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Radiocarbon evidence for extensive plate-boundary rupture about 300 years ago at the Cascadia subduction zone

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THE Cascadia subduction zone, a region of converging tectonic plates along the Pacific coast of North America, has a geological history of very large plate-boundary earthquakes[1,2], but no such earthquakes have struck this region since Euro-American settlement about 150 years ago. Geophysical estimates of the moment magnitudes (M_w) of the largest such earthquakes range from 8 (ref. 3) to $9\frac{1}{2}$ (ref. 4). Radiocarbon dating of earthquake-killed vegetation can set upper bounds on earthquake size by constraining the length of plate boundary that ruptured in individual earthquakes. Such dating has shown that the most recent rupture, or series of ruptures, extended at least 55 km along the Washington coast within a period of a few decades about 300 years ago[5]. Here we report 85 new ^{14}C ages, which suggest that this most recent rupture (or series) extended at least 900 km between southern British Columbia and northern California. By comparing the ^{14}C ages with written records of the past 150 years, we conclude that a single magnitude 9 earthquake, or a series of lesser earthquakes, ruptured most of the length of the Cascadia subduction zone between the late 1600s and early 1800s, and probably in the early 1700s.

Earthquake size increases with rupture length. Whereas ruptures rarely extend more than 250 km during subduction-zone earthquakes near M_w 8 (refs 6–8), ruptures nearly 1,000 km long produced the largest twentieth-century earthquakes—M_w 9.2 in Alaska and M_w 9.5 in Chile[9]. We infer possible magnitudes of plate-boundary earthquakes along the Cascadia subduction zone by estimating the length of fault rupture during prehistoric earthquakes. Although the Cascadia plate boundary is not exposed on land, rupture length can be estimated from the extent of sudden coseismic subsidence along the subduction zone. Such subsidence, inferred to record elastic extension of the North America plate or faulting within it[3,10,11], caused sudden submergence and burial of wetland soils at many estuaries along the Pacific coast from northern California to southern British Columbia[1,11–17]. Entombed tree stumps and herbaceous plants rooted in the tops of buried soils[18,19], commonly capped by sheets of tsunami-deposited sand[14,16,20–22], reinforce the inference of earthquake-induced subsidence for the youngest of the buried soils at many Cascadia estuaries.

We used two methods of radiocarbon dating and several types of plant fossils to date the time that the youngest soil suddenly subsided (Fig. 1). High-precision ^{14}C ages measured in Seattle were obtained by proportional counting of gas derived from blocks of tree rings from the outer and inner parts of stumps of trees killed by submergence at four sites (Table 1; ages from sites Cp and Nw on Fig. 1 were reported earlier[5]). Other high-precision ages at our most northerly site (PA, Fig. 1) came from a stick in tsunami-laid sand above the youngest soil and from below-ground stems (rhizomes) and attached leaf bases of a tidal-marsh herb that probably grew in the sand soon after its deposition. For each of three of the stump sites (Cp, Nw and Nh) and four other sites (Fig. 1), we used accelerator mass spectrometer (AMS) ^{14}C methods at the New Zealand laboratory to date the stems and leaves of seven or eight individual herbs (Table 1). These herbs probably died, like the trees, from the effects of earthquake-induced subsidence[18,19].

These procedures increase the resolution of the dating in two ways. (1) Dating of the earthquake-killed plants reduces uncertainty in relating the age of dated material to the time of an earthquake. Annual rings in the trees show how many years probably elapsed between formation of the dated rings and the time of the earthquake(s) that killed the trees[19]. The AMS-dated herbs probably grew within a few years of the subsidence that killed them[18]. However, dated parts of many of the herbs include

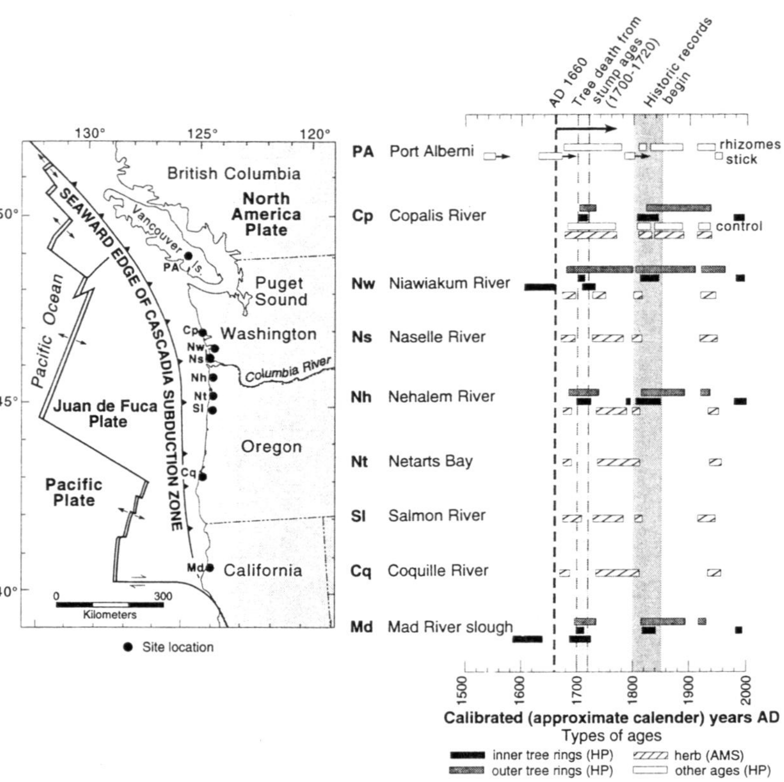

FIG. 1 Cascadia subduction zone, sites sampled for ^{14}C dating, and calendar age ranges corresponding to single ^{14}C ages and means of ^{14}C ages from each site (Table 1). Horizontal bars in column on right show calendar age ranges at two standard deviations calculated from ^{14}C ages (at one standard deviation) using error multipliers of 1.0 (New Zealand laboratory) and 1.6 (Seattle laboratory)[29,31]. Blank, shaded and pattern fills within bars mark ranges for Port Alberni (PA) high-precision (HP) ages and means of other types of ages. Small arrows on bars for the stick age from PA indicate that it is a maximum age for tsunami deposition. Ranges for stump ages have been shifted to the right by 5 years (outer-ring ages), 40 years (most inner-ring ages), 60 years (lower inner-ring range at Md), or 80 years (lower inner-ring range at Nw); such shifts are illustrated in Fig. 2 for ages from a single stump at Md. Herb and outer-ring age ranges indicate that subsidence occurred after AD 1660 (heavy dashed vertical line); historical records of the past 200 years restrict subsidence to before about 1850 and probably before about 1800 (vertical shaded bar). Shaded interval between 1700 and 1720 shows likely time of subsidence inferred from the least ambiguous ages from southern Washington and northern California.

perennial stems that may predate subsidence by more than a few years (see below). (2) Analytical errors can be reduced by averaging ages (Table 1) from single plants that died at or about the same time[23]. Contemporary death has been tested at Mad River slough (Md, Fig. 1), where matching the ring-width patterns implies that the dated stumps died within four years of one another[19]. Ages grouped by sample type at each site passed a χ^2 test for contemporaneity[23] at the 95% level.

Mean ages for each sample type (Table 1) do not differ statistically among sites. Stump means overlap at one standard deviation, both for inner rings and for outer rings. Although many herb means differ from each other at one standard deviation, all herb means passed the χ^2 test for contemporaneity at the 95% level.

Despite agreement by sample type, AMS ages on earthquake-killed herbs appear systematically greater than high-precision ages on earthquake-killed trees (Table 1). The mean age for eight herbs from the Nehalem site (179 ± 15 ^{14}C-yr BP) is significantly greater than the mean age of rings averaging five years before tree death from three stumps at this site (128 ± 09 ^{14}C-yr BP). Herb ages are also greater, though not significantly at the 95% level, than a high-precision age on the outer 10 rings of a stump at the Copalis site. Further, the mean herb age of 161 ± 15 ^{14}C-yr BP at the Niawiakum River exceeds the range of ^{14}C ages that correspond (according to the calibration curve of Fig. 2) to AD 1700–1720, the likely time of tree death at this site (see below).

Neither of two possible explanations—systematic age differences between measurements from different laboratories, and dating of long-lived parts of herbs—appears to account fully for the disagreements between AMS-herb ages and stump ages. No systematic differences have been apparent between the Seattle and New Zealand laboratories in age comparisons among ^{14}C laboratories[24,25]. In our only interlaboratory comparison, the outermost ring of a stump at the Copalis River ('control' in Table 1 and Fig. 1) gave a mean AMS age 26 ± 24 ^{14}C-yr greater than a high-precision age on the outer 10 rings of the stump. We speculate that some fraction of the woody or decay-resistant parts of many of the AMS-herb samples grew as much as one or two calendar decades before the earthquake(s) that killed the nearby trees. Woody perennial stem bases made up 50–90% by weight of most samples of the herb *Potentilla pacifica* (70% of herb samples). Samples of the stems of *Juncus balticus* (15% of herb samples) included parts of its resistant rhizomes. However, dating of samples consisting mostly of the annual leaves of a sedge, probably *Carex lyngbyei*, at the Coquille River gave the greatest of the AMS mean ages (Table 1), and we found no relation between the proportion of woody or resistant material in dated samples and their ^{14}C ages.

Converted to ranges (95% confidence interval) of calibrated (approximately calendar) years, the means of the herb and outer-ring ages show that the most recent coseismic subsidence at each site occurred after AD 1660 (Fig. 1). This is the earliest date consistent with the herb means at each of the seven herb-dated sites. The outer-ring stump means exclude ages earlier than 1680 at three of the herb sites (Cp, Nw, Nh) and at Mad River slough.

Inner-ring ages from stumps narrow the time of subsidence in California and Washington to the early 1700s. Ages on three different blocks of rings from a stump at Mad River slough limit tree death to about 1700–20; these ages eliminate other possible dates by matching distinctive steps (wiggles) in the calibration curve that relates radiocarbon time to calendar time (Fig. 2). Similar wiggle matching for a stump at the Niawiakum River in southern Washington implies tree death between about 1710 and 1730 (refs 5, 26). If all the dated stumps in southern Washington died within a few years of one another, 40-year-before-death ages (inner-ring) from six of these stumps can be averaged and the resulting mean—209 ± 06 ^{14}C-yr BP—can be used to further narrow the time of subsidence in southern Washington[5]. This time is between 1703 and 1715, as estimated with recently revised data for ^{14}C calibration[26].

Both high-precision ages from the tsunami deposit at Port Alberni are consistent with tsunami deposition after the middle 1600s (Fig. 1). The rhizomes, which should shortly postdate the tsunami deposit into which they grew, formed no earlier than 1670. The tsunami probably coincided with the most recent coseismic subsidence on the southwest coast of Vancouver Island[21].

TABLE 1 Radiocarbon ages on plant remains near the top of the youngest buried soil

Site	Distance (km)*	No of ages	Least age	Weighted mean age	Greatest age
High-precision ages on inner tree rings that average 40 years before tree death					
Copalis River	740	3	199 ± 15	207 ± 09	219 ± 19
Niawiakum River	685	3	189 ± 20	210 ± 09	219 ± 13
Nehalem River	585	1		211 ± 13	
Mad River slough	60	2	202 ± 11	214 ± 08	225 ± 10
High-precision ages on inner tree rings that average 60 or 80 years before tree death					
Niawiakum River	685	1		301 ± 10	(rings 75–86)
Mad River slough	60	1		282 ± 14	(rings 59–61)
High-precision ages on outer tree rings that average five years before tree death					
Copalis River	740	1		112 ± 11	
Nehalem River	585	3	124 ± 14	128 ± 09	132 ± 11
Mad River slough	60	4	098 ± 14	120 ± 08	137 ± 14
High-precision age on outer tree rings 1–20					
Niawiakum River	685	1		152 ± 30	
High-precision ages on rhizomes and attached leaf bases of a tidal-marsh herb and a stick in tsunami-deposited sand					
Port Alberni	980	1		145 ± 12	(herb)
Port Alberni	980	1		261 ± 14	(stick)
AMS age on a control sample consisting of an outer tree ring formed one year before tree death					
Copalis River	740	7	091 ± 41	138 ± 17	177 ± 46
AMS ages on the rooted leaves and stems of tidal-marsh herbs					
Copalis River	740	7	067 ± 42	139 ± 17	165 ± 44
Niawiakum River	685	8	120 ± 41	161 ± 15	272 ± 47
Naselle River	660	8	121 ± 44	162 ± 16	232 ± 45
Nehalem River	585	8	102 ± 41	179 ± 15	275 ± 44
Netarts Bay	550	8	133 ± 63	188 ± 18	212 ± 41
Salmon River	510	7	114 ± 43	157 ± 17	199 ± 49
Coquille River	320	8	069 ± 71	192 ± 17	242 ± 45

High-precision gas-proportional ^{14}C ages (in ^{14}C-years before AD 1950) were measured through long decay counting of large samples (original weight 60–90 g) in heavily shielded counters at the Seattle laboratory[26,29]. Reported errors do not include an error multiplier estimated at $\leqslant 1.6$. Ages on inner and outer tree rings come from stumps of Sitka spruce (*Picea sitchensis*) with the exception of one outer-ring age measured on hardwood at the Nehalem River. The number of dated rings is 10 or 20 for Washington samples and 3–10 for Oregon and California samples. The two high-precision ages from Port Alberni were measured on the rhizomes (below-ground stems) and attached leaf bases of the herb *Triglochin maritima* and on a bark-free stick (species unidentified). A radon correction[26] accounts for the difference between some calendar age ranges reported here and in 1991[5]. AMS ages (in ^{14}C-years before AD 1950) were measured by accelerator mass spectrometry at the New Zealand laboratory. An estimate of total analytical error is reported with each age. AMS herb samples (5–62 mg) consist of leaves of Lyngby's sedge (*Carex* cf. *C. lyngbyei*) at Coquille River, and leaf bases and subaerial stems of Pacific silverweed (*Potentilla pacifica*) and soft rush (*Juncus* cf. *J. balticus*) at Copalis River, Niawiakum River, Naselle River, Nehalem River, Netarts Bay and Salmon River. Herb samples were cleaned before AMS analysis by scraping in water under a microscope and were pretreated three times using standard procedures[30]. Two AMS accelerator targets were prepared for each herb sample from the same CO_2 gas. Except for 8 of 61 samples, where only one target yielded an age, the mean of the two target ages is the reported age for each of the other samples. Mean inner-ring and outer-ring stump ages and mean AMS-herb ages for each site were calculated through averaging weighted by the inverse square of laboratory-reported errors[31]. The standard deviation of the mean of eight AMS ages from the New Zealand laboratory on a stump control sample from Copalis River (138 ± 17 ^{14}C-yr BP; 'control' on Fig. 1) suggests that reported errors on AMS ages encompass all internal analytical variability[25,32].

* Distance north of Cape Medicino, which is at the southern end of the Cascadia subduction zone (Fig. 1).

Historical documents imply that the subsidence at all dated sites predates initial Euro-American exploration (latest AD 1700s) or settlement (early 1800s). The documents make no mention of earthquakes that could have caused coastal subsidence along a large part of the Cascadia subduction zone, particularly after widespread Euro-American settlement of coastal areas began about 1850 (refs 27, 28). Such evidence against nineteenth- and twentieth-century subsidence eliminates many younger calendar age ranges not already ruled out by wiggle matching of stump ages (Figs 1 and 2).

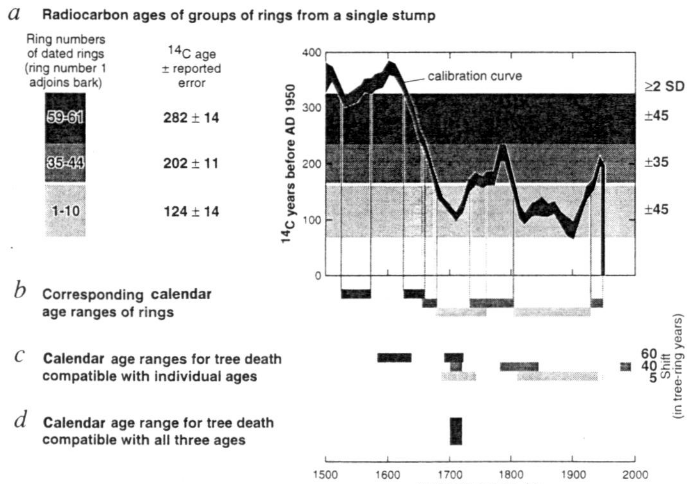

FIG. 2 High-precision ^{14}C ages and corresponding calendar age ranges for selected tree rings cut from a single stump rooted in the youngest buried soil at Mad River slough (Md, Fig. 1). *a*, Ages for three different groups of rings intersect different parts of the ^{14}C calibration curve, which relates ^{14}C time to calendar time[26]. Two-standard-deviation errors for each age, calculated using an error multiplier of 1.6, are shown on the right edge of the diagram. *b*, Horizontal bars show the corresponding calendar age ranges, shaded as in *a*. *c*, Ranges have been shifted to the right by the number of years between the dated rings and the bark. The time at which the dated tree could have died is limited to the narrow range shown in *d* (AD 1700–1720) where the ranges for all three ages overlap.

Taken together, the radiocarbon and historical evidence imply rupture along at least 900 km of the plate boundary (Table 1, Fig. 1), either in a single M_w 9 earthquake or through a series of lesser earthquakes. Because of uncertainties that include poorly understood disagreements between stump and herb ages (discussed above), the evidence merely limits the duration of possible series. Serial earthquakes could not have spanned more than the 190 years between AD 1660 and 1850. A series might have begun with a rupture of a few hundred kilometres off the Oregon coast, where we obtained the greatest of the mean herb ages (Cq, Nt and Nh, Fig. 1). But the occurrence of such a series is not confirmed by the least herb mean from Oregon (S1) or by the similarity between stump ages at the Nehalem River and those in southern Washington and northern California (Md). If a prolonged series of earthquakes began in California and proceeded northwards (or began in Washington and went southwards), it could not have lasted as long as the series of three earthquakes near M_w 8 off Colombia and Ecuador between 1942 and 1979. These earthquakes ruptured, from south to north, about 500 km of subduction zone in 37 years[7]. By contrast, the earthquake or earthquakes that killed the dated trees at sites 680 km apart in Washington and California occurred in less than 20 years.

Having failed to show age differences as large as those in the Colombia–Ecuador example, our dating strengthens the possibility that one plate-boundary earthquake ruptured most of the length of the Cascadia subduction zone in the early 1700s. Such a rupture would have had an area larger than 50,000 km^2, as judged from rupture widths inferred from geodetic and heat-flow data[10]. This area implies an earthquake magnitude close to 9—near the upper end of the range of magnitudes considered possible at the Cascadia subduction zone[3,4]. □

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