Paleoseismology: A Search for Ancient Earthquakes in Puget Sound

John Adams

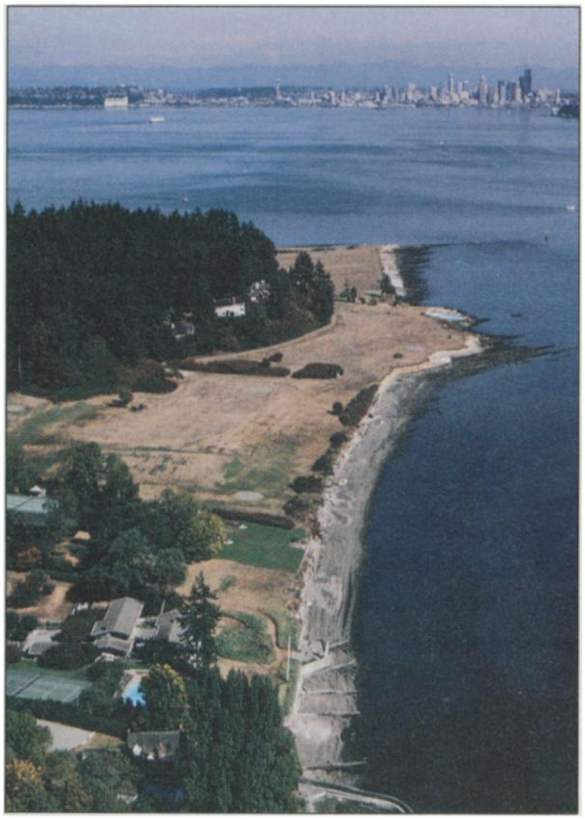
Seattle was strongly shaken by moderate earthquakes deep under Puget Sound in 1949 and again in 1965, the latter alone causing $12 million worth of damage. Consequently, seismic zoning maps have been devised to ensure safe construction practices and so mitigate future damage from such earthquakes. A flurry of geological research in the mid- to late 1980s showed that the Pacific Northwest has in addition been shaken by great earthquakes (magnitude greater than 8) on the Cascadia subduction zone (the area under the continental shelf and coast where tectonic plates collide), the most recent just 300 years ago (*1*).

Work by Atwater (*2*) and other scientists showed that these great earthquakes on the Cascadia subduction zone had left a geological imprint on the Pacific coast from northern California to Vancouver Island, even though no such earthquake is known from the brief historical record. The most obvious evidence was the sudden subsidence of tidal marshes, sometimes associated with sand layers interpreted as tsunami deposits (*1*).

However, the evidence was circumstantial, so scientists also searched for indications of earthquake shaking such as liquefaction (in which the shaken sediment behaves like a fluid) and slope failures. Drowned trees on submerged landslides in Lake Washington had been known for some years and had been dated to roughly the same period as one of the coastal subsidence events. Did the landslides record the shaking from a great subduction earthquake? At first, it seemed they might.

The answer, as revealed in five reports (*3–7*) on pages 1611 to 1623 of this issue, has turned out to be even more remarkable. In a synergistic collaboration, each group of researchers uncovered a part of the puzzle. Together, the evidence shows that a large earthquake occurred less than 1100 years ago, immediately beneath Seattle, and not deep under the city (the 1965 earthquake was at 59 km depth), nor far to the west (as had the Cascadia subduction earthquakes).

These results are an application of a new field of study—paleoseismology—established mainly over the last 15 years. Paleoseismology is the study of the evidence for prehistoric earthquakes—before the direct evidence of historical observations and instrumental seismograms were available—and it has been an extremely useful field in North America, which has a relatively short historical record. Early workers studied active faults to establish their rates of movement. Researchers, notably Lensen and Wellman in New Zealand (*8*) and Wallace and Sieh in California (*9*), then found places where the slip during individual earthquakes could be identified and dated, leading to an earthquake prehistory. In other places, the active faults were offshore or buried, so later researchers have been seeking and interpreting earthquake crustal deformation or shaking effects. Attribution of these effects to a paleo-earthquake is more difficult, because although earthquakes cause multiple synchronous effects, the same effects may also result from other environmental processes acting independently. The challenge is to assemble a strong circumstantial case for a single earthquake origin, and the key is demonstrating the synchronicity of the effects. The results presented in this issue build as complete a case as has ever been achieved by paleoseismology.



An uplifting site. Oblique view of an uplifted marine terrace at Restoration Point. The platform, which underlies the grass-covered surface in the central part of the photograph, was abruptly uplifted 7 meters, probably during a large earthquake that occurred 1000 to 1100 years ago. A view to the east across Puget Sound toward Seattle is shown. [Photo by Robert Bucknam, U.S. Geological Survey]

For starters, a marine terrace representing a sudden, 7-m uplift of Restoration Point, Bainbridge Island, was discovered 5 km west of Seattle (*3*). Peat analyzed by carbon dating shows that the uplift happened between 500 and 1700 years ago. Just to the north, one site shows no evidence for uplift and another farther north shows subsidence in the same time frame. Dating at further sites to the south and east suggest a sudden regional uplift (*10*), again in the same time period. Although there is no fault rupture—in the sense of a sharp offset of the surface—the juxtaposition of uplift and subsidence is consistent with movement on a south-dipping reverse fault buried in the crust (*3*). The inferred fault occurs very close to a long-known east-west trending gravity anomaly, now termed the Seattle Fault, and the amount of uplift suggests an earthquake of magnitude 7 or larger.

An immediate effect of the sudden uplift during the earthquake was a local tsunami as the displaced water sloshed in the narrow channels. At two sites north of Restoration Point, Atwater and Moore (*4*) found unusual sand layers in tidal marsh deposits. Such layers have recently been recognized as representing sand washed onshore by tsunamis. Vegetation and wood associated with the sand layers are dated to between 850 and 1250 years ago, showing a temporal association with the Restoration Point uplift.

The ground shaking from the earthquake caused rock avalanches in the Olympic Mountains that dammed streams to form lakes (*5*). Drowned trees in the lakes date to between 1000 and 1300 years ago, the same period as the uplift. Closer to Restoration Point, the shaking induced landslides in three parts of Lake Washing-

The author is in the Geophysics Division, Geological Survey of Canada, Ottawa K1A 0Y3, Canada.

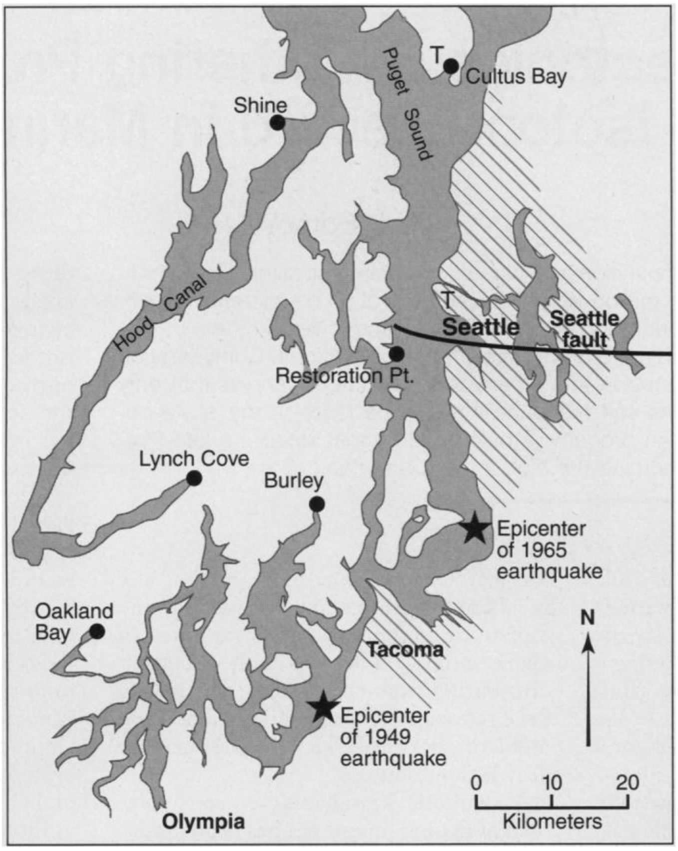
ton. These large landslides carried trees in growth position to the bottom of the lake. Initial coring and dating of the trees was performed by divers working under difficult conditions (6). Economics fortuitously intervened, as the commercial value of the drowned trees was sufficient to justify their recovery by barge, resulting in very large samples for analysis. Carbon-14 dating had previously established an age of about 1000 years for all three landslides, consistent with a single triggering event. A pair of high-precision carbon-14 dates gives the best estimate for the age of the event, between 1000 and 1100 years ago. Detailed tree ring counting—dendrochronology—could provide a more precise calendar date and also confirm that the trees on the three landslides died at the same time, but suitable samples have not been obtained.

About the same time as the landslides, sediment on the bottom of Lake Washington was resuspended and moved downslope as turbidity currents that appear to have multiple, but simultaneous origins (7). The most dominant turbidity in the top 2 m of sediment was deposited about 940 to 1280 years ago, consistent with it being caused by the earthquake. Other turbidites may represent the shaking from previous earthquakes, potentially giving a history of shaking from both near and far earthquakes.

Perhaps the single key to success in paleoseismology is precise dating. Improvements in the field have resulted from the application of high-precision carbon-14 dating, the combination of high-precision dating with tree ring counts to resolve ambiguity in converting carbon-14 years to calendar years (*11*), and direct application of dendrochronology. Success has come not only from applying or developing new concepts (this is still a new field), but also from luck. Luck was on the side of these scientists. At West Point, Seattle, Atwater and Moore found a Douglas fir log uprooted by the tsunami. Tree ring correlation showed that the tree died in the same season of the same year as the drowned trees on one of the Lake Washington landslides (6). Here was the final link in the chain of effects that pointed conclusively to an earthquake cause: two phenomena in different bodies of water, and so implausibly coincidental if they did not have a common earthquake cause.

The paleoseismological studies in the five reports therefore demonstrate a large earthquake occurred little more than a thousand years ago in the shallow crust under Seattle. Deformation and shaking effects suggest a magnitude of 7 or greater. Shallow crustal earthquakes of this size are not unknown in the northwest—the 1872 earthquake (magnitude about 7) is ascribed to the Lake Chelan area 150 km northeast of Seattle—but for one to have occurred so close to Seattle and so recently is unexpected. Perhaps earthquakes of this size could occur anywhere in the Puget Lowlands Strait of Georgia region. If so, the major cities of Seattle and Vancouver may be at greater risk than anticipated, for such a shallow, nearby earthquake would be much more devastating than even a great earthquake on the distant Cascadia subduction zone. A Cascadia earthquake would cause strong long-duration shaking at Seattle, but a repeat of the paleo-earthquake would cause extremely strong shaking, tsunamis in Puget Sound, and meters of ground uplift and subsidence over large populated areas.

There has not yet been time to assess the hazard implications of the Seattle Fault: to do so will need an interpretation of the earthquake activity on the fault [current microearthquakes in this area are monitored by the University of Washington and the U.S. Geological Survey (USGS)], strain changes across the fault (monitored by a USGS geodetic network), an estimate of the length and slip of the known paleo-earthquake, and most importantly the dates of any previous earthquakes. Thus there is still considerable work for paleoseismologists.



Ancient earthquake. Map shows location of Restoration Point, site of the uplifted terrace, and Lake Washington, where trees sent to the bottom by landslides were cored and dated. Solid line indicates the Seattle Fault. T marks locations of tsunami deposits. [Adapted from (*3*)]

REFERENCES AND NOTES

1. B. F. Atwater, *J. Geophys. Res.* **97**, 1901 (1992).
2. _____, *Science* **236**, 942 (1987).
3. R. C. Bucknam, E. Hemphill-Haley, E. B. Leopold, *ibid.* **258**, 1611 (1992).
4. B. F. Atwater and A. L. Moore, *ibid.*, p. 1614.
5. R. L. Schuster, R. L. Logan, P. T. Pringle, *ibid.*, p. 1620.
6. G. C. Jacoby, P. L. Williams, B. M. Buckley, *ibid.*, p. 1621.
7. R. E. Karlin and S. E. B. Abella, *ibid.*, p. 1617.
8. G. J. Lensen, *Geol. Soc. Am. Bull.* **79**, 545 (1968); H. W. Wellman, *Nature* **237**, 275 (1972).
9. R. E. Wallace, *Geol. Soc. Am. Bull.* **81**, 2875 (1970); K. E. Sieh, *J. Geophys. Res.* **83**, 3907 (1978).
10. Perhaps not all related to the fault causing the uplift of Restoration Point, see Bucknam *et al.* (*3*).
11. B. F. Atwater, M. Stuiver, D. K. Yamaguchi, *Nature* **353**, 156 (1991).