Part 3

The orphan's parent 津波の親地震

A TRANS-PACIFIC REUNION took place in 1996. Orphaned for nearly 300 years, the 1700 tsunami in Japan was reunited, on the pages of a scientific journal, with an earthquake and tsunami in North America (p. 94-95). The orphan dated the earthquake to the evening of January 26, 1700 (p. 42-43) and gave its approximate size as magnitude 9.

Today the 1700 tsunami is securely linked to a giant North American earthquake. The tie was strengthened in 1997 by tree-ring dating that narrowed the time window for a great Cascadia earthquake to the months between August 1699 and May 1700 (opposite; p. 96-97). The earthquake's enormity was confirmed in 2003 through improved estimates of the orphan tsunami's size and from computer simulations of Cascadia earthquakes and of the tsunami itself (p. 98-99). The tsunami's written record in Japan has become clearer, too, with discovery in 1998 of the Miho headman's account, authentification in 2002 of the Nakaminato shipwreck certificate, and explanation in 2004 of a discordant date from Tsugaruishi (p. 62).

The fault that broke in 1700 has been reloading for future Cascadia earthquakes. If the fault behaves as it has the last few thousand years, the earthquakes will happen sporadically at intervals ranging from a few centuries to a millenium (p. 100-101). Sometimes the fault may break along its entire length; at other times it may break piecemeal.

Today, public officials are taking steps to prepare coastal communities for Cascadia tsunamis, and engineers are using new seismic-hazard maps that allow for shaking from Cascadia earthquakes as large as magnitude 9 (p. 102-105). The story of the orphan tsunami of 1700 continues through these public-safety efforts.

By elimination 消去法によって

No other place rivals Cascadia as the orphan tsunami's source.

POTENTIAL SOURCES OF THE 1700 TSUNAMI

Subduction zone Line shows upper edge of plate-boundary fault. Teeth point down fault (p. 8).

MIHO'S HEADMAN WONDERED what made the 1700 tsunami (p. 78, columns 9-16). That mystery grew as 20th-century historians collected accounts of its orphan waves from Kuwagasaki to Tanabe (p. 54, 62). Geologic clues in North America, summarized in Part 1, show that the tsunami could have originated at the Cascadia subduction zone. But might the waves' real source lie elsewhere?

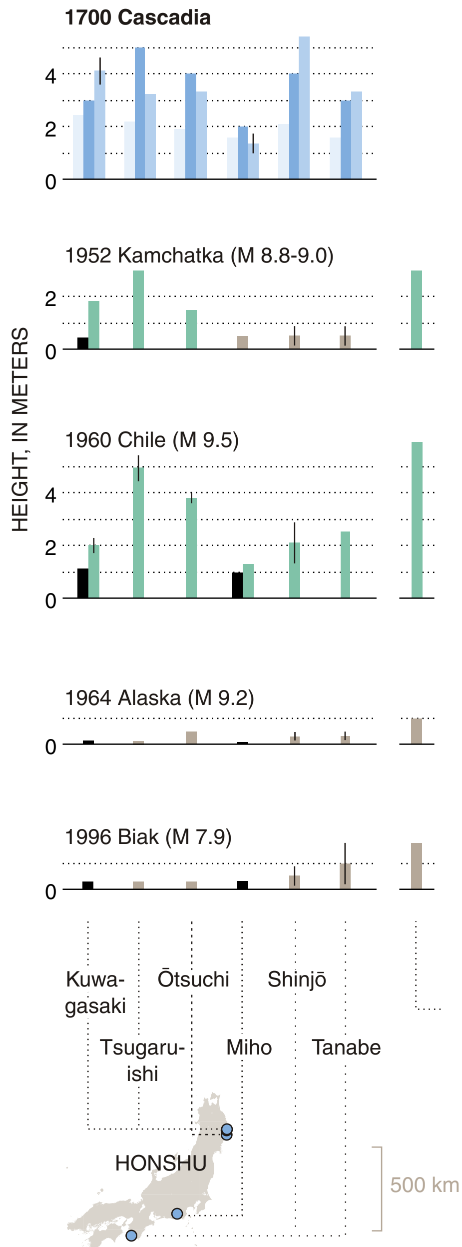
There is no reason to believe that the 1700 tsunami began in the seas directly off Japan. No precursory earthquake was felt along the Japan Trench at Tsugaruishi or along the Nankai Trough at Miho (p. 54). Nor did the tsunami coincide with a Japanese storm (p. 72).

Other potential sources around the Pacific Rim conflict with the tsunami's year or height. South American catalogs give sources for tsunamis recorded in Japan in 1687, 1730, and 1751, but not for any tsunami in 1700 (p. 54). The 20th century's third-largest earthquake, in Kamchatka, produced a tsunami in Japan with heights of a few meters in the north but less than 1 m in the south (graph, right; map, opposite). The 1964 Alaska tsunami, from the century's second-largest earthquake, radiated mainly off the long side of the area of a sea-floor uplift—southeastward, away from Japan—and therefore crested no more than 1 m high in Japan. An eastern Indonesian tsunami in 1996 amounted to little in Japan except on tips of southern peninsulas.

A CASCADIA SOURCE for Japan's orphan tsunami of 1700 was proposed by Satake and others (1996). Kerr (1995) and Kanamori and Heaton (1996) commented on the breakthrough.

SPANISH AMERICA in 1700 included the Pacific coast from Peru to central Chile (Haring, 1963)—sources of the tsunamis recorded in Japan in 1586, 1687, 1730, and 1751 (p. 54). Spaniards described 19 tsunami-causing earthquakes in Peru and Chile between 1650 and 1750 (Lomnitz, 1970; Lockridge, 1985). Among these, the event closest to 1700 was one that damaged northern Chile in 1705. In Mexico, shaking on June 30, 1700 was recorded both on the Pacific coast and inland, and other temblors were recorded inland on September 29, 1699 and on March 30, 1700 (García and Suárez, 1996, p. 106).

TSUNAMI HEIGHTS IN JAPAN



Height relative to tide, except as mentioned in notes below.

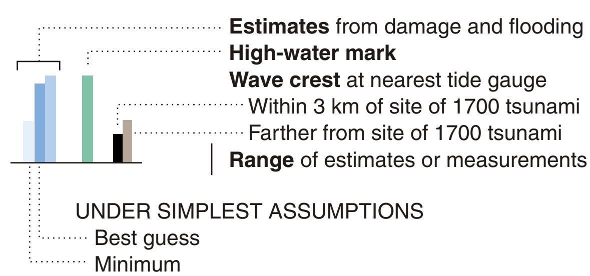
Estimates **A**, **B**, and **C**, p. 48, 56-57, 64, 82, 88, and 90.

Relative to TP (green); From The Central Meteorological Observatory (1953, p. 39, 45-48)

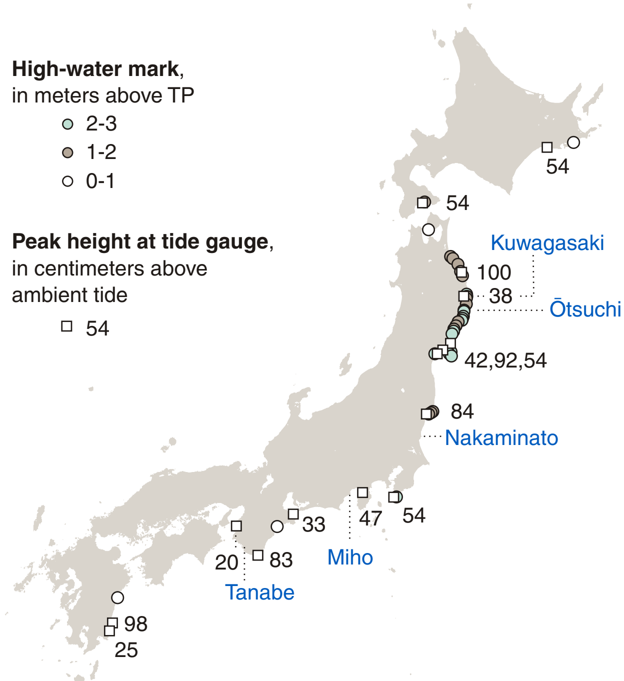
Heights in green documented on p. 49, 55-56, 65, 82-83, and 88. Tide-gauge data from Miyako and Shimizu stations (p. 46, 73, 83).

Tide-gauge data: 14 cm at Miyako, 6 cm at Shimizu (Hatori, 1965).

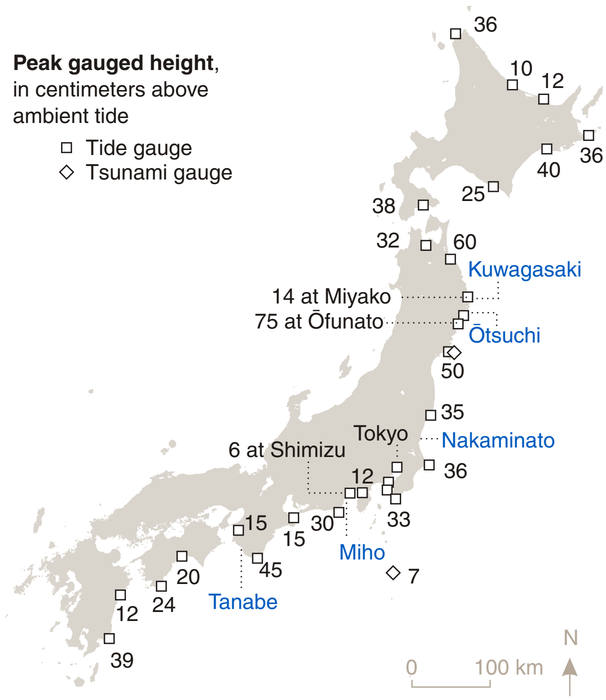
Watanabe (1998, p. 235-236)



1952 KAMCHATKA TSUNAMI: HIGH WATER MAINLY NORTH



1964 ALASKA TSUNAMI: MINIMAL IN JAPAN



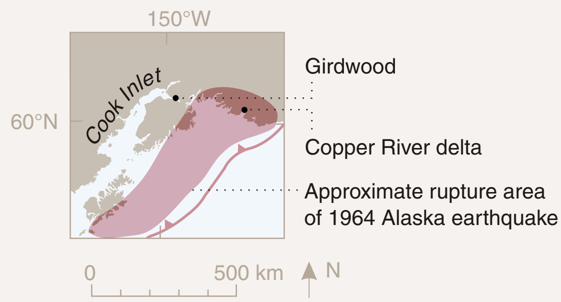
FOR FURTHER CONTRAST with the 1960 Chile tsunami, compare both these maps with the ones on page 55. The Kamchatka tsunami heights are from The Central Meteorological Observatory (1953, p. 39, 45-58); the Alaskan data, from Hatori (1965).

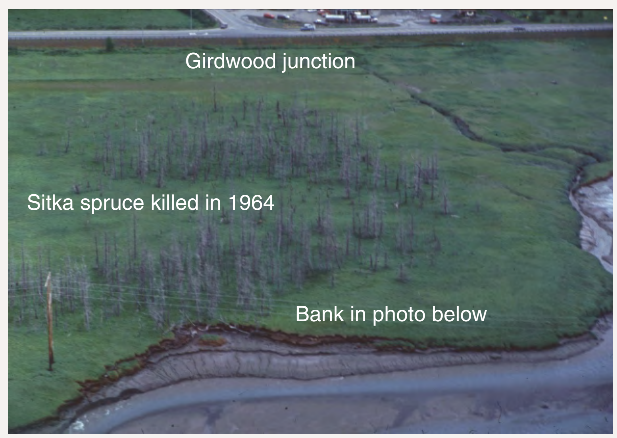
TP, a vertical datum near mean sea level.

Alaskan ancestors

EVIDENCE AGAINST an Alaskan source for the 1700 tsunami includes not just the modest size of the 1964 Alaska tsunami in Japan but also the geologic history of pre-1964 Alaska earthquakes.

The immediate predecessor of the 1964 Alaska earthquake predates 1700 by 400 years or more. At upper Cook Inlet, where a buried soil marks land subsidence from 1964 (p. 14-15), an underlying buried soil dates the penultimate subsidence event to A.D. 1000-1200 (below). Similarly at the Copper River delta, uplifted in 1964, the penultimate uplift occurred about 1100-1300.





1991

2003

ON PREDECESSORS to the 1964 Alaska earthquake, see Combellick (1991), Plafker and others (1992), and Hamilton and Shennan (2005).

THE PHOTOS show the shore of Turnagain Arm at Girdwood. Lower image courtesy of Ian Shennan.

Tree-ring tests 年輪のテスト

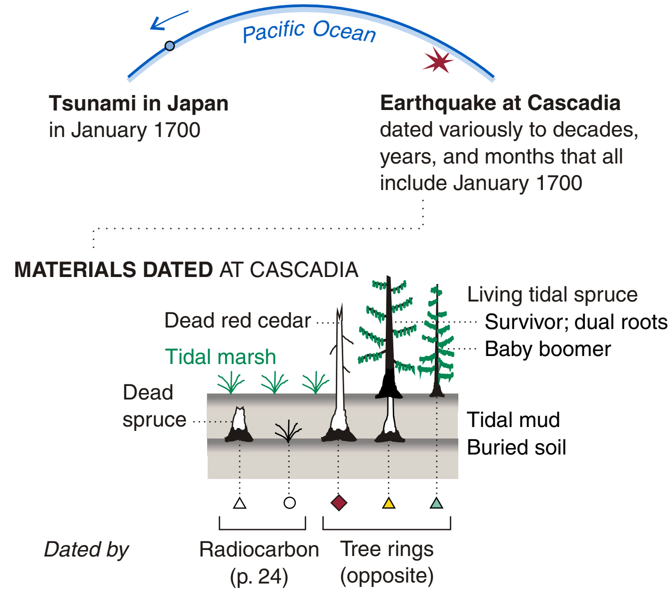
A great Cascadia earthquake killed red-cedar trees between August 1699 and May 1700.

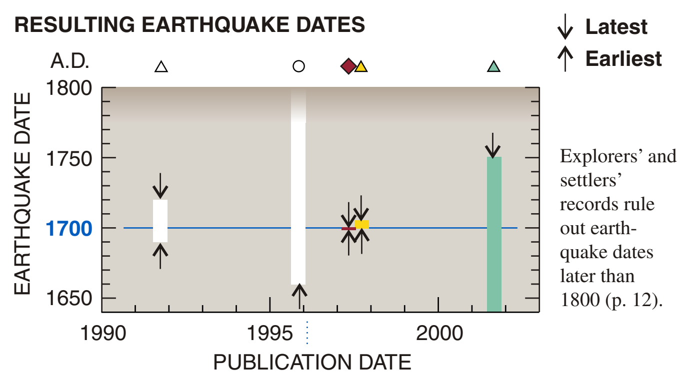
IN 1996, soon after Japanese researchers assigned a Cascadia earthquake to January 1700, North Americans sought to test the date. Radiocarbon had already been pushed to its limits in dating the death of earthquake-killed trees as exactly as 1695-1720 (p. 24-25). But there remained the possibility of dating, to the year and growing season, the trees' final months of growth.

That work had begun in 1987 with sampling of the red-cedar trunks standing in tidal wetlands of four Washington estuaries (photos, p. 16, 24; red diamonds, right). The victims contain a climatic bar code: year-to-year variation in the width of their annual rings. They share the code with old trees that safely witnessed the earthquake from high ground (cartoon, opposite). Witnesses felled by loggers in 1987 give the year for each bar in the code. Matching of the ring-width patterns thus yields dates for the victims' rings.

Dating a victims' year of death, however, requires samples that preserve the tree's final ring. The samples dated in the 1980s came instead from weather-beaten trunks. So in the summer of 1996, to ask trees whether they died from an earthquake in January 1700, geologists unearthed bark-bearing roots attached to the already-dated trunks. Tree-ring scientists then checked the ring-pattern match between root and trunk. The work yielded, for each of eight trees, a final-ring date. In all but one case, the tree died after completing the 1699 growing season and before the start of the next—in the window between August 1699 and May 1700.

As a further test, tree-ring scientists dated the onset of stress in Sitka spruce that barely survived post-earthquake tides (yellow triangles). The trees endured the submergence by sprouting roots into the new, higher ground. Several dozen such survivors remained in southern Washington and northern Oregon in the early 1990s. In half of them the width or anatomy of annual rings changed in 1700-1710 (examples in box, opposite).



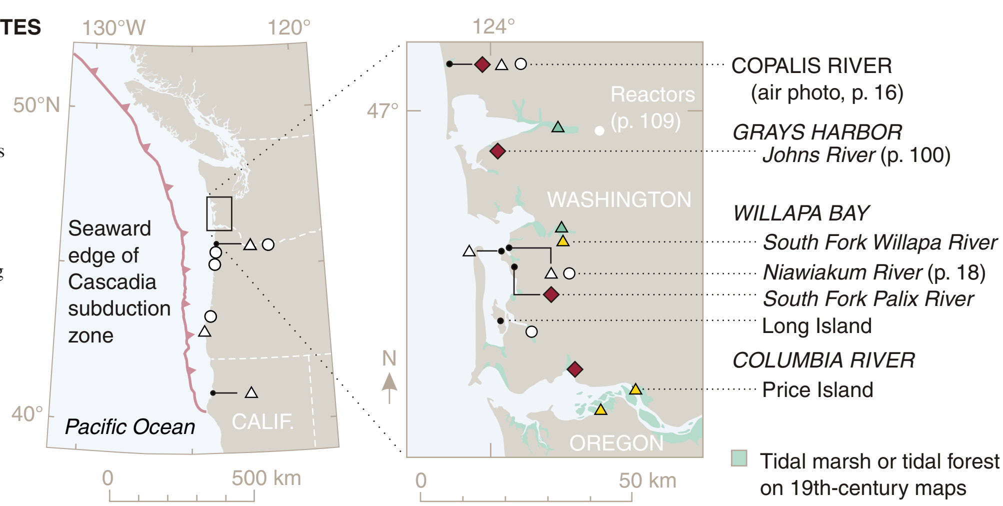


In early 1996, a Cascadia earthquake was assigned to January 26, 1700 by linkage to a tsunami in the written history of Japan (p. 42, 94).

BEST-DATED SITES

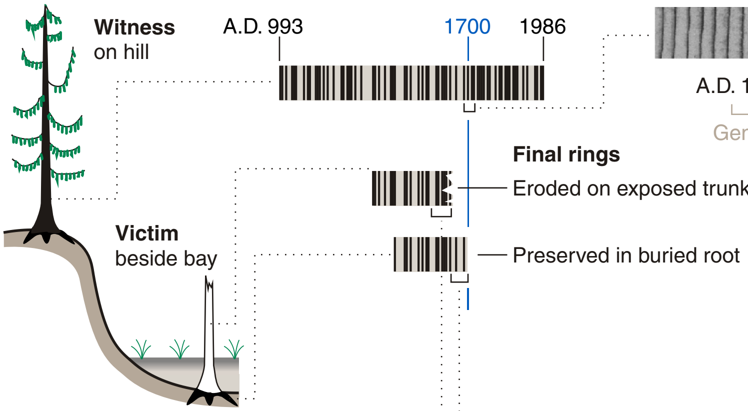
RING-WIDTH PATTERNS were matched to date the ring next to bark in the roots of eight red cedar (Yamaguchi and others, 1997; Jacoby and others, 1997). Seven of these trees died between the 1699 and 1700 growing seasons; the other survived until 1708. The ring-width measurements from the trunks of witnesses and victims are archived at ftp://ftp.ncdc.noaa.gov/pub/data/paleo/treering as rwl files wa129 through wa133.

STRESS IN SURVIVING SPRUCE was documented by Jacoby and others (1997). Aside from a few dozen survivors, living spruce of Washington's tidal forests postdate 1700. Most of the trees postdate 1750 because of a lag in colonizing lands that brackish tides were rebuilding (Benson and others, 2001).

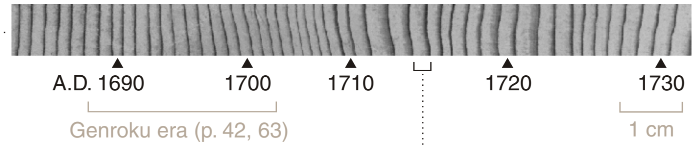


◆ Matched ring-width patterns of western red cedar

BAR-CODE ANALOGY



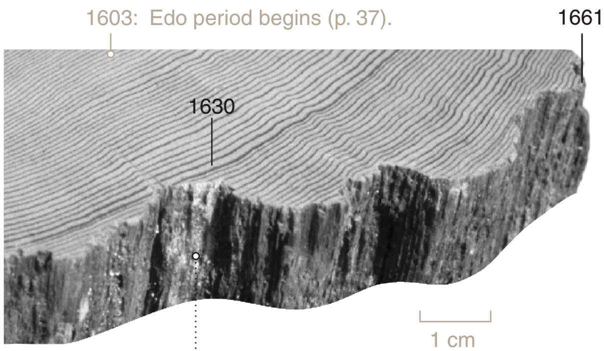
WITNESS'S INTACT TRUNK, WILLAPA BAY



One year's growth begins in spring and early summer with light-colored "early wood." The growing season concludes in late summer or early fall with dark "late wood."

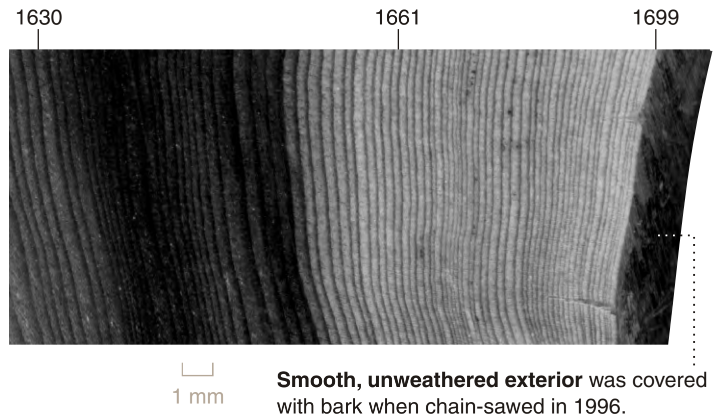
In buried roots of red-cedar victims (example below), the 1699 ring contains both early wood and late wood—evidence that the trees lived through the 1699 growing season.

VICTIM'S WEATHER-BEATEN TRUNK, WILLAPA BAY



Rough, weather-beaten exterior Bark and tens of outer rings lost to centuries of wind, rain, decay, insects, birds, and fire.

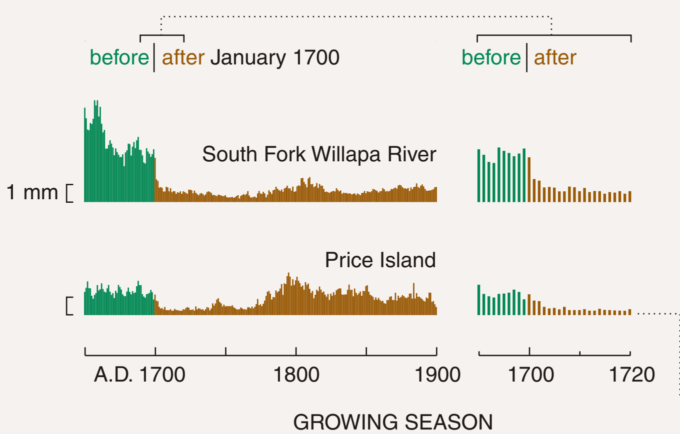
INTACT ROOT OF THAT VICTIM (p. 92)



Smooth, unweathered exterior was covered with bark when chain-sawed in 1996.

△ Signs of stress in surviving Sitka spruce

RING WIDTHS OF TWO SURVIVORS



SURVIVORS' GROVE, COLUMBIA RIVER

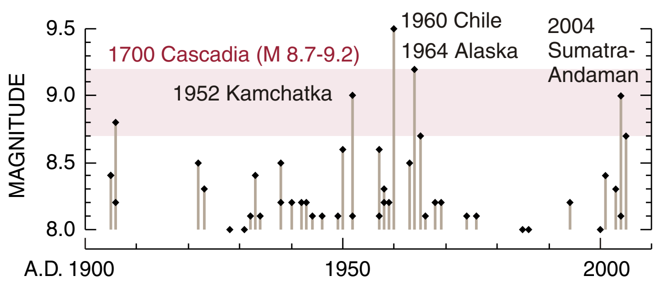
Price Island, 1994

ON TREE-RING DATING see Stokes and Smiley (1968), Fritts (1976), and Schweingruber (1988). **Witness** is red cedar from land above the reach of post-earthquake tides, at Long Island—from one of 19 used to make a master bar code for A.D. 993-1986 (Yamaguchi and others, 1997). **Victim** tree is PX-782, a stump along the South Fork Palix River (entire cross-section of root, p. 92). **Survivor** data is from Jacoby and others (1997).

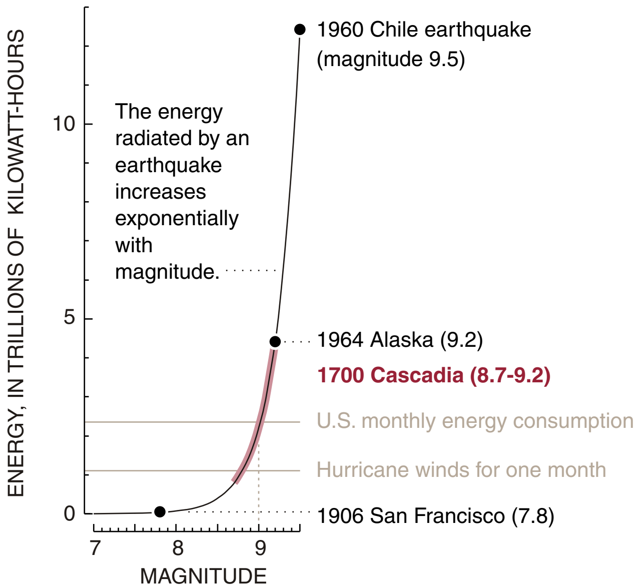
Magnitude 9 マグニュード9

The 1700 Cascadia earthquake probably attained a magnitude between 8.7 and 9.2.

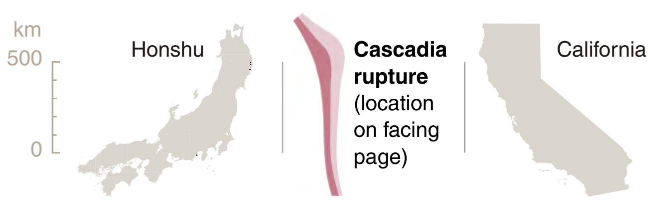
MAGNITUDE 8.7-9.2 COMPARED WITH MAGNITUDES OF GREAT EARTHQUAKES SINCE 1900



ENERGY RADIATED, ON LINEAR SCALE



RUPTURE AREA COMPARED WITH HONSHU AND CALIFORNIA



EARTHQUAKE MAGNITUDES from Kanamori (1977), Johnson and others (1994, p. 24), http://earthquake.usgs.gov/docs/sign_eqs.htm, Satake and others (2003), and Lay and others (2005). For comparison with 1960 Chile and 1964 Alaska, the most appropriate size of the 2004 Sumatra-Andaman earthquake is M 9.0 (footnote, p. 5). The linear energy scale is adapted from Johnson (1990).

U.S. ENERGY CONSUMPTION is for the year 2001 (www.eia.doe.gov/emeu/cabs/contents.html).

HURRICANE WIND ENERGY computed as 1.5 x 10^{12} watts per day for a wind speed of 40 meters per second (90 miles per hour) in a radius of 60 km (www.aoml.noaa.gov/hrd/tcfaq/D7.html). The hurricane-force winds of Hurricane Isabel had about this combination of speed and area when the storm made landfall in North Carolina on September 18, 2003

A MAGNITUDE OF 9 makes an earthquake unusually enormous. Only two twentieth-century earthquakes surpassed M 9.0 (left). In several minutes, an earthquake of M 9.0 radiates as much energy as the United States consumes in a month, or twice the energy a hurricane's winds would release if they blew nonstop for a month (middle graph).

The 1700 Cascadia earthquake probably was such a giant. It likely broke at least 1,000 kilometers of the boundary between the subducting Juan de Fuca Plate and the overriding North America Plate—a rupture about as long as California, or about the length of Japan's main island, Honshu (lower left). On the seaward half of the rupture, the plates probably lurched past one another by about 20 meters. The magnitude was probably in the range M 8.7-9.2.

These estimates depend, in part, on assumptions about what fault area broke during the 1700 earthquake. By the assumptions in red at right, the break extends about 1,100 km coastwise and averages nearly 100 km in width. The fullest seismic slip takes place offshore, where the break is shallow (dark). Onshore the slip diminishes toward depths where the fault is too warm for brittle failure (light).

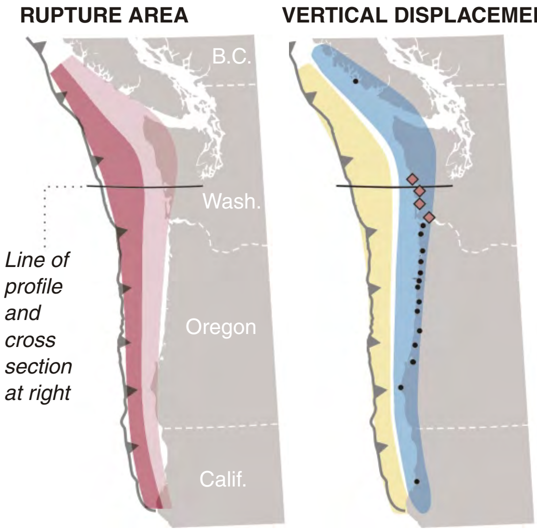
This picture has gained support from orbiting satellites of the Global Positioning System. GPS measurements help define mostly offshore areas where the downgoing Juan de Fuca Plate is currently coupled with the overriding North America Plate. Farther inland, the plates episodically creep a few centimeters past one another (green).

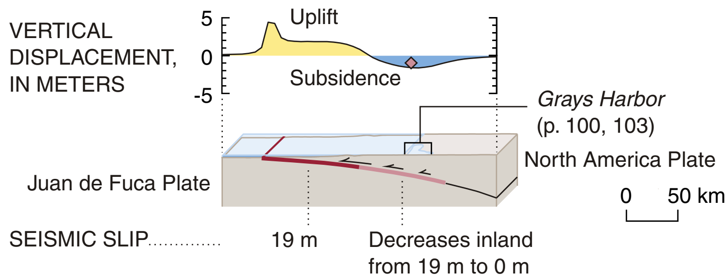
Resulting estimates of fault-rupture areas provide a starting point for simulating, by computer, the sea-floor displacement that triggered the 1700 tsunami. Offshore the sea floor rises several meters as the North America Plate lurches up the inclined fault. Near the coast, the seafloor and the adjacent land fall as much as two meters as this plate stretches (cartoons, p. 10). The simulated deformation varies with the rupture width and the slip amount—two of the main contributors to earthquake size.

Additional simulations track the resulting tsunami across the Pacific Ocean (p. 74-75). The modeled tsunami heights in Japan can then be compared with the heights estimated from damage and flooding by the orphan tsunami (bar graph, opposite). The comparisons rule out a Cascadia parent of M 8.0-8.5, whose tsunami would not likely exceed 1 m high in Japan. Instead, the inferred combinations of rupture area and seismic slip correspond to Cascadia earthquakes of M 8.7-9.2, with the best fit at M 9.0.

MAGNITUDE 8.7-9.2 explains three sets of reconstructed tsunami heights in Japan (p. 48), six assumed rupture areas at Cascadia, and various amounts of seismic slip in each of these rupture areas (Satake and others, 2003). The rupture depicted on the facing page is among three found consistent with geologic evidence for coastal subsidence like that on pages 16 and 17. The range M 8.7-9.2 excludes errors from ignoring bottom friction in computing the tsunami's advance through shallow water off Japan.

Rupture and deformation from a hypothetical 1700 earthquake





Assumed area of seismic slip
- Full slip
- Decreases inland to zero

Computed displacement
- Uplift
- Subsidence

Subsidence inferred from coastal geology
- ◆ Dated to 1699-1700 (p. 96-97)
- • Dated less exactly

Modern motions that help define the rupture area in 1700

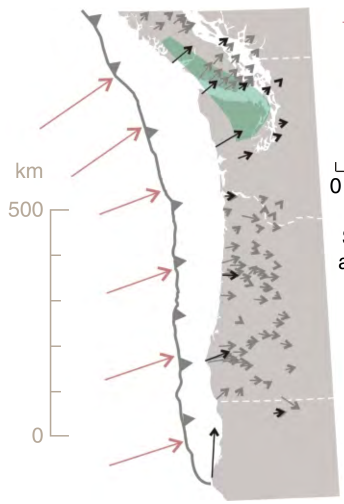


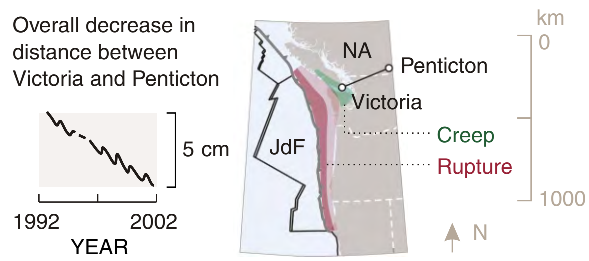
Plate convergence
Juan de Fuca Plate relative to coastal part of North America Plate

Onshore motion
Coastal part of North America Plate dragged inland by Juan de Fuca Plate. Measured by Global Positioning System (GPS), continuously (black) or intermittently (gray)

0 4 cm/yr
Scale for all arrows

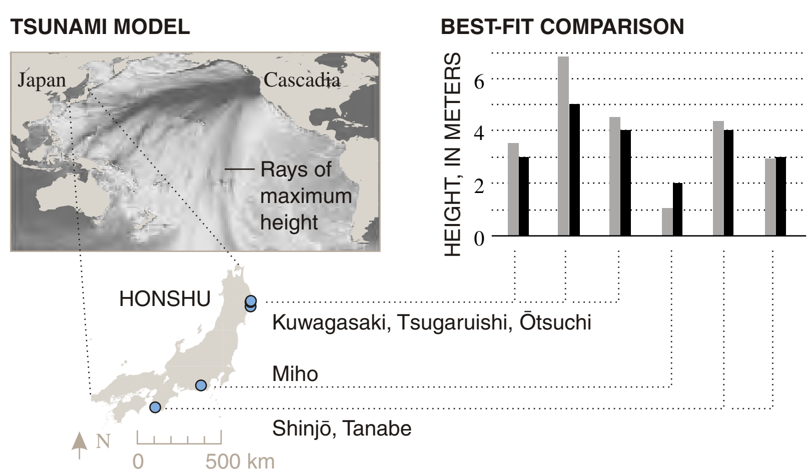
Area of episodic creep
Inferred from reversals in motion at GPS stations. About 2 cm of plate-boundary slip per event, at intervals of 13-16 months.

DAILY GPS DATA, SMOOTHED TREND



The North America Plate (NA) shortened between Victoria and Penticton by 5 cm between 1992 and 2002, probably from being stuck to the subducting Juan de Fuca Plate (JdF) in the area of the inferred 1700 rupture (red and pink). But the continent also extended on occasion, during episodes of creep on a deeper part of the plate boundary (green). The extension produces the sawteeth on the graph.

Modeled Japanese tsunami heights for the earthquake, compared with heights inferred from flooding and damage



Height of 1700 tsunami in Japan
- Computed with trans-Pacific model at left and on pages 74-75, for earthquake rupture area and slip shown above. The earthquake size is M 9.0.
- Estimated from flooding and damage (the "**B**" heights on p. 48, 56-57, 64-65, 80-81, and 88-91)

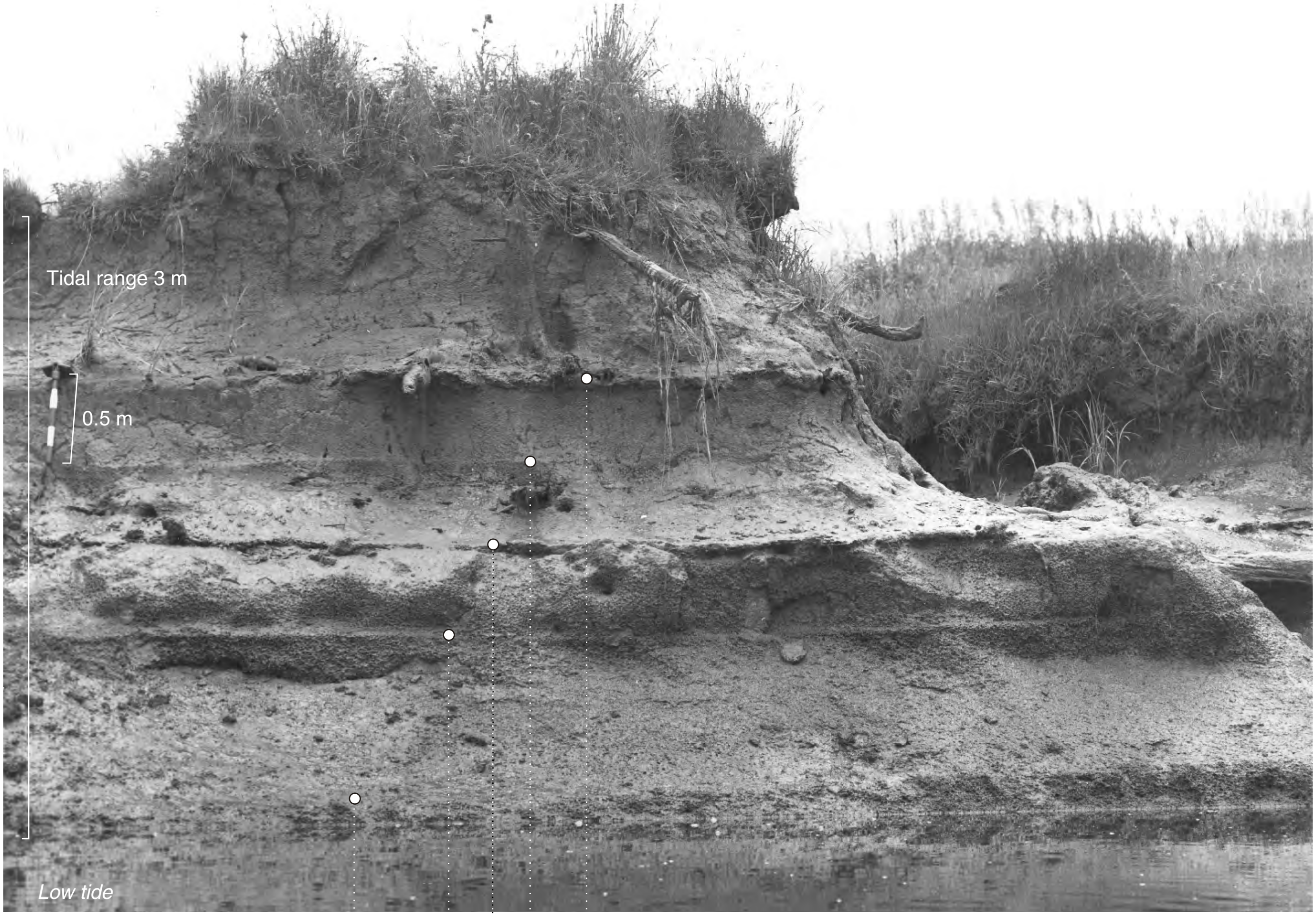
THE INFERRED RUPTURE AREA and seismic slip (top) and modeled heights (bottom) are from Satake and others (2003).

GPS VECTORS in the middle map exclude northward motion relative to stable North America (Wang and others, 2003).

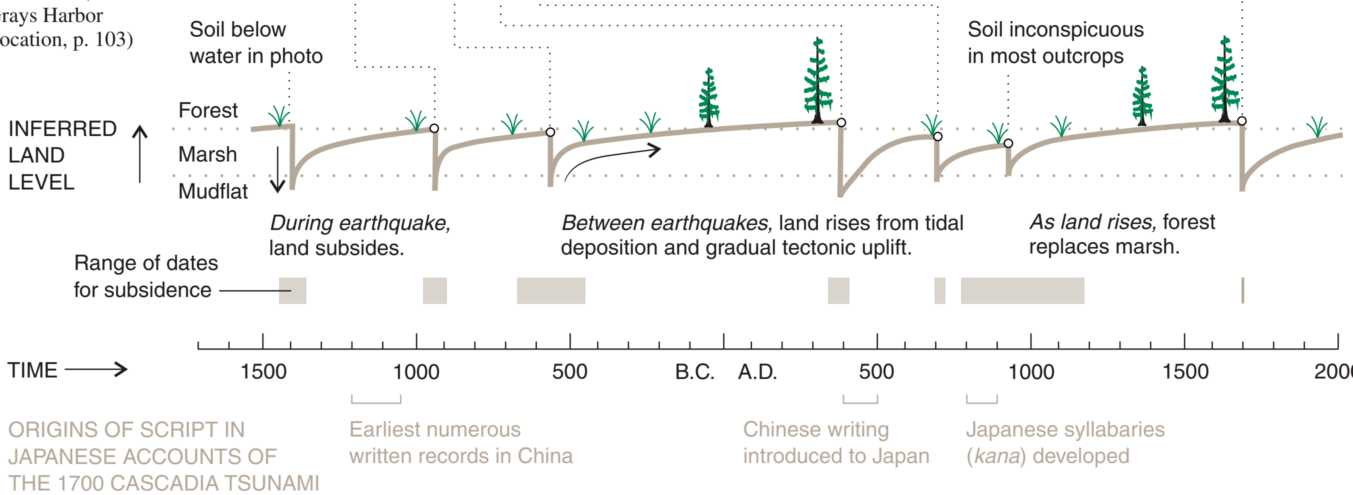
ON PLATE COUPLING and episodic creep, see Dragert and Hyndman (1995), Dragert and others (2001), Miller and others (2002), Rogers and Dragert (2003), Szeliga and others (2004), and Melbourne and others (2005).

Muddy forecast 泥から森へ

How will history repeat itself at Cascadia?



Johns River,
Grays Harbor
(location, p. 103)



THE EARTHQUAKE TIMELINE applies to Grays Harbor, Willapa Bay, and the Columbia River estuary (location map, p. 96). The gray bars span 95-percent confidence intervals from radiocarbon dating reported by Atwater and others (2004). The pictured outcrop adjoins site JR-1 of Shennan and others (1996).

ASIAN SCRIPTS in accounts of the 1700 tsunami evolved through at least five of the intervals between great Cascadia earthquakes. Writings from China's Shang dynasty—inscribed into cattle scapulas and turtle shells—date to 1200-1050 B.C. (Keightley, 1978, p. 228). Early examples of Chinese characters written in Japan date to the 5th century A.D. (Seeley, 2000, p. 4-6, 16-25). Japanese phonetic symbols became commonplace by early in the 11th century (Seeley, 2000, p. 76).

THE NEXT GREAT CASCADIA EARTHQUAKE is inevitable. The Cascadia plate boundary has repeatedly broken in great earthquakes during past millenia (summary graphs, below). Since 1700 the fault has been accumulating strain that future earthquakes will release (p. 99).

That next earthquake may have already happened by the time you read this, or it may come lifetimes later. Cascadia makes earthquakes on an irregular schedule.

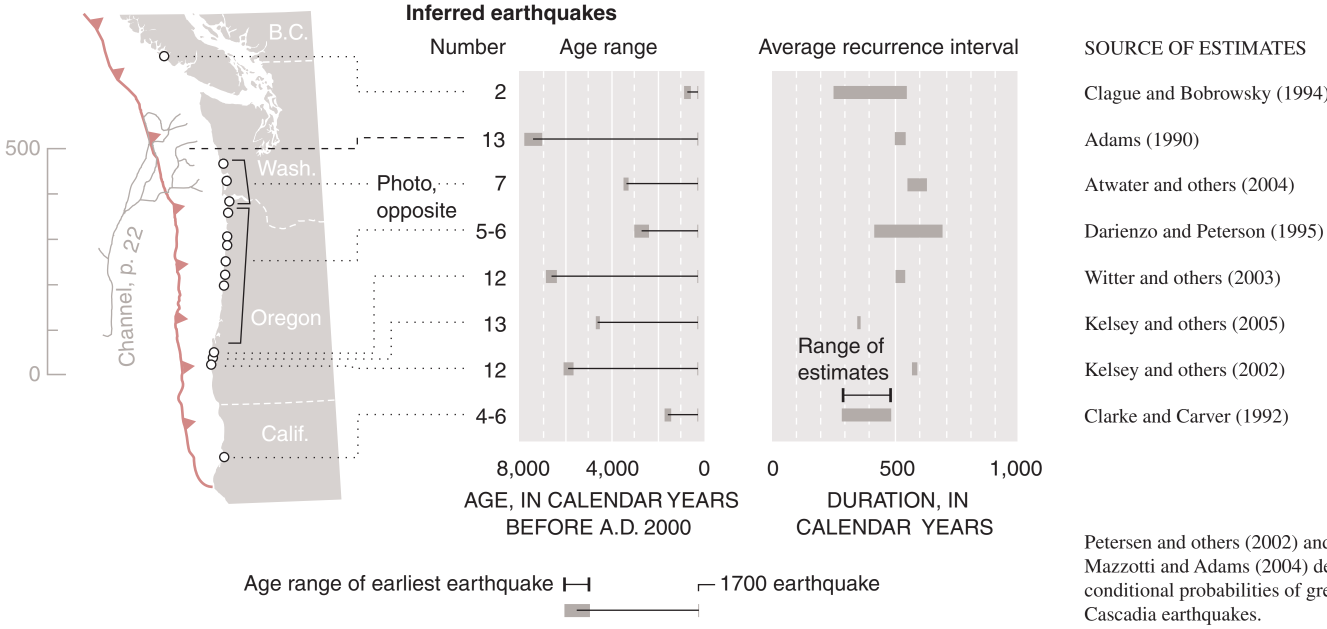
In the example of irregularity at left, a low-tide outcrop in Washington displays buried soils from each of five great earthquakes of the past 3,000 years. Another buried soil lies below low tide, and still another is too poorly preserved to form a visible ledge.

The full sequence tells of seven earthquakes from the past 3,500 years. The six intervals between them average about 500 years but range from a few centuries to a millennium. The two longest intervals are marked by extensive remains of forests. Trees from the more recent of these long intervals enabled demanding tests of correlation with the January 1700 tsunami in Japan (p. 96-97).

During Cascadia's next great earthquake, will the plate boundary rupture along its full length, as in 1700, or will it break one piece at a time? Either behavior would be consistent with geologic records of great Cascadia earthquakes. Piecemeal rupture can't be ruled out (p. 24-25), especially if Cascadia behaves like subduction zones where successive earthquakes differ in size (box, below).

For now it is prudent to assume, simplistically, that the next great Cascadia earthquake has a one-in-ten chance of occurring in the next 50 years, and that it may attain magnitude 9 (p. 102-105). The one-in-ten odds follow from an average interval of 500 years if the fault lacks memory of when it last broke. The magnitude-9 assumption leaves a margin of safety in case of lesser events.

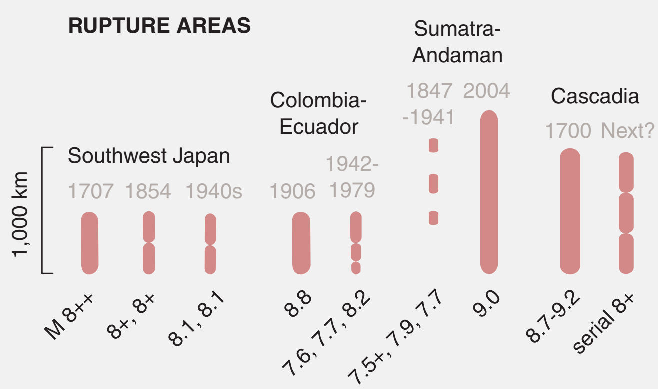
AVERAGE INTERVALS BETWEEN GREAT CASCADIA EARTHQUAKES



Petersen and others (2002) and Mazzotti and Adams (2004) derive conditional probabilities of great Cascadia earthquakes.

Versatile faults

A SUBDUCTION ZONE that breaks in a long rupture may also rupture in shorter pieces. At Japan's Nankai Trough, the rupture area of a single earthquake in 1707 slipped next in a pair of lesser earthquakes in 1854 and again in two parts in the 1940s (map, p. 85). Similarly in South America and South Asia, single earthquake ruptures have spanned the areas of multiple, smaller breaks. Variable rupture can be expected at Cascadia as well.



Japan, Ando (1975); Colombia-Ecuador, Kanamori and McNally (1982); Sumatra-Andaman, Bilham and others (2005).

High-enough ground 安全な高さとは？

What places offer refuge from a Cascadia tsunami?

PLANS FOR FLEEING TSUNAMIS in North America have been shaped by the Japanese accounts of the 1700 tsunami. The accounts, along with Native American traditions, have spurred such planning by providing eyewitness evidence for a giant Cascadia tsunami. Moreover, because the Japanese accounts suggest a Cascadia earthquake of magnitude 9, they provide a basis for evacuation signs and maps, such as those at right. Since 1997, tsunami mapping at Cascadia has been based on computer modeling of a Cascadia earthquake of M 9.1. The modelers chose this magnitude to resemble the one inferred, in 1996, from heights of the 1700 tsunami in Japan.

Since 1997, tsunami modeling has identified inundation-prone areas in cities and towns along Washington's outer coast and on parts of the Oregon coast (index map, facing page). Evacuation maps based on the modeling serve most of the U.S. mainland population at risk from a great Cascadia tsunami. That at-risk population exceeded 150,000 year-round residents in the year 2000, as judged from census totals for areas within 1 km (0.6 mi) of tidewater.

The tsunami mapping helps citizens and public officials identify areas of probable danger and of probable safety. The evacuation map for Gearhart, for example, shows where to assemble on high ground. The inundation map for Grays Harbor, opposite, similarly identifies a likely island of safety above a simulated tsunami in Westport. Farther inland at Aberdeen, the map depicts inundation that could turn logs into battering rams.

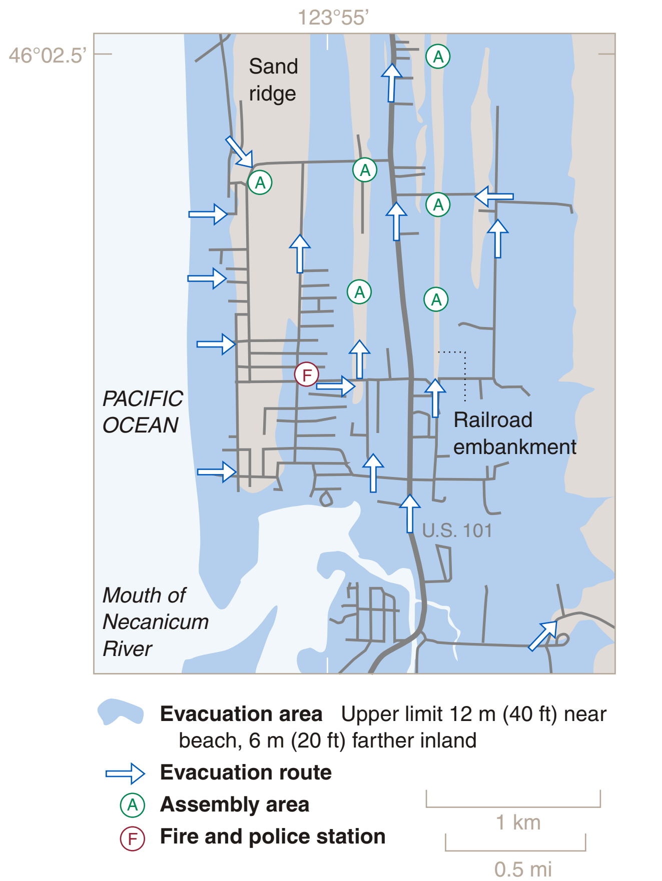
The models fit geologic evidence for the 1700 tsunami. The areas of computed inundation commonly contain sand sheets from the flooding in 1700. Sequences of computed water levels, such as those graphed opposite, show multiple waves like those recorded by tide gauges (p. 19, 49, 73) and by sediment layers (p. 18-19).

In simulations, the model tsunami has the advantage of overrunning freshly subsided land—land lowered as much as 1.5 meters (5 feet) during the parent earthquake. This is the subsidence anticipated on page 10, inferred from geology on pages 16-17, dated to 1700 or thereabouts on pages 24-25 and 96-97, and computed for a model rupture on page 99. The coast's subsidence during an earthquake increases the hazard from the ensuing tsunami.

ROADSIDE ADVICE IN HOQUIAM, WASHINGTON

2003

TSUNAMI EVACUATION MAP FOR GEARHART, OREGON



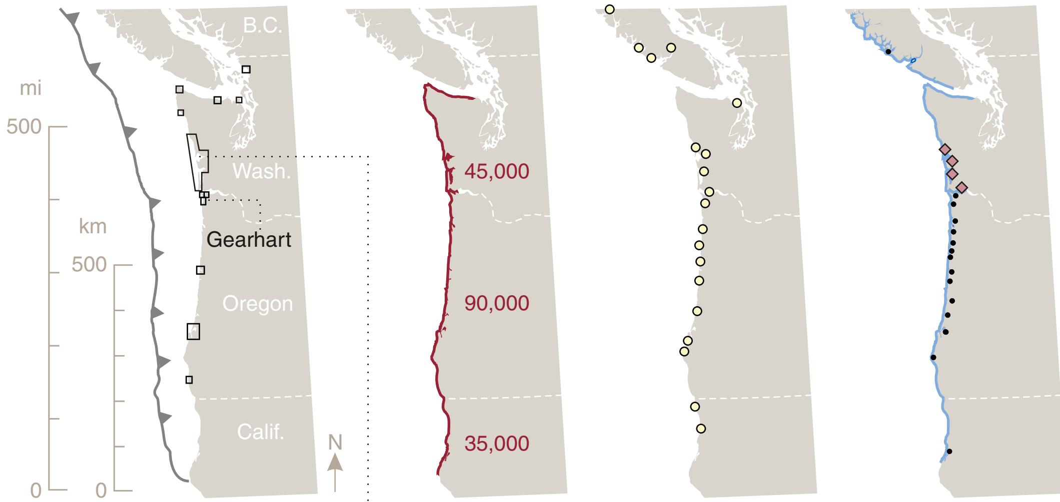
THE FIRST MAPS of hazards from a Cascadia tsunami showed potential inundation in northern California. They were based on a computer model in which a hypothetical wave is 10 m high in offshore waters 50 m deep (Bernard and others, 1994; Toppozada and others, 1995).

OREGON'S LEGISLATURE soon mandated tsunami-inundation mapping of their entire coast. Under Senate Bill 379, passed in 1995 and implemented as Oregon Revised Statutes 455.446 and 455.447, new schools, hospitals, fire stations, and police stations shall not be constructed in areas subject to flooding by tsunamis, except where no alternative sites exist (http://www.leg.state.or.us/ors/455.html).

EVACUATION MAPS cover the Oregon towns of Bandon, Brookings, Charleston, Coos Bay, Depoe Bay, Gearhart (above), Gold Beach, Lincoln Beach and vicinity, Manzanita, Nehalem, Nestucca, Netarts, Newport, Oceanside, Port Orford, Rockaway Beach, and Seaside (http://sarvis.dogami.state.or.us/earthquakes/coastal/tsubrochures.htm), and the Washington communities of Aberdeen, Bay Center, Clallam Bay, Copalis, Cosmopolis, Hoquiam, Ilwaco, Long Beach, Neah Bay, North Cove, Ocean City, Ocean Park, Ocean Shores, Pacific Beach, Port Angeles, Port Townsend, Quilleyute, Raymond, Sound Bend, and Westport (http://www.dnr.wa.gov/geology/hazards/tsunami/evac/; http://emd.wa.gov/5-prog/prgms/eq-tsunami/tsunami-idx.htm). Locations in index (p. 125-133).

ELEMENTS OF TSUNAMI RISK FOR A CASCADIA EARTHQUAKE LIKE THAT OF 1700

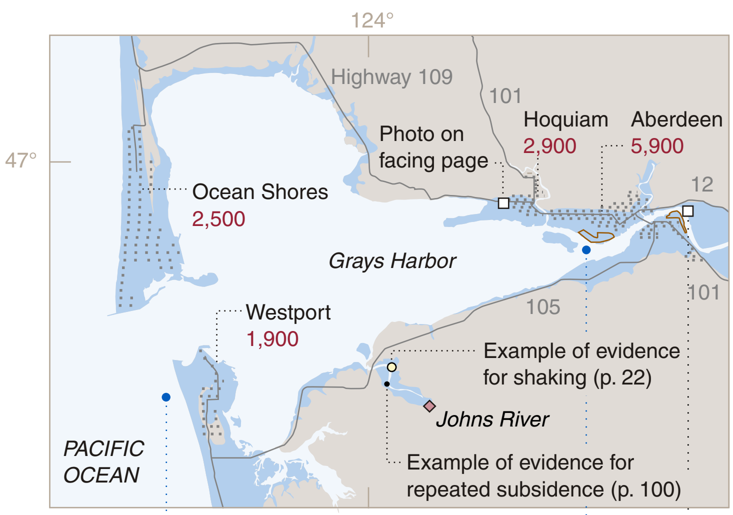
TSUNAMI HAZARD MAPPED FOR M 9 EARTHQUAKE — POPULATION WITHIN 1 KM OF U.S. SHORE — EVIDENCE FOR 1700 TSUNAMI — HAZARD POTENTIALLY INCREASED BY LOWERING OF LAND DURING EARTHQUAKE



HAZARD MAPS were prepared by Priest and others (1997; 1998; 1999a,b; 2000b; 2002) and by Walsh and others (2000; 2002a,b; 2003a,b; 2004). Their state-by-state index is at http://www.pmel.noaa.gov/tsunami/time/.

COASTAL POPULATION, tallied from U.S. Census data for the year 2000, is listed by jurisdiction at http://www.pmel.noaa.gov/tsunami/time/workshop/population.shtml. We round the figures down to the nearest 5000 (left) or 100 (below).

EXAMPLE FOR GRAYS HARBOR, WASHINGTON



Coastal subsidence
- Computed (above; p. 99)
- Dated to 1699-1700 (p. 96-97)
- Dated less exactly (p. 24-25)

Sand sheet probably deposited by 1700 tsunami (example, p. 18)

Tsunami hazard zone Land subject to flooding in numerical simulations of a tsunami from a Cascadia earthquake of magnitude 9.1

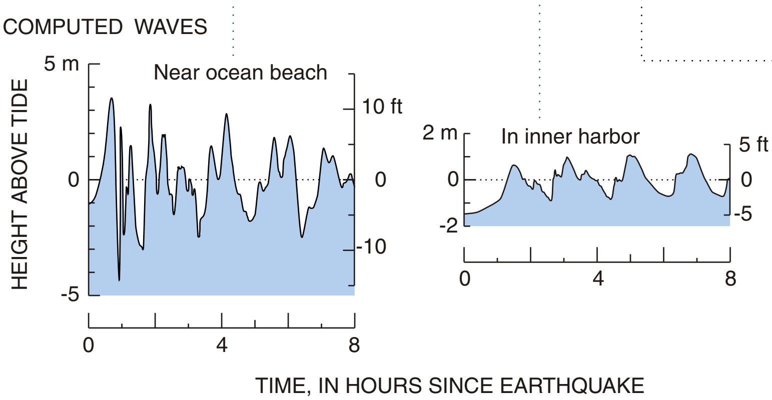
Population center Number in red gives year-2000 population in census blocks within 1 km of seashore or bayshore. 1,900

Log yard Potential source of battering rams during a tsunami, like the tsunami-borne debris on pages 55 and 80

0 10 km

0 10 mi

N



LOG YARD AND HOMES IN HAZARD ZONE

2002

GRAYS HARBOR HAZARD MAP and wave-train simulations, from Walsh and others (2000), are based on computer modeling of an assumed earthquake rupture 1,050 km long and, on average, 70 km wide (Myers and others, 1999; Priest and others, 2000a). The seismic slip is uniform along the length of this hypothetical rupture. Tide stage is held steady near mean tide level. Not depicted is the slightly greater tsunami modeled for a rupture that includes a patch of greater-than-average slip off Washington (asperity model of Walsh and others, 2000).

PHOTO from Washington Department of Ecology digital coastal atlas (http://apps.ecy.wa.gov/website/coastal_atlas/viewer.htm), image 0208081033_378.

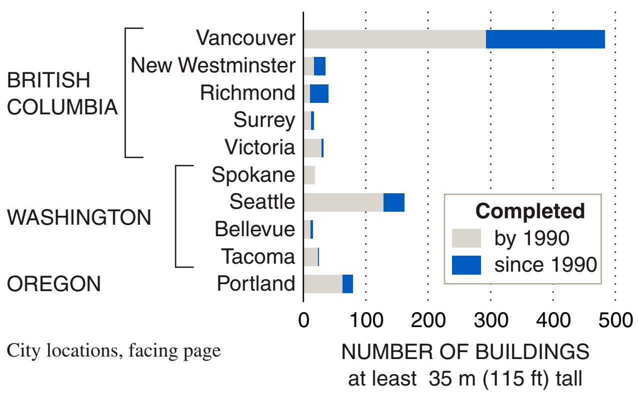
Seismic waves 地震動

Tall buildings await Cascadia's next great earthquake.

SHORT, TRADITIONAL BUILDINGS

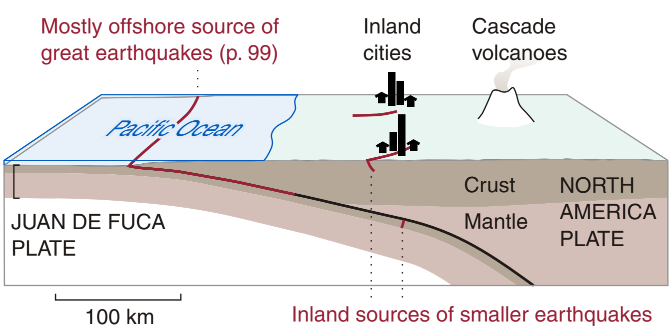
Seattle, 1884

TALL URBAN BUILDINGS



City locations, facing page

EARTHQUAKE SOURCES



THE URBAN CORRIDOR between Vancouver, British Columbia, and Eugene, Oregon, can expect minutes of shaking from a great Cascadia earthquake. The shaking poses less of a threat to the region's traditional wood-framed houses than to larger structures that are slender and flexible. Tall buildings, long bridges, and steel aqueducts sway most readily at periods of a second or more. Great earthquakes excel in exciting such long-period motion. A common result, seen in 1985 in Mexico City, is damaging resonance between the ground and the long-period structures founded on it.

Despite its inland location, the urban corridor from Vancouver to Eugene lies within range of damaging ground motions from great Cascadia earthquakes. Long-period waves from subduction earthquakes can travel hundreds of kilometers inland without losing much of their punch. In addition, the waves can get trapped and amplified in sedimentary basins like those beneath Seattle and Tacoma.

Only recently did these threats become certain enough to affect building design. Among Cascadia's nearly 900 high-rises, more than half were completed by 1990 (graph). Not until 1994 did building codes in Washington and Oregon begin to reflect the great-earthquake threat. Even then, designers of newer structures faced a moving target as the credible size of a Cascadia earthquake rose to M 9 (p. 98-99), and as newly found urban faults augmented the hazard (block diagram).

The prospect of great Cascadia earthquakes influences the mapping of earthquake hazards in the western United States, especially for ground motions of long period. According to the maps at right, plate-boundary ruptures at Cascadia contribute to the hazard of long-period seismic shaking across Washington, Oregon, and northern California, particularly in the western parts of those states.

OLD SEATTLE BUILDINGS from lithograph at University of Washington Libraries, Special Collections, UW347. Tall-building tallies from http://www.emporis.info/en/. In the block diagram, geologic boundaries are based on interpretations by Parsons and others (1998) and Brocher and others (2003).

ON INLAND EARTHQUAKE SOURCES in the North America crust, see Bucknam and others (1992), Johnson and others (2001), Nelson and others (2003), and Sherrod and others (2004). On earthquakes within the underlying Juan de Fuca Plate, see Frankel and others (2002a) and Atkinson and Casey (2003).

TALL BUILDINGS SWAY at fundamental periods of 1-6 seconds (Building Seismic Safety Council, 2001, p. 106). The 1985 Michoacan earthquake of M 8.0 caused inordinate damage to Mexico City high rises with fundamental periods of 1 second, at a distance 400 km from this subduction earthquake's source (p. 9; see also Scawthorn and Celebi, 1987).

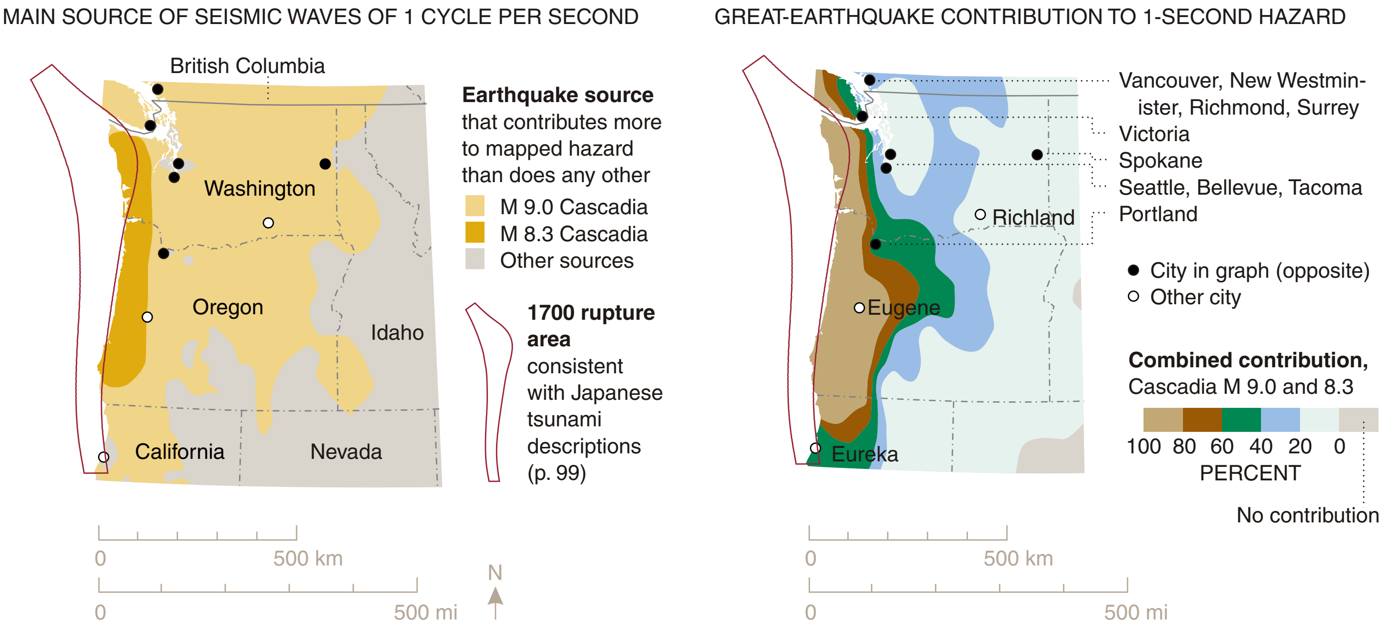
BY LASTING A MINUTE OR MORE, a great Cascadia earthquake would likely cause more damage than would shaking of similar strength in a briefer earthquake (Tremblay, 1998).

STRONG SHAKING has been measured for earthquakes up to M 8.3 (Atkinson and Boore, 2003); ground motions for M 9 are extrapolations (Heaton and Hartzell, 1989). Beneath Seattle, a sedimentary basin several kilometers deep amplifies weak shaking at periods of 1-5 seconds (Pratt and others, 2003).

THE UNIFORM BUILDING CODE extended its seismic zone 3, for high hazard, throughout western Washington and western Oregon in 1994 (Atwater and others, 1995).

FOR ADDITIONAL INFORMATION on ground-shaking hazards at Cascadia, see Yeats (2004), Ballantyne and others (2005), and Cascadia Region Earthquake Workgroup (2005).

LONG-PERIOD SHAKING: WHERE AND HOW MUCH DO GREAT CASCADIA EARTHQUAKES CONTRIBUTE TO THE HAZARD?



THE MAPS ABOVE are derived from the 2002 version of national maps of earthquake shaking hazards in the United States (Frankel and others, 2002b; maps at http://eqhazmaps.usgs.gov/). The national maps show the combined effect of hundreds of earthquake sources (such as the sources cartooned opposite). Companion maps and graphs deaggregate the shaking to show contributions from the individual sources (Harmsen and others, 2003). The deaggregations above were provided by Stephen C. Harmsen.

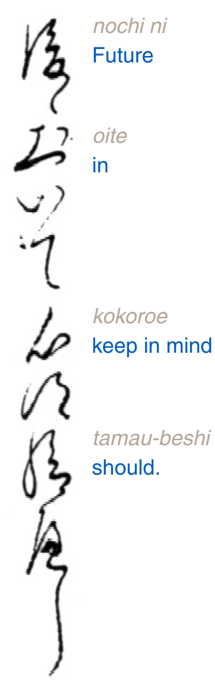
ASSUMPTIONS ABOUT CASCADIA earthquakes built into the national maps:

- Either the earthquakes attain M 9 with ruptures about 1,000 km long, or they are limited to M 8.3 ruptures 250 km long. These end-member scenarios were introduced in previous national hazard maps (Frankel and others, 1996, p. 16-17).
- M 9 is as plausible as M 8.3. "For 2002, we assigned a weight of 0.5 for each scenario... For 1996, the weights were 0.67 for the M 8.3 scenario and 0.33 for the M 9.0 scenario. Since 1996, the M 9.0 scenario has gained credibility" (Frankel, and others, 2002b, p. 11).
- At a given place along the subduction zone, the mean recurrence interval for great earthquakes (either M 8.3 or M 9) is 520 years and the median interval 440 years. If the probability of earthquake occurrence does not vary with time within a recurrence interval, the resulting probability of either kind of event is about 10 percent in 50 years (Peterson and others, 2002, p. 2163-2164).

IN CANADA, great Cascadia earthquakes contribute to the hazard mapped for the proposed 2005 edition of the national building code. The assumed earthquake size is M 8.2, on the premise that only a nearby part of an M 9 rupture, comparable in size to a M 8.2 rupture, governs a site's shaking hazard (Adams and Atkinson, 2003, p. 260).

Shaking-hazard maps of the United States and Canada, including those above, do not yet reflect the long duration expected of great Cascadia earthquakes. An earthquake of M 9 would last several times longer than the largest earthquake expected of inland faults in the urban corridor. Engineers are beginning to grapple with how to design for shaking so prolonged.

It was a lack of seismic shaking that perplexed the Miho headman as he contemplated the orphan tsunami of 1700 (p. 54, 78-79). He or a later compiler recommended keeping the event in mind (right). Today, solved by geologic links to a distant earthquake, the headman's puzzle serves as a reminder to guard against infrequent earthquakes and tsunamis of extraordinary size.



"Miho-mura yōji oboe," p. 78, columns 15-16.