

Part 1

Unearthed earthquakes 発掘された地震痕跡

THROUGH MOST OF THE 20TH CENTURY, North America's Cascadia region was thought incapable of generating earthquakes larger than magnitude 7.5. Any tsunami striking the region's coasts would come from afar, leaving hours for warning and evacuation. Yet by century's end, Cascadia had its own recognized source of earthquakes of magnitude 8 to 9 and of tsunamis that would reach its shores in a few tens of minutes.

That recognition began in the early 1980s. Earth scientists were then beginning to debate Cascadia's potential for great earthquakes—shocks of magnitude 8 or higher. Despite hints from oral histories of native peoples, there seemed no way to learn whether great earthquakes had ever struck the region.

Fortunately, the earthquakes had written their own history. They wrote it most clearly in the ways that great earthquakes of the 1960s in Chile and Alaska wrote theirs—by dropping coasts a meter or two, by sending sand-laden sea water surging across the freshly lowered land, and by causing shaken land to crack.

Those geologic records soon gave Cascadia a recognized history of great earthquakes. In the late 1980s, at bays and river mouths along Cascadia's Pacific coast, researchers found the buried remains of marshes and forests that subsidence had changed into tidal mudflats. They also found that the burial began with sand delivered by tsunami or erupted in response to shaking. In a few places they even found the hearths of native people who had used the land before its submergence and burial.

But researchers quickly reached an impasse in this attempt to define, from events recorded geologically, Cascadia's earthquake and tsunami hazards. How great an earthquake should a school or hospital be designed to withstand? How large a tsunami should govern evacuation plans on the coast? There seemed no way to know whether Cascadia's plate-boundary fault can unzip all at once, in a giant earthquake of magnitude 9, or whether it must break piecemeal, in series of lesser shocks.

Earthquake potential 地震の可能性

Can Cascadia do what other subduction zones have done?

CASCADIA'S CONVERGING PLATES pose a triple seismic threat. The subducted Juan de Fuca Plate contains sources of earthquakes as large as magnitude 7. Large earthquakes can also radiate from faults in the overriding North America Plate. And the enormous fault that forms the boundary between the plates can produce great earthquakes, of magnitude 8 or 9.

This current picture began taking form in the 1960s, when early ideas about continental drift and seafloor spreading came together as the theory of plate tectonics. The Juan de Fuca Plate was identified as a remnant of a larger tectonic plate that had mostly disappeared beneath North America during 150 million years of subduction.

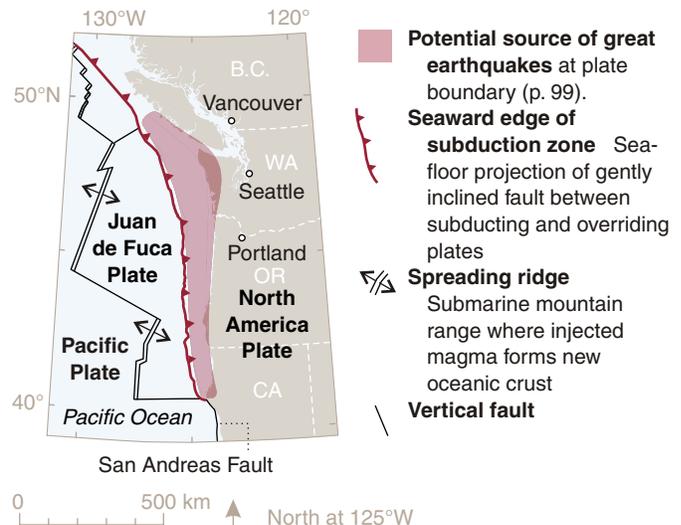
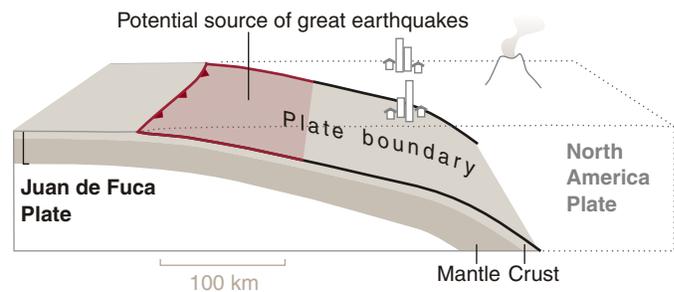
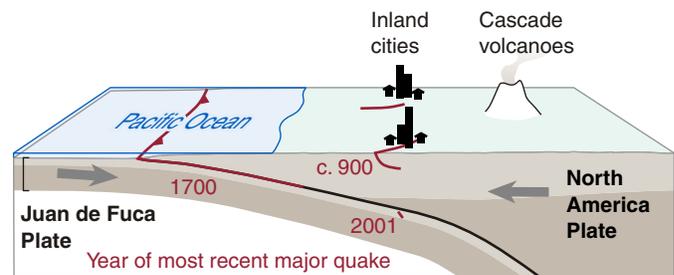
By the early 1980s, geophysicists had shown that the Juan de Fuca Plate continues to subduct at an average rate of 4 meters per century. But there was no consensus on how the plates move past one another. The plate boundary lacked a recognized history of earthquakes, even at the shallow depths where the rocks might be cool and brittle enough to break (pink in block diagram and map, right).

An earthquake in 1985 provided disturbing images of what can happen when such a plate boundary fails. On September 19th of that year, a subduction earthquake of magnitude 8 generated seismic waves that devastated Mexico City, 400 km from the earthquake source (facing page, top). More than 300 modern buildings collapsed or were damaged beyond repair, 10,000 lives were lost, and another 300,000 persons were left homeless. Could a great Cascadia earthquake have similar effects at inland cities like Vancouver, Seattle, and Portland?

Though few Earth scientists were then taking the idea seriously, some broached the possibility of a Cascadia earthquake of magnitude 9. Cascadia looked like it might have as much source area as the 1964 Alaska earthquake, of magnitude 9.2 (compare the Cascadia and Alaska maps on these two pages). It was even possible to imagine a Cascadia earthquake as large as the 1960 Chile mainshock, the 20th century's largest earthquake at magnitude 9.5.

THE THEORY OF PLATE TECTONICS holds that Earth's outer shell consists of moving plates composed of crust and rigid upper mantle (Sullivan, 1991; Oreskes, 2003). Riddihough (1984) used seafloor magnetic anomalies, first mapped by Raff and Mason (1961), to reconstruct the past 7 million years of convergence between the Juan de Fuca and North America Plates. Tanya Atwater's animations of these and other plate motions can be downloaded at <http://emvc.geol.ucsb.edu/>. EARLY IDEAS on Cascadia's great-earthquake potential were reviewed by Heaton and Hartzell (1987), Rogers (1988), Hyndman (1995), and Rogers and others (1996). Heaton and Hartzell (1986, p. 688-694) proposed that Cascadia might produce earthquakes as large as the 1964 Alaska and 1960 Chile events. Beck and Hall (1986) inferred that long-lasting seismic waves, and their resonance in ancient lake deposits, contributed to Mexico City's earthquake losses in 1985.

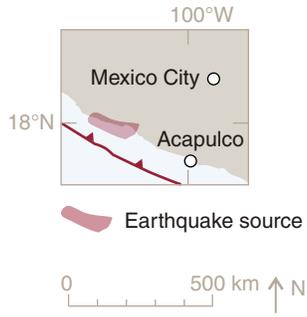
EARTHQUAKE SOURCES AT CASCADIA



EARTHQUAKE ANALOGS ON FACING PAGE

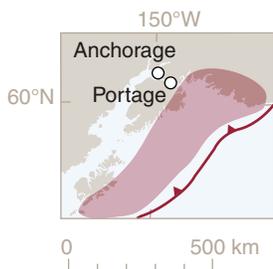


MEXICO, 1985, M 8.1



Tall buildings shortened by collapse of entire stories, Mexico City.

ALASKA, 1964, M 9.2



The maps on this page are at the same scale as the Cascadia map on the facing page.

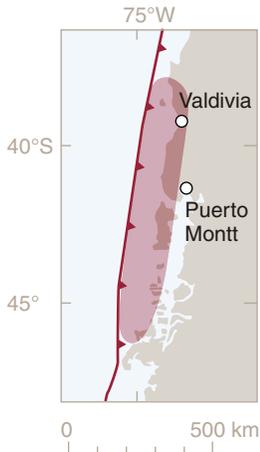


Remains of highway bridge, Portage. Wooden pilings pierce deck they used to support. Aerial view, p. 14.



School torn by landslide, Anchorage.

CHILE, 1960, M 9.5



Cracked street and variably damaged buildings, Valdivia.



Broken sewer main, Puerto Montt.

EARTHQUAKE SOURCES (fault rupture areas) inferred from aftershocks for Mexico (UNAM Seismology Group, 1986) and Alaska (Plafker, 1969, p. 6) and from aftershocks and land-level changes for Chile (Cifuentes, 1989, p. 676).

PHOTOS from the Karl V. Steinbrugge collection, National Information Service for Earthquake Engineering, University of California, Berkeley. Photographers: Karl Steinbrugge, Rodolfo Schild (Valdivia), and anonymous (Portage).

Tsunami potential 津波の可能性

Is Cascadia further threatened by its own Pacific tsunamis?



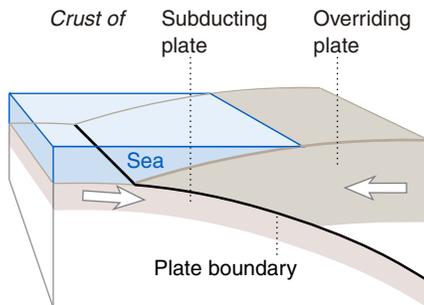
THE POTENTIAL for a great Cascadia earthquake carries with it the threat of an ensuing tsunami. And the tsunami that follows a great subduction earthquake often does more harm than the earthquake itself.

The giant Chilean earthquake of 1960, for instance, left many houses standing above the earthquake source (Valdivia photo, previous page). But the tsunami that followed erased entire villages, including Queule (above). In total, the 1960

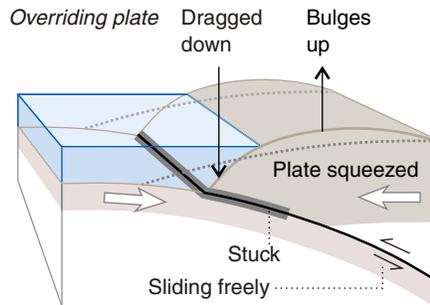
tsunami took an estimated 1,000 lives in Chile. It also claimed 61 in Hawaii and 138 in Japan.

You can make a tsunami in a bathtub by sweeping your hand through the water. During a great subduction earthquake, the role of the hand is played by a moving tectonic plate. The plate displaces water from beneath by warping the sea floor (below). It is this tectonic warping, not the seismic shaking, that acts as the hand in the tub.

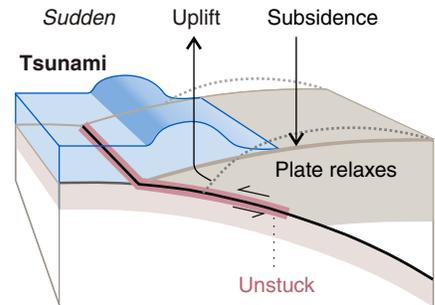
MAKING A TSUNAMI



OVERALL, a tectonic plate descends, or "subducts," beneath an adjoining plate. But it does so in a stick-slip fashion.



BETWEEN EARTHQUAKES the plates slide freely at great depth, where hot and ductile. But at shallow depth, where cool and brittle, they stick together. Slowly squeezed, the overriding plate thickens.



DURING AN EARTHQUAKE the leading edge of the overriding plate breaks free, springing seaward and upward. Behind, the plate stretches; its surface falls. The vertical displacements set off a tsunami.



Such sea-floor deformation during the 1964 Alaska earthquake generated a tsunami that reached Cascadia's shores four hours later. Warnings had been issued, and the tsunami had lost height by spreading out as it radiated toward far reaches of the Pacific Rim. Even so, the Alaskan waves swept four children off an Oregon beach and killed another dozen persons in northern California.

Before and after the 1960 tsunami in Queule, Chile, 2 km inland from the sea. Warned by the M 9.5 earthquake or by early signs of the tsunami, most residents managed to reach high ground before surges of seawater swept away their homes.

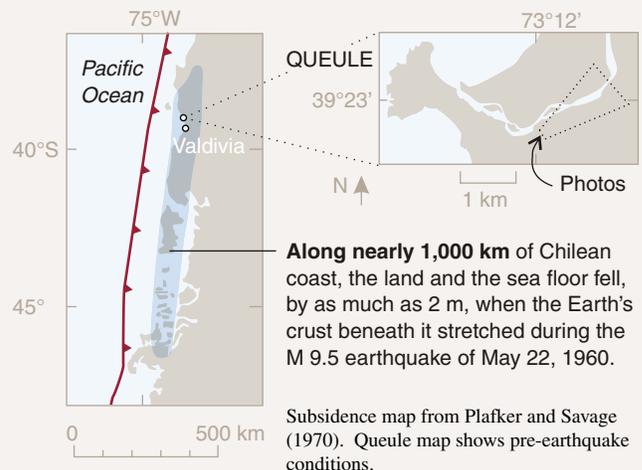
A QUEULE SURVIVOR recalled seeing the village's houses floating off like an armada (Atwater and others, 1999, p. 5, 15). Photographs by Wolfgang Weischet (1963, p. 1245-1246); prints courtesy of Pierre Saint-Amand.

TEXTBOOKS on tsunamis include Murty (1977), Dudley and Lee (1998), and Bryant (2001). On historical tsunamis in the United States, see Lander and others (1993) for the Pacific coast and Lockbridge and others (2002) for the Atlantic.

Downwarped coast

THE PLATE MOTION that drives a tsunami can also lower a coast (cartoons, opposite). When fault slip during the 1960 earthquake stretched the overriding South America plate, the Earth's surface fell throughout a belt 1,000 km long (map, right). In Queule, near the axis of the downwarp, the entire landscape dropped 2 meters. Hence tides cover former riverbanks in the postearthquake photo above.

Similar coastal subsidence accompanied the 1964 Alaska earthquake (p. 14) and several earthquakes in southwest Japan (p. 91). Coastal subsidence accordingly provides pivotal evidence for the past occurrence of great Cascadia earthquakes—clues Earth scientists began using in the late 1980s (p. 16).



Flood stories 洪水の言伝え

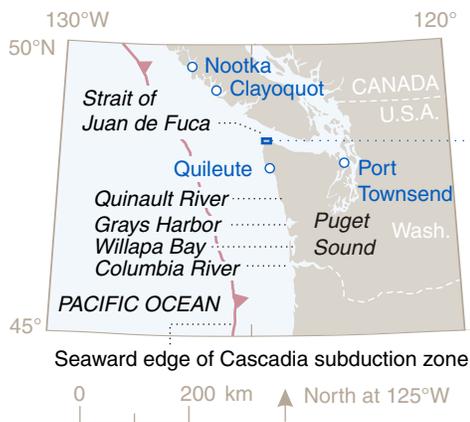
Cascadia's own tsunamis may have entered Native American lore.

OLD WRITINGS FROM CASCADIA offer few hints that the region's subduction zone produces great earthquakes or tsunamis. Such events are unknown from the records of early explorers like Bruno de Hezeta y Dudagoifia, who mapped the mouth of Washington's Quinault River in 1775; James Cook, who named Cape Flattery a few years later; and George Vancouver, who surveyed Puget Sound, Grays Harbor, and the lower Columbia River in the early 1790s. The Lewis and Clark Expedition recorded no signs of Pacific coast earthquakes or tsunamis while exploring that river in 1805 and 1806.

The oral traditions of Cascadia's native peoples, however, tell of flooding from the sea. The example at right, one of the first written, comes from James Swan's diary for a rainy Tuesday in January 1864 at Neah Bay, Washington Territory, home of the Makah tribe. Swan's informant, Billy Balch, was a Makah leader.

Balch recounts a sea flood in the "not very remote" past. It began by submerging the lowland between Neah Bay and the Pacific Ocean. Next, the water receded for four days. Rising again "without any swell" the sea covered all but the highest ground on both sides of the Strait of Juan de Fuca. It dispersed tribes, stranded canoes in trees, and caused "numerous" deaths. "The same thing happened" at Quileute, 50 km south of Neah Bay.

Balch mentions no earthquake. Did the sea flood have a remote origin, like the tsunami from Alaska in 1964? Or did a tsunami of nearby origin prove more memorable than the Cascadia earthquake that triggered it?



The diary refers to the places in blue.



EARLY EXPLORATION summarized from Hayes (1999, p. 37-93).

ORAL TRADITIONS of Cascadia earthquakes and tsunamis are summarized in a comprehensive collection by Ludwin and others (2005). Swan (1870, p. 57-58) recounts Billy Balch's story; Doig (1980, p. 62-65) puts it in context of Swan's diary-keeping. Swan (1857, p. 417) defines the Chinook jargon *hias* (or *hyas*).

MAP at right excerpted from "Makah Indian Reservation in Washington Territory by J.G. Swan, 1862" (National Archives and Records Administration, RG 75, #995). Shorelines probably based on mapping by the U.S. Coast Survey.

DIARY OF JAMES SWAN FOR JANUARY 12, 1864 ▷

Billy also related an interesting tradition. He says that "ankarty" but not "hias ankarty" that is at not a very remote period the water flowed from Neeah bay through the Waatch prairie, and Cape Flattery was an Island. That the water receded and left Neeah Bay dry for four days and became very warm. It then rose again without any swell or waves and submerged the whole of the cape and in fact the whole country except the mountains back of Clyoquote. As the water rose those who had canoes put their effects into them and floated off with the current which set strong to the north. Some drifted one way and some another and when the waters again resumed their accustomed level a portion of the tribe found themselves beyond Nootka where their descendants now reside and are known by the same name as the Makahs—or Quinaitchechat. Many canoes came down in the trees and were destroyed, and numerous lives were lost. The same thing happened at Quillehuyte and a portion of that tribe went off either in canoes or by land and formed the Chimakum tribe at Port Townsend.

There is no doubt in my mind of the truth of this tradition. The Waatch prairie shows conclusively that the waters of the ocean once flowed through it. And as this whole country shows marked evidence of volcanic influences there is every reason to believe that there was a gradual depression and subsequent upheaval of the earths crust which made the waters to rise and recede as the Indian stated.

The tradition respecting the Chimakums and Quillehuytes I have often heard before from both those tribes.

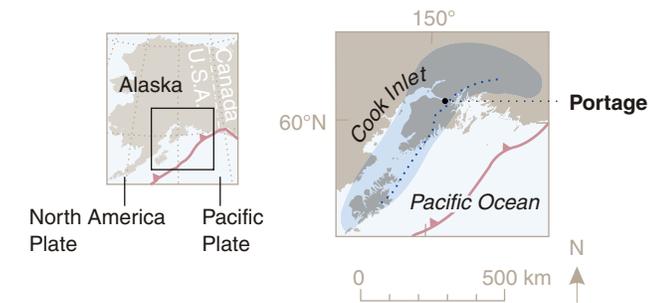
Billy also related an interesting tradition. He says that "antiquity" but not "bias antiquity," that is at not a very remote period the water flooded from Nechabay, through the Waatch Prairie, and Cape Flattery was an Island. That the water receded and left Nechabay Bay dry for four days and became very warm. It then rose again without any swell or waves and submerged the whole of the cape and in fact the whole country except the mountains back of Clyoquot. As the water rose those who had canoes put their effects into them and floated off with the current which set strong to the north. Some drifted one way and some another and when the water again assumed their accustomed level a portion of the tribe found themselves beyond Nechabay where their descendants now reside and are known by the same name as the Makahs on Quinaitchee. Many canoes came down in the trees and were destroyed and numerous lives were lost. The same thing happened at Quillechuyto and a portion of that tribe went off either in canoes or by land and found the Chemalucum tribe at port Townsend.

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Alaskan analog アラスカの例

Ghost forests and a buried soil naturally record the 1964 earthquake.



-  **Tectonic subsidence during the 1964 Alaska earthquake**
Maximum 2.3 m; axis at dotted line. Inferred cause described, p. 10-11.
-  **Seaward edge of subduction zone** Low-angle fault at plate boundary; teeth point down the fault plane, as on p. 8.

SOME EARTHQUAKES write their own history. In a classic example, the giant Alaska earthquake of March 27, 1964, was accompanied by regional subsidence that lowered vegetated land into Cook Inlet. The results remain easy to see at Portage, near the axis of the earthquake's downwarp. Trees stand dead because the land subsided 1.5 meters during the earthquake—far enough to admit tides into former meadows, willow thickets, cottonwood groves, and stands of Sitka spruce. Tides brought in silt and sand that buried this former landscape in the first decade after the earthquake.

Like the Portage garage, opposite, the spruce victims were falling by 1998. Their stumps, however, remain in growth position, entombed by the tidal silt. These serve as natural archives of the 1964 earthquake—and as a guide to identifying signatures of past great earthquakes at Cascadia.

TIDAL FLOODING A FEW WEEKS AFTER EARTHQUAKE, TWENTYMILE RIVER

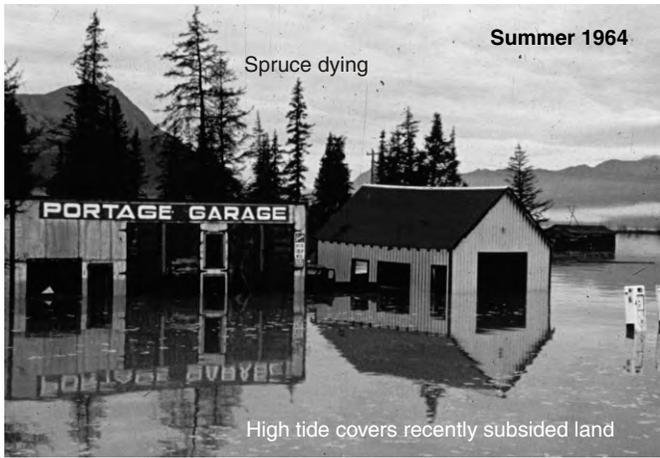


AIRPHOTO from U.S. Army, Mohawk series M-64-82. Probably taken during high tide of April 14, 1964 — 18 days after the March 27 earthquake.

THE TECTONIC COMPONENT of the subsidence near Portage amounted to 1.5-1.7 m (Plafker, 1969, plate 1). The railroad grade settled another 1 m, on average, in response to seismic shaking (McCulloch and Bonilla, 1970, p. 81).

THE SUBSIDENCE at Portage created intertidal space that the silt and sand filled (Ovenshine and others, 1976). Much of the fill dates from the first months after the earthquake, when individual high tides left layers as much as 2 cm thick (opposite; Atwater and others, 2001b). The deposition was speeded by a 10-m tide range and ample sources of sediment (Bartsch-Winkler, 1988).

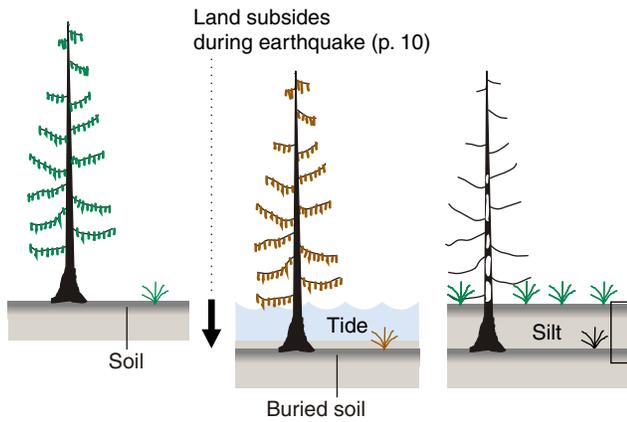
GHOST FOREST AT PORTAGE GARAGE



Before earthquake

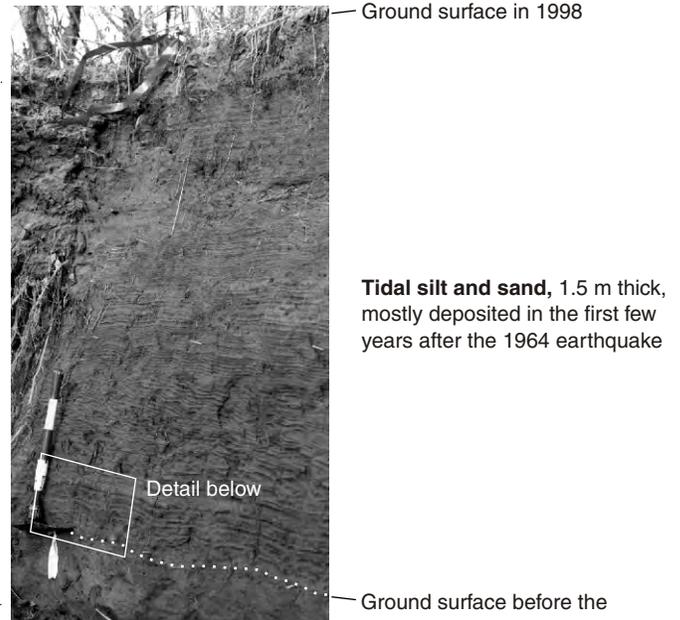
Several months after earthquake

Several decades after earthquake



By lowering land into a bay or river mouth, subsidence during an earthquake produces a lasting record of the earthquake's occurrence.

TIDAL SILT AND SAND ABOVE BURIED SOIL, TWENTYMILE RIVER



Sunken shores 海岸の沈降

Land occasionally drops along Cascadia's Pacific coast.



Copalis River; very high fair-weather tide, December 1997

IT WAS ONLY A MATTER OF TIME before someone would recognize Portage look-alikes at Cascadia. In the late 1980s, spurred by controversy about Cascadia's great-earthquake potential, geologists checked bays and river mouths along Cascadia's Pacific coast. At nearly every one they found evidence that land had dropped.

These signs of subsidence include ghost forests—groves of weather-beaten trunks that stand in tidal marshes of southern Washington. First documented in the early 1850s, they are composed entirely of western red cedar, a long-lived conifer known for rot-resistant wood.

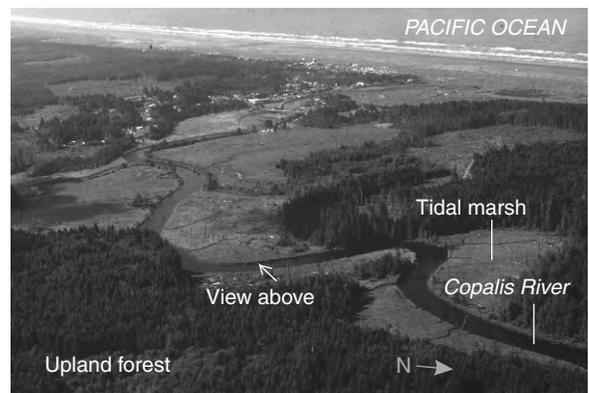
More common are victim trees preserved only as stumps beneath the marshes. Thousands of such stumps can be seen in banks of tidal streams in southern Washington (example opposite), hundreds more at estuaries in Oregon and northern California. The main victim is Sitka spruce—the species whose rotting trunks were falling at Portage in the fourth decade after their deaths in 1964 (p. 15).

Most common of all are the buried remains of tidal marshes. In streambanks and sediment cores, muddy tidal deposits abruptly overlie peaty marsh soils.

THE LOWERING OF LAND by Cascadia earthquakes has been inferred in dozens of reports. Recent examples include details from Oregon (Kelsey and others, 2002; Witter and others, 2003; Nelson and others, 2004) and Washington (Atwater and others, 2004) and a regional compilation (Leonard and others, 2004). IN THE UPPER PHOTO, spruce saplings live high on the tallest of the dead trees. Several of the tall trunks fell between 1997 and 2003.

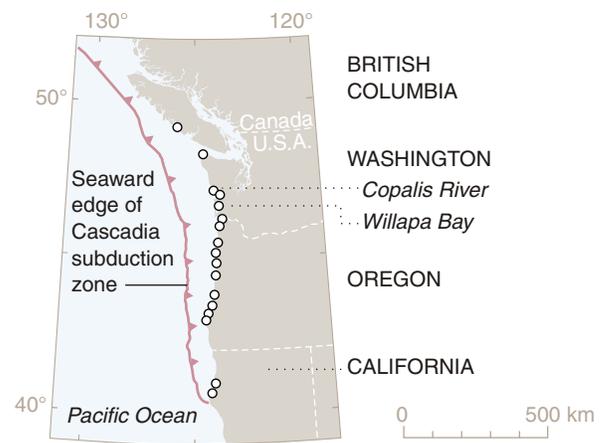
JAMES GRAHAM COOPER (1830-1902), wintered at Shoalwater (now Willapa) Bay in 1853-1854, while serving as naturalist for a railway survey. He described the bay's ghost forests of western red cedar to illustrate the wood's durability. He inferred that the trees had spent their lives "above high-water level, groves of this and other species still flourishing down to the very edge of inundation" (Cooper, 1860, p. 26). As to what killed the trees, Cooper proposed gradual sinking into quicksand. Now it is clear that the land dropped suddenly (evidence opposite), and that subsidence resulted from stretching of solid rock (right cartoon, p. 10).

GHOST FOREST IN TIDAL MARSH

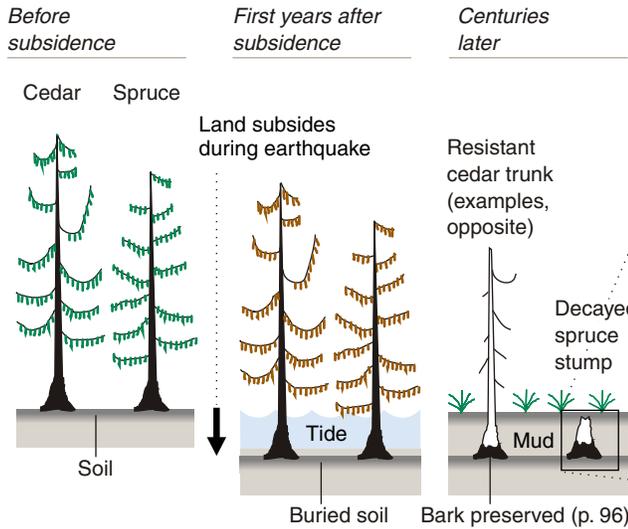


Ordinary tide, August 1991

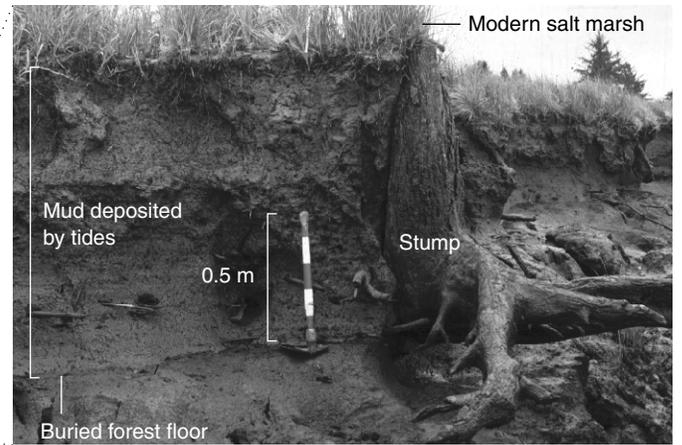
SUBSIDED SITES ALONG CASCADIA'S PACIFIC COAST



○ Bay or river mouth where buried soils record earthquake-induced submergence in the past 5000 years.



SPRUCE STUMP EXHUMED IN BANK OF TIDAL STREAM



Naselle River, Willapa Bay

Whodunit

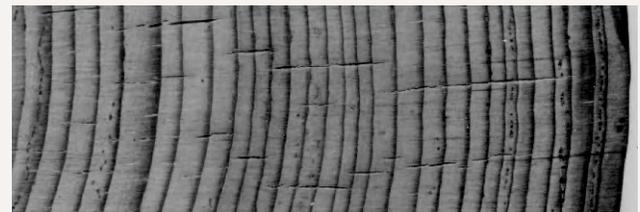
WHAT ALLOWED TIDES to kill forests and bury marshes along Cascadia’s Pacific coast? At first, in the late 1980s, geologists couldn’t rule out gradual rise of the sea. But soon they convicted abrupt fall of the land that was accompanied by tsunami and shaking (p. 18 and 20), and which happened in the same decades at different places along a shared fault (p. 24).

Sudden subsidence provides a simple explanation for tree rings like those at right. The rings record the final decades of life for a Sitka spruce killed by postearthquake submergence at Willapa Bay, like the one in the photo above. Wide to the end, the rings suggest that the tree was healthy right up to the time of its death. The rings show no sign of lengthy suffering from gradual drowning and salt-water poisoning from a drawn-out sea-level rise.

Sudden lowering of land also explains remarkable preservation of buried marsh soils at Cascadia. Some of the soils retain delicate remains of plants that had been living on them at the time of submergence. Tidal-flat mud above such soils entombed herbaceous leaves and stems, in growth position, before they had time to rot. Such leaves and stems decay in a few years on modern marshes. Their preservation in tidal-flat mud above buried marsh soils implies that the change from marsh to tidal flat took a few years at most.

THOUGH HUNDREDS OF TREES succumbed to postearthquake submergence at Portage in 1964 (p. 14-15), some of those immersed in fresh water managed to live a few months beyond the March 27 earthquake. Their bark adjoins light-colored early wood from the 1964 growing season. Not imagining such survival, Atwater and Yamaguchi (1991) misinterpreted incomplete outer rings at Cascadia as evidence for sudden submergence during a growing season, between May and September. The trees in question are spruce that died from the Cascadia earthquake now dated to January 1700. As at Portage, some of the submerged spruce survived into the next growing season or later (Jacoby and others, 1995).

WIDE OUTER RINGS OF SPRUCE STUMP



One annual ring, composed of cells added early (light) and late (dark) in growing season, which runs May to September

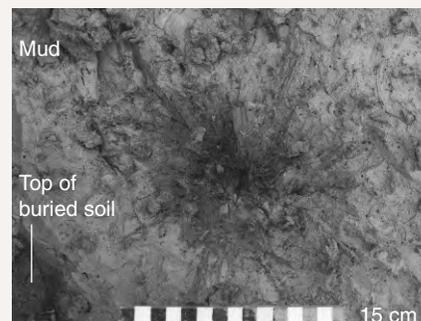
1 cm Final ring

Bay Center, Willapa Bay

LEAVES AND STEMS OF MARSH GRASS



Living tuft of the grass *Deschampsia caespitosa* on the high part of a tidal marsh.



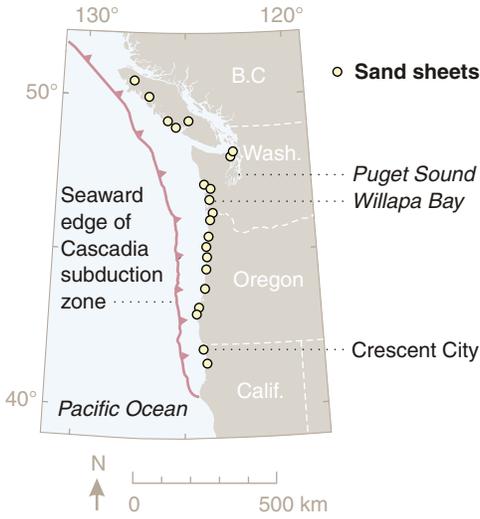
Fossil tuft interred by tidal-flat mud after subsiding circa A.D. 400 (p. 100). Plan view, mostly 1-2 cm above buried soil.

Niawiakum River, Willapa Bay

Sand sheets 地層中の砂層

Tsunamis overran newly dropped land along Cascadia's Pacific coast.

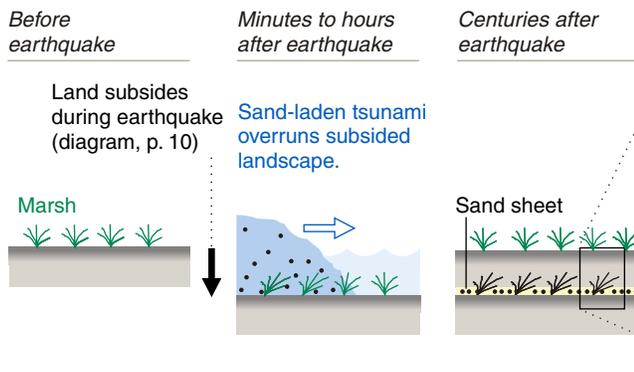
SIGNS OF CASCADIA TSUNAMIS



WHILE MAPPING Cascadia's signs of sudden subsidence, geologists in the 1980s and 1990s found associated evidence for tsunamis. That evidence consists of sand sheets beside bays and river mouths (dots on map, left). The sand came from the sea; it tapers inland and contains the microscopic siliceous shells of marine diatoms. Beside muddy bays the sand alternates with layers of mud (photos below) that probably settled out in lulls between individual waves in a tsunami wave train (modern example, opposite).

At most sites, the sand arrived just before tidal mud began covering a freshly subsided soil (cartoons below). Neither a storm nor a tsunami of remote origin explains this coincidence with subsidence. The simplest explanation is a tsunami from an earthquake in which a tectonic plate, in a seismic shift, abruptly displaces the sea while lowering the adjoining coast. The resulting tsunami then overruns the lowered land (cartoon, p. 10).

AT TSUNAMI LAYS DOWN A SHEET OF SAND

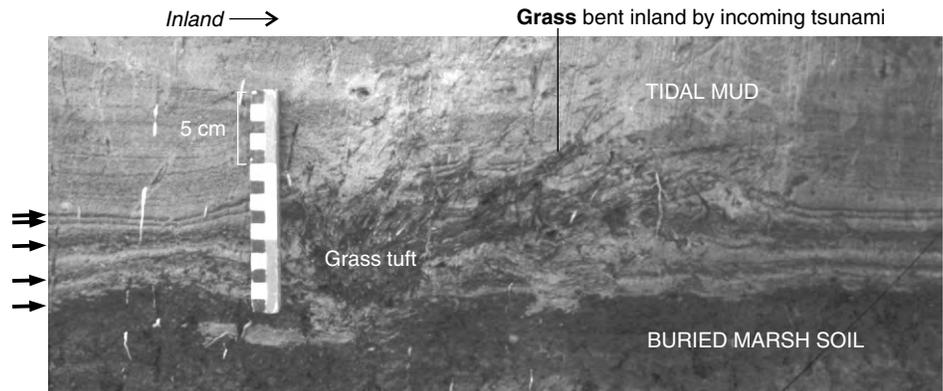


Mud deposited by tides since 1700. Contains coarse silt but lacks sand except just above a subsided, buried soil. Mud thickness, 80 cm

Buried soil of marsh that subsided in 1700

SAND SHEETS from tsunamis of great Cascadia earthquakes have been identified along Cascadia's Pacific coast (compilation by Peters and others, 2003) and at northern Puget Sound (Williams and others, 2005). Some cover archaeological sites (p. 20-21) and the floors of coastal lakes (Hutchinson and others, 1997). Constituents include microscopic marine fossils (Hemphill-Haley, 1996). Sand sheets in British Columbia record Alaskan waves of 1964 in addition to the 1700 Cascadia event (Clague and others, 2000).

A SMALL TSUNAMI on April 25-26, 1992, in northern California, provides further evidence that the Cascadia subduction zone generates tsunamis of its own. The parent earthquake, of magnitude 7.1, probably broke the Cascadia plate boundary near its southern end. The tsunami crested 0.5 m above tides at Crescent City, where it lasted eight hours (Oppenheimer and others, 1993).



→ **Sandy layer**, each the likely record of an onrushing wave in the tsunami train that began the evening of January 26, 1700 (inferred timing, p. 42-43). The sandy layers alternate with mud that probably records the slack water of crested waves.

Niawiakum River, Willapa Bay (Oyster locality of Atwater and Hemphill-Haley, 1997)

Chilean counterparts

THE TSUNAMI associated with the giant 1960 Chile earthquake deposited sand in Chile. The deposit was noted soon afterward at several northern sites. Additional examples were documented decades later near Maullín, where tsunami sand had settled on subsided pastures.

Likewise in Japan, on the far side of the Pacific, the 1960 tsunami deposited sand onshore. For example, it

coated plains beside Miyako Bay with alternating layers of sand and silt. The layers probably represent several of the dozens of 1960 tsunami waves recorded by the Miyako tide gauge. Those waves were numerous because, like the Cascadia tsunamis simulated on pages 37, 74-75, and 103, the 1960 Chile tsunami reflected off shorelines and resonated in bays.

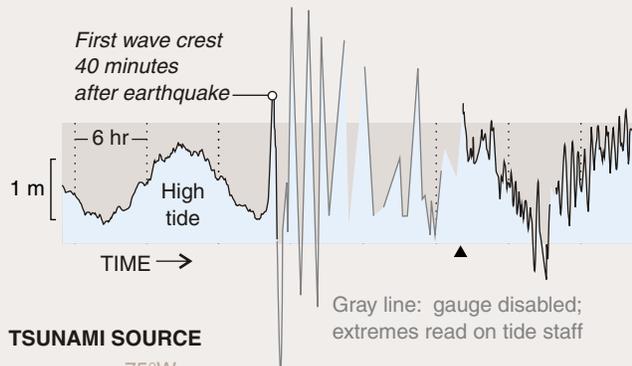
In Chile

TSUNAMI DEPOSIT NEAR MAULLÍN

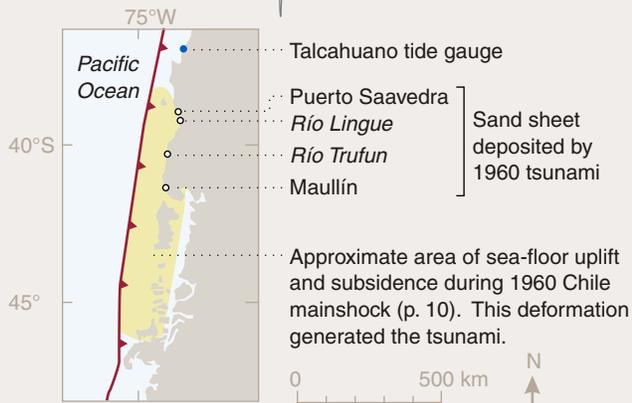


Pasture soil **Sand sheet** deposited by 1960 tsunami; later etched by high tides

WAVE TRAIN AT TALCAHUANO TIDE GAUGE



TSUNAMI SOURCE

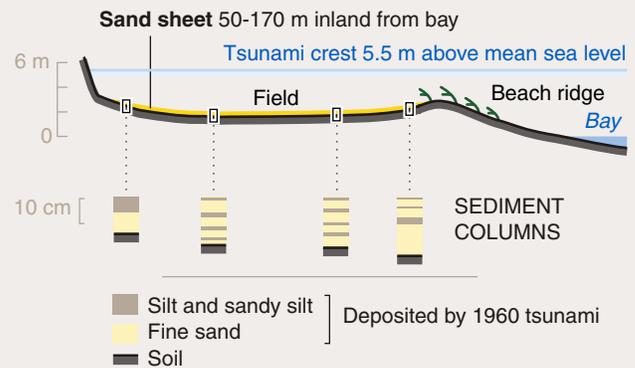


The parent earthquake took place 1710-1715 G.M.T., 22 May 1960

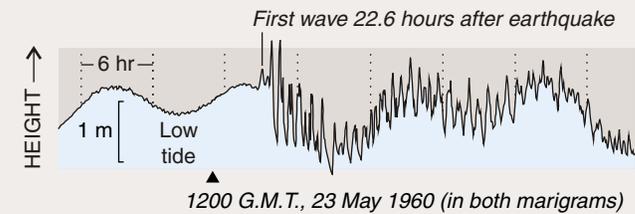
SAND SHEETS were noted by Wright and Mella (1963, p. 1371, 1372, 1389) and, near Maullín, by Cisternas and others (2005). Tide-gauge data redrawn from Sievers and others (1963, sheet 3). Tsunami source inferred from land-level changes mapped by Plafker and Savage (1970).

In Japan

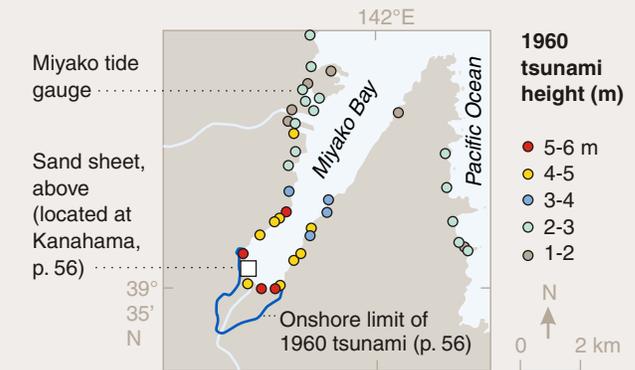
TSUNAMI DEPOSIT BESIDE MIYAKO BAY



WAVE TRAIN AT MIYAKO TIDE GAUGE



TSUNAMI HEIGHTS BESIDE MIYAKO BAY (location, p. 51)



G.M.T., Greenwich Mean Time

AT MIYAKO BAY the 1960 tsunami deposits contain microscopic marine fossils (Onuki and others, 1961) in addition to the multiple layers illustrated above (redrawn from Kitamura and others, 1961b). Details on the marigram, p. 46; sources for the mapped tsunami heights, p. 55.

In harm's way 危險地域

Earthquake-induced submergence ruined Cascadia campsites.

IN A YUROK MYTH recorded a century ago, Thunder wants people to have enough to eat. He thinks they will if prairies can be made into ocean. He asks Earthquake for help. Earthquake runs about, land sinks, and prairies become ocean teeming with salmon, seals, and whales.

In cruel reality, native people paid a price for whatever they gained when Cascadia's great earthquakes changed tidal prairies into shallow arms of the sea. First they faced horrific tsunamis, like the one implied by the story of a sea flood that swept canoes into trees (p. 12). Survivors then watched tides relentlessly cover their subsided, bayside fishing camps.

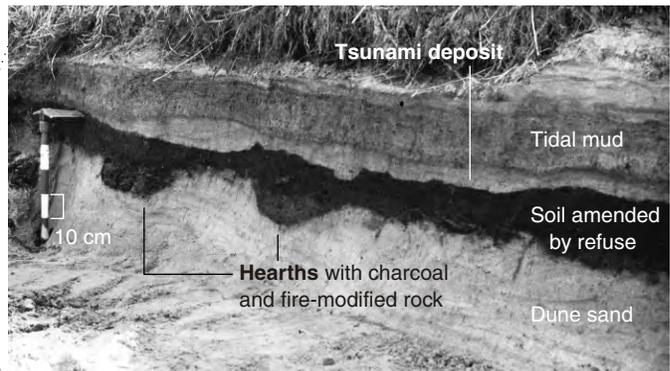
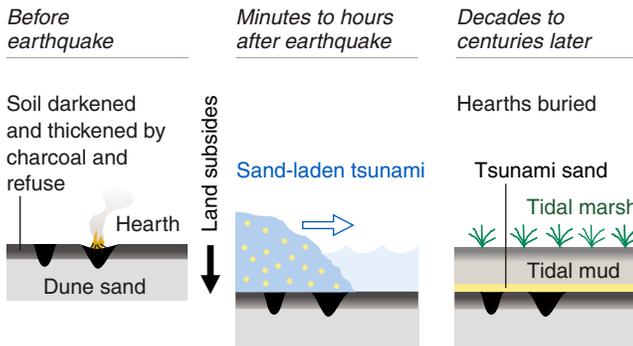
Several archaeological sites tell wordlessly of the waves and tides that overran them. Each lies buried beneath tidal mud. Some are also coated with tsunami sand. In the 1980s

and 1990s, geologists noticed them while studying buried soils in the banks of tidal streams (examples below and opposite).

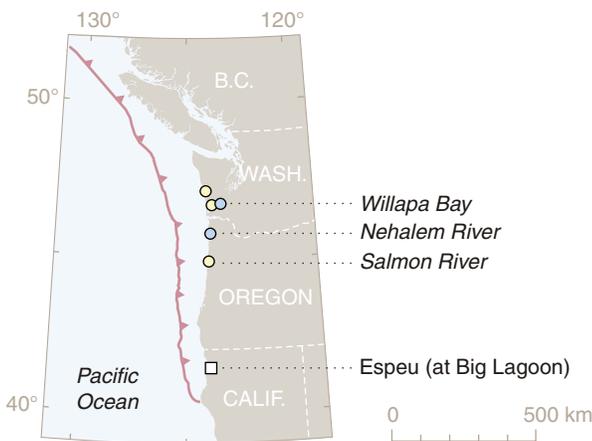
Most of the archaeological sites stand out for their broken stones. The estuaries' muddy banks rarely contain sand, much less stones. But native peoples brought in pebbles and cobbles. They baked them in hearths, then used them to heat water in woven baskets and wooden boxes. Thermally shocked, the stones shattered.

Did a tsunami put out the campfires? None of the identified sites tells a story so dramatic. And something else must have driven people from the fishing camp on the facing page. Probably it was abandoned a century or two before the earthquake that sank it.

FORMER FIRE PITS, OREGON



Salmon River, site 35LNC64



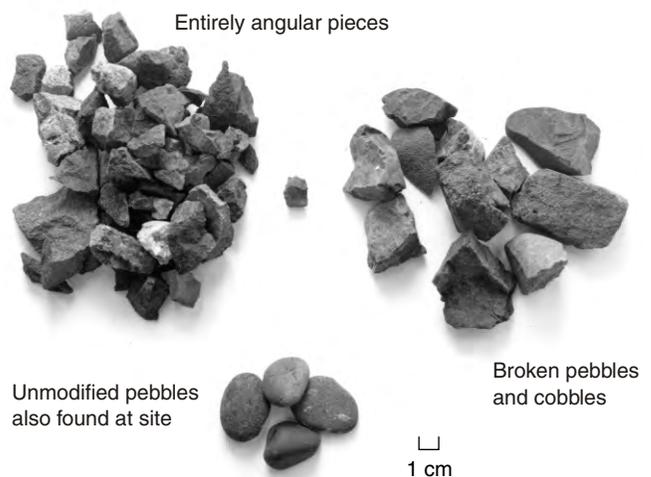
Campsites ruined by a great Cascadia earthquake

- Covered by tsunami sand and tidal mud
- Covered by tidal mud only

□ Residence of Yukok teller of "How the prairie became ocean"

ANN OF ESPEU, of the Yurok tribe, recounted "How the prairie became ocean" to the ethnographer Alfred L. Kroeber (1876-1960) between 1900 and 1908 (Kroeber, 1976, p. 460).

FIRE-MODIFIED ROCK, WASHINGTON



Niawiakum River, Willapa Bay, site 45PC102

EARTHQUAKE-INDUCED SUBSIDENCE has been inferred from burial of archaeological sites in Oregon (Minor and Grant, 1996; Hall and Radosevich, 1998) and Washington (Cole and others, 1996; source of rock photo).

A weaver's fate

WHAT BECAME OF THE MAKER of the woven object at right?

In 1991, before salvage by an archaeologist, the weaving protruded from an eroding tidal bank of Oregon's Nehalem River. It rested on the lowest centimeter of tidal mud that covers a buried marsh soil. Its radiocarbon age matches the time when the marsh changed into a tidal flat. Did the tsunami from a great Cascadia earthquake snatch the weaving from a coastal village? Did the weaver survive?

A PIECE OF THE WEAVING gave a radiocarbon age (173 ± 44 ^{14}C yr B.P.; GX-17835) statistically indistinguishable from the mean of 16 ages on stems and leaf bases found rooted in the soil and entombed in the overlying mud (179 ± 15 ^{14}C yr B.P.; Nelson and others, 1995; graphed on our p. 25).

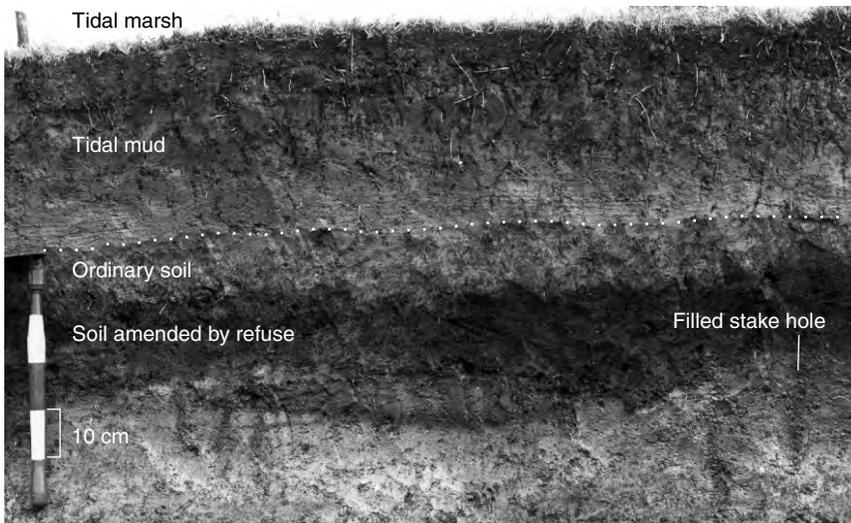


1 cm



1 km north of Wheeler; "Down-stream" site of Grant (1992).

ABANDONED FISHING CAMP, WASHINGTON



Two fishing weirs, exposed at very low tides at Willapa Bay, Washington, probably predate the 1700 Cascadia earthquake. A bark-bearing stave dates to 1400-1650. In the adjoining bank, archaeologically sterile soil records a time when the site lay abandoned. This soil separates a culturally darkened soil from the earthquake's signature—the abrupt upward change to distinctly laminated mud that postearthquake tides laid on subsided land.

A FENCE IN WATER, a fishing weir blocks fish or directs them into traps. Dozens of prehistoric examples have been reported from the coast between southeast Alaska and northern California (Moss and Erlandson, 1998). The weirs above jut into the tidal Willapa River on the bank opposite downtown South Bend (site 45PC103, Atwater and Hemphill-Haley, 1997, p. 69-71 and figs. 29, 30).

Currents and cracks 水中土石流と液状化

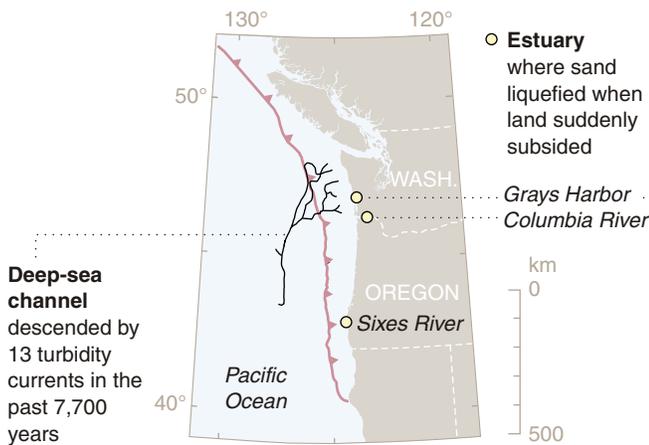
Cascadia earthquakes avalanched sea-floor mud and quickened coastal sand.

DID THE EARTH QUAKE while land subsided and tsunamis began along Cascadia's Pacific coast? This key question went unanswered until the early 1990s, when two lines of evidence pointed to seismic shaking.

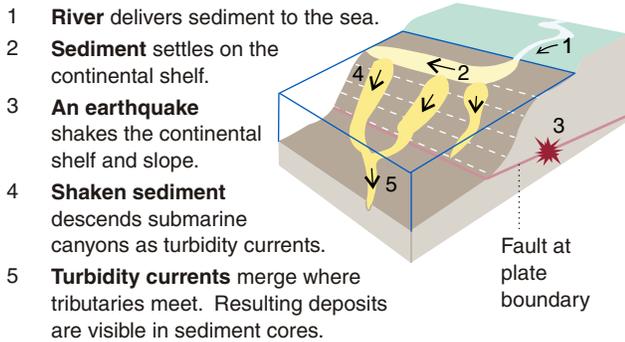
First, shaking offshore was shown to explain bottom-hugging muddy flows (turbidity currents) that repeatedly descended submarine channels (cartoon below).

Second and crucially, shaking onshore was found to have accompanied the coastal subsidence. The shaking liquefied loose, wet sand, turning it to quicksand. Water expelled from the liquefied sand erupted through cracks onto freshly subsided land (right). Today, these conduits are easy to spot because water plucks sand grains from the cracks more easily than it scours the sticky mud beside them.

EVIDENCE FOR SHAKING



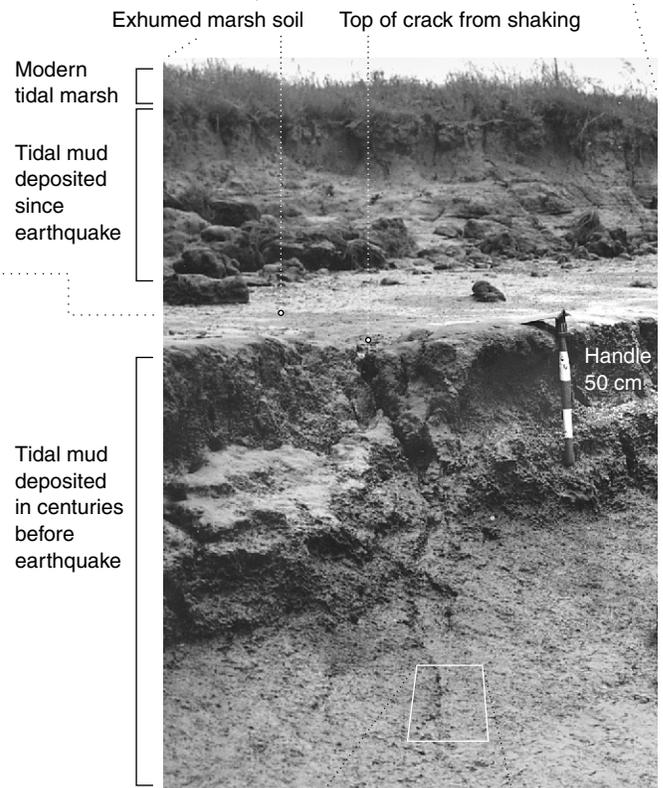
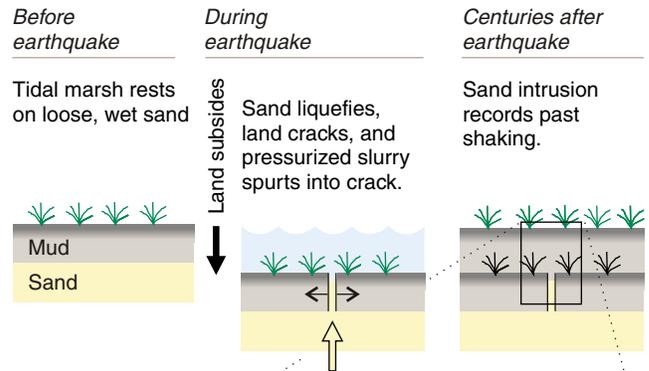
SHAKING LEAVES A DEEP-SEA DEPOSIT



ON TURBIDITE EVIDENCE for great Cascadia earthquakes, see Adams (1990; source of the above cartoon) and Goldfinger and others (2003).

LIQUEFACTION during the 1700 Cascadia earthquake produced sand dikes along the Columbia River. These were discovered in the early 1990s by Stephen Obermeier (Peterson, 1997; Obermeier and Dickenson, 2000). Probably correlative intrusions were later found at Grays Harbor (right) and at Sixes River, Oregon (Kelsey and others, 2002, p. 310-312). The 1964 Alaska earthquake generated dikes near Portage (cracks in photo, p. 14; Walsh and others, 1995).

SHAKING YIELDS A SAND-FILLED CRACK



A sand dike—a vertical sand-filled crack—rises to the top of a marsh soil, seen above in a natural low-tide outcrop. In the plan view at right, the dike cuts sharply across the mud.



Johns River, Grays Harbor (p. 103). In lower photo, the grooves in the mud are from scraping tool.

Mud Sand Mud

Strength of shaking

TO DESIGN A SCHOOL to withstand a great Cascadia earthquake, an engineer needs to know what shaking to expect. Researchers have sought guidance from records of past shaking at Cascadia, thus far with little success.

To estimate ancient ground motions, a logical first step is to identify sand that an earthquake liquefied. The sand's resistance to liquefaction can then be measured, and the results compared with those from sand that did or did

not liquefy at known levels of shaking.

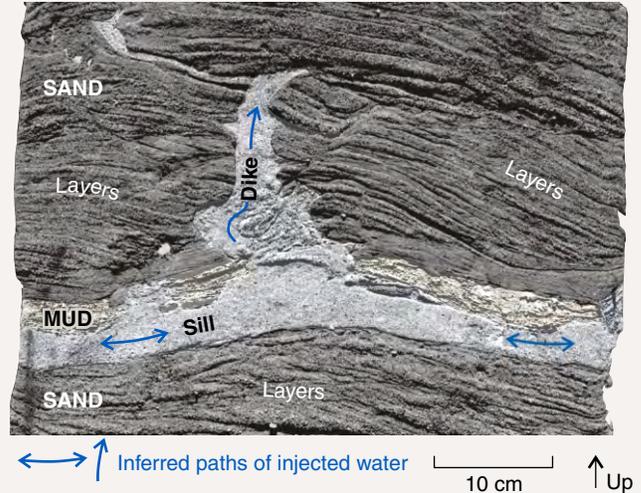
However, sand that liquefies can look just the same as it did before. It can retain its original sedimentary layers after expelling the water that drives intrusions. In the photo below, a sill and offshooting dikes show that sand liquefied somewhere below them. How can that source sand be identified, so that its resistance to liquefaction can guide the design of schools that resist earthquakes?

SEDIMENT SLICER BESIDE COLUMBIA RIVER

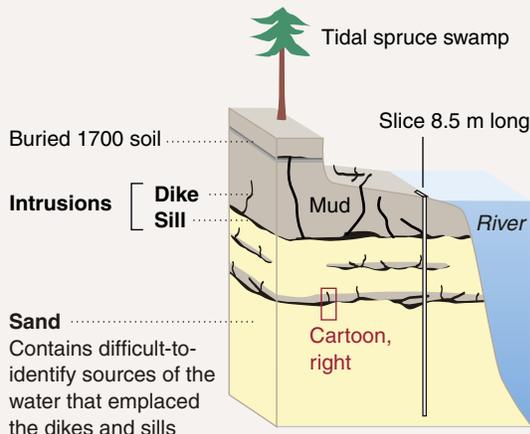


Photo by Bill Wagner, Longview Daily News, September 2000

INTRUSIONS IN VERTICAL SLICE



SCHEMATIC DISTRIBUTION OF INTRUSIONS

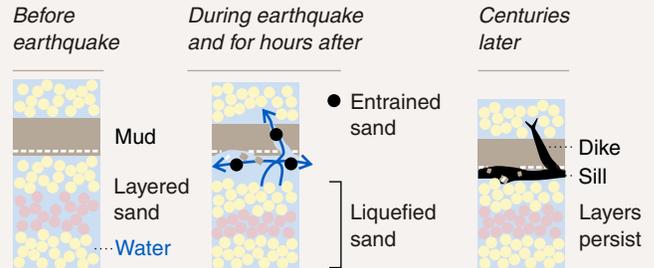


PEAK SURFACE ACCELERATIONS of 0.15-0.35 g were inferred from the localized absence of near-surface sand dikes along the Columbia River 35-60 km inland from the Pacific coast (Obermeier and Dickenson, 2000). Deeper liquefaction features, like those at upper right, cast doubt on these proposed upper bounds (Atwater and others, 2001a; Takada and Atwater, 2004).

DURING LIQUEFACTION, sand sheared by shaking loses strength through an increase in pore-water pressure that decreases grain-to-grain contact. Partial collapse of the grain structure then drives much of the water out. However, where the expelled water escapes diffusely, the primary sedimentary layers in liquefied sand can remain nearly intact (Lowe, 1975; Owen, 1987; Liu and Qiao, 1984).

ADDED TINTS highlight the intrusions and mud bed in the slice photo.

INFERRED EMPLACEMENT OF INTRUSIONS



Loose sand, thinly layered, is interbedded with mud. Water occupies the space between sand grains.

Sand liquefies; grains lose contact with one another. They then settle into a more compact arrangement. The compaction drives out water, which initially percolates too slowly to erase sedimentary layers. However, where dammed by a mud bed, the water ponds and begins streaming sideways, moving grains against gravity. Locally it erodes the mud from beneath and breaks through the mud into sand above.

Intrusions provide the sole conspicuous sign that liquefaction occurred meters beneath them. Though more compact than it had been before the earthquake, the layered sand that liquefied retains most of its original sedimentary layering.

Magnitude 9? マグニチュード9?

Geologists reach an impasse on Cascadia's potential for a giant earthquake.

MAXIMUM EARTHQUAKE SIZE remained a big unknown for Cascadia through the early 1990s.

By then, geologists had identified signs of earthquake-induced subsidence, and attending tsunamis, at estuaries from southern British Columbia to northern California. They knew that nearly all sites had dropped most recently within the past 400 or 500 years, and that the southern Washington coast subsided in the decades after A.D. 1680 (box, below).

These findings spurred a radiocarbon experiment designed to detect coastwise differences—if any—in the time of earthquake-induced subsidence. Any such differences would limit earthquake size by limiting fault-rupture length.

The experiment ended up denying neither the giant-earthquake hypothesis nor its serial alternative (opposite). The most exact of the ages show that trees nearly 700 km apart, in southern Washington and northern California, died from earthquake-induced subsidence during the same few decades. Either a single giant earthquake or a swift series of merely great earthquakes could have done the job.

But the experiment succeeded in narrowing the time window for Cascadia's most recent giant earthquake, or great-earthquake series, to the period 1695-1720. And unbeknown to the experimenters, an orphan tsunami in 1700 had long been puzzling earthquake historians in Japan.



Natural clocks

Red-cedar wedge, Washington



Chehalis River, 1987 (David Yamaguchi sampling)



Spruce-root slab, Oregon



Nehalem River, 1991 (Brian Atwater)



Tiny stems and leaves, Oregon



Nehalem River, 1991 (Alan Nelson)

| MATERIAL DATED (and year first measured) | AGE OF MATERIAL RELATIVE TO TIME OF EARTHQUAKE | METHOD (and typical uncertainty) | EVENTUAL COASTWISE EXTENT | TIME WINDOWS FOR MOST RECENT GREAT EARTHQUAKE as inferred by 1995 |
|--|--|---|--|--|
| Peat and other plant remains in or above buried soil (1986) | Commonly decades or centuries older, or decades younger | Conventional radiocarbon (± 50 ^{14}C yr) | Most estuaries, southern B.C. to northern Calif. | <p>1700</p> <p>1650 YEAR A.D. 1800</p> <p><i>Written history rules out the occurrence of any great Cascadia earthquake after 1800 and probably since 1775 (p. 12).</i></p> |
| Rings of weather-beaten trunks of western red cedar killed by post-earthquake tides (1988) | Outermost preserved ring older by intervals unknown until 1996, when the trees' final rings were dated in bark-bearing roots (p. 96) | Ring-width pattern matching to calendar year (p. 97) | Four estuaries in southern Washington | |
| Rings of bark-bearing roots of Sitka spruce killed by postearthquake tides (1990) | Typically older by amounts known, to within a few years, from counts of annual rings | High-precision radiocarbon (± 10 -15 ^{14}C yr) | Four estuaries (facing page) | |
| Leaves and stems of herbaceous plants killed by post-earthquake tides (1993) | Older by a decade or two at most for woody stems of perennials; by a few years at most for leaves | AMS radiocarbon (± 50 ^{14}C yr) | Seven estuaries (facing page) | |

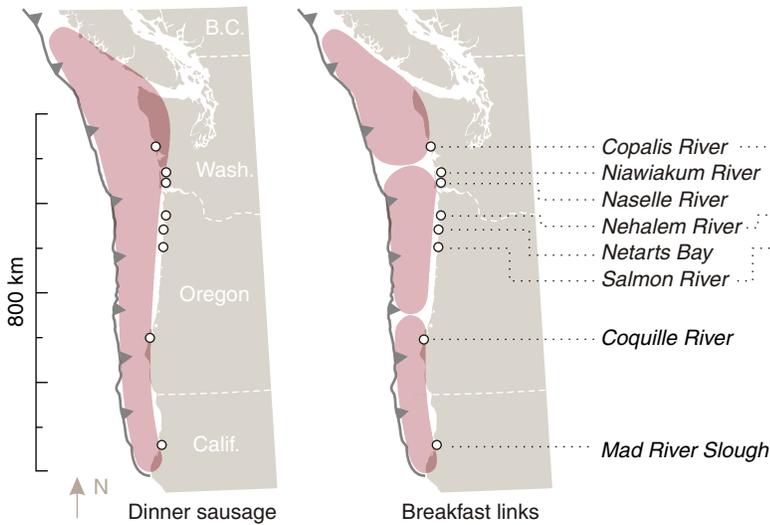
For examples of differences in geological and analytical precision, see Atwater and Hemphill-Haley (1997, p. 84 [soil Y] versus p. 89).

\pm , standard deviation reported by lab. ^{14}C yr, radiocarbon years (graphed, opposite). AMS, accelerator mass-spectrometry, used to date small samples.

HYPOTHESES: ALL AT ONCE OR A PIECE AT A TIME?

Giant earthquake, M 9

Series of lesser events, M 8+

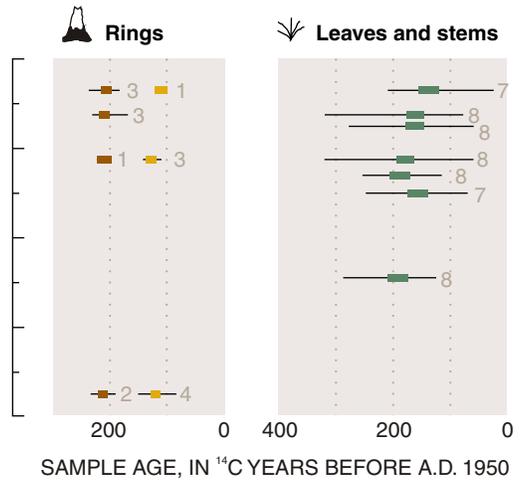


SKEPTICS of the giant-earthquake hypothesis felt that a series of lesser earthquakes is “more consistent with observations at other subduction zones” (McCaffrey and Goldfinger, 1995).

THE RADIOCARBON AGES at right were reported by Atwater and others (1991) and Nelson and others (1995). Each black error bar spans the ranges of individual ages. Each green-coded plant yielded one or two individual ages.

INCONCLUSIVE TEST: DEATH AT THE SAME TIME?

The remains of earthquake-killed plants yielded ages that are neither statistically different nor necessarily the same within each of the three groups color-coded below.



— Mean ages, ± 1 standard error. Wood coded by mean number of ring years before tree death: 40 — 5 —
 — 3 Range of sample ages
 Number of plants dated

Uncommonly exact

RADIOCARBON AGES rarely pin down the time of an event. To narrow the time of Cascadia’s most recent giant earthquake (or serial great earthquakes) to 1695-1720, isotopists and geologists pushed radiocarbon precision to its limits. They took advantage of quirks in the radiocarbon timescale, and they maximized geological and analytical precision in sampling and measurement.

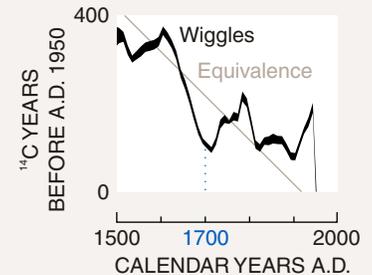
Radiocarbon time has been called rubberband time. It stretches and shrinks because radioactive carbon is produced in Earth’s atmosphere by cosmic rays whose flux waxes and wanes. Trees use radiocarbon as part of the atmospheric carbon dioxide from which they make their annual rings. Tree rings thus yield radiocarbon ages that wiggle away from straight-line equivalence of radiocarbon and calendar time. One of the tallest jags spans most of the century before A.D. 1700 (graph at right).

The dating to 1695-1720 relied on finding this tall jag in the annual rings of earthquake-killed spruce. Ring counts adjust for the time lag between the dated rings and the tree-killing earthquake. The radiocarbon ages themselves, like those that define the calibration curve, were measured at uncommon precision on cellulose whose carbon the trees took from the atmosphere by photosynthesis shortly before the dated rings formed.

Sample selection was guided by red-cedar evidence that the earthquake followed the 1680s (graph, left). This evidence, honed in the late 1990s (p. 96-97), would strengthen Cascadia’s link to a tsunami in Japan.

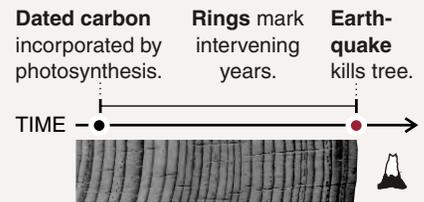
CALIBRATION CURVE

Relates radiocarbon ages (above) to calendar dates. Derived from tree rings of known date. Wood of unknown date can be matched to a wiggle by the radiocarbon dating of rings that are known numbers of ring years apart.



GEOLOGICAL PRECISION

Tree rings give exact difference between age of dated material and time of earthquake.



ANALYTICAL PRECISION

Analyzed for weeks in shielded counters, tree rings can be dated with uncertainties of 10-20 ¹⁴C years. Cellulose, the skeleton of wood, is first extracted to limit the dated carbon to the years the rings formed.



Seattle, 1996 (Phil Wilkinson)

THE RANGE 1695-1720 contains the 95-percent confidence interval; at most there is a 1-in-20 chance that the dated event occurred outside the range. Stuiver and others (1991) reviewed controls on the radiocarbon timescale. The calibration curve is from Stuiver and others (1998).

