Tree-ring evidence for an A.D. 1700 Cascadia earthquake in Washington and northern Oregon

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ABSTRACT

Geologic evidence and radiocarbon dating indicate that a subduction earthquake, or series of earthquakes, occurred about 300 yr ago along the Pacific Northwest coast of the United States. Some radiocarbon dates come from remnants of the myriad trees drowned by coincident subsidence. At several coastal lowland locations in Washington and northern Oregon, we located two or more trees that survived partial submergence and lived to the 1990s. Many of them were damaged by shaking and/or inundation. Some survivors recorded the event(s) by anomalous changes in ring width or anatomy of their annual rings. The disturbance initiating the changes can be dated to between the growing seasons of A.D. 1699 and 1700. One killed tree has a last ring of A.D. 1699. Tree-ring dated evidence of disturbance extends along about 100 km of coastal Washington and northern Oregon. These results support the inference that a great (M_w~8) earthquake or larger at the Cascadia subduction zone generated the historical tsunami that struck Japan in January 1700.

INTRODUCTION

At more than a dozen locations along the coast of Washington, Oregon, and northern California, there is evidence of coseismic land surface lowering (due mainly to subsidence and partially to liquefaction) and tsunamis (Atwater et al., 1995); all are attributed to earthquake(s) along the Cascadia subduction zone (Fig. 1). Part of the evidence is the burial of soils, plants, and even trees in intertidal mud or sand overlain by intertidal mud (e.g., Atwater and Yamaguchi, 1991; Jacoby et al., 1995). High-precision radiocarbon dating restricted the date of probable earthquake(s) to between A.D. 1680 and 1720 (Atwater et al., 1991; Nelson and Atwater, 1993; and Nelson et al., 1995). Previous tree-ring analysis placed a post–A.D. 1685–1687 limit on event(s) near the Copalis and Cedar Rivers (Yamaguchi et al., 1989) and preliminary analyses of survivors indicated disturbance between 1860 and 1720 (Benson et al., 1994). The annual rings of living trees that survived the earthquake(s) and trees killed by the earthquake(s) can be further analyzed to restrict the date(s) of the event(s) to within one year. Herein we report evidence of ring width changes, anatomical changes, and a death date that place the time of an event along 100 km of coast to between the growing seasons of 1699 and 1700. Yamaguchi, et al. (1997) confirm death after the 1699 growing season for six Red Cedar killed by the event(s) in southern Washington. The tree-ring dating determines the minimum extent of a probable single event in late 1699 or early 1700 and provides important information for seismic hazards evaluation.

GEOLOGIC AND ECOLOGICAL SETTING

At several estuaries along the Washington and Oregon coasts, there are buried soils and sand layers interpreted as tsunami deposits; both occur about a meter below present-day high tides (Atwater, 1987, 1992). Sitka Spruce (*Picea sitchensis*) and Western Red Cedar (*Thuja plicata*) grow along the coastal margin and in marshes surrounding these estuaries (Burns and Honkala [1990] and our own observations from northern California to Alaska). Because they often grow at elevations only marginally above high tide, these trees are particularly susceptible to inundation from land surface lowering caused by seismic activity.

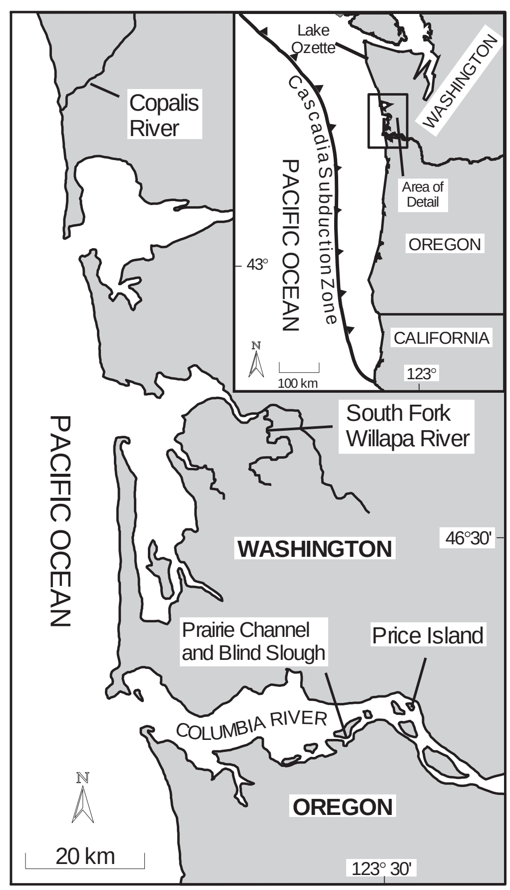

Figure 1. Map of study area. Enlarged map shows sampling sites for all trees listed in Figure 2. Disturbed or killed trees have been found along 100 km from Copalis River to the Columbia River at Blind Slough.

Data Repository item 9756 contains additional material related to this article.

We searched many coastal sites in northern Oregon and Washington for trees which might be old enough to have recorded the event(s) and also for remnants of trees which might have been killed by the event(s). We found four sites (Fig. 1) with two or more trees which lived through the event(s). The southernmost site, Blind Slough–Prairie Channel, is in Oregon on the southern shore of the Columbia River. Nearby is the Price Island site on the northern shore of the Columbia. The South Fork of the Willapa River is roughly 65 km to the north and drains into Willapa Bay. The northernmost site is the Copalis River estuary. A red cedar killed by the event was found at Copalis, just upstream from a group of red cedar trees killed by inundation attributed to coseismic subsidence (Atwater and Yamaguchi, 1991; Atwater, 1992).

A buried soil has been identified at all sites except Blind Slough–Prairie Channel. At this site, the age of the trees implies that before the event(s) they grew on a soil contemporaneous with the buried soil at nearby Price Island. Buried soils at both Willapa and Copalis have been radiocarbon dated to ~300 years B.P. (Atwater et al., 1991; Nelson and Atwater, 1993; and Nelson et al., 1995).

TREE-RING INVESTIGATIONS

Core samples were taken from a total of 33 living Sitka spruce trees and one red cedar that were established earlier than 1700. Many other cores were taken from trees that were too young to record the event(s). Samples were collected between 1992 and 1996.

All samples were then cross dated, which is the establishment of a calendar year for each annual ring in each sample, following standard dendrochronological procedures (Cook and Kairiukstis, 1990). Rings were counted backwards from the bark year, known from the date of collection. The ring width series for each core were then measured. Each series was then visually compared with others from the same tree, then with other trees from the same site. By comparing several cores from a site, missing, false, and microscopic rings were identified and dated. Statistical comparisons were also made to check the correlations between tree-ring width series. A reiterative comparison program called COFECHA was used; it removes the low-frequency variation and compares the higher frequency (year to year) variations (Holmes, 1983). In some cases, direct core-to-core comparisons were made under microscopic examination. Each of the four sites were cross dated independently, and were then compared across sites as a final confirmation of correct dating. Statistical comparisons and cross dating greatly increase efficiency in crossdating, but the ultimate confirmation should be based on visual comparisons (Pilcher, 1990).

The Copalis River site lacked living trees old enough to cross date the killed cedar tree collected there. We therefore cross dated it with a long time series developed from red cedar trees located to the north in Ozette by Jozsa et al. (1983, Fig. 1).

RING WIDTH AND ANATOMICAL CHANGES

After all samples were cross dated, they were examined for anatomical features and ring width changes which might indicate disturbance. Coseismic subsidence, as well as seismic shaking, is likely to have altered the growth environment of the survivor trees. Such subsidence would result in increased waterlogging and possibly tidal inundation, of the trees' root zones. In addition to ring-width changes, root-zone saturation produces distinct changes in tree-ring anatomy, including increased numbers of traumatic resin canals (sap conducting tubes formed by altered surrounding cells) and reaction wood (Coutts and Phillipson, 1978a, 1978b; Phillipson and Coutts, 1978; Coutts, 1981; Kozlowski et al., 1991). The reaction wood comprises thick-walled, denser cells that often form wider rings (Timell, 1986). Whereas cambial growth is usually diminished by flooding in most flood-intolerant species, some trees may respond positively for a year or two, followed by a marked decline. Kozlowski et al. (1991, p. 317) stated "Sometimes the decrease in growth occurs so long after flooding that other causes are sought." Seismic shaking is likely to result in tilted trees, which typically exhibit reaction wood following such tilting.

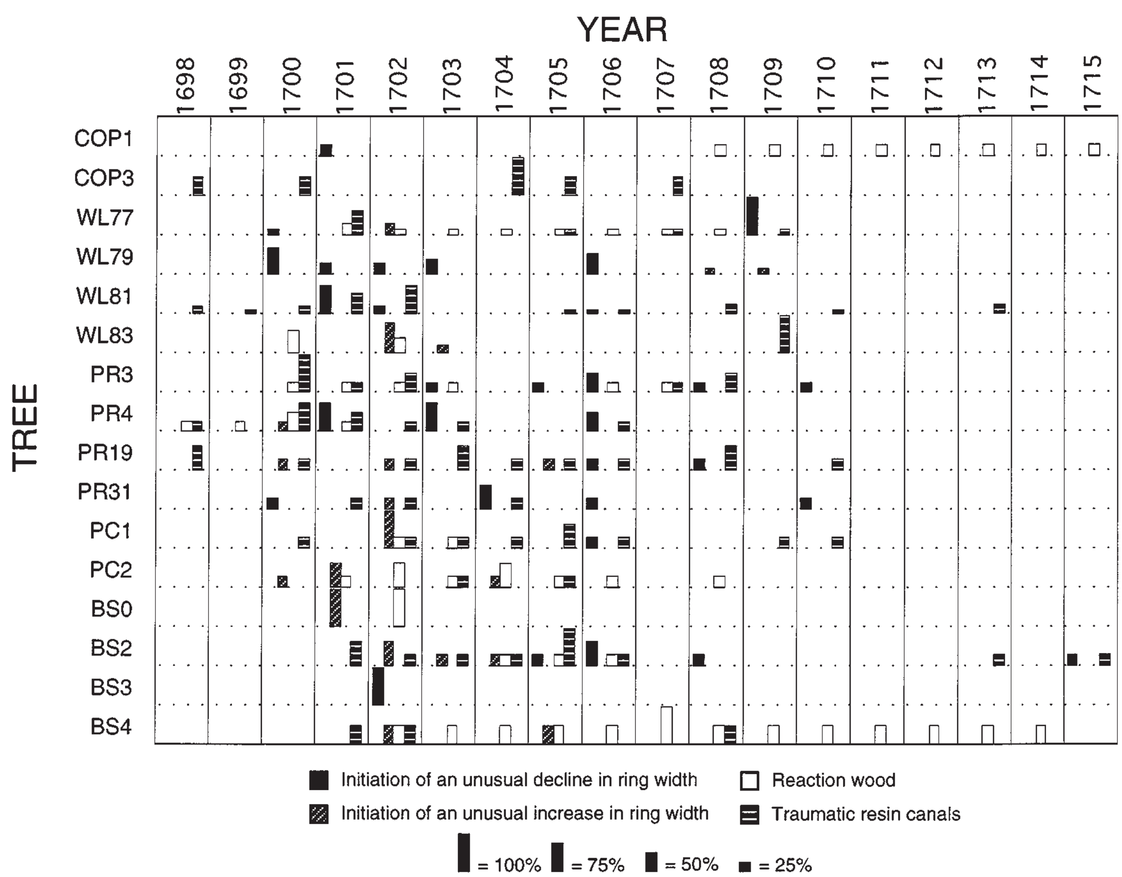

Figure 2. Bar plots representing the percentage of cores within each tree which express four anatomical features attributed to changes in growth environment. Trees are represented on the vertical axis, with a scale of 0% to 100% for anatomical features of each tree. Horizontal axis represents calendar years.

There were 15 trees that showed some evidence of disturbance initiating in 1700 or soon after (Fig. 2), and 5 from Price Island appeared to be undisturbed. Fourteen could not be clearly placed in either category. There are both unusual decreases and increases in ring width in the disturbed trees (Fig. 2). Figure 3 shows ring widths for several individual trees and for an average of 5 undisturbed trees from Price Island. Increasing numbers of traumatic resin canals also start appearing in 1700 (Fig. 2) and are present in 10 survivors by 1702. The reaction wood could be a response to tilting or flooding, but only two trees show it in 1700 (Fig. 2).

At Blind Slough–Prairie Channel, two trees (PC1 and PC2) show anatomical and ring width changes beginning in 1700; three trees (BS0, BS2, and BS3) show changes beginning in 1701; and one tree (BS3) begins to decline in 1702. Note that the ring widths (Fig. 3) of BS3 decline abruptly and remain suppressed for several decades, while the ring widths of PC2 increase dramatically and then return to average levels.

At Price Island, four trees show a clear decline after 1699 (Fig. 2). All four of the disturbed trees at Price Island show some changes in anatomy in 1700, although PR4 and PR19 also show changes in 1698 and 1699. By 1706 the growth of all four Price Island trees has declined greatly (Figs. 2 and 3). Some partially buried trees grew new adventitious root systems. These are roots grown from the trunk of a tree at a higher level to adjust for partial burial and/or an increase in water table elevation. This type of root system was observed at Price Island, where several of the trees have been blown down and their root systems exposed. The upper adventitious roots are about a meter above the initial root systems (Benson, et al., 1994).

At the Willapa River site, all four survivor trees show suppressed growth after 1699. Trees WL77, WL79, and WL83 show a response in 1700, while WL81 shows a marked decline in 1701. The ring widths of trees WL79, WL81, and WL83 remain suppressed through the present day.

At the Copalis River (Fig. 2), tree COP1 declined beginning in 1701 on one side of the tree only and then grew reaction wood on that side for several decades. Tree COP3 shows traumatic resin canals frequently, but without any clear pattern.

We sampled a dead red cedar tree that grew on the bank of the Copalis River at the upper end of a stand of dead cedar trees believed to have been killed by the earthquake (Atwater and Yamaguchi, 1991; Atwater, 1992). The trunks of all the dead cedar trees have lost their outer rings due to decay and/or fire. On this particular tree, only the root section had bark and an intact outer ring around most of the root except at the top, where slight abrasion caused a loss of outer cells. For a statistical comparison with the Ozette ring-width data (Jozsa et al., 1983), we averaged the three trunk cores with measurements from three radii of the root section. The best matching position occurs when the outer year of the dead tree series is placed at 1699; correlation value (r) is 0.21 and a Student's t value (t) is 3.7 for a common period of 300 yr. For the longest trunk core, the results are $r = 0.23$, $t = 3.8$ for a common period of 257 yr. These results are significant at the 0.95 level and resulted from allowing any matching position to be considered from 1400 to 1740. There are a few other statistical matches with slightly higher r values, but with lower Student's t values. Lower Student's t values, lack of consistency, and much shorter common periods indicate the other matches are by chance alone. Plotting of the dead tree data and comparison with the Ozette time series show agreement in certain extreme years of 1657 (wide), 1691 (narrow), and patterns of change around late 1650s, 1670, and late 1670s–early 1680s. The last ring in the root of the tree is a complete ring for 1699, indicating that the event occurred after the end of the growing season of 1699 but before the beginning of the growing season in 1700.

Figure 2 clearly shows that an event on or after the fall of 1699 affected all four sites. Each of the sites shows some effect in 1700, but not every tree at each site shows an effect in 1700. This may be due to differences between sites, between trees within sites, and between different sides of the same tree. Small differences in elevation, soil stability, and groundwater salinity would all affect the trees' responses to disturbance.

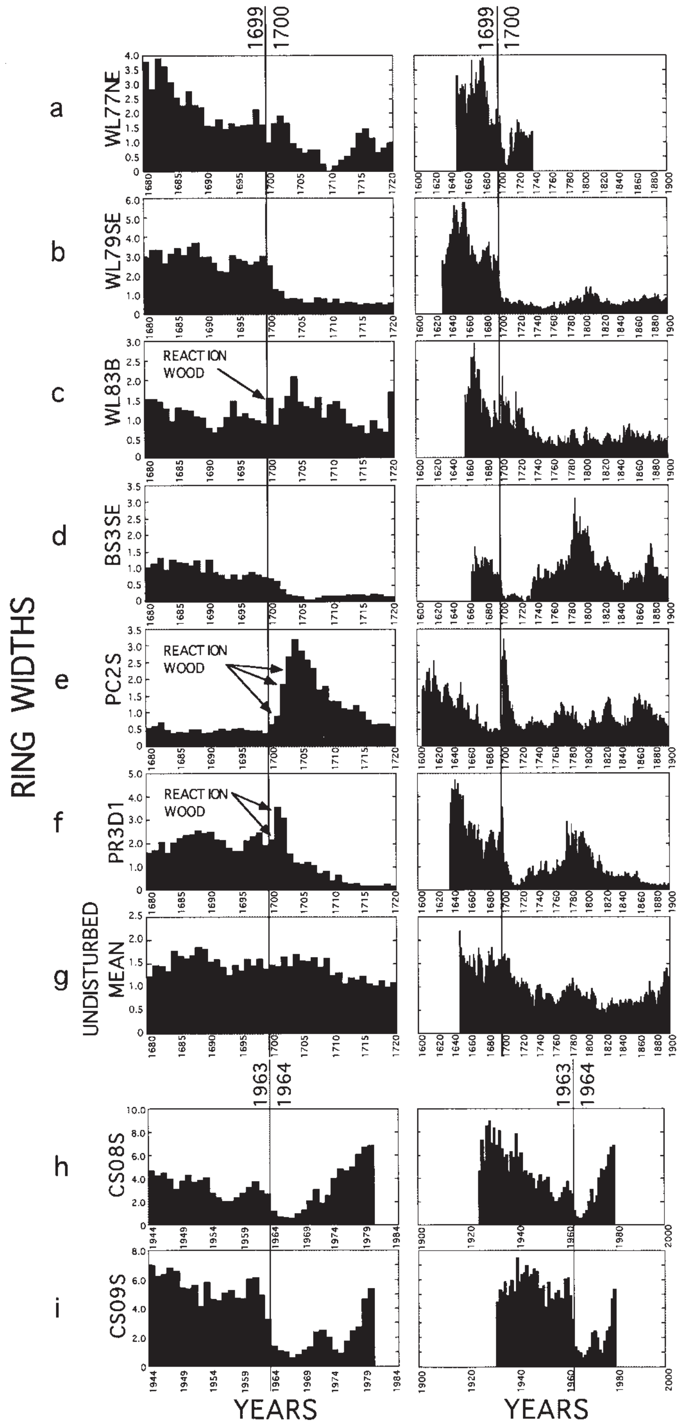

Figure 3. Ring width plots. Vertical axes are ring widths in millimeters; horizontal axes are calendar years. Plots a–e are core samples from survivor trees. Plot f is a section from a survivor which was subsequently blown down. Plot g is an arithmetic mean of five undisturbed trees from Price Island. All are Sitka Spruce except BS3, which is Western Red Cedar. The response varies from a decrease to an increase. As indicated some increases are reaction wood, which can be induced by tilting or inundation. In some cores and trees the initiation of change occurs in 1700, but the greatest change may be delayed by one or even two years. Note that in some cores growth decline persists for several decades indicating continued site degradation as one would expect in a subsided area. There are obviously other similar changes in ring width, but only in the 1699–1700 transition is there such agreement between the trees in recording disturbance in ring widths or other anatomical changes. Plots h and i are core samples from two Sitka Spruce which were disturbed by but survived the March 1964 Alaska earthquake. Note that the narrowest ring is a few years after the event.

Due to storage of growth substances, the narrowest rings can be several years after the event (Kramer and Kozlowski, 1979). The initiation of anatomical changes and changes in ring width date the disturbance. An analogous situation exists at Cape Suckling, Alaska (Fig. 3; Sheppard and Jacoby, 1989), where spruce trees survived the 27 March 1964 earthquake (M_w = 9.2, Plafker, 1969).

CONCLUSIONS

The combined dating of the initiation of anatomical features indicating flooding and/or disturbance in survivor trees and the death date for the killed cedar place a subsidence event along a distance of at least 100 km of the Washington–northern Oregon coast between the growing seasons of 1699 and 1700. Satake et al. (1996) presented analysis of information about a tsunami that struck Japan on 27 January 1700. From historical records and analysis of tsunami effects from known giant (M_w~9) earthquakes at other circum-Pacific locations, they infer that the 1700 tsunami was caused by a great (M_w~8), possibly giant, coastal earthquake in western North America. The absence of paleoseismic evidence for other locations and the previously published paleoseismic evidence from the Cascadia subduction zone lead Satake et al. (1996) to conclude that Cascadia is the likely source. These tree-ring analyses give independent evidence for a subduction earthquake that could be related to the historical tsunami of January 1700.[1]

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REFERENCES CITED

Atwater, B. F., 1987, Evidence for great Holocene earthquakes along the outer coast of Washington State: Science, v. 236, p. 942–944.

Atwater, B. F., 1992, Geologic evidence for earthquakes during the past 2000 years along the Copalis river, southern coastal Washington: Journal of Geophysical Research, v. 97, p. 1909–19.

Atwater, B. F., and Yamaguchi, D. K., 1991, Sudden, probably coseismic submergence of Holocene trees and grass in coastal Washington state: Geology, v. 19, p. 706–709.

Atwater, B. F., Stuiver, M., and Yamaguchi, D. K., 1991, Radiocarbon test of earthquake magnitude at the Cascadia subduction zone: Nature, v. 353, p. 156–158.

Atwater, B. F., Nelson, A. R., Clague, J. J., Carver, G. A., Yamaguchi, D. K., Bobrowsky, P. T., Bourgeois, J., Darienzo, M. E., Grant, W. C., Hemphill-Haley, E., Kelsey, H. M., Jacoby, G. C., Nishenko, S. P., Palmer, S. P., Peterson, C. D., and Reinhart, M. A., 1995, Summary of coastal geologic evidence for past great earthquakes at the Cascadia subduction zone: Earthquake Spectra, v. 11, p. 1–18.

Benson, B. E., Jacoby, G. C., and Yamaguchi, D. Y., 1994, A possible tree-ring record of coseismic subsidence and volcanic eruption in southwest Washington: Geological Society of America—Abstracts with Programs, v. 26, no. 7, p. 300.

Burns, R. M., and Honkala, B. H., 1990, Silvics of North America; Volume 1, Conifers: Agriculture Handbook 654: Washington, D.C., Forest Service, U.S. Department of Agriculture, 675 p.

Cook, E. R., and Kairiukstis, L. A., editors, 1990, Methods of dendrochronology: Boston, Massachusetts, Kluwer Academic Publishers, 394 p.

Coutts, M. P., 1981, Effects of waterlogging on water relations of actively growing and dormant Sitka Spruce seedlings: Annals of Botany, v. 47, p. 747–753.

Coutts, M. P., and Phillipson, J. J., 1978a, The tolerance of tree roots to waterlogging, I. Survival of Sitka Spruce and Lodgepole Pine: New Phytologist, v. 80, p. 63–69.

Coutts, M. P., and Phillipson, J. J., 1978b, The tolerance of tree roots to waterlogging, II. Adaptation of Sitka Spruce and Lodgepole Pine to waterlogged soil: New Phytologist, v. 80, p. 71–77.

Holmes, R. L., 1983, Computer-assisted quality control in tree-ring dating and measurement: Tree-Ring Bulletin, v. 43, p. 69–75.

Jacoby, G., Carver, G., and Wagner, W., 1995, Trees and herbs killed by an earthquake ~300 yr. ago at Humboldt Bay, California: Geology, v. 23, p. 77–80.

Jozsa, L. A., Parker, M. L., Johnson, S. G., and Bramhill, P. A., 1983, Chronology building from the Olympic peninsula for tree-ring dating at Ozette, *in* Gleeson, P. F., ed., Ozette dendrochronological studies: Pullman, Washington, Laboratory of Anthropology, Washington State University, 27–56 p.

Kozlowski, T. T., Kramer, P. J., and Pallardy, S. G., 1991, The physiological ecology of woody plants: San Diego, California, Academic Press, 657 p.

Kramer, P. J., and Kozlowski, T. T., 1979, Physiology of woody plants: Orlando, Florida, Academic Press, 811 p.

Nelson, A. R., and Atwater, B. F., 1993, Radiocarbon ages of earthquake-killed plants along the Cascadia subduction zone: Eos (Transactions, American Geophysical Union), v. 74, p. 199–200.

Nelson, A. R., Atwater, B. F., Bobrowsky, P. T., Bradley, L. A., Clague, J. J., Carver, G. A., Darienzo, M. E., Grant, W. C., Kreuger, H. W., Sparks, R., Stafford, T. W., and Stuiver, M., 1995, Radiocarbon evidence for extensive plate-boundary rupture about 300 years ago at the Cascadia subduction zone: Nature, v. 378, p. 371–374.

Phillipson, J. J., and Coutts, M. P., 1978, The tolerance of tree roots to waterlogging, III. Oxygen transport in Lodgepole Pine and Sitka Spruce roots of primary structure: New Phytologist, v. 80, p. 341–349.

Pilcher, J. R., 1990, Sample preparation, cross-dating, and measurement, *in* Cook, E. R., and Kairiukstis, L. A., eds., Methods of dendrochronology: Boston, Massachusetts, Kluwer Academic Publishers, p. 40–51.

Plafker, G., 1969, Tectonics of the March 27, 1964 Alaska earthquake: U.S. Geological Survey Professional Paper, v. 543-I, 74 p.

Satake, K., Shimazaki, K., Tsuji, Y., and Ueda, K., 1996, Time and size of a giant earthquake in Cascadia inferred from Japanese tsunami records of January 1700: Nature, v. 379, p. 246–249.

Sheppard, P. R., and Jacoby, G. C., 1989, Application of tree-ring analysis to paleoseismology: Two case studies: Geology, v. 17, p. 226–229.

Timell, T. E., 1986, Compression wood in gymnosperms, Volume 1: New York, Springer-Verlag, 706 p.

Yamaguchi, D. K., Woodhouse, C. A., and Reid, M. S., 1989, Tree-ring evidence for synchronous rapid submergence of the southwestern Washington coast 300 years B.P. [Abs.]: Eos (Transactions, American Geophysical Union) Supplement, Fall Meeting, v. 70, p. 1332.

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[1]Data Repository item 9756, tree-ring width measurements, is available on request from Documents Secretary, GSA, P.O. Box 9140, Boulder, CO 80301. E-mail: editing@geosociety.org. The tree-ring width data will also be placed in the International Tree-Ring Data Bank and the cores archived at the Tree-Ring Laboratory at Lamont-Doherty Earth Observatory.