lanches that are included in a recent inventory of landslide dams (*10*). These 29 rock avalanches were triggered by earthquakes of magnitudes 6.0 or greater (*4*). Thus, while rock avalanches have diverse origins, a significant number of them are caused by earthquakes. (iii) In New Zealand, the distribution of lakes dammed by landslides has approximated the locations of shallow earthquakes of magnitude 6.5 or greater (*11*).

The rock avalanches that formed Jefferson, Lower Dry Bed, and Spider Lakes, and perhaps Lena Lake, provide evidence that strong shaking accompanied abrupt tectonic displacement in western Washington. Similarities in radiocarbon age, summarized in figure 1 of (*1*), permit correlation of these avalanches with displacement that has been inferred for one or more structures: the nearby Saddle Mountain East fault; the Seattle fault, about 75 km away; and the boundary between the subducting Juan de Fuca plate and the overriding North America plate, 100 to 200 km to the west. Similarities in age also permit correlation with block slides 1000 to 1100 years ago into Lake Washington, near Seattle (*12*). Taken together, these correlations demonstrate that large prehistoric earthquakes occurred in the Puget Sound region.

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7. Geographic coordinates: Hamma Hamma River rock avalanche, 47°35.89′N, 123°8.72′W; Lake Cushman rock avalanche, 47°29.87′N, 123°18.60′W.
8. The calibrated ages (2σ range) were derived from the conventional radiocarbon ages by means of a computer program [M. Stuiver and P. J. Reimer, *Radiocarbon* **28**, 1022 (1986)] using a laboratory error multiplier of 2. As used in the text, "years ago" refers to years before 1990.
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Tree Ring Correlation Between Prehistoric Landslides and Abrupt Tectonic Events in Seattle, Washington

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Radiocarbon ages of submerged trees on landslide deposits in Lake Washington, Seattle, indicate that the most recent slides in three separate areas may have occurred simultaneously about 1000 years ago. Tree ring crossdating shows that seven bark-bearing trees from one of these recent slides and a tree 23 kilometers to the northwest in a probable tsunami deposit on the shore of Puget Sound died in the same season of the same year. The close coincidence among the most recent lake landslides, a probable tsunami, abrupt subsidence, and other possible seismic events gives evidence for a strong prehistoric earthquake in the Seattle region.

Although most landslides are not seismic in origin, they sometimes can be triggered by seismic events. In this report we describe and date landslides in Lake Washington using drowned trees and suggest that recent landslides, possibly concurrent at three sites, were induced by an earthquake. Lake Washington, situated within metropolitan Seattle [see map in (*1*)], contains areas where forested uplands recently slid into the water. Trees were removed from the lake as navigational hazards in 1919 (*2*). The removed trees were primarily Douglas fir [*Pseudotsuga menziesii* (Mirb.) Franco]. In all, 149 trees were removed from southeast of Mercer Island, 26 west of Mercer Island, and 11 near Kirkland. All of these trees were in water from between depths of 20 and 40 m. Later, Gould *et al.* (*3*) sampled trees rising from a landslide bench near Kirkland, at a depth of 30 m and 200 m from shore. A radiocarbon age of the outer wood from one of the trees indicated that the landslide occurred sometime between 800 and 1400 years ago (*4*). Drowned trees are still numerous enough to have attracted log-salvage endeavors in 1991 and to provide an opportunity to date the landslides and to evaluate whether they occurred at the same time.

To compare the ages of other trees and slides with the Kirkland date, we focused our study on the age and morphology of landslides near Mercer Island. Side-scanning sonar surveys revealed that three large slide lobes were located within 1.3 km along the shore of southeastern Mercer Island. The slides measure as much as 500 to 750 m from head scarp to toe. Individual trees, block and crevasse features, and zones of disrupted lake bottom were evident in the images. The slides are bounded on some perimeters by boulders and aprons of small debris. Bathymetric lobes in the lake correspond closely to these landslide features (*5*). Above the lake level, the slides exhibit 40- to 50-m-high head scarps that slope 40° to 45° toward the lake. Zones of large-scale hummocky ground also delineate the slide areas. The slides traveled 200 to 400 m into the lake, and the elevation drop between the head scarp tops and upper surfaces of the submerged slide masses is about 100 to 120 m.

Although many small-scale landslides are also present in the area, historical documents (*6, 7*) record no landslides in the Seattle area or the Puget Sound lowland as large as the ancient slides in Lake Washington. Landslides have been associated with historical earthquakes in the Puget Sound region (*6, 8*). All were small except for a thin 800-m section of a near-vertical bluff that fell into the Tacoma Narrows a few days after the 1949 earthquake (*8*).

Conventional radiocarbon measurements of outer rings of four trees from landslide lobes southeast of Mercer Island and of one tree from a slide west of Mercer Island yielded ages of 1000 to 1300 years ago (*9*). These ages are indistinguishable, within radiocarbon errors, from the date for the Kirkland slide. In addition, dates from four other trees indicate limiting ages for landslides at about 1550 to 1850, 2200 to 2800 (two trees), and 2850 to 3250 years ago (*10*). These ages are limiting

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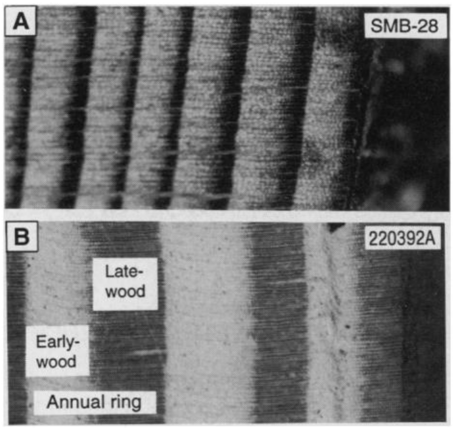

Fig. 1. Outer rings of two trees that died 894 to 997 A.D. (*13, 16*). (**A**) Sample SMB-28 is from a landslide in Lake Washington, Seattle, southeast of Mercer Island. (**B**) Sample 220392A is from an excavation at West Point, 23 km northwest of the Mercer Island site. The excavation exposed the tree on a probable tsunami sand deposit that showed evidence of abrupt subsidence of at least 1 m [see (*16*)]. Tree ring crossdating indicates that seven bark-bearing trees, including SMB-28, from Lake Washington and the West Point tree all died in the same year and that the last rings of all eight trees show full development of latewood but no initiation of the next year's growth. Therefore all trees also died in the same season. The narrower rings of SMB-28 are magnified two times more than 220392A for comparison of the last latewood cells. Note the partial collapse of the thin-walled earlywood cells as a result of incipient decay in the West Point sample.

because they were measured on heartwood rings formed decades before the trees were killed by submergence in the lake. Outer sapwood rings had decayed away (*11*). The agreement in dates from the recent slides at three locations raises the possibility that they were triggered by a common mechanism. To improve the dating, two high-precision dates were obtained for one tree from a slide southeast of Mercer Island (*12*). Two 15- or 16-year blocks were analyzed from the outer and center portions, respectively, of a cross section with outer rings and bark intact. The tree section had 236 rings, and therefore the centers of the two blocks were about 221 years apart. The 15-year outer block age range was 891 to 997 A.D. after calibration (2σ range). The range of ages for the 16-year inner block, after calibration and adding the 221 years to each value, was 894 to 1007 A.D. (2σ range) (*13*). The mutual age range of 894 to 997 A.D. is the best age estimate for a triggering event; more cautiously it is described as about 1000 to 1100 years ago. In addition to the Lake Washington slides, radiocarbon dates of about 1000 to 1350 years ago were obtained from two other sites 70 km to the west, where it is hypothesized that drainage was blocked by movement of the Saddle Mountain fault (*1, 14*). The correspondence of Lake Washington landslide dates with ages for abrupt subsidence along the Pacific Coast (*15*), uplift (*1*), subsidence and tsunami (*16*), and rock avalanches (*17*) suggests that there was a seismic trigger [see figure 1 of (*1*)].

Despite this apparent coincidence, and in consideration of the uncertainty of even high-precision radiocarbon dating, tree ring analysis is required to confirm that the events were simultaneous. We therefore studied the ring-width patterns of samples from the submerged trees off Mercer Island. All of our samples from Lake Washington with enough size and preservation for tree ring analysis are from Douglas fir. Although much of the wood is well preserved, outer sapwood is decayed away from most of the standing trees and logs, except where the trunks were buried in landslide deposits (*11*). Southeast of Mercer Island seven samples were recovered by a barge crane, with full sapwood out to the bark year on some portion of the circumference. A typical number of sapwood rings is about 45. Full cross sections cut from these trees provided us with enough rings for positive crossdating (*18*) and revealed the anatomy of the last growth ring before the trees died as a result of submersion (Fig. 1A). Crossdating was achieved by measuring all of the individual annual ring widths from multiple radii (two to four) for each tree sample and by making statistical comparisons between these and samples obtained by SCUBA (*19*) diving. The statistical crossdating was then verified by direct microscopic comparison between each individual radius examined (*18*). Ring-width crossdating was aided by matching of fire scars, as Douglas fir, with its unusually thick bark, can survive repeated fires that cause distinct trauma in subsequent rings or nonfatal scarring. That several of these scars crossdate among most of the specimens indicates that fires repeatedly swept through the entire forest (*20*). All seven samples with complete outer rings present died in the same year and season. In all cases the outer ring is fully developed, and there is no indication of initiation of the next year's growth. Thus the trees must have died in the fall, winter, or early spring.

We also attempted to crossdate the rings among other samples from west of Mercer Island and samples from southeast of Mercer Island. The longest sample from west of Mercer Island has only 63 rings. A tentative correspondence was established, but the crossdating is not significant. Until better samples are obtained from west of Mercer Island and also Kirkland we cannot confirm that the landslides were simultaneous, although the radiocarbon dates from the three sites overlap.

The most convincing evidence supporting seismic triggering of the landslides comes from a bark-bearing Douglas fir log from West Point, at the margin of Puget Sound, 23 km northwest of the southeast Mercer Island location. According to Atwater and Moore (*16*), the log came to rest on a tidal marsh along with sand that probably represents a tsunami. This probable tsunami was likely triggered by the same event that also caused at least 1 m of subsidence of the marsh and rapid sedimentation that partially buried and preserved the log (*16*). The section has mainly reaction wood rings (response to lateral stress or tilting) in major inner portions as might be expected for a tree subject to strong winds or substrate instability such as might occur along a coastline. The outermost 16 rings of this specimen yielded radiocarbon age between 1000 to 1300 years ago (*16, 21*). High-precision dating suggests that sand emplacement and subsidence occurred 1000 to 1100 years ago (*16, 21*). These ages are contemporary with the three recent landslides and high-precision date from Lake Washington.

We crossdated the landslide trees and the West Point log by measuring ring widths along four radii of the West Point section. The radii were first crossdated with each other. These data were then compared to measurements from the south Mercer Island samples that had outer rings intact (*22*). Computer crossdating indicated that the outer rings were formed in the same year and did not indicate any other significant crossdating positions (see Fig. 2). Additionally, we made skeleton plots (*18, 23*) of the samples, established patterns of individual ring features, compared the plots, and made visual comparisons of the samples, ring by ring, to determine the crossdating. The results reveal that the West Point tree and all the bark-year trees from the landslides south of Mercer Island died in the same season of the same year (see Figs. 1 and 2).

The simultaneous occurrence of landslides at three locations around Lake Washington would be unusual. If they are contemporaneous, a common trigger mechanism must be considered. Most probable mechanisms are seismic accelerations or saturation and slope failure; or both saturation and a smaller magnitude seismic shock could trigger landslides in weakened material. However, around Lake Washington no large translational-block landslides have been recorded, even after extreme precipitation events.

In conclusion, the data show that three landslides, within the limits of radiocarbon dating, occurred during a time of other tectonic events in the region (*1, 16, 17*) and that one of these landslides occurred during the same season of the same year as a probable tsunami deposit on Puget Sound and coastal subsidence (*16*). The approximate radiocarbon correlations among slope failures, a tsunami, and abrupt tectonic movement—as summarized on figure 1 of (*1*)—provide strong evidence of an earthquake. Our precise tree ring crossdating between slope failure and abrupt tectonic movement emphasizes the potential for large earthquakes in the Seattle metropolitan region.

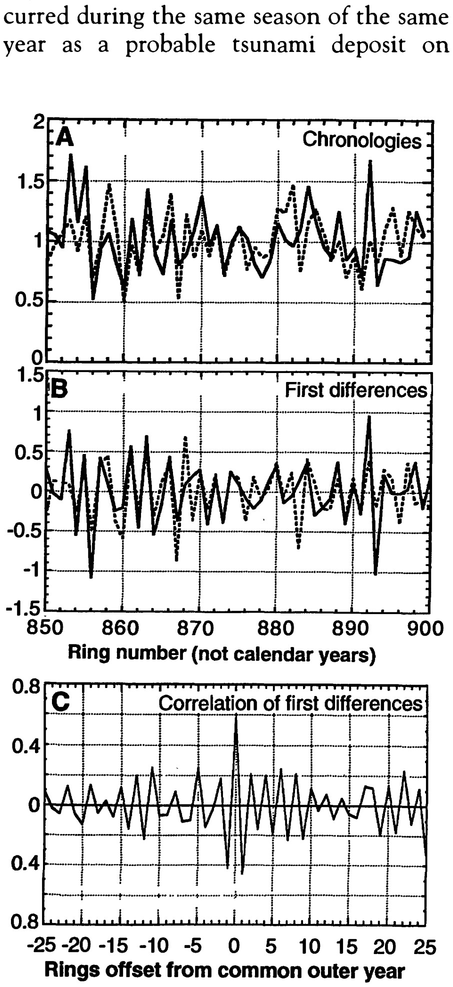

Fig. 2. **(A)** Plot of the last 50 years of the ring-width indices from the bark-bearing trees southeast of Mercer Island (solid line) and the last 50 years of the West Point tree (dashed line). Indices are the measured ring widths divided by a growth-trend line to produce dimensionless indices that are then averaged for each year for all the radii included in the chronologies. The inner rings (fewer than 850) of the West Point tree are somewhat distorted reaction wood (see text). **(B)** Plot of the first differences of the Lake Washington (solid line) and West Point (dashed line) chronologies. The changes in ring widths from year to year or first differences can serve as a better comparison between ring-width patterns than the ring widths themselves. **(C)** Plot of the correlations between first differences at different positions. By far the highest correlation is when the outer years are aligned as the same year. The negative correlations at an offset of ±1 year are typical for these types of comparisons. As noted in (*18*), the final dating is made by visual comparison. These plots are only presented as partial illustrations of the ring-width patterns.

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9. Sample numbers and ages in ^{14}C yr B.P. are as follows: Southeast of Mercer Island: Beta 33959, 1170 ± 50; Beta 39937, 1120 ± 60; Beta 39938, 1110 ± 50; Beta 40623, 1210 ± 50; and west of Mercer Island: Beta 33962, 1155 ± 40. All ages are adjusted for ^{13}C/^{12}C ratio.
10. Sample numbers and ages in ^{14}C yr B.P. are as follows: Beta 33961, 1725 ± 60; Beta 39936, 2290 ± 60; and Beta 39951, 2460 ± 60; The second two ages are combined in the text because of possible differences in outer wood decay and radiocarbon error they may be the same age. Beta 24359, 2840 ± 60. All adjusted for ^{13}C/^{12}C ratio.
11. Sapwood of conifers is generally far less resistant to decay than heartwood, which is impregnated with more extractives and toxins as part of the transition from sapwood to heartwood [A. J. Panshin and C. deZeeuw, *Textbook of Wood Technology* (McGraw-Hill, New York, 1970), pp. 53–59].
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13. The outer high-precision date was 1121 ± 15 ^{14}C yr B.P. (rings formed 0 to 15 years before tree death; QL 4575). Inner sample (rings formed 221 to 236 years before tree death; QL 4576) was 1304 ± 15 ^{14}C yr B.P. For calibration, a lab multiplier of 1.6 was used. According to revised calibration data (M. Stuiver and P. J. Reimer, *Radiocarbon*, in press) the outer date has intercepts at 898, 902, and 960 A.D. The single intercept of the inner date is 688. Addition of the 221 years between samples suggests that the 898 and 902 dates are most likely. The reason for the asymmetry of the range is the varying steepness of the calibration curve near the interception points.
14. Radiocarbon dates for outer rings of two stumps in Price Lake and a small unnamed lake, presumably dammed by displacement of the Saddle Mountain fault, are Beta 47963, 1180 ± 70, and Beta 47964, 1240 ± 70. See regional map in (*1*). These rings are not necessarily near the bark because there is much decay from these stumps.
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18. If there are few missing or false rings, standard procedures in modern crossdating are surface preparation to reveal clearly all rings, measurement of all rings, and statistical comparison of resulting data with a program such as COFECHA, CATRAS, or CROS. Then the statistically suggested dates are tested by direct comparison of ring patterns. This last step is requisite for confirmed dating. J. R. Pilcher, in *Methods of Dendrochronology*, E. R. Cook and L. A. Kairiukstis, Eds. (Kluwer, London, 1989), pp 43–49; M. G. L. Baillie, *Tree-Ring Dating and Archaeology* (Croom Helm, London, 1982), pp 80–85.
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20. The various samples retrieved from south of Mercer Island reveal that the area was covered by mature forest dominated by Douglas fir, with trees of up to 290 to 350 years in age. There were also a few western red cedar (*Thuja plicata* Donn ex D. Don), but the samples of this species recovered for this study have much decay and only a few wide, uniform rings, which make these samples ill-suited for crossdating.
21. The outer 16 rings of the bark-bearing West Point log, Beta 52539, gave an age of 1160 ± 60 ^{14}C yr B.P. (without correction for ^{13}C/^{12}C ratio). High-precision dating of herbaceous stems on which the log was deposited, QL-4623, gave an age of 1108 ± 16 ^{14}C yr B.P. This age compares well with the 1121 ± 15 age for the bark-bearing tree off southeast Mercer Island (*13*).
22. All the samples from Lake Washington are somewhat complacent, meaning that they show little variation in ring widths, in comparison to moisture-stressed trees in the American Southwest. In spite of this lower year-to-year variation, the Lake Washington trees from southeast of Mercer Island crossdate unequivocally with each other and with the West Point tree. We also measured the widths of the latewood of all the bark-bearing trees and the West Point tree and crossdated these data. The statistical comparisons were not quite as good, but the variations in latewood widths were helpful in the visual crossdating. In the statistical comparison, we checked all positions along the 350-year chronology from the Lake Washington trees. The outer 50 rings of the West Point tree have less reaction wood than inner rings, and these outer ring widths respond more to local climate, similar to the Lake Washington trees. We have not yet found a suitable absolutely dated chronology in the region long enough to crossdate with the Lake Washington chronology.
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