cause earthquakes in Washington or Oregon?

A: Historical data and theory suggests that earthquakes only provoke other shocks within a limited area around the fault rupture. Distant earthquakes have no direct effect on Washington and Oregon. Earthquakes in California, Alaska and Japan are caused by the interaction of different plates than the earthquakes in the Pacific Northwest. However, the 1992 Landers earthquake in southern California caused an increase in tiny earthquakes in geothermal areas as far away as The Geysers in northern California.

8 Could bridges collapse due to seismic activity in the Pacific Northwest?

A: Yes, even modern bridges have sustained damage during earthquakes, leaving them unsafe for use. More rarely, some bridges have failed completely due to strong ground motion. Several collapsed in the Northridge earthquake in January 1994, even though they had been strengthened. The January, 1995 Kobe, Japan earthquake also caused many bridges to fail. It is important to note that both of these earthquakes produced accelerations far exceeding the design criteria used in the design of the failed structures. Because the bridges in our urban areas vary in their size, materials, siting, and design, they will be affected differently by any given earthquake. Major bridge design improvements occurred in the 1970's. Bridges built before the mid 1970's have a significantly higher risk of suffering structural damage during a moderate to large earthquake compared with those built after 1980. The 1970's was a decade of evolution for bridge design, so bridges built during this time may or may not have these improvements. Much of the interstate highway system in the Pacific Northwest has been built in the mid to late 1960's. The Washington State Department of Transportation should be consulted for further information about the seismic resistance of individual structures maintained by the state. Many other bridges are under other jurisdictions, but most have been evaluated.

9 Should I buy earthquake insurance for my house?

A: That is an individual decision, which depends on the risk that homeowners are financially willing to take. It also depends on their confidence in the quality of their homes, since there is quite a large deductible on most policies. Commonly the policies only pay for damage exceeding 5 to 10% of the value of a house. Some seismologists do have earthquake insurance.

10 Can earthquakes be predicted?

A: Although scientists have long tried to predict earthquakes, no reliable method has been discovered. Seismicity in the Pacific Northwest has only been extensively studied for a couple of decades, and seismologists are still trying to understand the frequency and hazards of earthquakes in our region.

11 Is one Seattle area neighborhood safer than another?

A: There is no Seattle area neighborhood that is immune from possible earthquake damage. The age of the structure and the type of geology in the area are two factors that will affect the vulnerability to earthquakes. There are ways to perform a seismic retrofit on older homes. The Project Impact web page has information on home retrofits. Another valuable resource is the Cascadia Regional Earthquake Workgroup (CREW). The American Red Cross has a variety of earthquake preparedness publications.

12 What fault lines pass under Mt. Saint Helens?

A: Mt. Saint Helens is located on the St. Helens Fault Zone (SHZ). This is a strike-slip fault. Right at Mount St. Helens there is a gap and a step in the SHZ. This step causes the crust to pull apart inside the gap, creating a zone of weakness where volcanic material can more easily reach the surface. It will help you to understand this if you draw some pictures of a step in a strike-slip fault, with arrows to show the direction of movement. Many volcanos are found in similar circumstances. The St. Helens Fault Zone was not discovered until after the eruption of Mt. St. Helens (1980). In 1981 a magnitude 5+ earthquake on the SHZ had thousands of aftershocks which “lit up” the fault.

13 What is the best web site for Volcano information?

A: The best site for information about volcanoes in the Pacific Northwest is the **Cascade Volcanic Observatory (CVO)**. In addition, the University of Washington has a **Volcanoes web page**. The Smithsonian also has an excellent website of **World Volcanoes**.

14 There seems to be a great deal of activity on the webicorders, but there are not any events listed on the “Recent Events” list. What is going on?

A: Only earthquakes with magnitudes greater than 1.5 are on the list of recent events. It is possible that several earthquakes have taken place that were all of magnitude less than 1.5. Also, it takes the seismology lab time to analyze each earthquake and properly determine its magnitude. Some smaller events in the magnitude 2 range may not be posted on the list until three days after they occur. There is also the large possibility that the activity on webicorders is not seismic. Weather conditions such as wind and heavy rain will cause plenty of spikes and glitches. The instrument that is producing unusual signals may be broken. Outages in our network can last hours, days, or months, depending on the cause of the failure and our ability to access the instrument. Some instruments are at high elevations or remote locations, and fixing them takes longer than other, easier to access instruments. The PNSN has more than 150 stations. Temporary problems with a few stations at any given time will not interfere with our ability to identify and analyze seismic activity in the Pacific Northwest.

Episodic Tremor and Slip in the Pacific Northwest*

Every 14 months the Pacific Northwest experiences slow slip on a fault that is the equivalent of about a magnitude 6.5 earthquake. While a typical earthquake of this magnitude happens in less than 10 seconds, the duration of these slip events is two to several weeks. The most recent event occurred from January 14 through February 1, 2007.

In the Pacific Northwest, the Juan de Fuca plate is subducting (or dipping) beneath the North American plate from northern California to Vancouver Island. These plates slide past each other along the solid green, dashed yellow and dashed red lines in Figure 1. The Cascadia subduction zone, as it is called, experiences large earthquakes, perhaps as large as the 2004 Sumatra earthquake, once every 500 years on average. The last one was about 300 years ago in January 1700. The slip during these earthquakes, occurring on the "locked" zone in the figure, is thought to accommodate most, if not all, of the relative motion between the North American plate and the Juan de Fuca plate. Down dip of this locked zone (red dashed lines), the plates must still slide past each other. However, instead of rupturing in devastating earthquakes, much of that slip appears to be occurring during the Episodic Tremor and Slip (ETS) events (labeled "slip" in the figure).



Figure 1. Courtesy of H. Dragert, Geological Survey of Canada

EarthScope and other research projects have installed Global Positioning System (GPS) stations near the Northwest Pacific coast to record ETS events. These instruments are continuously moving to the northeast relative to the stable interior of North America because the Juan de Fuca plate is pushing on the North American plate (green arrow in Figure 1). During an ETS event, the stations above the ETS zone slip backwards (the red arrows in the figure). Seismometers also record the slip. These signals initially were considered to be noise from wind or other sources, however, by filtering and analyzing the seismograms, it was discovered that tremor produces signals that are similar on many seismometers and that the signals move across a network of seismometers at the speed of waves generated by earthquakes. Tremors typically originate where the two plates meet at depths of 30-45 km. These tremors may be related to high fluid pore pressure in the rock resulting from dehydration reactions as the subducting plate heats up and undergoes increasing pressure.

One of the most exciting areas of research to emerge from joint GPS and seismic monitoring is the discovery of ETS. Japanese researchers were the first to identify periodic slip events, however, with the installation of more GPS stations, this phenomena has been detected in Cascadia and many other subduction zones around the world. In Cascadia, initial recognition of slow faulting led to the identification of eight additional events with a regular 14-month periodicity and the forecasting of future events. Since then, five predicted events have occurred with the same periodicity. Further study has shown that ETS events likely occur all along the Cascadia subduction zone but with different periodicity (see Figure 2.). For example, ETS events occur beneath Northern California every 11 months and off the

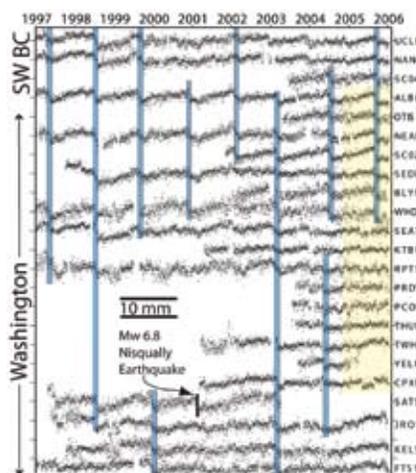


Figure 2. Plot of East-West position vs time for 23 GPS sites (eastward motions are positive). The blue vertical lines mark ETS events where multiple stations temporarily move westward.

coast of central Oregon approximately every 18 months.

The 2007 ETS event began under the southern Puget Sound area to the southwest of Seattle and propagated north northwest into Vancouver Island, Canada at a rate of 10 km per day (Figure 3). Over a three-week period, it is estimated that there was 3 cm of slip and that the amount of energy released was equivalent to a magnitude 6.6 earthquake. An account of this event and two previous ETS events as they unfolded can be found at <http://www.pnsn.org/WEBICORDER/DEEPTREM/fall2006.html>. These ETS events can effect the magnitude and timing of future large earthquakes within the subduction zone and thus are important in advancing our understanding of the seismic hazards in the region. As more GPS, strainmeters and seismometers are installed in Cascadia and near other subduction zones, it is hoped that answers to many more questions about these events will be found.

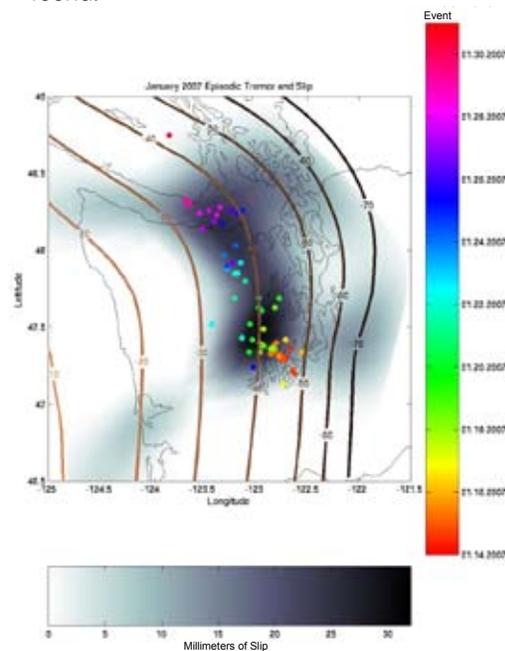


Figure 3. From January 14, 2007 until February 2, 2007, tremor migrated from the south Puget Sound region to southern Vancouver Island at about 10 km per day (colored dots). Amount of slip is inferred from GPS data.

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* From EarthScope's OnSite Newsletter winter/spring 2007

Part 2: Subduction Zone Volcanism*

Subduction zones recycle oceanic crust back into the mantle

If new crust continually forms along mid-ocean ridges and then spreads away from the ridges (Figure 4), where does it go? One possibility entertained by a few scientists was that the Earth was expanding over time and seafloor spreading resulted from this expansion. Much evidence weighed against this expansion model, and the correct interpretation is that oceanic crust and the top of the underlying mantle eventually sink back into Earth's interior along what are known as subduction zones. Subduction zones were first recognized as regions of frequent, powerful earthquakes arranged in inclined sheets extending far into the mantle from near the surface. The shallow ends of these sheets of earthquakes begin beneath the oceans, commonly near the submarine valleys or "trenches" that run parallel to the margins of some continents and volcanic island chains. The earthquakes are deeper in the mantle at greater distances away from the trench in the direction of the continent or island chain. Rocks have to be relatively cold to crack and create earthquakes (if hot, they bend easily and flow, like stiff clay), so the inclined sheets of earthquakes show the locations of cold slabs of rock that penetrate into the mantle, beginning at the deep ocean trenches. Scientists have since gathered much additional evidence that oceanic crust eventually sinks back down (subducts) into the mantle. Because of the relative motion of the plates, subduction zones are sometimes referred to as convergent plate boundaries. The deadly Indian Ocean

tsunami of December 26, 2004, resulted from faulting and a powerful earthquake along the subduction zone adjacent to the island of Sumatra, Indonesia.

Subduction Zones—Homes for the Second-Most Abundant Volcanoes on Earth

Subduction zones are home for the second most abundant volcanoes on Earth, and these are the most important for people because of the hazards they pose and also because they create watersheds, fertile soils, recreation areas, and many ore deposits. At subduction zones, active volcanoes are lined up along the margin of the non-subducting plate (sometimes referred to as the overriding or upper plate, or in miner's terms the "hanging wall"). The upper plate can be made of either continental or oceanic crust. Subduction-zone volcanoes encircle much of the rim of the Pacific Ocean, forming what is known poetically as the Ring of Fire. The Ring of Fire includes the active volcanoes of the Andes and Central America, the Cascades (Figure 9; northern California to southern British Columbia), the Aleutians (Alaska), Kamchatka and the Kuriles (Russia), Japan, the Philippines, the island chains of Tonga and Kermadec extending south to New Zealand, and a branch forming the Izu-Bonin and Marianas island chains (southwest Pacific). Along the Ring of Fire, oceanic crust subducts beneath most of the landmasses surrounding the Pacific Ocean. This contrasts with the Atlantic Ocean where subduction only takes place in small areas along the Lesser Antilles (Caribbean) and the South Sandwich Islands (between South America and Antarctica). Another major area of subduction zone volcanoes is in Java and Sumatra (Indonesia), due to subduction of the Indian Ocean seafloor.

Water Induces the Melting of Rocks Deep below Subduction-Zone Volcanoes

Different subducting plates dive into the mantle at different slopes and sink to increasing depths away from the plate boundary (illustrate this by slowly sliding a sheet of paper off the edge of your desk). The volcanoes usually sit in a line above where the subducting plate passes through about 100 kilometers (60 miles) depth in the Earth. Depending on the subducted plate's steepness, this line of volcanoes can be close to (steeply dipping plate), or far from (gently dipping plate), where the oceanic plate starts to descend into the mantle. The earliest

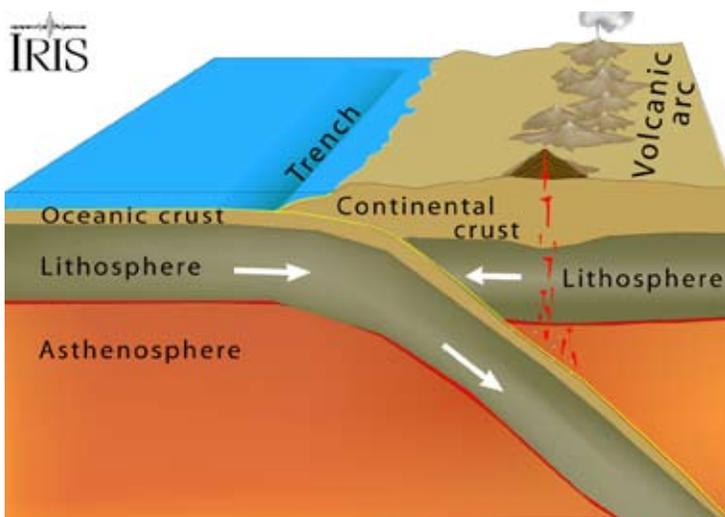


Figure 8. Ocean-continent subduction zone. The lithospheric (aka tectonic) plate is comprised of the crust and upper mantle (green zone).

* From: VOLCANISM IN A PLATE TECTONIC PERSPECTIVE, By Tom Sisson. in the USGS publication: Living with a Volcano in your Backyard -- An Educator's Guide with Emphasis on Mount Rainier, by Carolyn Driedger. Download entire guide:

<http://vulcan.wr.usgs.gov/Outreach/Publications/GIP19/framework.html>

theory for the origin of subduction-zone volcanoes was that the sinking plate releases water as it warms up in the mantle (think of the plate as sweating). This water causes small amounts of melting in the hotter rocks of the nearby mantle. These low-density basaltic magmas then rise toward the surface. Some of these basaltic magmas feed volcanoes directly, but most basaltic magmas cool to varying degrees and shed dense crystals, thereby changing in chemical composition to andesitic and dacitic magmas. Hot basaltic magmas may also incorporate and melt rocks from the crust, leading to similar or greater changes in composition and thus in density, viscosity, and temperature. An alternate theory is that the subducting plate itself heats up enough to melt by small amounts, creating magmas that rise to the surface. Because it is conceptually easy, this idea of plate melting is commonly presented in introductory science textbooks; however, calculations of the temperatures of sinking plates have long shown that the plates do not generally get hot enough to melt. Notable exceptions are where the subducting plate has only recently formed at a mid-ocean ridge and is still hot when it begins to subduct. Temperatures sufficiently high for melting are also inconsistent with the abundant deep, powerful subduction-zone earthquakes that require rocks to be cold enough to crack.

How Adding Water Melts Hot Rock

The ability of water or steam to induce melting in hot mantle rocks is similar in principle to the ability of salt to melt ice on a road or sidewalk. As a rule, adding a chemical substance that can dissolve in a liquid but not in a solid promotes the conversion of the solid to the liquid. Salt will dissolve in water, but practically none can be incorporated into the structure of ice. Adding salt to ice will melt some of the ice, as long as the ice is already close to its melting temperature. Because melting absorbs heat (the atoms need energy to move quickly and freely in a liquid), adding salt to ice also lowers the temperature below the freezing point of fresh water. This is why salt-ice mixtures are used to lower the temperature in old-fashioned ice cream makers. At the high pressures of subduction zones, much water can dissolve in magma, but very little can be absorbed into hot mantle rocks. The release of water from the subducting plate therefore partly melts the adjacent hot mantle and cools it slightly. The localization of volcanoes to 100 kilometers (60 miles) above the subducting plate may indicate the breakdown of a specific water bearing mineral, either in the subducting plate or in the adjacent mantle, leading to copious melting.

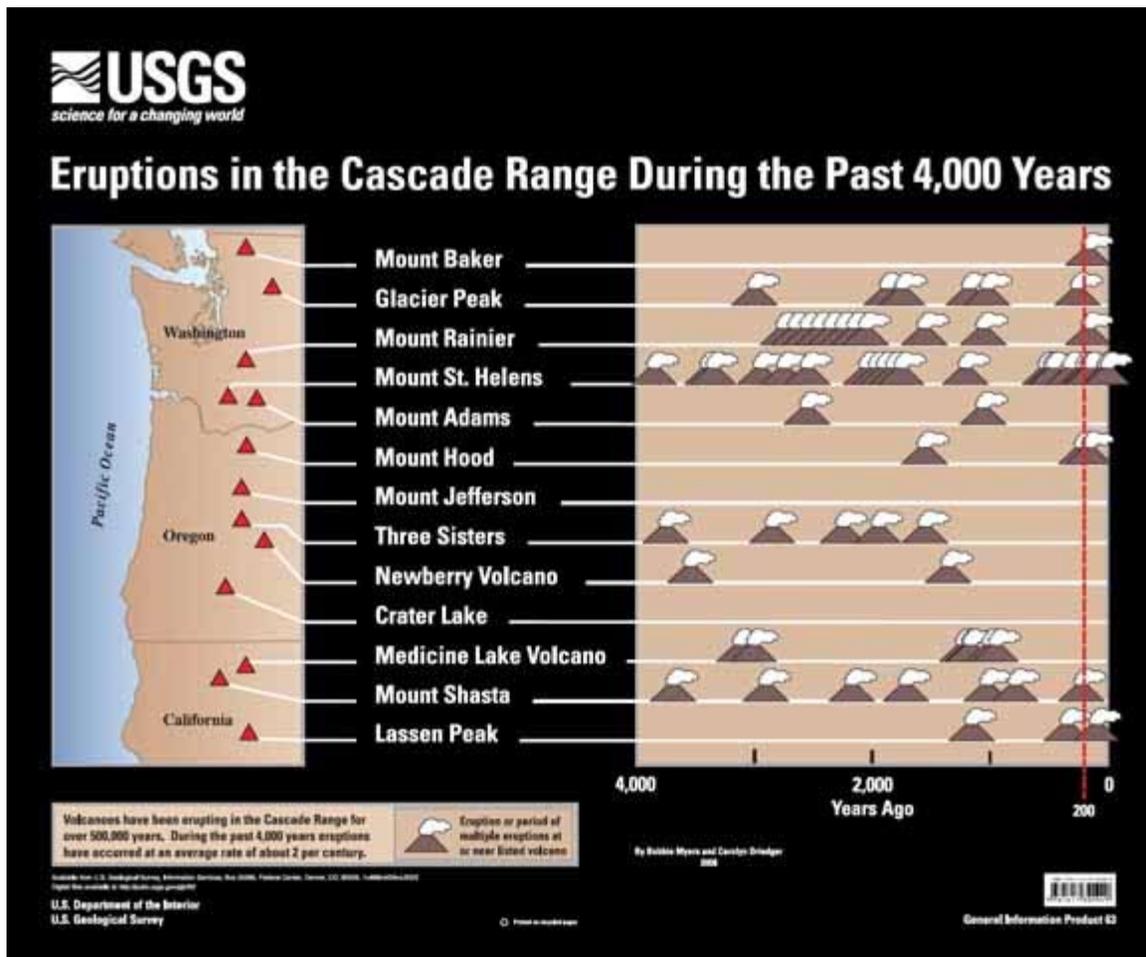


Figure 9. Map on left shows the major peaks of the Cascade Range. The graph on the right shows the eruption history of each volcano over the last 4,000 years. The red line marks 200 years ago, indicating that at least seven volcanoes have been active in historic time.

A FLASH-rollover interactive file, **Volcanoes Rollover**, of this graphic allows you to touch each volcano to get information about each volcano using the above graphics is on IRIS' website:

http://www.iris.edu/hq/programs/education_and_outreach/animations/interactive#W