Prehistoric Rock Avalanches in the Olympic Mountains, Washington
Author(s): Robert L. Schuster, Robert L. Logan, Patrick T. Pringle
Source: *Science*, New Series, Vol. 258, No. 5088 (Dec. 4, 1992), pp. 1620-1621
Published by: American Association for the Advancement of Science
Stable URL: http://www.jstor.org/stable/2882062
Accessed: 08/12/2009 19:31

17. S. G. Wakeham and R. Carpenter, *Limnol. Oceanogr.* **21**, 711 (1976).
18. For core 15, 100 years were subtracted from the raw ^{14}C date to account for its position 6 cm below the turbidite. The quoted uncertainties are one standard deviation estimates of counting error plus estimated uncertainties due to the $\delta^{13}C$ correction. Uncertainties on the dates ranged from about ±80 to ±192 years.
19. D. S. McCullough, *U.S. Geol. Surv. Prof. Pap. 543B* (1966).
20. J. I. Hedges, J. R. Ertel, E. B. Leopold, *Geochim. Cosmochim. Acta* **46**, 1869 (1982).
21. R. C. Bucknam, E. Hemphill-Haley, E. B. Leopold, *Science* **258**, 1611 (1992).
22. S. E. B. Abella, unpublished data.
23. B. F. Atwater, *Science* **236**, 942 (1987).
24. ______, *J. Geophys. Res.* **97**, 1901 (1992).
25. M. E. Darienzo and C. D. Peterson, *Tectonics* **9**, 1 (1990).
26. J. R. Wilson, M. J. Bartholomew, R. J. Carson, *Geology* **7**, 235 (1979).
27. B. F. Atwater and A. L. Moore, *Science* **258**, 1614 (1992).
28. B. F. Atwater and D. K. Yamaguchi, *Geology* **19**, 706 (1991).
29. We thank the captain and crew of the R/V *Thompson* and R/V *Barnes* for their help in coring operations. Radiocarbon analyses were done by Beta Analytic, Inc. Laboratory assistance was provided by R. Chartier, S. Weaks, J. Das, H. Zhang, A. Morsell, and R. Burnley. We thank J. Yount, B. F. Atwater, W. B. Lyons, and two anonymous referees for reviews. This research was partially supported by U.S. Geological Survey/National Earthquake Hazards Reduction Program grant 1434-92-G-1288 (R.E.K.), an A. W. Mellon Foundation grant, and National Science Foundation grant BSR82-143464 to W. T. Edmondson, which supported the ship operations.

24 July 1992; accepted 6 November 1992

Prehistoric Rock Avalanches in the Olympic Mountains, Washington

Robert L. Schuster, Robert L. Logan, Patrick T. Pringle

Rock avalanches blocked streams in the Olympic Mountains southwest of Puget Sound during the past few thousand years. Limiting radiocarbon ages indicated that three or four of six avalanches occurred from 1000 to 1300 years ago or shortly thereafter. Most of the dates were from the outer preserved rings of trees drowned behind avalanche dams. These three or four avalanches may be coeval not only with one another but also with abrupt tectonic deformation in western Washington. No rock avalanches in the Olympic Mountains are known to have resulted from storms or earthquakes during the past century. The avalanches strengthen the case that a large prehistoric earthquake occurred in the Puget Sound region.

Prehistoric earthquakes in western Washington have been inferred from features that suggest abrupt uplift (*1*), abrupt subsidence (*2, 3*), and tsunamis (*2, 3*). Although all of these features are consistent with earthquake-induced deformation, none of them demonstrates seismic shaking. Seismic shaking could be recorded by rock avalanches, which can be triggered by large earthquakes (*4*). We found 11 large prehistoric rock avalanches in mountains southwest of Puget Sound. We propose that at least three of these avalanches represent strong shaking in western Washington, and that this shaking may have accompanied abrupt vertical tectonic movement in the region.

The 11 rock avalanches are in the southeastern Olympic Mountains. All of the avalanches consist primarily of large boulders derived from Tertiary basalt, which is widespread on the south, east, and north sides of the range (*5*). Five of the avalanches blocked streams and produced small lakes (300 to 800 m long) in which trees died. The dams were 10 to 20 m high and as much as 300 m long.

Radiocarbon ages were obtained from plant remains associated with six of the rock avalanches (Table 1). At Jefferson Lake, Lower Dry Bed Lake, Spider Lake, and Lena Lake [see figure 1 of (*1*)], we dated the outer 10 to 30 rings preserved in bark-free trunks of separate standing dead trees (snags) that protrude from the lakes at times of low water (Fig. 1) (*6*). For each snag, we assumed that the dated rings predated the avalanche by no more than 100 years. The assumption is based on the belief that the trees died within a year of being drowned behind a rock-avalanche dam and on circumstantial evidence that the trunks have lost fewer than 100 external rings to postavalanche decay and erosion. At the Hamma Hamma River, we dated detrital wood and charcoal in lacustrine deposits behind a now-breached avalanche dam, and at Lake Cushman we dated stumps from a quarry in an avalanche (*7*).

The radiocarbon ages show that three or four of the six avalanches may have happened at the same time. The ages for the snags at Jefferson, Lower Dry Bed, and Spider Lakes overlap one another at or near 1 standard deviation. Snags at Lena Lake yielded somewhat greater ages; either the avalanche there is somewhat older or the dated snags have lost more rings than assumed. The other two avalanches yielded ages that are distinctly older (Hamma Hamma River) or younger (Lake Cushman). The weighted mean of the radiocarbon ages from Jefferson, Lower Dry Bed, and Spider lakes (1197 ± 23 ^{14}C years before the present) corresponds to a calibrated (approximately calendric) age in the range 1000 to 1300 years ago (*8*).

Three points suggest that strong shaking triggered most or all of the six avalanches, whatever their ages: (i) The basalt that avalanched is not known to have failed historically, either during storms or during the largest 20th-century earthquake at Puget Sound, which occurred in 1949 with a magnitude of 7.1 and a hypocentral depth of 54 km [(*9*); epicenter shown in figure 1 of (*1*)]. (ii) Worldwide, earthquakes triggered 29 of 71 rock ava-

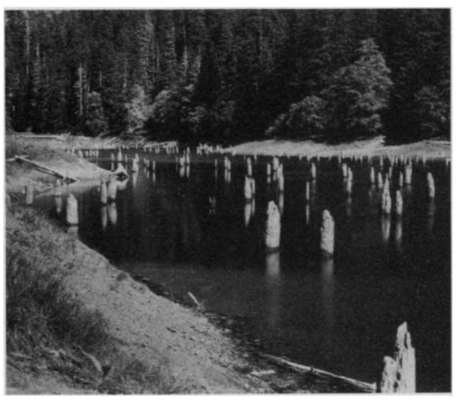

Fig. 1. Drowned snags extending above surface of Spider Lake at low-water level, September 1992.

Table 1. Radiocarbon ages (*13*) of wood and charcoal associated with rock avalanches in the Olympic Mountains

Avalanche location*	Sample (Beta-)	Age (^{14}C yr B.P.)
Lake Cushman (*7*)	50539	400 ± 50
	50540	420 ± 50
Jefferson Lake	42123	1150 ± 50†
	42124	1210 ± 50†
Lower Dry Bed Lake	50544	1180 ± 50
Spider Lake	50550	1260 ± 50
	50602	1180 ± 60
Lena Lake	32671	1340 ± 50†
	32672	1300 ± 50†
Hamma Hamma River (*7*)	50598	2900 ± 60
	39798	2960 ± 80†

*See figure 1 of (*1*). †$\delta^{13}C$ not measured. Age normalized to assumed $\delta^{13}C$ of −25 per mil.

R. L. Schuster, U.S. Geological Survey, Box 25046, Mail Stop 966, Denver, CO 80225.
R. L. Logan and P. T. Pringle, Washington Department of Natural Resources, Division of Geology and Earth Resources, Post Office Box 47007, Olympia, WA 98504–7007.

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.

REFERENCES AND NOTES

1. R. C. Bucknam, E. Hemphill-Haley, E. B. Leopold, *Science* **258**, 1611 (1992).
2. B. F. Atwater, *J. Geophys. Res.* **97**, 1901 (1992).
3. ——— and A. L. Moore, *Science* **258**, 1614 (1992).
4. A study of the classes of landslides caused by 40 major historic earthquakes has estimated minimum Richter magnitudes (M_L) required for triggering various types of landslides: (i) $M_L \geq 4.0$: rock falls, rock slides, soil falls, and disrupted soil slides; (ii) $M_L \geq 4.5$: soil slumps and soil block slides; (iii) $M_L \geq 5.0$: rock slumps, rock block slides, slow earth flows, soil lateral spreads, rapid soil flows, and subaqueous landslides; (iv) $M_L \geq 6.0$: rock avalanches, and (v) $M_L \geq 6.5$: soil avalanches [D. K. Keefer, *Geol. Soc. Am. Bull.* **95**, 406 (1984)].
5. R. W. Tabor and W. M. Cady, *U.S. Geol. Surv. Misc. Inv. Ser. Map I-994* (1978).
6. The lack of preserved bark on the dated parts of the drowned trees precluded precision tree-ring cross-dating of the year of tree death.
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.
9. L. L. Noson, A. Qamar, G. W. Thorsen, *Wash. Div. Geol. Earth Res. Inform. Circ. 85* (1988).
10. J. E. Costa and R. L. Schuster, *U.S. Geol. Surv. Open-File Rep. 91-239* (1991).
11. N. D. Perrin and G. T. Hancox, *Proceedings of the 6th International Symposium on Landslides*, Christchurch, New Zealand, 10 to 14 February (Balkema, Rotterdam, 1992), vol. 2, p. 1457.
12. G. C. Jacoby, P. L. Williams, B. M. Buckley, *Science* **258**, 1621 (1992).
13. Reported ages (^{14}C year B.P.) are conventional radiocarbon ages, corrected for the measured $^{13}C/^{12}C$ ratio with 1 standard deviation in the age derived from statistics of counting radioactive disintegrations. Ages are reported with respect to 1950 A.D.

14. We would like to thank B. F. Atwater and R. F. Madole for critical reviews.

24 July 1992; accepted 22 October 1992

Tree Ring Correlation Between Prehistoric Landslides and Abrupt Tectonic Events in Seattle, Washington

Gordon C. Jacoby, Patrick L. Williams, Brendan M. Buckley

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

G. C. Jacoby and B. M. Buckley, Tree-Ring Laboratory, Lamont-Doherty Geological Observatory, Palisades, NY 10964.
P. L. Williams, Earth Sciences Division, Lawrence Berkeley Laboratory, University of California, Mail Stop 50E, 1 Cyclotron Road, Berkeley, CA 94720.