


Research Article

Age of the late Holocene Bonneville landslide and submerged forest of the Columbia River Gorge, Oregon and Washington, USA, by radiocarbon dating

Nathaniel D. Reynolds^{a*} , Jim E. O'Connor^b, Patrick T. Pringle^c, Alex C. Bourdeau^d and Robert L. Schuster^e

^aCowlitz Indian Tribe, Cultural Resources Department, 1055 9th Ave, Longview, WA 98632, USA [retired]; ^bU.S. Geological Survey, 2130 SW 5th Ave., Portland, OR 97201, USA; ^cCentralia College, 600 Centralia College Blvd., Centralia, WA 98531, USA [retired]; ^dU.S. Fish and Wildlife Service Region 1, 20555 SW Gerda Lane, Sherwood, OR 97140, USA [retired] and ^eU.S. Geological Survey, 1711 Illinois Street, Golden, CO 80401, USA [retired]

Abstract

The late Holocene Bonneville landslide, a 15.5 km² rockslide-debris avalanche, descended 1000 m from the north side of the Columbia River Gorge and dammed the Columbia River where it bisects the Cascade Range of Oregon and Washington, USA. The landslide, inundation, and overtopping created persistent geomorphic, ecologic, and cultural consequences to the river corridor, reported by Indigenous narratives and explorer accounts, as well as scientists and engineers. From new dendrochronology and radiocarbon dating of three trees killed by the landslide, one entrained and buried by the landslide and two killed by rising water in the impounded Columbia River upstream of the blockage, we find (1) the two drowned trees and the buried tree died the same year, and (2) the age of tree death, and hence the landslide (determined by combined results of nine radiocarbon analyses of samples from the three trees), falls within AD 1421–1455 (3 σ confidence interval). This result provides temporal context for the tremendous physical, ecological, and cultural effects of the landslide, as well as possible triggering mechanisms. The age precludes the last Cascadia Subduction Zone earthquake of AD 1700 as a landslide trigger, but not earlier subduction zone or local crustal earthquakes.

Keywords: Bonneville landslide, Columbia River Gorge, Submerged forest of the Columbia, Bridge of the Gods

(Received 26 April 2021; accepted 3 February 2022)

INTRODUCTION

The late Holocene Bonneville landslide dammed the Columbia River in the Columbia River Gorge where the river bisects the volcanic arc of the Cascade Range in the U.S. Pacific Northwest. This report describes new analysis of landslide age by radiocarbon dating three trees killed by the landslide—two drowned by rising water of the impounded Columbia River and one killed by uprooting and burial within the landslide itself. Our analysis builds on a long history of earlier studies of the landslide, its consequences, and several attempts at dating, which we first summarize. We then describe the sampled trees, collected decades ago, including their acquisition and provenance. Our analysis consists of two steps: (1) dendrochronology to show all three trees indeed died the same year; and (2) radiocarbon analysis of multiple samples from each of the trees, combined to give a precise estimate of tree death, and hence landslide occurrence.

The Bonneville Landslide and the “Submerged Forest”

The Bonneville landslide is a 15.5 km² rockslide-debris avalanche (Coe, 2019; Fig. 1) within the larger Cascade landslide

complex in the central part of the 1000-m-deep Columbia River Gorge (Fig. 2). Landslides have continuously widened the canyon, especially on the north side where south-dipping, clay-rich contacts within weathered volcanoclastic rocks promote south-moving mass movements (Waters, 1973; Palmer, 1977; Sager, 1989; Schuster and Pringle, 2002; Pierson et al., 2016). The Bonneville landslide headed from 1040 m on Table Mountain, descended to the tidal Columbia River and 2 km across the valley bottom, blocking it with a 90–120 m high lobe of bedrock blocks and granular matrix (Palmer, 1977). Recent mapping and analysis show parts of the Cascade landslide complex and other Gorge landslides are seasonally active (Pierson et al., 2016; Tong and Schmidt, 2016), but the Bonneville landslide itself is stable.

The Bonneville landslide impounded a temporary lake 75–80 m deep to an elevation of ~85 m NAVD (Hodge, 1938; all elevations referenced to North American Vertical Datum of 1988), containing as much as 10 km³ of water (as estimated from 30 m resolution digital elevation data) and extending >200 km upriver (O'Connor and Burns, 2009; O'Connor et al., 2021). Subsequent overtopping of the landslide dam incised a 12 km-long new channel around the southern margin of the landslide and lowered the level of the temporary lake, eventually to the historic low-water elevation of ~14.5 m above the remaining blockages. These obstructions formed a series of rapids known as the Cascades that impounded the river ~11.5 m (low-water drop, greater at

*Corresponding author email address: <ndalereynolds@gmail.com>

Cite this article: Reynolds ND, O'Connor JE, Pringle PT, Bourdeau AC, Schuster RL (2022). Age of the late Holocene Bonneville landslide and submerged forest of the Columbia River Gorge, Oregon and Washington, USA, by radiocarbon dating. *Quaternary Research* 109, 65–82. <https://doi.org/10.1017/qua.2022.7>

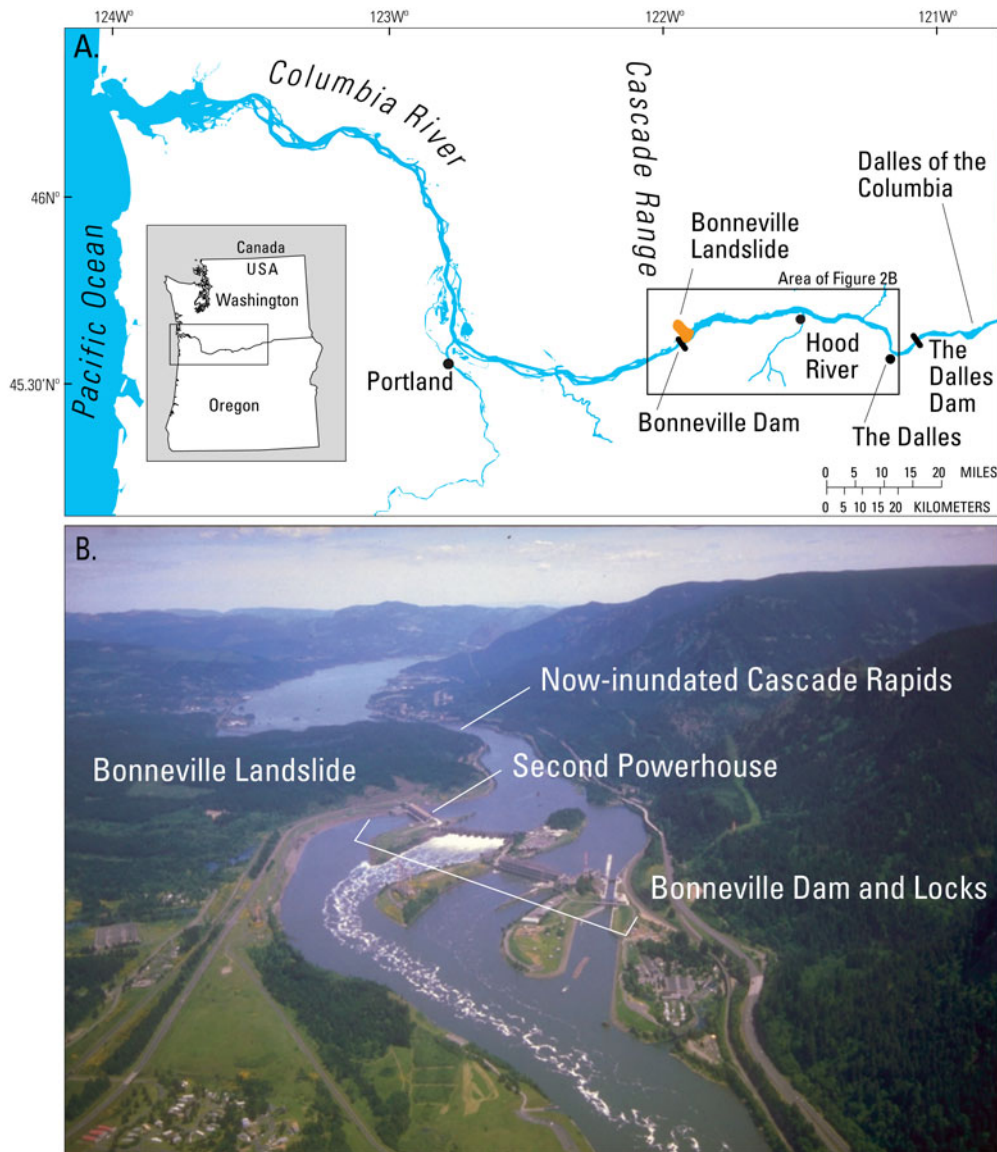


Figure 1. Locations of interest. (A) Regional map of the lower Columbia River, showing location of Bonneville landslide, Bonneville Dam, and the area of the map of drowned forest shown in Figure 2B. (B) View east and upriver of Bonneville Dam and Locks and the toe of the Bonneville landslide, which descended from the north (left) and blocked and displaced the Columbia River two km southward. Bonneville Dam was closed in 1938, inundating the remains of the submerged forest. The second powerhouse was constructed in the late 1970s and early 1980s; excavation for the foundation and the tailrace channel uncovered the Powerhouse tree used in this analysis. U.S. Army Corps of Engineers photograph, ca. 1995.

high flows) above the pre-landslide river level, which was likely close to the historic pre-damming, low-water level below the Cascades rapids of 3.0 m. The still-impounded river above the Cascades rapids extended 68 km upstream to the foot of the bedrock rapids and falls known as “The Dalles of the Columbia.” This sequence was elaborated in Indigenous cultural narratives of the “Bridge of the Gods,” which described the blockage, upstream impoundment, breaching, and appearance of the Cascades rapids (Lee and Frost, 1844; Gibbs, 1854; Tappan, 1854; Saylor, 1900; Condon, 1910; Judson, 1910; Lyman, 1915; Clark, 1952, 1953; Lawrence and Lawrence, 1958; Deloria, 1997; Budhwa, 2002). The sequence of events and features was first fully written in a geologic narrative by Williams (1916).

One consequence of the historically persistent ~11.5 m impoundment above the Cascade rapids was the “submerged forest” of the Columbia, as named by Frémont in 1843 (Frémont and

Smucker, 1856, p. 335). The submerged forest consisted of snags protruding from the river and flanking beaches at low water within the remnant-impounded reach of the river (Fig. 2). William Clark’s journal entry for October 30, 1805, during the westward leg of the Lewis and Clark expedition, is the first written Western observation of the submerged forest. He noted, in his free-form spelling and grammar, “the stumps of Pine trees are in many places are at Some distance in the river” (Moulton, 2002, pp. 354–355). Clark’s initial description of the submerged snags was followed by those of many explorers and geologists (summarized by Barry, 1935; Lawrence, 1936; and O’Connor, 2004), even meriting a footnote in Lyell’s foundational *Principles of Geology* (1832). Not until the early twentieth century, however, was the submerged forest understood to be the remains of a forest fringing the pre-landslide Columbia River, when river

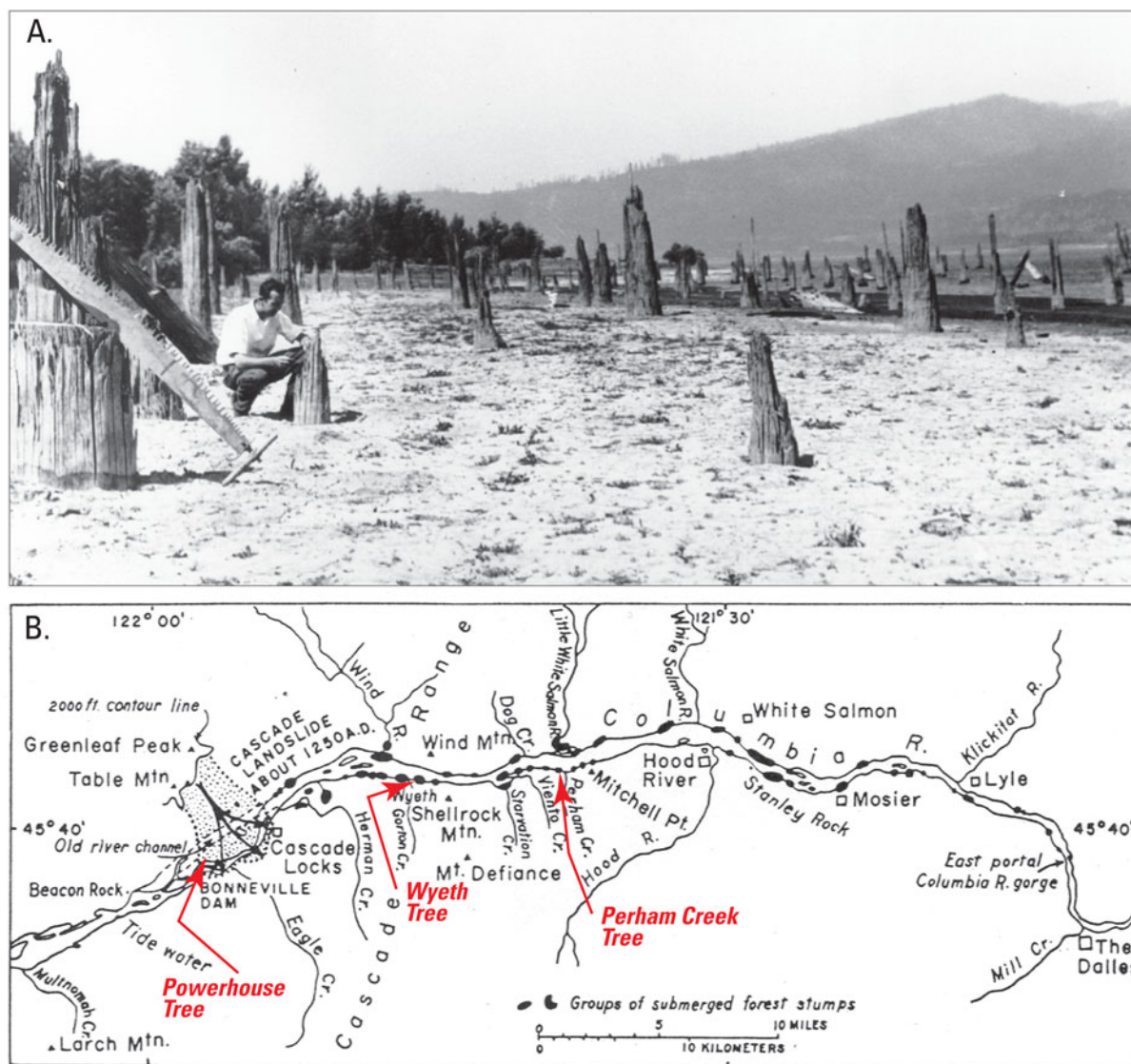


Figure 2. The submerged forest of the Columbia. (A) The Wyeth group of submerged snags exposed at low flow on August, 21, 1934. Accompanying caption reads “Section of douglas fir submerged forest off Wyeth, Oregon. Douglas fir, cedar, and some oak.” This photograph, by Thornton T. Munger of the U.S. Forest Service, shows Donald B. Lawrence in the course of his dendrochronology studies. Photograph courtesy of the Oregon Historical Society, negative number OrHi 95467. (B) Map of submerged forest stumps as it appeared in Lawrence and Lawrence (1958), annotated with collection locations of Powerhouse, Wyeth, and Perham Creek samples.

elevation was ~ 11.5 m lower (Gilbert, 1899, 1900; Harza, 1916; Williams, 1916; Hodge, 1932; Holdredge, 1937). The submerged forest was most thoroughly studied by Lawrence (1936, 1937), who counted ~ 3000 standing snags of Douglas-fir, western redcedar, ponderosa pine, and Garry oak in groups extending 60 km upriver of the landslide dam.

After Williams' (1916) compelling assessment linking the drowned forest to the landslide, subsequent studies mostly focused on the cause and consequences of the landslide, first motivated by the search for dam sites on the lower Columbia River (Hodge, 1932, 1938; Holdredge, 1937; Palmer, 1977). These studies ultimately led to the building and 1938 closure of Bonneville Dam (Fig. 1B), cutting of remnant submerged forest snags in the reservoir area as hazards to navigation, and the subsequent drowning of the Cascades rapids and submerged forest stumps by Lake Bonneville, the dam's reservoir.

Another persistent line of inquiry has been the landslide's effects on pre-contact Indigenous cultures in the region (Lawrence and Lawrence, 1958; Sanger, 1967; Browman and Munsell, 1969; Minor, 1984; Bourdeau, 1999; Schuster and Pringle, 2002; O'Connor, 2004). Key aspects include potential effects on fish passage (Lawrence and Lawrence, 1958; Sanger, 1967; Hutchinson and Hall, 2019) and effects of Indigenous settlement patterns and movements in the region (Pettigrew, 1981; Lunney and Taylor, 2000; Bourdeau 2004).

More recently, possible triggering mechanisms have spurred research into the Bonneville landslide (e.g., Schuster and Pringle, 2002) and other landslides in the region (e.g., Schuster et al., 1992; Schulz et al., 2012; Leithold et al., 2018, 2019; LaHusen et al., 2020; Struble et al., 2020). These studies have mostly evaluated evidence for initiation by the last Cascadia Subduction Zone earthquake of AD 1700 or by rupture of a

shallow crustal fault, but hydrological causes also have been evaluated (e.g., Henn *et al.*, 2015; Struble *et al.*, 2021).

Previous Assessments of Landslide Age

Central to understanding the causes and consequences of the Bonneville landslide is its timing. Approaches to dating have varied, including interpreting indigenous and explorer narratives (Barry, 1935), dendrochronology (Gilbert, 1900; Lawrence, 1936, 1937; Hodge, 1938; Pringle *et al.*, 2002; Weaver and Pringle, 2003), radiocarbon dating (Lawrence and Lawrence, 1958; Minor, 1984; O'Connor *et al.*, 1996; Pringle *et al.*, 2002), lichenometry (Reynolds, 2001), and thermoviscous remanent magnetism (Smith and Verosub, 1994). These studies have given conflicting results, ranging from AD 1100 (Minor, 1984) to AD 1775 (Barry, 1935), a range causing substantial uncertainty with respect to hazard assessments, understanding of ecological and cultural effects, and plausible triggering mechanisms such as earthquakes.

The first assessments were dendrochronologic, either by counting rings of trees growing on and presumably post-dating the landslide or by attempting to cross-date the landslide by comparing tree-ring width patterns from cut samples of the submerged forest with nearby live trees. From counts of “rings in the stumps of trees which had grown on the landslide,” Gilbert (1900, p. 99–100) suggested the landslide was “not less than 350 years old” (ca. AD 1550). Hodge (1938, p. 916–917) reported an attempt at cross-dating, but found no evident correlation or overlap between the drowned trees and nearby live trees. He did note, however, the oldest trees on the landslide were 250 years old, thereby giving a minimum age (ca. AD 1690) for the landslide. Lawrence (1936, 1937) conducted the most detailed study, excavating and cutting rounds from six trees of the submerged forest as well as three live trees from nearby valley slopes. From ring-width patterns, he concluded at least four of the submerged forest trees died the same year, consistent with them being killed by rapid impoundment of the Columbia River, probably within days or weeks of the landslide. But like Hodge (1938), he could not correlate the submerged trees with live trees, thus concluding the landslide preceded the ca. AD 1720 germination of his oldest sampled live tree (Lawrence, 1936). Later, from ring counts of trees growing on the landslide and thus inferred to postdate the landslide, Lawrence (1937) concluded the landslide dated to sometime before AD 1562, similar to Gilbert’s (1900) conclusion. Weaver and Pringle (2003) also counted annual rings for tens of old trees growing on the surface of the landslide, showing the landslide dated to before AD 1550.

Lawrence and Lawrence (1958) provided the first radiocarbon analyses for landslide age by dating samples of two of the submerged forest snags (Table 1). The resulting ages of 670 ± 300 and 700 ± 200 ^{14}C yr BP (obtained before the now-standard practice of calibrating radiocarbon age results to calendar years) led them to propose the landslide blocked the river ca. AD 1250. Since these very early radiocarbon analyses, more radiocarbon dating has been performed in connection with archaeological and geologic investigations conducted in the late 1970s and 1980s during construction of the second Bonneville Dam powerhouse and channel excavated into the southern margin of the landslide (Fig. 1B). Radiocarbon ages compiled by Minor (1984; Table 1) include five samples of wood from material buried in the landslide or in Columbia River alluvium below the landslide. These ranged from 5550 ± 90 ^{14}C yr BP to 400 ± 70 ^{14}C yr BP. One

sample came from the outer rings of a “tree covered by landslide debris” excavated during construction of the second powerhouse. This sample of what we term the Powerhouse tree (Table 2) gave an age of 830 ± 60 ^{14}C yr BP, leading Minor to suggest the landslide occurred ca. AD 1100. In making this assessment, Minor (1984, p. 10) dismissed the 400 ± 70 ^{14}C yr BP age from detrital wood fragments in alluvium below slide debris as “inconsistent with its order in the stratigraphic sequence,” speculating that “it may date a secondary deposit on top of Bonneville landslide deposits.” Schuster and Pringle (2002) later obtained two younger ages, 360 ± 50 ^{14}C yr BP and 410 ± 50 ^{14}C yr BP, from the same Powerhouse tree, contrasting with the 830 ± 60 ^{14}C yr BP age obtained by Minor (1984). These results, in conjunction with the previously dismissed 410 ± 50 ^{14}C yr BP age reported by Minor (1984), led Schuster and Pringle (2002) to suggest the landslide was younger, dating between AD 1670 and AD 1760, possibly coincident with and triggered by the most recent Cascadia subduction zone earthquake of January 26, 1700 (Satake *et al.*, 1996; Atwater *et al.*, 2005).

NEW DENDROCHRONOLOGIC AND RADIOCARBON ANALYSIS

Our study consists of new dendrochronologic and radiocarbon analyses of the Powerhouse tree and two of Lawrence’s rounds excavated and cut from the submerged forest in 1934—one from the Perham Creek site and another from the Wyeth site (Fig. 2; Table 2). Because these samples have complicated histories and prior analyses affecting interpretation, we initially detail their provenance. We follow with our new dendrochronologic assessment of whether these three trees died the same year. Concluding they do, we use new radiocarbon analyses to determine a precise age estimate for their demise and thus the time of the Bonneville landslide.

Sources of Data

The Powerhouse Tree

During the 1970s, the U.S. Army Corps of Engineers constructed a second powerhouse at Bonneville Dam, north of the original 1938 structure and on the toe of the Bonneville landslide (Fig. 1B; Sager, 1989). During excavation for the foundation, an 18-m-long, bark-bearing Douglas-fir tree bole and root wad, but missing branches, was retrieved from deep within the landslide deposit (Fig. 3A). The tree showed no evidence of pre-burial decay; thus we infer it was living at the time of entrainment and burial by the landslide. Upon excavation, it was cut into various sections, many of which were intended for display at regional museums and interpretive centers. It was from a sample of this tree that Minor (1984) obtained a radiocarbon age indicating a date of ca. AD 1100 for the landslide. Schuster and Pringle (2002) later obtained radiocarbon ages from a section of this tree indicating the landslide occurred as recently as AD 1700. These samples were later determined to have possibly been contaminated by wood preservative applied to the surface of the section they sampled.

Our current analysis is bolstered by discovery of a different portion of the Powerhouse tree—a single cross-section round from the main stem of the tree on display at the Willamette Locks Museum in Oregon City, Oregon, USA (Fig. 3B). In contrast to the previously sampled portion of the Powerhouse tree from the Columbia Gorge Interpretive Center, this round shows no evidence of preservative.

Table 1. Radiocarbon ages from previous and current studies directly relevant to age of the Bonneville landslide.

Sample identification	Location (WGS84)		Material dated	Lab ID	Corrected conventional radiocarbon age	Reported uncertainty (1 σ error)	$^{13}\text{C}/^{12}\text{C}$	Offset	Calibrated age (3 sigma range; 99.7% probability)	Source	Comments
	Latitude	Longitude			^{14}C yr BP	yr	‰	yr			
Lawrence Wyeth stump no. 2	45.695	-121.767	Douglas fir	M-722	670	300	-		AD 530-1950	Lawrence and Lawrence (1958); Crane and Griffin (1959, p. 175-176)	Analysis conducted of slice of entire round; uncertainty based on counting uncertainty plus "best estimate about the additional uncertainties attendant in the measurement of the particular sample" (Crane and Griffin, 1958); location estimated from Lawrence and Lawrence (1958) map and description
Garry oak	45.711	-121.476	Garry oak	M-761	700	200	-		AD 667-1698 (98.8%)	Lawrence and Lawrence (1958); Crane and Griffin (1959, p. 176)	Analysis conducted of slice of entire round; uncertainty based on counting uncertainty plus "best estimate about the additional uncertainties attendant in the measurement of the particular sample" (Crane and Griffin, 1958); location estimated from Lawrence and Lawrence (1958) map and description
BDH-1094	45.650	-121.934	Wood fragments (unspecified)	Beta-9958	400	70	-		AD 1386-1675 (98.6%)	Minor (1984)	Elevation 11.6 m (NAVD88); within Columbia River alluvium beneath landslide, at very base of slide debris according to U.S. Corps of Engineers (1977) geotechnical boring log
BDH-1082	45.650	-121.934	Wood fragments (unspecified)	Beta-9957	3670	80	-		2456-1743 BC	Minor (1984)	Elevation 8.8 m (NAVD88); within "uniform micaceous sand" above "Reworked slide debris" in U.S. Corps of Engineers (1977) geotechnical boring log
BDH-1407	45.650	-121.934	Wood fragments (unspecified)	Beta-9959	4770	80	-		3801-3331 BC (99.6%)	Minor (1984)	Elevation -2.7 m (NAVD88); within "Reworked slide debris" in U.S. Corps of Engineers (1977) geotechnical boring log
Sample B	45.650	-121.934	Wood from small oak tree	Beta-9961	5550	90	-		4708-4155 BC (98.2%); 4140-4052 BC (1.5%)	Minor (1984)	Elevation -11.2 m (NAVD88); within Columbia River alluvium beneath landslide
Sample A	45.650	-121.934	Douglas fir (Powerhouse tree)	Beta-9960	830	60	-		AD 1024-1302 (99.6%)	Minor (1984; 1993 writ. commun.)	Elevation 13.2 m (NAVD88); within slide debris; sample of outermost 20 rings; relation to preserved bark uncertain
BON#2	45.650	-121.934	Douglas fir (Powerhouse tree)	Beta-105793	410	50	-29.1		AD 1404-1646	Schuster and Pringle (2002)	Sample of 15 rings bark-covered root, centroid 120 rings from bark; possibly contaminated with wood preservative polyethylene glycol
BON#1	45.650	-121.934	Douglas fir (Powerhouse tree)	Beta-92227	360	50	-26.8		AD 1425-1640	Schuster and Pringle (2002)	Sample of 20 rings from bark-covered root, centroid 20 rings from bark; possibly contaminated with wood preservative polyethylene glycol

(Continued)

Table 1. (Continued.)

Sample identification	Location (WGS84)		Material dated	Lab ID	Corrected conventional radiocarbon age	Reported uncertainty (1 σ error)	$^{13}\text{C}/^{12}\text{C}$	Offset	Calibrated age (3 sigma range; 99.7% probability)	Source	Comments
	Latitude	Longitude			^{14}C yr BP	yr	‰	yr			
Powerhouse C 2-6	45.650	-121.934	Douglas fir (Powerhouse tree; rings 2-6)	WW-5346	655	30	-23.6	132.0	AD 1267-1400	This study	Dendrochronology sample pow01e, rings 2-6
Powerhouse C 130-134	45.650	-121.934	Douglas fir (Powerhouse tree; rings 130-134)	WW-5347	470	30	-22.1	4.0	AD 1396-1495	This study	Dendrochronology sample pow01e, rings 130-134
Wyeth X-1 (8-17)	45.695	-121.767	Douglas fir (rings 8-17)	CAMS-83271	560	40	-24.9	114.5	AD 1295-1446	This study	Lawrence sample; location approximate; dendrochronology sample wye01a, rings 8-17, measured from pith but not counting partly formed first ring
Wyeth X-2 (104-113)	45.695	-121.767	Douglas fir (rings 104-113)	CAMS-83272	525	40	-21.6	18.5	AD 1300-1465	This study	Lawrence sample; location approximate; dendrochronology sample wye01a, rings 104-113, measured from pith but not counting partly formed first ring
Wyeth X 1-5	45.695	-121.767	Douglas fir (rings 1-5)	WW-5349	625	30	-24.3	124.0	AD 1281-1409	This study	Lawrence sample; location approximate; dendrochronology sample wye01a, rings 1-5, measured from pith but not counting partly formed first ring
Wyeth X 119-123	45.695	-121.767	Douglas fir (rings 119-123)	WW-5350	490	45	-21.4	6.0	AD 1302-1368 (8.4%); AD 1380-1528 (90.4%)	This study	Lawrence sample; location approximate; dendrochronology sample wye01a, rings 119-123, measured from pith
Perham Creek 1-1 (6-15)	45.701	-121.646	Douglas fir (rings 6-15)	CAMS-83273	870	60	-22.6	200.5	AD 1016-1285	This study	Lawrence sample; location approximate; dendrochronology sample per01a, ring 6-15, measured from pith
Perham Creek 1-2 (87-96)	45.701	-121.646	Douglas fir (rings 87-96)	CAMS-84538	670	40	-24.0	119.5	AD 1259-1409	This study	Lawrence sample; location approximate; dendrochronology sample per01a, rings 87-96, measured from pith
Perham Creek 1 (66-70)	45.701	-121.646	Douglas fir (rings 66-70)	WW-5348	675	30	-22.2	143.0	AD 1269-1398	This study	Lawrence sample; location approximate; dendrochronology sample per01a, rings 66-70, measured from pith

Location coordinates in decimal degrees, WGS84; all locations approximate and based on original source documents and maps

Elevations relative to North American Vertical Datum of 1988 (NAVD88), adjusted +1.02 m from original reporting in NGVD29 on basis of VDatum v.4.1.2 transformation (<https://vdatum.noaa.gov/>).

Corrected radiocarbon ages (in ^{14}C yr BP) are calculated on basis of Libby half-life of 5568 years. The error stated is +/- 1 standard deviation (sigma) on basis of combined measurements of the sample, background, and modern reference standards. Age referenced to year 1950 Common Era (CE). Where no measurements of $^{13}\text{C}/^{12}\text{C}$, a value of -25‰ assumed for determining corrected conventional age.

Offsets assigned uncertainty of +/- 1 year for purposes of Oxcal "combine" analysis.

Calibrated 3-sigma calendar year age intercepts, in years relative to Common Era (CE), on basis of OxCal version 4.4.2 (5) (Bronk Ramsey, 2020) using IntCal20 Northern Hemisphere radiocarbon age calibrator curve (Reimer et al., 2020) and a laboratory error multiplier of 1; where multiple intercepts, we list all ranges of >1% likelihood; BCE indicates before common era

Sampled ring intervals measured from pith except for the Wyeth

Table 2. Summary of analyzed trees, including locations, current locations, ring counts, associated samples.

Measurement Ray	Location (WGS84)		Elevation Meters (NAVD88)	Measurement Ray	Number of measured rings	Radiocarbon sample ID	Radiocarbon sample interval, measured from innermost measured ring	Repository	Comments	
	Latitude	Longitude								
Powerhouse	45.65	-121.934	13.2	pow01a	100			Columbia Gorge Interpretive Center, Skamania, Washington, USA	From round cut from 2 m above rootball; adhering bark; pith not present; missing innermost ring relative to pow01b; outermost two rings decomposed and not measured	
				pow01b	103				From round cut from 2 m above rootball; adhering bark; pith not present	
				pow01da	105				pow01d also from round cut from 2 m above rootball, includes pith and adhering bark but composed of two sections, a and c, separated by unmeasurable decomposed section of four rings; pow01da consists of pith and innermost 105 rings; pow01dc consists of outermost 32 rings and adhering bark	
				pow01dc	32					
				pow01e	136	Powerhouse C 2-6	2-6			Willamette Locks Museum, Oregon City, Oregon, USA
						Powerhouse C 130-134	130-134			
				pow01f	130			From same round as pow01e but four innermost rings excised by collection of pow01e and two outermost rings decomposed and not measured		
Wyeth	45.695	-121.767	15	wye01a	127	Wyeth X-1 (8-17)	8-17	World Forestry Center, Portland, Oregon, USA	Pith and innermost partially formed ring not measured; attached bark	
						Wyeth X-2 (104-113)	104-113			
						Wyeth X 1-5	1-5			
						Wyeth X 119-123	119-123			
				wye01b	120			Pith and innermost 7 rings excised by collection of wye01a and not measured; bark missing but outermost ring same as outer ring of wye01a		

(Continued)

Table 2. (Continued.)

Measurement Ray	Location (WGS84)		Elevation		Number of measured rings	Radiocarbon sample ID	Radiocarbon sample interval, measured from innermost measured ring	Repository	Comments
	Latitude	Longitude	Meters (NAVD88)						
Perham Creek	45.701	-121.646	15		179	per01a		World Forestry Center, Portland, Oregon, USA	Lawrence sample Perham 1; no bark preserved; pith present; outer 32 rings inferred missing on basis of Lawrence ring count of 212 (which probably included pith)
					181	per01b			Lawrence sample Perham 1; no bark preserved; pith not counted and innermost five rings excised by collection of per01a; outer 25 rings inferred missing on basis of Lawrence ring count of 212 (which probably included pith)

All analyzed trees were Douglas fir (*Pseudotsuga menziesii*)

Location coordinates in decimal degrees, WGS84; all locations approximate and based on original source documents and maps

Elevations relative to North American Vertical Datum of 1988 (NAVD88), adjusted + 1.02 m from original reporting in NGVD29 on basis of VDatum v.4.1.2 transformation (<https://vdatum.noaa.gov/>); Lawrence sample elevations estimated on basis of

"low-water" elevation as shown in U.S. Army Corps of Engineers (1948, Appendix L, Plate 1)

Radiocarbon sample IDs as specified in Table 1

Our dendrochronologic analyses are based on both the Columbia Gorge Interpretive Center sample (for which contamination by preservative does not affect analysis or results) and the Willamette Locks Museum sample. We used three rays (radially oriented wedges cut from center to edge) obtained from a cut round of the Powerhouse tree stored at the Columbia Gorge Interpretive Center. This round was cut from ~2 m above the rootball, from which we extracted samples POW01a (100 rings), POW01b (103 rings), and POW01d (split into two incomplete parts). None of the sampled rays are complete from pith to bark, but the rays readily can be pieced together by ring tracing for a total ring count of 141 rings below preserved bark. We also analyzed two rays obtained from the round stored at the Willamette Locks Museum, sample POW01e (136 rings from outermost annual ring to pith) and POW01f (131 rings), oriented 65° to the first cut. POW01f is missing five innermost rings and pith owing to extraction of POW01e (Table 2). This round was cut from higher in the tree and hence has fewer total rings.

Our new radiocarbon dates of the Powerhouse tree derive from two 5-ring samples from the innermost and outermost sections of the uncontaminated round stored at the Willamette Locks Museum.

Trees of the submerged forest—Donald Lawrence samples from Wyeth and Perham Creek

In August and September of 1934, Lawrence (1936) collected six separate samples of standing snags of the submerged forest (Fig. 2). Because the above-ground portions of the snags had an unknown number of missing rings from erosion and decay, he excavated 1–2 m into the alluvium burying the base of each snag until reaching bark (Fig. 4A), where Lawrence (1936) reported excellent preservation of both bark and wood in the reducing conditions of the water-saturated sand and silt enclosing the stumps. Lawrence and a crew of Civilian Conservation Corps workers dug to below bark level and then, by crosscut saw, sliced rounds including the attached bark, which he affixed to the sampled round by wire banding. The six samples were four rounds of Douglas-fir and one of western redcedar from the Wyeth area, ~15 km upriver of the landslide, and a single round of Douglas-fir from near the Perham Creek confluence with the Columbia River, ~25 km upriver of the landslide (Fig. 2B). Lawrence's (1936) ring counts on the sampled trees ranged from 115–325.

It was from these samples that Lawrence correlated ring-width patterns that led him to conclude these trees died in the same year. The wood Lawrence and Lawrence (1958) sampled for radiocarbon dating was from cross sections of two samples: the largest 325-ring Douglas-fir in the Wyeth group sampled in 1934, and a Garry oak near the upriver end of the submerged forest that probably was collected in 1936–1937 (Lawrence and Lawrence, 1958; Table 1).

Some of Lawrence's samples were displayed in the Lewis and Clark Centennial Exposition's Forestry Building in Portland, Oregon, but these apparently were destroyed by fire in 1964. In 1987, Donald Lawrence knew of no existing samples of the submerged forest (personal communication with Patrick Pringle at that time). Our attempts in the 1990s to retrieve additional samples from Lake Bonneville were unsuccessful. In 2001, alerted by a museum curator, we fortuitously discovered four rounds of trees originally cut by Lawrence in 1934. The samples were stored at the World Forestry Center in Portland, Oregon, where they had been recently accessioned as part of the personal materials of



Figure 3. Powerhouse tree. (A) Photocopied photograph from February 17, 1978, issue of the Skamania County Pioneer of tree being extracted during the 1978 excavation of the second Bonneville Dam powerhouse; courtesy of Tim Collins, Bencor Corp., personal communication to Pringle, 1998. (B) Sampling the round conserved at Willamette Locks Museum; photograph by Patrick Pringle.

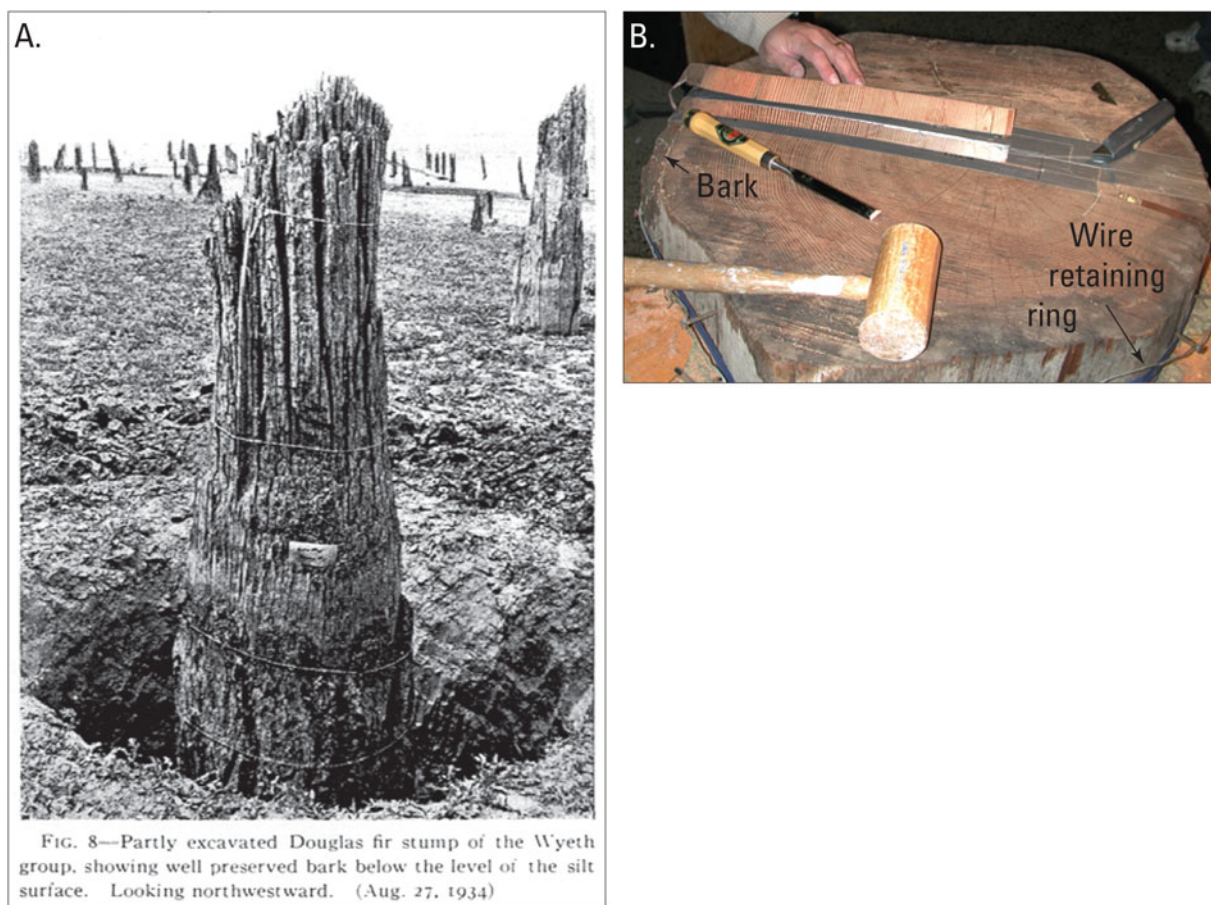


Figure 4. Wyeth Tree. (A) Photographic figure from Lawrence (1936) showing excavation of bark-bearing snag from the Wyeth group of submerged and partly buried trees, possibly the sample preserved at the World Forestry Center. (B) Unlabeled round preserved at World Forestry Center, inferred to be one of Donald Lawrence's Wyeth group samples. Cut wedge is sample WYE01a.



Figure 5. Perham Creek tree. (A) Scanned photograph appearing in August 25, 1935, *Oregonian* (Lawrence, 1935) showing excavation in preparation for sampling a Douglas fir snag in the Perham Creek group of submerged trees, probably the sample preserved at the World Forestry Center; from Washington State University digital collection. (B) Labeled round preserved at World Forestry Center from which both sampled wedges were cut. (C) Note by Donald B. Lawrence that had been attached to the round in (B), documenting provenance of this key sample.

Thornton T. Munger, first director of the U.S. Forest Service's Pacific Northwest Forest and Range Experiment Station. Munger facilitated Lawrence's 1934 study, accompanied and photographed Lawrence's fieldwork (Fig. 2A), and prepared the Forestry Building exhibit that reportedly burned in 1964. Munger died in 1975, which may explain why Lawrence was unaware of these remaining samples in 1987.

The samples held by the World Forestry Center (Figs 4, 5) include the only known samples of the submerged forest, hence their provenance and completeness is critical to our analysis. These samples were unambiguously collected by Lawrence. Three had attached handwritten sample tags signed by

Lawrence and noting location and date of collection. One was unlabeled, but retained the wire ring and nails characteristic of Lawrence's strategy to preserve the outer bark (Fig. 4B). Of these four rounds, two with labels were from live trees felled in 1934, a Douglas-fir and cottonwood, and the other two (one labeled, one not) were Douglas-firs from the submerged forest. The labeled round was from Perham Creek (Fig. 5C). Lawrence (1936) reported only one sample from Perham Creek, and that it had 212 annual rings. The portion preserved at the World Forestry Center was checked, cracked, and missing bark (Lawrence's sample note describes that in this instance, the bark was peeled off during collection); we counted 186 annual growth

rings on the most-complete axis and infer the outermost 25 rings are missing (Lawrence apparently included the center pith in his ring counts; because we did not, our ring counts are one fewer than Lawrence's—a conclusion confirmed by our ring-width analyses described herein).

The unlabeled Douglas-fir sample (Fig. 4B) had 127 counted rings and bark (fixed to the round by nails and wire). We did not count or measure the pith and a very narrow, partly formed first ring. This round is almost certainly the 129-ring sample (by Lawrence's count) extracted from the Wyeth group in 1934 (Lawrence, 1936). From each of the Lawrence rounds of the submerged forest, we sampled two radial wedges for radiocarbon and ring-width analyses (Figs. 4B, 5B).

Assessing synchronicity of tree death

Did all trees die the same year? This question is critical to our subsequent radiocarbon assessment of landslide age. Only by knowing tree death was synchronous among the three analyzed trees can we relate and combine the radiocarbon analyses of the three trees. We assessed this question with dendrochronology, by examining ring-width patterns visually and statistically to establish correlation among the nine rays cut from three trees.

Dendrochronologic methods

All sampled rays were glued to mounts, sanded, and polished using progressively finer sandpaper, finishing with 1000-grit (9.5 μm) or finer paper. All polished rays were scanned with a high-resolution (0.01 mm) flatbed scanner. These scans were used in conjunction with image analysis software to count and measure the widths of the annual growth rings for the entirety of each sample (Fig. 6; Supplementary Table 1).

Our visual examination used the list method described by Phipps (1985) and Yamaguchi (1991). We also used a variation of the skeleton plot technique (Stokes and Smiley, 1968; Swetnam et al., 1985) to identify "marker rings" common between samples from different trees that might indicate simultaneous recording of regional climatic conditions or other factors affecting tree growth over a wide area.

Our quantitative assessment first entailed constructing a standardized chronology for each of the three trees (Fig. 7; Supplementary Table 2), which was done with the aid of the ARSTAN software (Cook and Krusic, 2008; Speer, 2010). Ring-width measurements were normalized in reference to a 32-year spline curve that was fit to each series, producing serially independent standard indices highlighting annual ring-width variability. The multiple series of indices from each tree were averaged within ARSTAN using bi-weight means. For the Powerhouse tree, all five sets of ring-width measurements were combined. For each of the Wyeth and Perham Creek trees, we combined the two series of ring-width measurements. The resulting standardized chronology for each tree is "floating," meaning its reference to a calendar age is unknown.

The possible correlations among these three standardized chronologies were evaluated with COFECHA software (Holmes, 1983; Grissino-Mayer, 2001), which quantifies correlations among ring-width series by calculating Pearson product-moment correlation coefficients, specified as r values. In comparing two series, the software examines all possible alignments of the ring-width indices and calculates the best potential matches from the resulting correlation values and associated t statistic, which is a function of the degree of correlation and the number of rings

in the aligned series. For example, two ring-width series compared over a length of 50 rings with a correlation (r) value of 0.3281 would allow one to reject the null hypothesis that the two series are unrelated at the $P=0.01$ level for a one-tailed (only positive correlations are of interest) test ($t=3.5$). Longer overlapping segments and higher correlation coefficients give higher t values, and therefore more secure matches. Ring-width correlations among two series are commonly judged to be conclusively matched—that is to mean from the same series of years—when $t > 6.0$ (Grissino-Mayer, 2001).

Dendrochronologic results

From visual examination of the nine sampled rays from the three trees, we identified narrow marker rings 7, 14, 30, 46, 54, 82, 85, and 109 rings below the bark among the samples, assuming the Perham sample is missing the outermost 25 rings (Fig. 6). Our analysis indicates marker rings 30, 54, 82, 85, and 109 below the bark were common to all three trees. The marker rings 7 and 14 below the bark were common to the Powerhouse tree and the Wyeth sample. These rings are now missing from the Perham Creek round, but Lawrence's handwritten note attached to the sample reported a narrow ring 13 rings below the bark, which is possibly the same as the 14th ring noted on the other trees. The markedly narrow ring (following a thick ring) 46 rings below the bark was common to almost all samples, but in many Powerhouse samples, the 45th ring is slightly narrower.

Our verification of the co-occurrence of these marker rings in Lawrence's samples supports his conclusion that trees of the submerged forest died the same year. This result is bolstered by identifying corroborating marker ring patterns in the Powerhouse tree, which was killed directly by the landslide. Moreover, the quantitative correlations among the standardized chronologies strongly indicate that all three trees died the same year, assuming the Perham tree is missing the outermost 25 rings as judged from Lawrence's description of the original sample (Fig. 8; Table 3). The Wyeth chronology, from a central site between the Powerhouse tree (15 km west) and the Perham Creek tree (10 km east), correlates strongly ($r > 0.5$, $t > 6$, $p < .0001$) with both the upriver and downriver chronologies. The match between the Powerhouse and Perham Creek chronologies is also highly significant ($r = 0.43$, $t = 5$, $p < .0001$), although not as strong, possibly a consequence of the 25 km distance between the two trees in an area of strong climatic gradients. Moreover, the correlations for the final ring being the same year for all three trees, assuming the Perham Creek tree is missing its outermost 25 rings, are much stronger than any alternative best-match correlations (Fig. 8).

Our conclusion, from both co-occurrence of marker rings and statistical assessment, is that all three trees died the same year. The Powerhouse tree died by entrainment and burial in the Bonneville landslide. The Wyeth and Perham trees died by drowning as the Columbia River quickly rose behind the 80-m-high landslide dam.

Radiocarbon dating the timing of tree death

The dendrochronologic evidence showing all three trees died the same year enables precise radiocarbon dating of the timing of tree death by taking advantage of multiple samples of different ages, but of known age relation (by ring count) to each other.

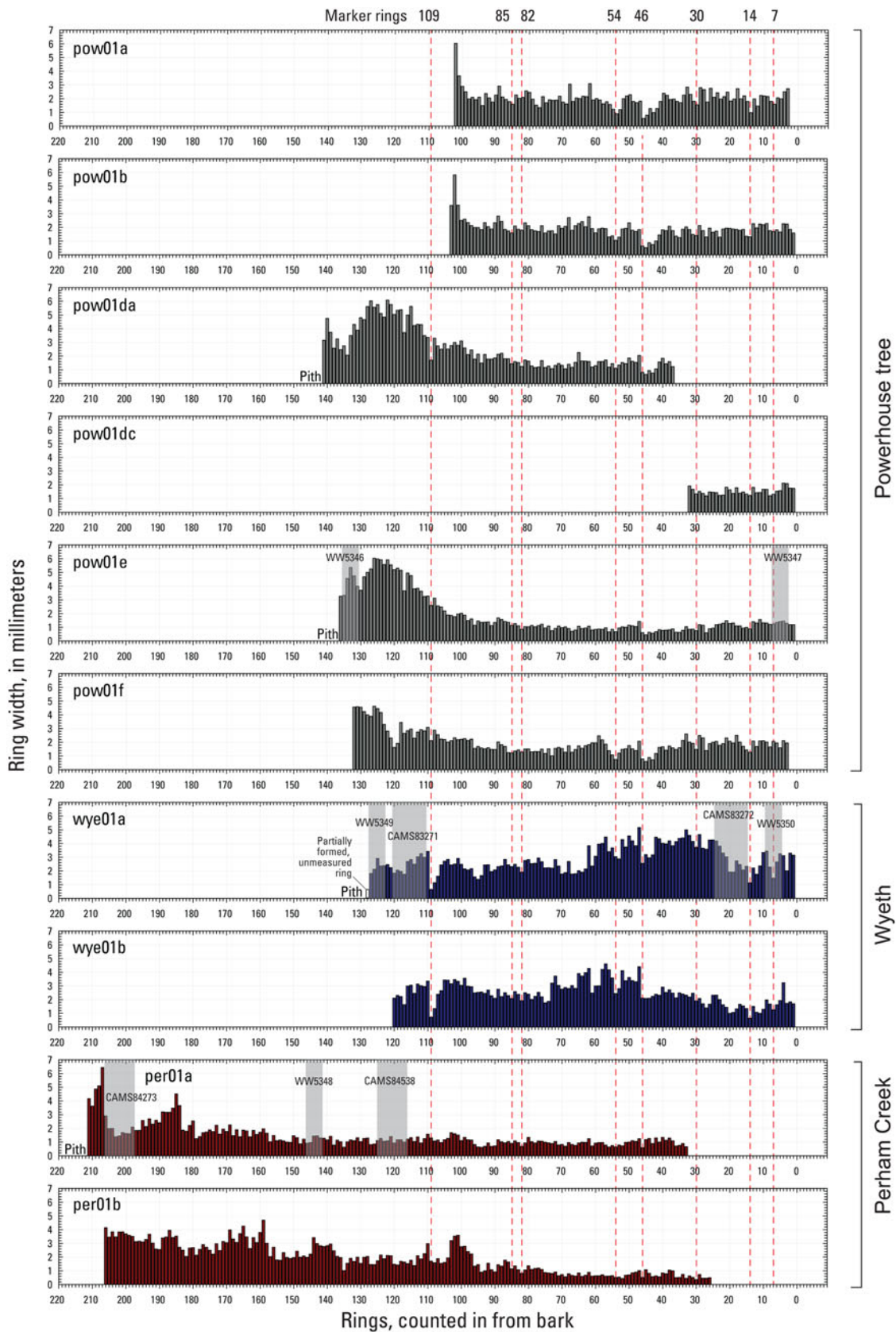


Figure 6. Ring-width measurements for all nine individual measurement rays from the three analyzed trees (ray pow01d consisted of multiple segments), referenced to year of tree death; marker rings indicated by dashed vertical red lines. Radiocarbon sample intervals shown by gray shading. Underlying data in Supplementary Table 1.

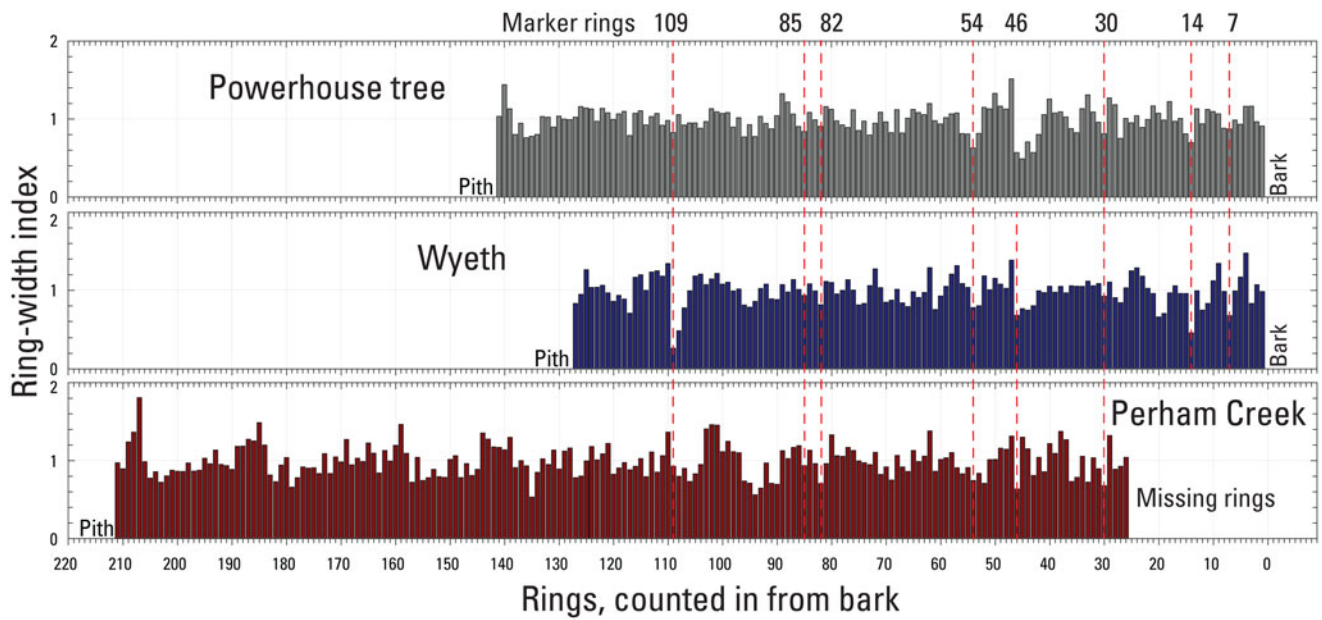


Figure 7. Standardized ring-width indices and marker rings (dashed vertical red lines) for each of the three trees, normalized in reference to a 32-year spline curve fit to each series and averaged using bi-weight means within the ARSTAN software (Cook and Krusic, 2008; Speer, 2010). Ring-width index values provided in Supplementary Table 2.

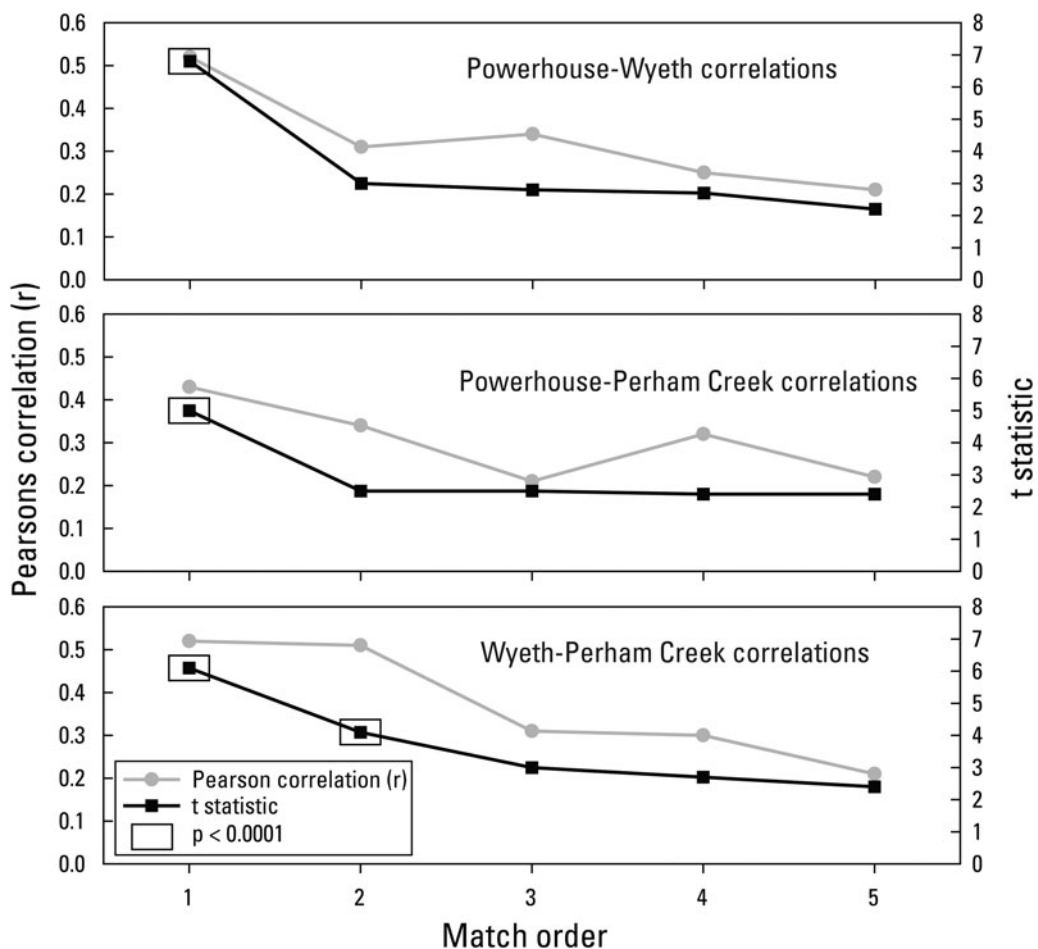


Figure 8. Top five matches by *t* statistic of lagged correlations among the standardized ring-width indices for the three trees. All correlations are significant at $p = .01$. In all cases, the best correlation by far, as measured by the *t* statistic, is for the case of the final ring of all three trees being from the same year (with the condition of the Perham Creek tree missing its outermost 25 rings).

Table 3. Correlation matrix among three index series; based on “MatchCorrelationsStandardizedIndices.xlsx.”

Tree pair			Last correlated ring					
Series 1	Series 2	Match rank	Series 1	Series 2	Years overlap	r	t	p value
Powerhouse	Wyeth	1	141	127	127	0.52	6.8	<0.0001
		2	88	127	88	0.31	3.0	0.0016
		3	141	64	64	0.34	2.8	0.0016
		4	141	114	114	0.25	2.7	0.0036
		5	112	127	112	0.21	2.2	0.013
Powerhouse	Perham Creek	1	116	186	116	0.43	5.0	<0.0001
		2	53	186	53	0.34	2.5	0.0063
		3	141	182	141	0.21	2.5	0.0062
		4	141	55	55	0.32	2.4	0.0019
		5	113	186	113	0.22	2.4	0.0096
Wyeth	Perham Creek	1	102	186	102	0.52	6.1	<0.0001
		2	127	51	51	0.51	4.1	<0.0001
		3	89	186	89	0.31	3.0	0.0015
		4	127	76	76	0.30	2.7	0.0042
		5	127	148	127	0.21	2.4	0.0089

Correlations are among the ring-width indices developed for each of three sampled trees (Supplementary Table 2). Last correlated ring indicates matched final ring for each sample (counted from pith) of the correlation. Years overlap indicates the number of correlated rings common to the ring-width indices of both trees. *r* is the Pearson product-moment correlation coefficient for the tentative match. *t* is the *t* statistic, a function of the correlation (*r*) and sample size (years overlap). *P* value indicates the one-tailed probability of the null hypothesis for the correlation.

Radiocarbon dating methods

We dated nine new samples in total—four from the submerged tree at Wyeth, three from the Perham Creek tree, and two samples from the Powerhouse tree entombed by the Bonneville landslide (Fig. 6; Table 1). Each sample consisted of a specified number of rings, 5 or 10, measured from the outermost ring under the bark. For the case of the Perham Creek tree, our ring count accounted for the outermost missing 25 rings from a total 211 rings, our revision of Lawrence’s original count of 212, as confirmed by our dendrochronological analysis.

Our first assessment was for two samples of ten rings each, spaced several decades apart, from the submerged trees at Wyeth and Perham Creek. These four samples were sent to Stafford Labs for processing and analyzed by acceleration mass spectroscopy at Lawrence Livermore Labs, California, USA (Table 1). The results from these analyses guided subsequent sampling targeted at steep segments of the radiocarbon calibration curve to improve precision (e.g. Svetlik et al., 2019). The second assessment was for two additional samples of the Wyeth tree, another sample of the Perham Creek tree, and two samples of the uncontaminated Powerhouse tree round stored at the Willamette Locks museum. These five samples were 5-ring segments, sent to the U.S. Geological Survey laboratory for pre-processing, including cellulose extraction, then analyzed by acceleration mass spectroscopy at Lawrence Livermore Labs.

All nine results were calibrated to calendar years using the software program OxCal version 4.4 (Bronk Ramsey, 2009) and the IntCal20 atmospheric radiocarbon decay curve (Reimer et al., 2020) (Table 1, Fig. 9A). Each result was further adjusted by using the “Offset” function of OxCal 4.4. We moved each

calibrated calendar-year probability distribution forward in time by the number of years between the centroid ring position of each sample and the bark (as determined from tree-ring counts and the verified missing outer 25 rings of the Perham round), so each calendar-year distribution represents the final year of tree growth (Fig. 9B). These nine measurements, offset on the basis of the dendrochronology results, were combined into a single probability distribution with the “Combine” function of OxCal 4.4. This approach applies Bayesian statistics to pool likelihoods from multiple probability distributions to resolve a single combined probability distribution, in this application representing the calibrated age of the final annual ring (Fig. 9B).

Radiocarbon dating results

Each of the individual radiocarbon-age results have calibrated calendar age uncertainties spanning several decades because of substantial variations in atmospheric ¹⁴C between AD 1000 and AD 1500 (Table 1; Fig. 9B). The results of the offset and combined analysis, however, provide a much more precise age for the timing of the synchronous tree death: a 2σ (95% probability) estimate of AD 1426–1448, and a 3σ (99.7% probability) estimate of AD 1421–1455. The Bonneville landslide and rapid drowning of the submerged forest almost certainly happened within this age range.

SUMMARY AND IMPLICATIONS

Our new age determination of AD 1421–1455 (3σ) for the Bonneville landslide derives from combined radiocarbon dating of a tree killed by entrainment in the landslide and two trees killed

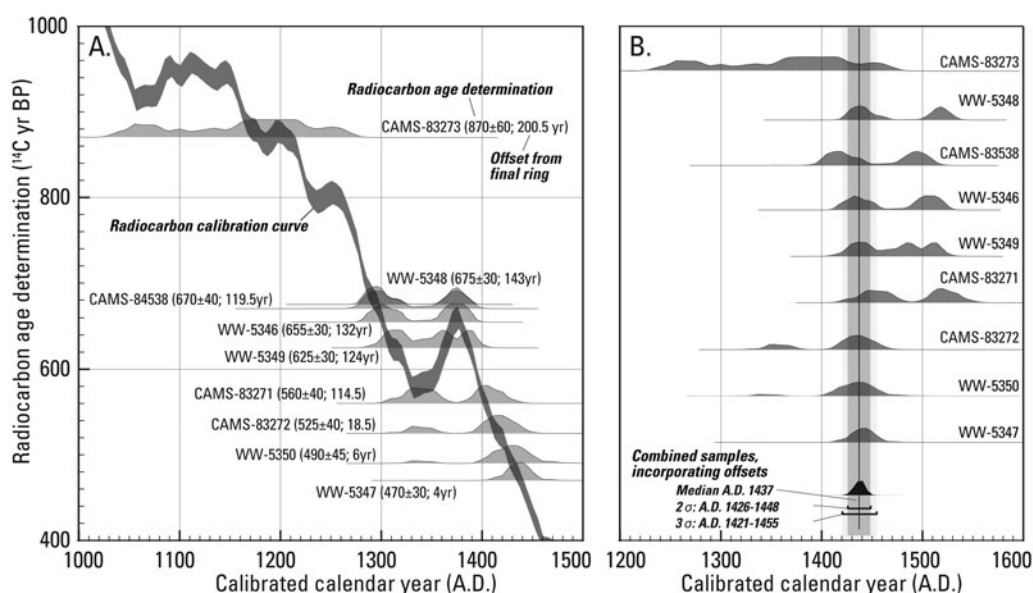


Figure 9. Radiocarbon age calibrations and combined age analysis. (A) Probability density functions of calendar age calibrations of radiocarbon age determinations (Table 1) based on IntCal20 Northern Hemisphere radiocarbon age calibration curve (Reimer et al., 2020). Calibrations by OxCal version 4.4.2 (r5) (Bronk Ramsey, 2009). (B) Combined age assessment of tree death accounting for offsets from final ring (annotated in A and accounting for 25 missing outer rings in the Perham Creek samples) by wiggle matching approach of Bronk Ramsey et al. (2001). Resulting three-sigma estimate of the final ring date of each tree is AD 1421–1455.

by drowning in the resulting impoundment of the Columbia River. This result is premised upon dendrochronologic analysis showing that all three trees died the same year.

Our results are consistent with the age of the oldest trees found on the landslide by Gilbert (1900), Lawrence (1958), and Weaver and Pringle (2003), all germinating after ca. AD 1550. The germination gap of about 100 years may represent ecesis time, growth to sampling height, fire history, or lifespan limits of Douglas-fir on the landslide. The age is also consistent with several previous radiocarbon ages, including calibrated assessments of Lawrence and Lawrence's (1958) results, the two analyses deemed contaminated by Pringle and Schuster (2002), as well as the discounted young age of Minor (1984), which calibrates to AD 1386–1675 (3 σ) (Table 1). Our results indicate a landslide age more than 150 years younger than the AD 1250 age estimated by Lawrence and Lawrence (1958) from their early radiocarbon dating of samples of the submerged forest, and more than 300 years younger than AD 1100 age proposed by Minor (1984).

Despite the well-preserved state of the submerged forest snags, tree death was nearly 600 years ago, explaining why Lawrence could not readily cross-date his samples with live trees. Cross-dating efforts continue, bolstered by longer records extracted regionally from long-lived trees, as well as those killed by past geologic events such as lahars and earthquake-formed lakes (Zhang and Hebda 2004, 2005; Yamaguchi, 2005; Pringle, 2014). It is likely such cross-dating, guided by the high-precision radiocarbon dating reported here, will reveal the exact year of the Bonneville landslide (Pringle et al., 2021).

Our refined date provides context for the cultural and ecologic consequences of the landslide, river blockage, subsequent incision, and downstream flooding. Upstream Indigenous settlements were quickly inundated, as recounted by oral histories (e.g., Clark, 1952). Even after the temporary impoundment receded, formation of the Cascades rapids from landslide remnants created local new portage and fisheries economies for Indigenous people,

thereby permanently altering landscape occupancy, resource acquisition, and trade patterns (Beckham, 1984; Minor, 1984). Some upstream village sites likely remained permanently flooded by the 11.5 m remnant ponding of river level upstream of the Cascades rapids (Strong, 1959). Downstream Indigenous settlements may have been affected by dam-breach flooding (Pettigrew, 1981; Bourdeau, 2004). Such flooding, indicated by boulder bars downstream of the breach and distinctly coarse sand and silt deposits in the downstream estuary, predate the AD 1479 Kalama eruption of Mount St. Helens (Atwater, 1994; O'Connor et al., 1996; Bourdeau, 2004; O'Connor and Burns, 2009).

The ecologic consequences also may have been significant. As reviewed by O'Connor (2004), a blockage \sim 75 m high may have hindered anadromous fish passage; if blockage lasted for more than the 3–5-year life history cycle of Pacific salmon, upper Columbia basin runs could have been significantly diminished, at least temporarily. It is also possible the landslide and remnant ponding upstream of the Cascades rapids enhanced fish passage into the upper Columbia basin by reducing the total fall of the Dalles of the Columbia—a scenario told in oral histories (Lawrence and Lawrence, 1958) and elaborated by Condon (1869) and O'Connor (2004).

Our more precise age also facilitates consideration of triggering mechanisms for the landslide. One possibility is a hydrologic trigger, wherein in a wet season or series of wet years help initiate motion, which is a possible factor for the catastrophic Oso slide in Washington State in 2014 (Henn et al., 2015) and for several landslides in Oregon (Struble et al., 2021). Another potential trigger is seismic shaking, which has caused many landslides and landslide dam disasters globally (Fan et al., 2019). Earthquake-landslide co-occurrence has been the subject of focused research in the Coast and Cascade ranges of the Pacific Northwest, with both Cascadia Subduction Zone quakes and rupture of shallow crustal faults (Schuster et al., 1992; Leithold et al.,

2018, 2019; LaHusen et al., 2020; Struble et al., 2020) identified as seismic triggers. Our AD 1421–1455 (3 σ) age for the Bonneville landslide shows it preceded the last great Cascadia Subduction Zone earthquake of AD 1700 (Atwater et al., 1995, 2005; Yamaguchi et al., 1997) by more than 250 years. The Bonneville landslide, however, may correlate with the penultimate “T2” megathrust rupture inferred from offshore turbidite deposits dating to AD 1402–1502 (Goldfinger et al., 2012). Alternately, a candidate for rupture of a local crustal fault is the recently discovered Gate Creek fault, which is marked by a fresh-appearing scarp cutting north into the Columbia River Gorge ~15 km east of the Bonneville landslide headscarp. Preliminary dating indicates the latest rupture was ca. AD 1350–1500, consistent with the landslide age (Bennett et al., 2021; O’Connor et al., 2021).

Acknowledgments. Curator David Popma alerted us to the presence and facilitated sampling of Lawrence’s two surviving rounds from the drowned forest at The World Forestry Center, Portland, Oregon, USA. U.S. Army Corps of Engineers permitted our sampling of the Willamette Locks round of the Powerhouse tree, which is held at the Willamette Locks Museum in Oregon City, Oregon, USA. Three additional samples of the Powerhouse Tree used in our dendrochronological analyses came from a section held at the Columbia Gorge Interpretive Center in Stevenson Washington, USA, which kindly permitted sampling. Radiocarbon analyses were funded by the U.S. Geological Survey. The manuscript was improved by reviews by Sean LaHusen, two Quaternary Research reviewers, and Quaternary Research editors Jeff Pigati and Derek Booth.

Supplementary material. The supplementary material for this article can be found at <https://doi.org/10.1017/qua.2022.7>.

REFERENCES

- Atwater, B.F., compiler, 1994. Geology of Holocene liquefaction features along the lower Columbia River at Marsh, Brush, Price, Hunting, and Wallace Islands, Oregon and Washington. *U.S. Geological Survey Open-File Report* 94-209, 64 pp.
- Atwater, B.F., Musumi-Rokkaku, S., Satake, K., Tsuji, Y., Ueda, K., Yamaguchi, D.K., 2005. *The Orphan Tsunami of 1700—Japanese Clues to a Parent Earthquake in North America*: U.S. Geological Survey Professional Paper 1707, 135 pp., (2nd edition, revised 2015).
- Atwater, B.F., Nelson A.R., Clague J.J., Carver G.A., Yamaguchi D.K., Bobrowsky P.T., Bourgeois J., et al., 1995. Summary of coastal geologic evidence for past great earthquakes at the Cascadia subduction zone. *Earthquake Spectra* **11**, 1–18.
- Barry, J.N., 1935. The drowned forest of the Columbia Gorge. *The Washington Historical Quarterly* **26**, 119–122.
- Beckham, S.D., 1984. “This place is romantic and wild”—an historical overview of the Cascades area, Fort Cascades, and the Cascades Townsite, Washington Territory. *Heritage Research Associates Report No. 27, A report to Portland District U.S. Army Corps of Engineers under Contract No. DACW57-83-C-0033*, 171 p.
- Bennett, S., Streig, A.R., Levinson, R., Roberts, N., Dunning, A., Wells, R.E., Madin, I.P., et al., 2021. The most recent earthquake on the Mount Hood fault zone, north-central Oregon: implications for cascading earthquake, landslide, and flood multi-hazards in the Columbia River Gorge. *Geological Society of America Abstracts with Programs* **53**, 6. <https://doi.org/10.1130/abs/2021AM-370262>.
- Bourdeau, A., 1999. Reconsidering the Late Prehistoric in the Columbia River Gorge. *Current Archaeological Happenings in Oregon (CAHO)* **2**. Association of Oregon Archaeologists.
- Bourdeau, A., 2004. *Geologically Complex: The Flood Plain of the Lower Columbia River, Results in Support of the Wapato Portage (45CLA) Cutbank Stabilization Project*. US Fish and Wildlife Service Report, Sherwood, Oregon.
- Bronk Ramsey, C., 2009. Bayesian analysis of radiocarbon dates. *Radiocarbon* **51**, 337–360.
- Bronk Ramsey, C., van der Plicht, J., Weninger, B., 2001. ‘Wiggle Matching’ Radiocarbon Dates. *Radiocarbon* **43** (2A), 2001, 381–389.
- Browman, D.L., Munsell, D.A., 1969. Columbia Plateau prehistory: cultural development and impinging influences. *American Antiquity* **34**, 249–264.
- Budhwa, R., 2002. *Correlations Between Catastrophic Paleoenvironmental Events*. PhD dissertation, Simon Fraser University, Burnaby, British Columbia.
- Clark, E.E., 1952. The Bridge of the Gods in fact and fancy. *Oregon Historical Quarterly* **53**, 29–38.
- Clark, E.E. 1953. The Bridge of the Gods. In: Clark, E.E., *Indian Legends of the Pacific Northwest*. University of California Press, Berkeley, California, pp. 20–23.
- Coe, D.E., 2019. *Bonneville landslide—Bridge of the Gods*. Washington Geological Survey, 1 sheet. https://www.dnr.wa.gov/publications/ger_presentations_coe_bonneville_landslide.pdf.
- Condon, T., 1869. Geological notes from Oregon. *Overland Monthly* **3**, 355–360.
- Condon, T., 1910. An Indian legend (chapter XIII). In: McCornack, E.C. (Ed.), *Oregon Geology, a Revision of “The Two Islands”... with a few tributes to the life and work of the author*. The J.K. Gill Company, Portland OR, pp. 163–166.
- Cook, E.R., Krusic, P.J., 2008. A tree-ring standardization program based on detrending and autoregressive time series modeling, with interactive graphics (ARSTAN). *Tree-Ring Laboratory, Lamont-Doherty Earth Observatory*, Columbia University, Palisades, NY.
- Crane, H.R., Griffin, J.B., 1958. University of Michigan radiocarbon dates II. *Science* **127** (3306), 1098–1105.
- Crane, H.R., Griffin, J.B., 1959. University of Michigan radiocarbon dates IV. *American Journal of Science Radiocarbon Supplement* **1**, 175–176.
- Deloria, V., 1997. *Red Earth, White Lies: Native Americans and the Myth of Scientific Fact*. Fulcrum Publishing, Golden, Colorado.
- Fan, X., Scaringi, G., Korup, O., West, A.J., Van Westen, C.J., Tanyas, H., Hovius, N., et al., 2019. Earthquake-induced chains of geologic hazards: patterns, mechanisms, and impacts. *Reviews of Geophysics* **57**, 421–503.
- Frémont, J.C., Smucker, S.M., 1856. *The life of Col. John Charles Frémont: and His Narrative of Explorations and Adventures, in Kansas, Nebraska, Oregon and California*. Miller, Orton & Mulligan, New York, NY, 493 pp.
- Gibbs, G., 1854. Geology of the Central Washington Territory. In: Henry, J., Baird, S.F., *Reports of explorations and surveys, to ascertain the most practicable and economical route for a railroad from the Mississippi River to the Pacific Ocean, 1853–54*. 1, pp. 474–485.
- Gilbert, G.K., 1899. Submerged forest of the Columbia River. *Science* n. ser. **10**, 777.
- Gilbert, G.K., 1900. Submerged Forest of the Columbia River. *Science* n. ser. **11**, 99–100. [January 19, 1900, paper read at the 12th annual meeting of the Geological Society of America, Columbia University, Washington D.C., Dec 27, 1899].
- Goldfinger, C., Nelson, C.H., Morey, A.E., Johnson, J.E., Patton, J.R., Karabanov, E., Gutierrez-Pastor, J., Eriksson, A.T., Gracia, E., Dunhill, G., 2012. Turbidite event history: methods and implications for Holocene paleoseismicity of the Cascadia subduction zone. *US Geological Survey Professional Paper* 1661, 170 pp.
- Grissino-Mayer, H., 2001. Evaluating cross-dating accuracy: a manual and tutorial for the computer program COFECHA. *Tree-Ring Research* **57**, 205–221.
- Harza, L.F., 1916. Report of possibility of power development at the Cascades of the Columbia River. In: National Preparedness Bulletin **5**, 37–51. Salem, Oregon, Office of the State Engineer.
- Henn, B., Cao, Q., Lettenmaier, D.P., Magirl, C.S., Mass, C., Brent Bower, J., Laurent, M. St., Mao, Y., and Perica, S., 2015. Hydroclimatic conditions preceding the March 2014 Oso Landslide. *Journal of Hydrometeorology* **16**, 1243–1249.
- Hodge, E.T., 1932. *Report of Dam Sites on the Lower Columbia River*. Pacific Division, Corps of Engineers, US Army, Portland, Oregon. 84. <https://hdl.handle.net/11681/19098>.
- Hodge, E.T., 1938. Geology of the Lower Columbia River. *Geological Society of America, Bulletin* **49**, 831–930.

- Holdredge, C.P.**, 1937. *Final Geological Report on the Bonneville Project*. US Army Corps of Engineers, Portland District (Portland, OR), 39 pp.
- Holmes, R.L.**, 1983. Computer-assisted quality control in tree-ring dating and measurement. *Tree-Ring Bulletin* **43**, 69–78.
- Hutchinson, I., Hall, M.**, 2019. Chinook salmon, late Holocene climate change, and occupational history of Kettle Falls, a Columbia River fishing station. *Environmental Archaeology* **25**, 397–410.
- Judson, K.B.**, 1910. *Myths and Legends of the Pacific Northwest: Especially of Washington and Oregon*. AC McClurg and Co., Chicago.
- LaHusen, S.R., Duvall, A.R., Booth, A.M., Grant, A., Mishkin, B.A., Montgomery, D.R., Struble, W., Roering, J.J., Wartman, J.**, 2020. Rainfall triggers more deep-seated landslides than Cascadia earthquakes in the Oregon Coast Range, USA. *Science Advances* **6**, eaba6790. <https://doi.org/10.1126/sciadv.aba6790>.
- Lawrence, D.B.**, 1935. Drowned trees of the Columbia yield part of their secret. *The Sunday Oregonian* (newspaper), August 25, 1935, p. 55.
- Lawrence, D.B.**, 1936. The submerged forest of the Columbia River Gorge. *Geographical Review* **26**, 581–592.
- Lawrence, D.B.**, 1937. Drowned forests of the Columbia River Gorge. *Geological Society of the Oregon Country Newsletter* **3**, 78–83.
- Lawrence, D.B., Lawrence, E.G.**, 1958. Bridge of the Gods legend, its origin, history, and dating. *Mazama* **40**, 33–41.
- Lee, D., Frost, J.H.**, 1844. *Ten Years in Oregon*. J. Collard, New York, 344 pp.
- Leithold, E.L., Wegmann, K.W., Bohnenstiehl, D.R., Joyner, C.N. and Pollen, A.F.**, 2019. Repeated megaturbidite deposition in Lake Crescent, Washington, USA, triggered by Holocene ruptures of the Lake Creek-Boundary Creek fault system. *Geological Society of America Bulletin* **131**, 2039–2055.
- Leithold, E.L., Wegmann, K.W., Bohnenstiehl, D.R., Smith, S.G., Noren, A., O'Grady, R.**, 2018. Slope failures within and upstream of Lake Quinault, Washington, as uneven responses to Holocene earthquakes along the Cascadia subduction zone. *Quaternary Research* **89**, 178–200.
- Lunney, M., Taylor J.M.**, 2000. Analysis of probable Bridge of the Gods landslide dam outburst sediments in the lower Columbia River basin: *Geological Society of America Abstracts with Programs* **32** (6), A-26.
- Lyell, C.**, 1832. *The Principles of Geology* 2. Johnson, New York, (reprint 1969).
- Lyman, W.**, 1915. Indian myths of the Northwest. *American Antiquarian Society* **25**, 375–395.
- Minor, R.**, 1984. Dating the Bonneville landslide in the Columbia River Gorge. Report to the Portland District US Army Corps of Engineers. *Heritage Research Associates Report* 31, 19 pp., Eugene, Oregon.
- Moulton, G.E.** (Ed.), 2002. *The Definitive Journals of Lewis and Clark* 5. University of Nebraska Press, Lincoln, Nebraska.
- O'Connor, J.E.**, 2004. The evolving landscape of the Columbia River Gorge: Lewis and Clark and cataclysms on the Columbia. *Oregon Historical Quarterly* **105**, 390–421.
- O'Connor, J.E., Burns, S.F.**, 2009. Cataclysms and controversy—aspects of the geomorphology of the Columbia River Gorge. In: O'Connor, J.E., Dorsey, R.J., Madin, I.P. (Eds.), *Volcanoes to Vineyards: Geologic Field Trips through the Dynamic Landscape of the Pacific Northwest*. *Geological Society of America Field Guide* **15**, 237–251.
- O'Connor, J.E., Pierson, T.C., Turner, D., Atwater, B.F., Pringle, P.T.**, 1996. An exceptionally large Columbia River flood between 500 and 600 years ago—breaching of the Bridge-of-the-Gods Landslide?. *Geological Society of America Abstracts with Programs* **28** (5), p. 97.
- O'Connor, J.E., Wells, R.E., Bennett, S.E.K., Cannon, C.M., Staisch, L.M., Anderson, J.L., Pivarunas, A.F., et al.**, 2021. Arc versus river—the geology of the Columbia River Gorge In: Booth, A.M., Grunder, A.L. (Eds.), *From Terranes to Terrains: Geologic Field Guides on the Construction and Destruction of the Pacific Northwest*. Geological Society of America Field Guide **62**. [https://doi.org/10.1130/2021.0062\(05\)](https://doi.org/10.1130/2021.0062(05)).
- Palmer, L.**, 1977. Large landslides of the Columbia River Gorge, Oregon and Washington. *Geological Society of America, Reviews in Engineering Geology* **3**, 69–84.
- Pettigrew, R.M.**, 1981. A Prehistoric Culture sequence in the Portland Basin of the Lower Columbia Valley. *University of Oregon Anthropological Papers* **22**, 1–207.
- Phipps, R.L.**, 1985. Collecting, preparing, cross-dating, and measuring tree increment cores. *United States Geologic Survey, Water-Resources Investigations Report* 85-4148. <https://doi.org/10.3133/wri854148>.
- Pierson, T.C., Evarts R.C., Bard J.A.**, 2016. Landslides in the western Columbia Gorge, Skamania County, Washington. *US Geological Survey Scientific Investigations Map* 3358. <https://doi.org/10.3133/sim3358>.
- Pringle, P.T.**, 2014. Buried and submerged forests of Oregon and Washington: time capsules of environmental and geologic history. *Western Forester* **59** (2), 14–15, 22.
- Pringle, P.T., O'Connor J.E., Schuster R.L., Reynolds N.D., Bourdeau A.**, 2002. Tree-ring analysis of subfossil trees from the Bonneville landslide deposit and the “submerged forest of the Columbia River gorge” described by Lewis and Clark (Abstract). *Geological Society of America Abstracts with Programs* **34** (5), 34.
- Pringle, P.T., Reynolds, N.D., O'Connor, J.E., Schuster, R.L., Weaver, R., Black, B.**, 2021. Tree-ring dating of the Bonneville landslide to late 1446 or early 1447 CE. *Geological Society of America Abstracts with Programs* **53**. <https://doi.org/10.1130/abs/2021AM-369596>.
- Reimer, P., Austin, W., Bard, E., Bayliss, A., Blackwell, P., Bronk Ramsey, C., Butzin, M., et al.**, 2020. The IntCal20 Northern Hemisphere radiocarbon age calibration curve (0–55 cal kBP). *Radiocarbon* **62**, 725–757.
- Reynolds, N.D.**, 2001. Dating the Bonneville landslide with lichenometry. *Washington Geology* **29**, 11–16.
- Sager, J.W.**, 1989. Bonneville Dam. In: Centennial Volume Committee (Galster, R.W., chairman), *Engineering Geology in Washington*. Washington Division of Geology and Earth Resources Bulletin 78 (1), 337–346.
- Sanger, D.**, 1967. Prehistory of the Pacific Northwest Plateau as seen from the interior of British Columbia. *American Antiquity* **32**, 186–197.
- Satake, K., Shimazaki, K., Tsuji, Y., Ueda, K.**, 1996. Time and size of a giant earthquake in Cascadia inferred from Japanese tsunami records of January 1700. *Nature* **379**, 246–249.
- Saylor, F.H.**, 1900. The Bridge of the Gods. *Oregon Native Son* **1**, 417–423.
- Schulz, W.H., Galloway, S.L., Higgins, J.D.**, 2012. Evidence for earthquake triggering of large landslides in coastal Oregon, USA. *Geomorphology* **141–142**, 88–98.
- Schuster, R.L., Logan, R.L., Pringle, P.T.**, 1992. Prehistoric rock avalanches in the Olympic Mountains, Washington. *Science* **258**, no. 5088, p. 1620–1621.
- Schuster, R.L., Pringle, P.T.**, 2002. Engineering history and impacts of the Bonneville landslide, Columbia River gorge, Washington-Oregon, USA. In: Rybar J., Stemberk J., Wagner P., (Eds.), *Landslides—Proceedings of the First European Conference on Landslides*. A.A. Balkema, Amsterdam, pp. 689–699.
- Skamania County Pioneer**, 1978. *Salvaged from excavation of Bonneville Dam...* (newspaper). February 17, 1978, p. 1.
- Smith, R.T., Verosub, K.L.**, 1994. Thermoviscous remnant magnetism of Columbia River Basalt blocks in the Cascade Landslide. *Geophysical Research Letters* **2**, 2661–2664.
- Speer, J.H.**, 2010. *Fundamentals of Tree-ring Research*. University of Arizona Press, Tucson AZ, 333 pp.
- Stokes, M.A., Smiley, T.L.**, 1968. *An Introduction to Tree-ring Dating*. University of Chicago Press, Chicago and London, 73 pp.
- Strong, E.**, 1959. *Stone Age on the Columbia River*. Portland, Oregon, Binford and Mort, 254 pp.
- Struble, W.T., Roering, J.J., Black, B.A., Burns, W.J., Calhoun, N., Wetherell, L.**, 2020. Dendrochronological dating of landslides in western Oregon: searching for signals of the Cascadia A.D. 1700 earthquake. *Geological Society of America Bulletin* **132**, 1775–1791.
- Struble, W.T., Roering, J.J., Burns, W.J., Calhoun, N.C., Wetherell, L.R., Black, B.A.**, 2021. The preservation of climate-driven landslide dams in western Oregon. *Journal of Geophysical Research: Earth Surface* **126**, e2020JF005908. <https://doi.org/10.1029/2020JF005908>.
- Svetlik, I., Jull, A., Molnár, M., Povinec, P., Kolář, T., Demján, P., Pachnerova Brabcova K., et al.**, 2019. The best possible time resolution: how precise could a radiocarbon dating method be? *Radiocarbon* **61**, 1729–1740.
- Swetnam, T.W., Thompson, M.A., Sutherland, E.K.**, 1985. Using dendrochronology to measure radial growth of defoliated trees. *United States Department of Agriculture, Forest Service Agricultural Handbook* 636.

- Tappan W.H.**, 1854. *Sub-Indian Agent Tappan Report to Isaac Stevens on the State of the Indian Affairs in the Lower Columbia Region*. September 30, 1854. Handwritten manuscript. United States, Bureau of Indian Affairs, Letters Received by the Office of Indian Affairs, 1824–81: Washington Superintendency, 1853–1880. (Washington, D.C.: National Archives and Records Service, 1958) Washington State Library Call # NW MICRO 979.7004 UNITED 1853 reel 17.
- Tong, X., Schmidt, D.**, 2016. Active movement of the Cascade landslide complex in Washington from a coherence-based InSAR time series method. *Remote Sensing of Environment* **186**, 405–415.
- Waters, A.C.**, 1973. The Columbia River Gorge—basalt stratigraphy, ancient lava dams, and landslide dams. In: Beaulieu J.D, (Ed.), *Geologic Field Trips in Northern Oregon and Southern Washington*. Oregon Department of Geology and Mineral Industries Bulletin 77, 133–162.
- Weaver, R., Pringle, P.T.**, 2003. Use of dendrochronology to date and better understand the Bonneville Landslide, Columbia River Gorge, Washington. *Geological Society of America Abstracts with Program* **35** (6), 80.
- Williams, I.A.**, 1916. The Columbia River Gorge: its geologic history interpreted from the Columbia River Highway. *The Mineral Resources of Oregon* **2** (3), 130 pp. Oregon Bureau of Mines and Geology, Corvallis, OR.
- Yamaguchi, D.K.**, 1991. A simple method for cross-dating increment cores from living trees. *Canadian Journal of Forest Research* **21**, 414–416.
- Yamaguchi, D.K.**, 2005. NOAA/WDS Paleoclimatology—Long Island, Willapa Bay—THPL-ITRDB WA129. *Correlation stats. (2005-09-14)*. NOAA National Centers for Environmental Information. <https://doi.org/10.25921/jsb0-7066>.
- Yamaguchi, D.K., Atwater, B.F., Bunker, D.E., Benson, B.E., Reid, M.S.**, 1997. Tree-ring dating the 1700 Cascadia earthquake. *Nature* **389**, 922–924.
- Zhang, Q.B., Hebda R.J.**, 2004. Variation in radial growth patterns of *Pseudotsuga menziesii* on the central coast of B.C., Canada. *Canadian Journal of Forest Research* **34**, 1946–1954.
- Zhang, Q.B., Hebda, R.J.**, 2005. Abrupt climate change and variability in the past four millennia of the southern Vancouver Island, Canada. *Geophysical Research Letters* **32**, L16708. <https://doi.org/10.1029/2005GL022913>.