The Geological Society of America
Field Guide 49

Tsunamis in the Salish Sea: Recurrence, sources, hazards

Carrie Garrison-Laney
Department of Earth and Space Sciences, University of Washington, Johnson Hall Rm-070, Box 351310, 4000 15th Avenue NE, Seattle, Washington 98195-1310, USA, and *Washington Sea Grant, University of Washington, 3716 Brooklyn Avenue NE, Box 355060, Seattle, Washington 98105-6716, USA*

Ian Miller
Washington Sea Grant, University of Washington, 1502 E. Lauridsen Boulevard #82, Port Angeles, Seattle, Washington 98362, USA

ABSTRACT

A tidal marsh at the head of Discovery Bay contains the longest record of tsunami deposits in Washington State. At least nine tsunami deposits dating back 2500 yr are preserved as fine sand layers in peaty tidal marsh deposits. Discovery Bay is a setting that amplifies tsunami waves, has an abundant sediment source, and a tidal marsh that traps and preserves tsunami deposits. The youngest deposit, bed 1, is probably from the 1700 A.D. Cascadia earthquake. Bed 2 has a newly revised age of 630–560 cal yr B.P. (1320–1390 A.D.), an age range that overlaps with the ages of tsunami deposits from Vancouver, British Columbia, and northern Oregon, as well as evidence for strong shaking in the region including submarine and sublacustrine slope failures. However, there is no geologic evidence for a late fourteenth-century earthquake or tsunami in any of the southwest Washington estuaries that record seven Cascadia earthquakes in the last 3500 yr. Discovery Bay bed 2 and similar-aged evidence in the region may represent a short rupture on the Cascadia subduction thrust, possibly centered west of the Strait of Juan de Fuca, that did not cause significant coastal subsidence. Other possible sources considered for bed 2 include a crustal fault earthquake, a tsunamigenic slope failure, or a transoceanic tsunami. Older tsunami deposits beds 3–9, which outnumber the number of Cascadia earthquakes in the last 2500 yr, are likely from a combination of Cascadia and non-Cascadia sources. Additional radiocarbon dating of beds 3–9 will improve age ranges and constrain potential sources.

SETTING AND TSUNAMI SOURCES

The Salish Sea region, within the forearc of the Cascadia subduction zone, includes the Strait of Juan de Fuca, Puget Sound, and the Strait of Georgia (Fig. 1). This region experiences earthquakes from three different sources (Fig. 2). First, very large (M 8–9) but infrequent Cascadia subduction zone earthquakes can cause strong shaking as far inland as Puget Sound, and can generate tsunamis via seafloor deformation (Fig. 2A), or by triggering tsunamigenic slope failures. The most recent earthquake and tsunami on the Cascadia subduction zone was a M 9.0 earthquake in 1700 A.D. (Atwater, 1987; Atwater et al., 2005; Yamaguchi et al., 1997).

The second earthquake source in the Salish Sea is shallow crustal earthquakes (Figs. 2B, 2C). Puget Sound is crossed by several major crustal faults that have produced large (~M 7)

Garrison-Laney, C., and Miller, I., 2017, Tsunamis in the Salish Sea: Recurrence, sources, hazards, *in* Haugerud, R.A., and Kelsey, H.M., eds., From the Puget Lowland to East of the Cascade Range: Geologic Excursions in the Pacific Northwest: Geological Society of America Field Guide 49, p. 67–78, doi:10.1130/2017.0049(04).

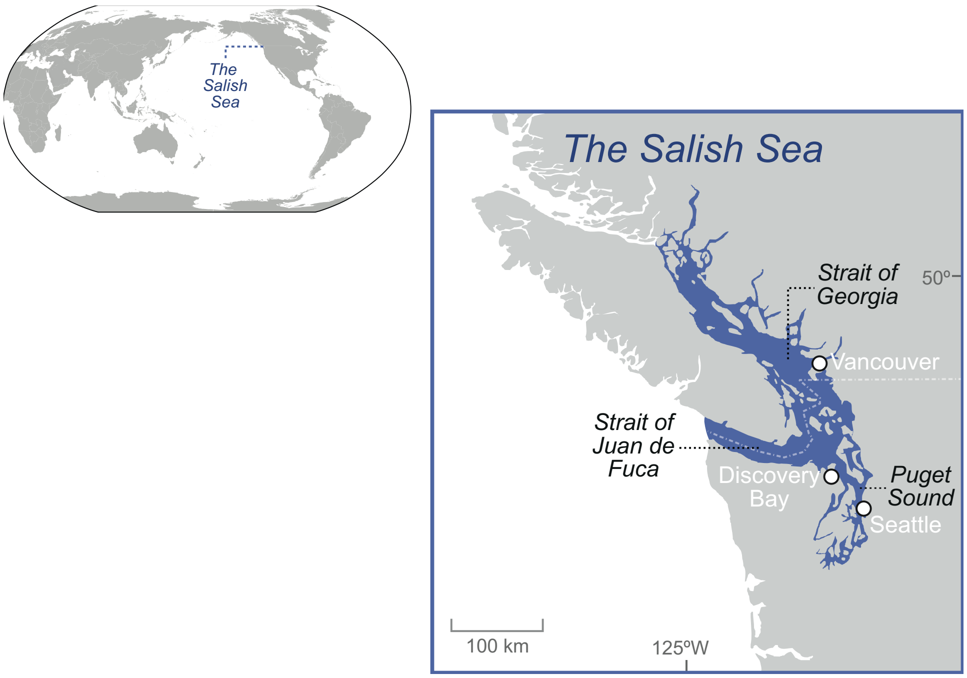


Figure 1. Location and area of the Salish Sea.

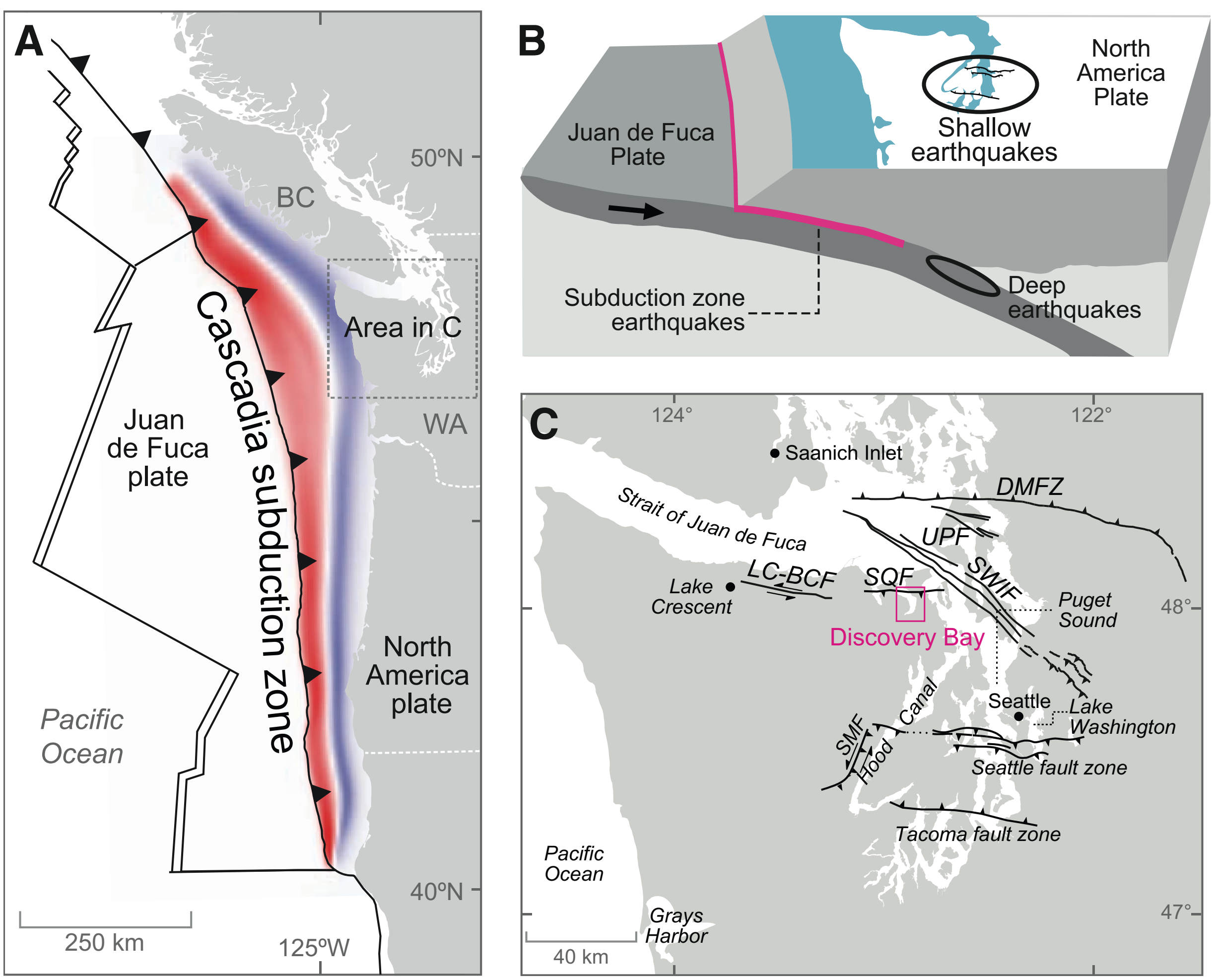


Figure 2.

earthquakes and locally generated tsunamis (Blakely et al., 2002; Brocher et al., 2001; Bucknam et al., 1992). The most recent large tsunami-generating crustal fault earthquake in Puget Sound was between 900 and 930 A.D. on the Seattle fault (Atwater and Moore, 1992).

Finally, the most frequent source of earthquakes in the Salish Sea region is deep earthquakes that occur within the subducting Juan de Fuca plate (Fig. 2B and Ludwin et al., 1991). Deep earthquakes over M 6.0 occur every 10–30 yr, and there have been six deep earthquakes in the Puget Sound region that were greater than M 6.0 in the past 100 yr (CREW, 2008). The most recent large deep earthquake was the M 6.8 Nisqually earthquake in 2001 (Creager and Xu, 2002). These deep earthquakes do not directly cause tsunamis via seafloor deformation; however, they can generate localized tsunamis when shaking triggers slope failures either underwater, or into a body of water. This happened in 1949 when a slope failure on the steep banks of Hood Canal near Tacoma, Washington, caused a tsunami that locally reached heights of ~2.5 m in the days following the M_w 7.1 Olympia earthquake (Chleborad, 1994).

Figure 2. (A) Tectonic setting of Cascadia subduction zone. Uplift shown in red, and subsidence shown in blue, illustrating an example of subduction zone earthquake deformation of the seafloor that would generate a tsunami. BC—British Columbia; WA—Washington. (B) Three sources of earthquakes in the Salish Sea region. (C) Location of shallow faults and Discovery Bay (pink box) near the entrance to Puget Sound on the Strait of Juan de Fuca. Select Holocene faults in black (adapted from Blakely et al., 2009; Nelson et al., 2007, 2014). Labels as follows: LC-BCF—Lake Creek–Boundary Creek fault; SQF—Sequim fault; DMFZ—Devils Mountain fault zone; UPF—Utsalady Point fault; SWIF—South Whidbey Island fault; SMF—Saddle Mountain faults.

TSUNAMI DEPOSITS AT DISCOVERY BAY

The tidal marsh at the head of Discovery Bay (Figs. 2C, 3) has the longest record of tsunami deposits in Washington State, with nine tsunami deposits dating back 2500 yr (Williams et al., 2005). Discovery Bay is a setting that amplifies tsunami waves, has an abundant sediment supply, and has a vegetated tidal marsh surface that acts as a sediment "trap" that preserves tsunami deposits (Fig. 3). The tsunami deposits at Discovery Bay are anomalous layers of muddy fine sand within muddy peat deposits (Fig. 4C). The deposits vary in maximum thickness between 1.0–11.5 cm, and have characteristics commonly observed in tsunami deposits, such as wide lateral extent, layers that thin and rise landward, graded bedding, and abundant marine diatoms (Williams et al., 2005).

DEPOSIT AGES

In 2007, clearing and restoration of an area of the marsh at Discovery Bay that had been previously diked allowed access to marsh deposits not available to Williams et al. (2005; Fig. 3). Figure 5 shows an outcrop from the restored area of the marsh. From this outcrop and another nearby, new radiocarbon samples were collected for the six youngest tsunami deposits. Figure 4A shows radiocarbon collection sites in the marsh, and Figure 6A shows a representation of the stratigraphic positions of a set of maximum and minimum sample ages that better constrain the age of bed 2.

The resulting new OxCal modeled (Bronk Ramsey, 2017; Reimer et al., 2013) age ranges for beds 1–6 are shown as probability densities in Figure 6B. Bed 1 is dated between 365 and 110 cal yr B.P. (1585–1840 A.D.), and is assumed to be from the 1700 A.D. Cascadia tsunami (earthquake Y in southwest Washington; Atwater, 1987; Atwater et al., 2005; Yamaguchi et al., 1997). Bed

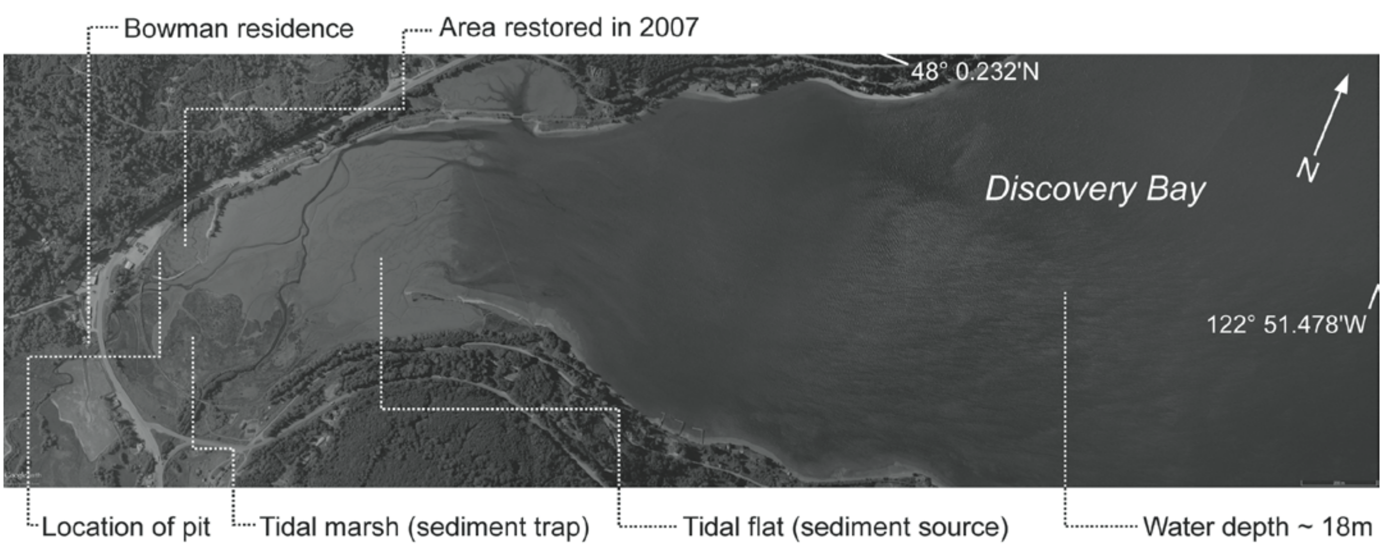


Figure 3. Google Earth image of Discovery Bay from 2009, showing the 2007 marsh restoration area, location of tidal flat source of tsunami deposit sediments, and tidal marsh areas. The Bowman residence was flooded in 1964 by the Alaska earthquake tsunami.

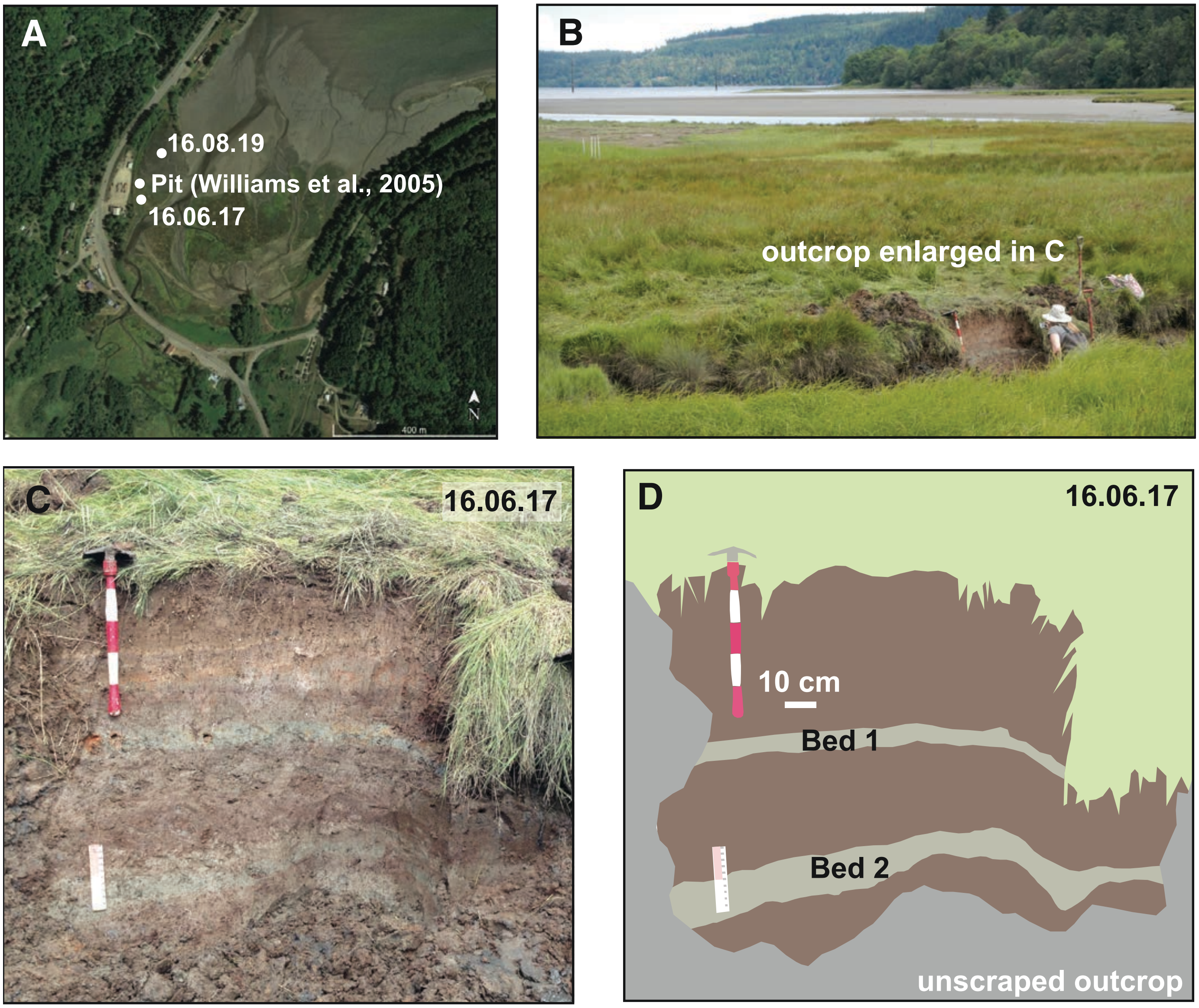


Figure 4. (A) Discovery Bay field sites, (B) overview of outcrop 16.06.17 looking to the northeast with exposed tidal flat in the background, (C) close-up of outcrop 16.06.17 showing beds 1 and 2, and (D) interpretation of outcrop 16.06.07. Bed 1 is probably from the 1700 A.D. Cascadia tsunami. Each increment on the shovel handle is 10 cm.

2 dates between 630 and 560 cal yr B.P. (1320–1390 A.D.), an age that is older than the previously published age for bed 2 of 500–300 cal yr B.P. Beds 3 and 4 are also older than previously published, now 1006–670 cal yr B.P. (944–1280 A.D.) and 1116–755 cal yr B.P. (834–1195 A.D.), respectively. New samples did not significantly change the age of bed 5, 1292–1205 cal yr B.P. (658–745 A.D.); but bed 6 was shifted younger to 1629–1273 cal yr B.P. (321–677 A.D.). The most significant age revision to originally published ages of Williams et al. (2005) from new radiocarbon samples is the narrower and older age range of bed 2. Additional sample dating will be necessary to similarly constrain the ranges of beds 3–6.

SOURCES OF BEDS 1–6

While Cascadia-generated tsunamis are likely the source of some of the tsunami deposits at Discovery Bay, the number of tsunami deposits suggests that additional sources must be considered as well. Seven Cascadia subduction zone earthquakes are recorded in southwest Washington estuaries within the past 2500 yr (Atwater and Hemphill-Haley, 1997; Atwater et al., 2003). Because there are at least nine tsunami deposits at Discovery Bay, there is not a one-to-one correlation with subduction zone events preserved on the coast. Because of this, the two additional tsunami deposits were generated by either smaller

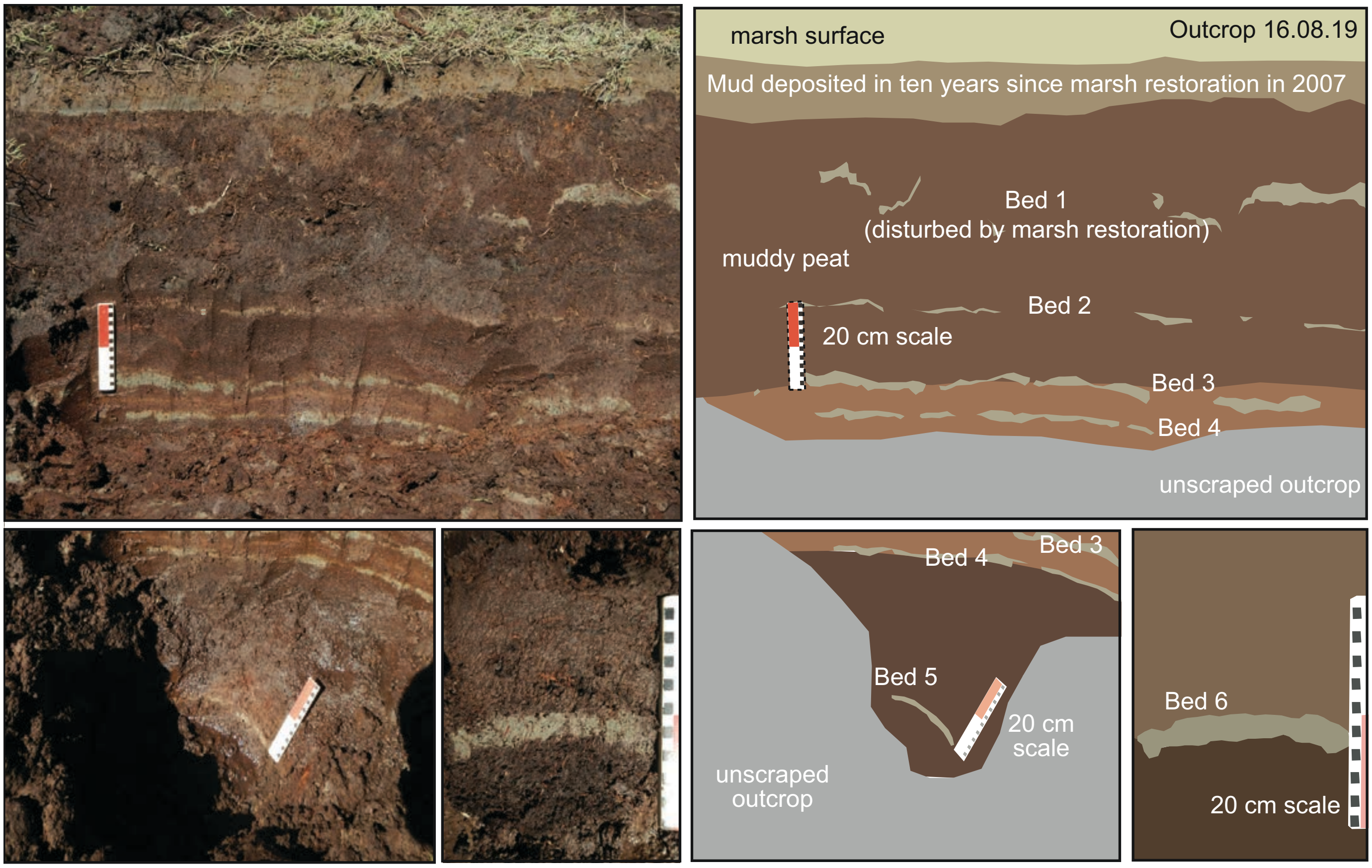


Figure 5. Outcrop of beds 1–6 tsunami deposits at Discovery Bay, and layer of mud that has aggraded on the marsh surface since it was restored in 2007. Photographs on left, annotation on right. Scale bar in each panel is 20 cm. Outcrop is at location 16.08.19 in Figure 4A.

Cascadia earthquakes (i.e., non–full-margin ruptures), crustal fault earthquakes, tsunamigenic slope failures (seismic or nonseismic), or transoceanic tsunamis.

Ascribing sources to each tsunami deposit at Discovery Bay is challenging because of the wide radiocarbon age ranges for most of the deposits. Without narrower radiocarbon age ranges, it is difficult to definitively assign sources to each of the tsunami deposits at Discovery Bay, but some sources are more likely than others when compared to the regional earthquake record, the characteristics of the deposits, and historical tsunami flooding.

Figure 7 shows the age ranges of beds 1–4 at Discovery Bay, and compares them to the age ranges of Cascadia earthquakes, select crustal fault earthquakes, and subaqueous slope failures that have occurred in the region over the last 1200 yr. From this comparison of ages, some correlations can be made. Because of its age, bed 1 is probably a deposit of the 1700 A.D. Cascadia earthquake tsunami (Williams et al., 2005). Bed 2's new age of 630–560 cal yr B.P. (1320–1390 A.D.) overlaps with the age ranges of tsunami deposits on Vancouver Island (Hutchinson and Clague, 2017; Clague and Bobrowsky, 1994) and north to central Oregon (Witter et al., 2008; Darienzo, 1991; Darienzo et al., 1994; Shennan et al., 1998; Graehl et al., 2015; Nelson et al., 2008); submarine slope failures in Puget Sound (Smith, 2012), Effingham Inlet (Enkin et al., 2013), and Saanich Inlet (Blais-Stevens et al., 2011); and turbidites in Lake Washington (Karlin et al., 2004) and Lake Crescent (Pollen, 2016). Bed 2 may also be from the same earthquake that formed turbidite T2 in the Juan de Fuca Channel (Goldfinger et al., 2012, 2017). A single radiocarbon age of the T2 deposit from the closest site to Discovery Bay (core M9907-11/-12, offshore dark-purple dot, Fig. 7) in the Juan de Fuca channel, has an adjusted age of 550–390 cal yr B.P. (1400–1560 A.D., Goldfinger et al., 2012, 2017), distinctly younger than bed 2; however, the two sigma OxCal modeled age range for the T2 event, which incorporates additional ages, is 648–316 cal yr B.P., which does overlap with bed 2. The limitations of radiocarbon dating (Nelson et al., 2006) preclude the possibility of determining whether only one, or more than one, earthquake produced all of the regional evidence around the time bed 2 was deposited.

Notably, the earthquake or earthquakes from around the time of bed 2 failed to preserve coastal subsidence or tsunami deposits

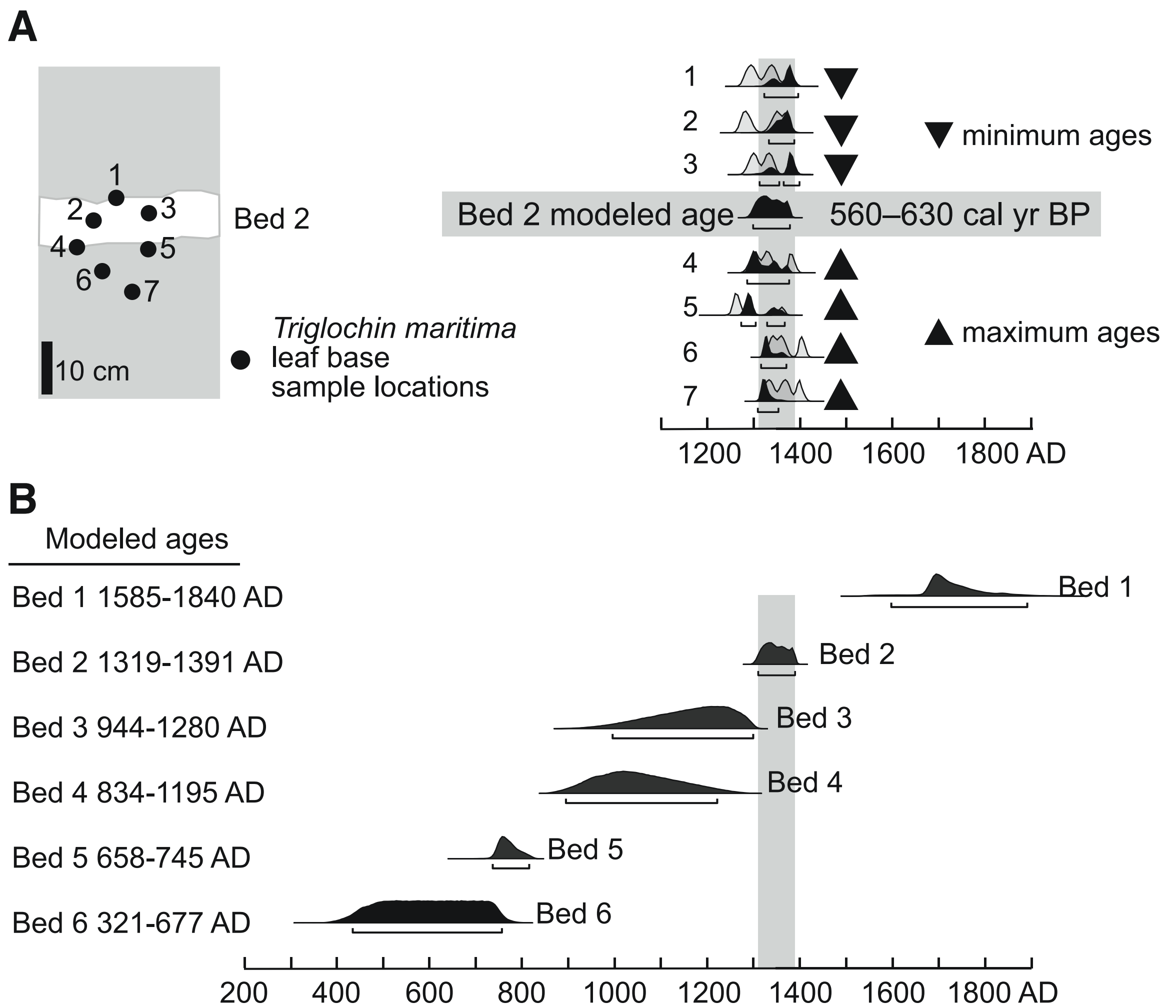
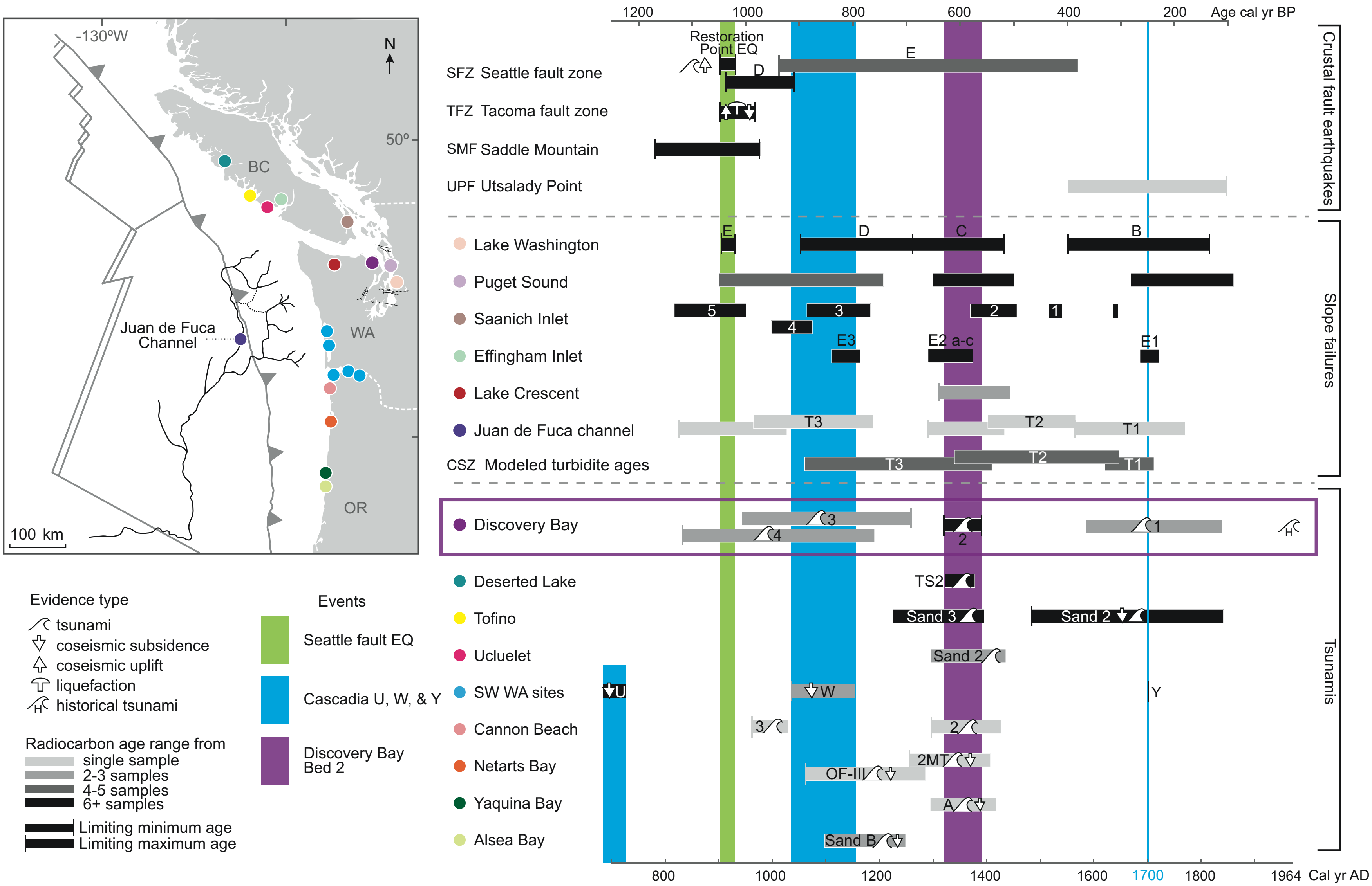


Figure 6. Radiocarbon dating at Discovery Bay. (A) Stratigraphic positions of radiocarbon samples of leaf bases of the marsh plant *Triglochin maritima* indicated by black dots (composite of two different outcrops) with respect to bed 2. *Triglochin maritima* leaf bases grow at or near the marsh surface, so they represent the age of a stratigraphic horizon from which they are collected better than roots or rhizomes. Minimum and maximum age samples for bed 2 are indicated by black triangles. Calibrated age probability distributions age model for samples 1–7 are shown with black shading. The new age for bed 2 is highlighted by vertical bar. (B) Modeled ages using new radiocarbon ages and ages from Williams et al. (2005) for beds 3, 4, 5, and 6. Age model made using OxCal v4.3.2 (Bronk Ramsey, 1995, 2009, 2017); r:5 calibrated with IntCal13 atmospheric curve (Reimer et al., 2013).

Figure 7. Comparison of grouped radiocarbon ages for earthquakes from Puget Lowland crustal faults (top), slope failures (center), and evidence for Cascadia earthquakes, including coseismic subsidence and tsunamis (bottom). Colored dots on map correspond to colored dots next to place names on age plot. Symbols under “Evidence type” indicate type of evidence on age plot. Vertical shading shows the age of the Seattle fault Restoration Point earthquake (green); SW Washington estuaries Cascadia earthquakes Y, W, and U (blue); and Discovery Bay bed 2 (purple). Age range bars are shaded to reflect the number of samples used to determine the range, and are bracketed as minimum or maximum ages where known. For locations of abbreviated crustal fault names, refer to Figure 2C. Citations as follows: SFZ (Atwater and Moore, 1992; Bucknam et al., 1992; Atwater, 1999; Nelson et al., 2014); TFZ (Sherrod, 2001; Sherrod et al., 2004; Nelson et al., 2014); SMF (Witter et al., 2008; Blakely et al., 2009; Barnett et al., 2015); UPF (Johnson et al., 2004); Lake Washington (Karlin et al., 2004); Puget Sound (Smith, 2012); Saanich Inlet (Blais-Stevens et al., 2011); Effingham Inlet (Enkin et al., 2013); Lake Crescent (Pollen, 2016); Cascadia and Juan de Fuca Channel turbidites shown with reported maximum and adjusted age ranges, and with modeled ages (Goldfinger et al., 2012, 2017); Discovery Bay (this study); Deserted Lake (Hutchinson and Clague, 2017); Tofino (Clague and Bobrowsky, 1994); Ucluelet Sand 2 (Clague and Bobrowsky, 1994); SW Washington sites (Atwater and Hemphill-Haley, 1997; Atwater et al., 2003; Atwater and Griggs, 2012); Cannon Beach (Ecola Creek) Sands 2 and 3 (Witter et al., 2008); Netarts Bay 2MT (Darienzo, 1991; Darienzo et al., 1994) OF-III (Shennan et al., 1998); Yaquina Bay buried soil A (Graehl et al., 2015); Alsea Bay Sand B (Nelson et al., 2008); historical tsunami flooding (*Port Townsend Leader*, 1964). BC—British Columbia; CSZ—Cascadia subduction zone; EQ—earthquake; OR—Oregon; WA—Washington.


-130°W
N
50°
BC
WA
OR
Juan de Fuca
Channel
100 km
Evidence type
tsunami
coseismic subsidence
coseismic uplift
liquefaction
historical tsunami
Radiocarbon age range from
single sample
2-3 samples
4-5 samples
6+ samples
Limiting minimum age
Limiting maximum age
Events
Seattle fault EQ
Cascadia U, W, & Y
Discovery Bay
Bed 2
1200
1000
800
600
400
200
Age cal yr BP
Restoration
Point EQ
SFZ Seattle fault zone
TFZ Tacoma fault zone
SMF Saddle Mountain
UPF Utsalady Point
Crustal fault earthquakes
Lake Washington
Puget Sound
Saanich Inlet
Effingham Inlet
Lake Crescent
Juan de Fuca channel
CSZ Modeled turbidite ages
Slope failures
Discovery Bay
Deserted Lake
Tofino
Ucluelet
SW WA sites
Cannon Beach
Netarts Bay
Yaquina Bay
Alsea Bay
Tsunamis
E
D
C
B
E3
E2 a-c
E1
T3
T2
T1
TS2
Sand 3
Sand 2
Sand 2
U
W
Y
2MT
OF-III
A
Sand B
800
1000
1200
1400
1600
1700
1800
1964
Cal yr AD
Figure 7.

in any of the estuaries of southwest Washington (Atwater and Hemphill-Haley, 1997; Atwater et al., 2003). These estuaries (light-blue dots, Fig. 7) record seven coseismically buried soils in the last 3500 yr, with tsunami deposits and liquefaction features accompanying some of the buried soils (Atwater and Hemphill-Haley, 1997; Atwater et al., 2003). The 1700 A.D. earthquake was dated, in part, by using tree rings of trees killed by coseismic subsidence in southwest Washington (Yamaguchi et al., 1997). One of the trees dated lived unscathed through the time of bed 2 (snag GR-777 on the Columbia River, oldest ring dates to 1293 A.D., Yamaguchi et al., 1997). Two other trees from Grays Harbor (snag JN-560) and Willapa Bay (snag PX-783) had oldest sampled rings from 1379 and 1335 A.D., respectively. These trees, living through or within the age range of bed 2 (1320–1390 A.D.), further attest to the lack of significant coastal subsidence in Washington during that time.

Not all buried soils from the southwest Washington estuaries have accompanying tsunami deposits. Of the last three buried soils in southwest Washington (Y, W, and U), only the most recent event (Y) has a tsunami deposit that accompanies the buried soil (Atwater and Hemphill-Haley, 1997). Reasons why these study sites may not have tsunami deposits for each buried soil may include a number of factors, including their distance inland, their location in protected embayments; or possibly because some earthquakes produced smaller tsunamis, or tsunami flows lost energy or dissipated as they flowed inland (Atwater and Hemphill-Haley, 1997).

If a Cascadia subduction zone earthquake formed bed 2, the lack of preserved coseismic subsidence in southwest Washington suggests that it would have been smaller than the 1700 A.D. earthquake. However, the abundance of tsunami deposits and evidence of shaking (slope failures) in northern Cascadia from the time of bed 2, suggests that tsunami-generating slip occurred along the northern end of the subduction zone at that time, perhaps centered west of the Strait of Juan de Fuca.

Another possibility is that some of the regional evidence from the time of bed 2 is from an intraplate earthquake or earthquakes. Submarine slope failures in Puget Sound, turbidites in Lake Washington, and slope failures in Effingham and Saanich Inlets, all attest to strong shaking in the Puget Sound region around the time bed 2 was deposited. Earthquake "E" in the Seattle fault zone (Fig. 7) has a very wide modeled age range that includes the age of bed 2 (Nelson et al., 2014), but this earthquake or others on the Seattle zone, if tsunamigenic, would have generated tsunamis that would likely have dissipated before reaching Discovery Bay (Williams et al., 2005). There is no other known crustal earthquake in the Puget Sound region from the time of bed 2 that could have generated a tsunami that could leave deposits on coastal Vancouver Island and northern Oregon, so a Cascadia subduction zone earthquake tsunami is the more likely source.

Beds 3 and 4 have ages that suggest that they might be from two known significant earthquakes, Cascadia earthquake W 913–793 cal yr B.P. (1037–1157 A.D.), and the Seattle fault earthquake of 900–930 A.D. (Atwater and Griggs, 2012; Atwater and Moore, 1992). Figure 7 shows that either bed 3 or 4 may correlate to Cascadia earthquake W from the coast of southwest Washington. Bed 4 overlaps with the Seattle fault earthquake between 900 and 930 A.D. Tsunami modeling shows that the tsunami generated by the Seattle fault earthquake is unlikely to have left deposits in Discovery Bay. However, strong shaking could have generated a tsunamigenic landslide in Discovery Bay. If so, bed 3 may be from earthquake W, and bed 4 from a secondary effect of the 900–930 A.D. Seattle fault earthquake.

The thicknesses of beds 1–9 at Discovery Bay compared to a deposit that was probably left by the 1964 Mw 9.2 Great Alaskan earthquake tsunami, suggest that deposit thickness may help distinguish locally generated from transoceanic tsunamis. A 1–2 mm lamina of mud to very fine sand, preserved in some parts of the marsh, is probably a deposit of the 1964 tsunami, which caused flooding of a residence at the head of Discovery Bay (Williams et al., 2005; *Port Townsend Leader,* 1964). The lamina's thickness is much thinner than beds 1–9, which have maximum thicknesses between 1.0–11.5 cm. This difference in tsunami deposit thicknesses suggests that beds 1–9 are probably from local rather than transoceanic tsunamis. Williams et al. (2005) observed other thin laminae in the marsh stratigraphy at Discovery Bay, which may also be deposits of transoceanic tsunamis.

VIEWING TSUNAMI DEPOSITS

Leaving from Seattle, we will take the Edmonds–Kingston ferry, and drive to Discovery Bay. On 20 October 2017, the first low tide of the day will be 1.15 m above mean lower low water at 10:38 a.m. PST. This tidal level or lower is required to look at marsh outcrops.

Stop 1 (47° 59′ 38.07″ N, 122° 53′ 15.34″ W). We will park along Highway 101 in the parking area shown in Figure 8, north of the marsh. After suiting up for slogging through mud, we will assemble near the kiosk shown in Figure 8, and walk south along the path to access the marsh near the location marked 1. Here we will take cores to look at as many as nine tsunami deposits preserved in the tidal marsh sediments. *Please note that you will need to obtain permission to take cores if you are not visiting this site as part of the GSA 2017 field trip.*

Stop 2. We will then walk north across the restored area of the marsh, taking care not to trample new marsh plants, to look at an outcrop created when an artificial channel was dug as part of marsh restoration. Here we will dig back the channel bank to expose beds 1–5. We will be able to compare the relative thicknesses and depths of the deposits to those we saw in cores at Stop 1. *Please note that you will need to obtain permission to dig back the bank if you are visiting this site as part of the GSA 2017 field trip.*

Stop 3. With the rising tide, we will move to higher ground and have a picnic lunch near the informational kiosk (3 on Fig. 7), and have views of the Discovery Bay tides coming in.

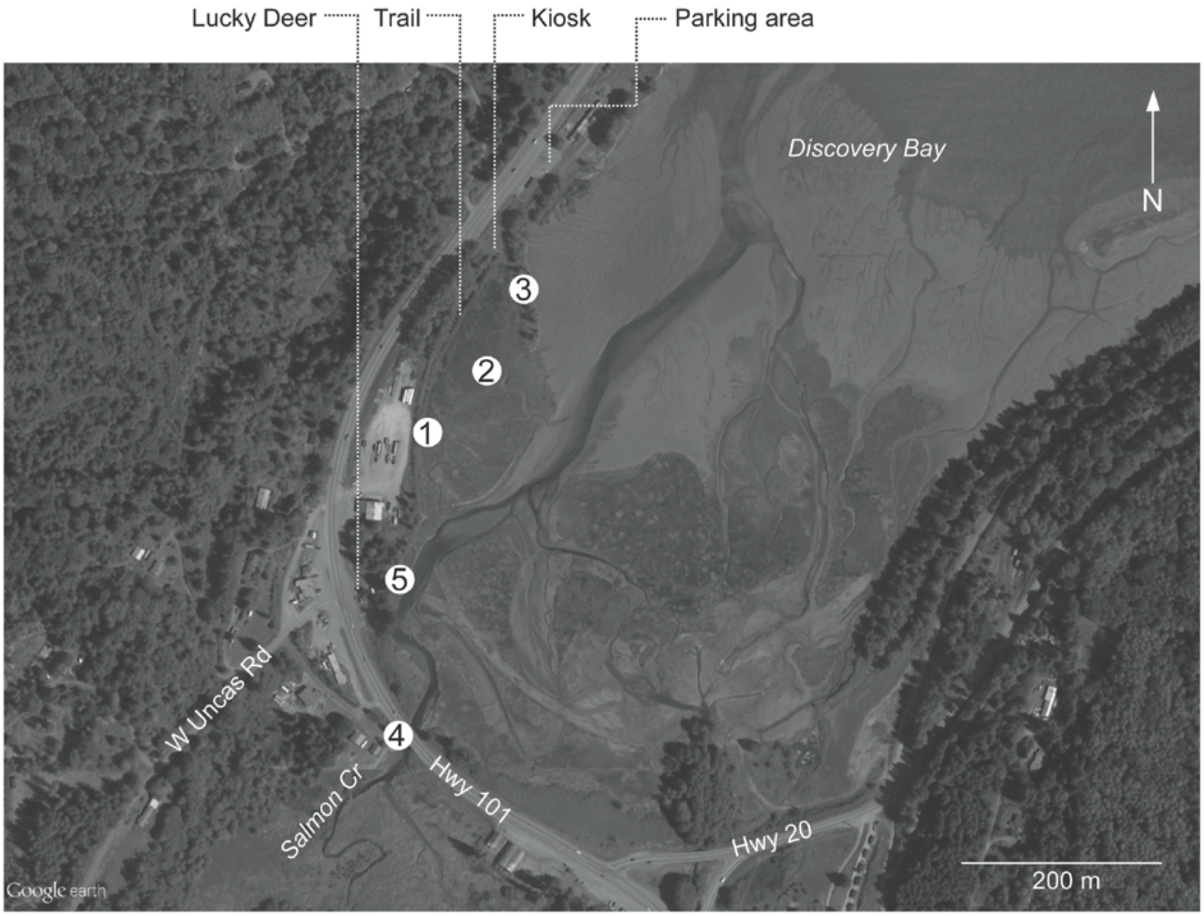


Figure 8. Discovery Bay field-trip landmarks and field stops.

Historic Flooding from 1964 Alaska Tsunami

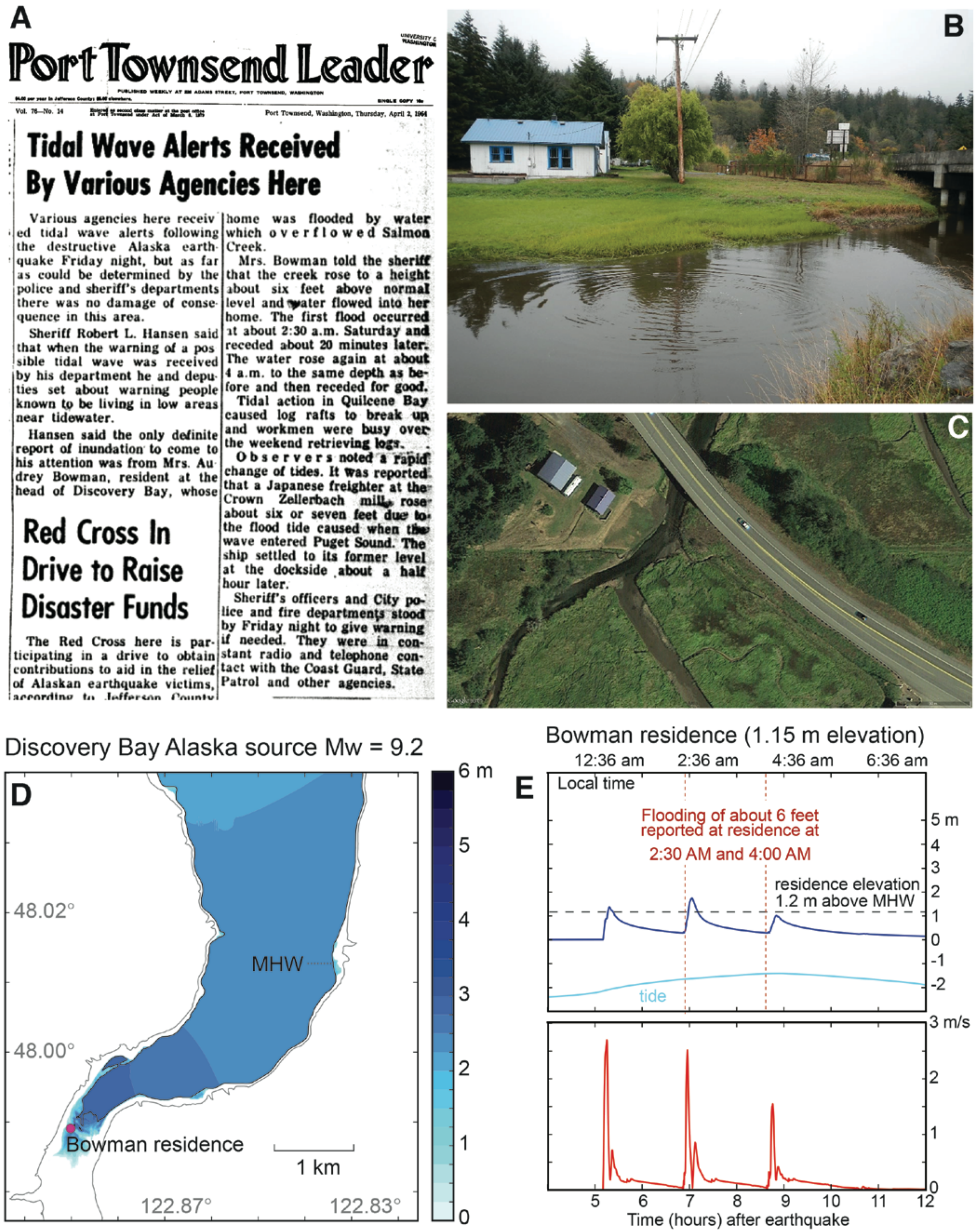
The 1964 Alaska tsunami caused flooding and damage along the west coast of the United States (Lander et al., 1993), including flooding at Discovery Bay. At the head of Discovery Bay, the tsunami caused two distinct waves of flooding at the residence of Mrs. Audrey Bowman, near the bank of Salmon Creek (4 on Fig. 8, and Figs. 9A–9C). The timing and the flood depths of both waves were observed by Mrs. Bowman. The first wave was at ~2:30 a.m., and then receded after ~20 min. The second wave occurred at ~4:00 a.m. Mrs. Bowman estimated the depth of the flooding to be ~6 ft (~2 m) above the normal level of Salmon Creek (*Port Townsend Leader,* 1964; Lander et al., 1993). Figure 9A shows a short article from the *Port Townsend Leader* from 2 April 1964 that describes the flooding.

Stop 4. From the information kiosk on the north end of the marsh, walk south on the path to the back of the Lucky Deer trading post (marked on Fig. 8). Walk (cautiously) across Highway 101 at the intersection of West Uncas Road. Walk along Highway 101 over the bridge above Salmon Creek to view the Bowman residence (4 on Fig. 8).

ALASKA TSUNAMI SIMULATION

An Alaska earthquake simulation was run using an earthquake source within the deformation area of the 1964 Great Alaska Earthquake (Tsunami Pilot Study Working Group, 2006; González et al., 2009). This simulated earthquake, though not an accurate depiction of the surficial deformation from the 1964 earthquake, was used to approximate a transoceanic tsunami in a probabilistic tsunami hazard assessment for Crescent City, California (González et al., 2014), and was used to simulate a transoceanic tsunami flow into Discovery Bay. The simulation was run using GeoClaw open source code (LeVeque et al., 2011; Berger et al., 2011; Clawpack Development Team, 2015). Figure 9D shows the maximum flooding from the Alaska tsunami simulation for Discovery Bay, and Figure 9E compares the similarities between the simulated flow depths and flow speeds at the Bowman residence with Mrs. Bowman's observations.

Stop 5. Walk (cautiously) back across Highway 101 to the bank of Salmon Creek behind the Lucky Deer trading post (Fig. 8). Here we will look at the results of a tsunami simulation of an Alaska source tsunami that agrees with Mrs. Bowman's



Port Townsend Leader

Vol. 76—No. 14 Port Townsend, Washington, Thursday, April 2, 1964

Tidal Wave Alerts Received By Various Agencies Here

Various agencies here received tidal wave alerts following the destructive Alaska earthquake Friday night, but as far as could be determined by the police and sheriff's departments there was no damage of consequence in this area.

Sheriff Robert L. Hansen said that when the warning of a possible tidal wave was received by his department he and deputies set about warning people known to be living in low areas near tidewater.

Hansen said the only definite report of inundation to come to his attention was from Mrs. Audrey Bowman, resident at the head of Discovery Bay, whose home was flooded by water which overflowed Salmon Creek.

Mrs. Bowman told the sheriff that the creek rose to a height about six feet above normal level and water flowed into her home. The first flood occurred at about 2:30 a.m. Saturday and receded about 20 minutes later. The water rose again at about 4 a.m. to the same depth as before and then receded for good.

Tidal action in Quilcene Bay caused log rafts to break up and workmen were busy over the weekend retrieving logs.

Observers noted a rapid change of tides. It was reported that a Japanese freighter at the Crown Zellerbach mill rose about six or seven feet due to the flood tide caused when the wave entered Puget Sound. The ship settled to its former level at the dockside about a half hour later.

Sheriff's officers and City police and fire departments stood by Friday night to give warning if needed. They were in constant radio and telephone contact with the Coast Guard, State Patrol and other agencies.

Red Cross In Drive to Raise Disaster Funds

The Red Cross here is participating in a drive to obtain contributions to aid in the relief of Alaskan earthquake victims, according to Jefferson County

Figure 9.

Figure 9. (A) *Port Townsend Leader* article from 2 April 1964 describing flooding of the Bowman residence at head of Discovery Bay from the 1964 Alaska tsunami; used with permission. (B) Bowman residence in 2016. Bridge on right is Highway 101. Salmon Creek is in the foreground. (C) Google Earth image of the Bowman residence, Highway 101, and Salmon Creek. (D) Tsunami simulation results showing maximum flow depth in m from an Alaska source tsunami. The pink dot shows the location of the Bowman residence in relation to Discovery Bay. (E) Results for tsunami simulation gauge at the location of the Bowman residence. Top curve is flow depth (m), and curve in bottom graph is current speed (m/s). Local time (PST) is given across the top, and the bottom shows hours since the earthquake occurred in Alaska. The simulated gauge data show three waves, and the vertical dotted lines show times of eyewitness observation of flooding in 1964. The light-blue curve below flow depth curve shows the tidal variation during the tsunami flooding in 1964. The tide curve shows vertical variation with respect to the *y*-axis, though its intercept is arbitrary.

observations, and find the trace of sand that may be a deposit of the 1964 Alaska tsunami. A discussion of tsunami deposit ages and sources will follow. This thin layer of sand is about 30 cm below the surface along the north bank of Salmon Creek, and is also present in core C-21of Williams et al. (2005).

End of trip. Return to Seattle via the Kingston–Edmonds ferry.

ACKNOWLEDGMENTS

We thank Brian Atwater for suggestions that greatly improved this research, and for help excavating mud and collecting radiocarbon samples. We also thank Ian Hutchinson, Karl Wegmann, and Harvey Kelsey for their reviews and helpful discussions, all of which improved this guide. This work was supported by the University of Washington, Department of Earth and Space Sciences; the Quaternary Research Center; the University of Washington, Department of Applied Mathematics; the U.S. Geological Survey; Washington Sea Grant; and GSA.

APPENDIX. GEOCLAW SIMULATION INFORMATION

GeoClaw tsunami simulations use an initial three-dimensional fault dislocation model of sea-floor deformation based on the Okada model (Okada, 1985). GeoClaw uses high-resolution finite volume methods to solve the depth-averaged two-dimensional shallow water equations using adaptive mesh refinement to follow wave propagation and zoom in on coastal regions. These simulations predict fluid flow onto dry land surfaces for areas of interest at high resolution. The topography and bathymetry DEM data used for the Puget Sound area is 1/3 arc-second resolution, 10 m cell size, with mean high water as zero elevation (Carnigan et al., 2014). In the simulation, the DEM was coarsened for areas farther away from Discovery Bay, and then refined ahead of wave arrival up to 2/3 arc-second resolution in a grid around the head of Discovery Bay.

REFERENCES CITED

Atwater, B.F., 1987, Evidence for Great Holocene earthquakes along the outer coast of Washington State: Science, v. 236, no. 4804, p. 942–944, doi:10.1126/science.236.4804.942.

Atwater, B.F., 1999, Radiocarbon dating of a Seattle earthquake to A.D. 900–930: Seismological Research Letters, v. 70, no. 2, p. 232.

Atwater, B.F., and Griggs, G.B., 2012, Deep-Sea Turbidites as Guides to Holocene Earthquake History at the Cascadia Subduction Zone—Alternative Views for a Seismic-Hazard Workshop: U.S. Geological Survey Open-File Report 2012-1043, 58 p.

Atwater, B.F., and Hemphill-Haley, E., 1997, Recurrence Intervals for Great Earthquakes of the Past 3,500 Years at Northeastern Willapa Bay, Washington: U.S. Geological Survey Professional Paper 1576, Denver, Colorado, U.S. Nuclear Regulatory Commission, and Washington, U.S. Government Printing Office; sold by U.S. Geological Survey, Information Services, 108 p.

Atwater, B.F., and Moore, A.L., 1992, A tsunami about 1000 years ago in Puget Sound, Washington: Science, v. 258, no. 5088, p. 1614–1617, doi:10.1126/science.258.5088.1614.

Atwater, B.F., Tuttle, M.P., Schweig, E.S., Rubin, C.M., Yamaguchi, D.K., and Hemphill-Haley, E., 2003, Earthquake recurrence inferred from paleoseismology: Developments in Quaternary Science, v. 1, p. 331–350, doi:10.1016/S1571-0866(03)01015-7.

Atwater, B.F., Musumi-Rokkaku, S., Satake, K., Tsuji, Y., Ueda, K., and Yamaguchi, D.K., 2005, The Orphan Tsunami of 1700—Japanese Clues to a Parent Earthquake in North America: United States: Seattle, Washington, University of Washington Press, U.S. Geological Survey Professional Paper 1707, doi:10.3133/pp1707, 135 p.

Barnett, E.A., Sherrod, B.L., Hughes, J.F., Kelsey, H.M., Czajkowskid, J.L., Walsh, T.J., Contreras, T.A., Schermere, E.R., and Carson, R.J., 2015, Paleoseismic evidence for late Holocene tectonic deformation along the Saddle Mountain fault zone, southeastern Olympic Peninsula, Washington: Bulletin of the Seismological Society of America, v. 105, no. 1, p. 38–71, doi:10.1785/0120140086.

Berger, M.J., George, D.L., Leveque, R.J., and Mandli, K.T., 2011, The GeoClaw software for depth-averaged flows with adaptive refinement: Advances in Water Resources, v. 34, no. 9, p. 1195–1206, doi:10.1016/j.advwatres.2011.02.016.

Blais-Stevens, A., Rogers, G.C., and Clague, J.J., 2011, A revised earthquake chronology for the last 4,000 years inferred from varve-bounded debris-flow deposits beneath an inlet near Victoria, British Columbia: Bulletin of the Seismological Society of America, v. 101, no. 1, p. 1–12, doi:10.1785/0120090360.

Blakely, R.J., Wells, R.E., Weaver, C.S., and Johnson, S.Y., 2002, Location, structure, and seismicity of the Seattle fault zone, Washington: Evidence from aeromagnetic anomalies, geologic mapping, and seismic refection data: Geological Society of America Bulletin, v. 114, no. 2, p. 169–177, doi:10.1130/0016-7606(2002)114<0169:LSASOT>2.0.CO;2.

Blakely, R.J., Sherrod, B.L., Hughes, J.F., Anderson, M.L., Wells, R.E., and Weaver, C.S., 2009, Saddle Mountain fault deformation zone, Olympic Peninsula, Washington; western boundary of the Seattle uplift: Geosphere, v. 5, no. 2, p. 105–125, doi:10.1130/GES00196.1.

Brocher, T.M., Parsons, T., Blakely, R.J., Christensen, N.I., Fisher, M.A., and Wells, R.E., 2001, Upper crustal structure in Puget Lowland, Washington: Results from the 1998 Seismic Hazards Investigation in Puget Sound: Journal of Geophysical Research, v. 106, no. B7, p. 13,541–13,564, doi:10.1029/2001JB000154.

Bronk Ramsey, C., 1995, Radiocarbon calibration and analysis of stratigraphy: The OxCal Program: Radiocarbon, v. 37, no. 2, p. 425–430, doi:10.1017/S0033822200030903.

Bronk Ramsey, C., 2009, Bayesian analysis of radiocarbon dates: Radiocarbon, v. 51, no. 1, p. 337–360.

Bronk Ramsey, C., 2017, OxCal software version 4.3.2; https://c14.arch.ox.ac.uk/oxcal/OxCal.html.

Bucknam, R.C., Hemphill-Haley, E., and Leopold, E.B., 1992, Abrupt uplift within the past 1700 years at southern Puget Sound, Washington: Science, v. 258, no. 5088, p. 1611–1614, doi:10.1126/science.258.5088.1611.

Carnigan, K.S., McLean, S.J., Eakins, B.W., Love, M.R., and Sutherland, M., 2014, Digital elevation model of Puget Sound, Washington: Procedures, Data Sources, and Analysis, https://www.ngdc.noaa.gov/dem/squareCellGrid/download/5164.

Cascadia Region Earthquake Workgroup (CREW), 2008, Cascadia Deep Earthquakes, Washington Department of Natural Resources Open File Report 2008-1, http://file.dnr.wa.gov/publications/ger_ofr2008-1_cascadia_deep_eq.pdf, 28 p.

Chleborad, A.F., 1994, Modeling and analysis of the 1949 Narrows landslide, Tacoma, Washington: Environmental & Engineering Geoscience, v. xxxi, no. 3, p. 305–327, doi:10.2113/gseegeosci.xxxi.3.305.

Clague, J.J., and Bobrowsky, P.T., 1994, Tsunami deposits beneath tidal marshes on Vancouver Island, British Columbia: Geological Society of America Bulletin, v. 106, no. 10, p. 1293–1303, doi:10.1130/0016-7606(1994)106<1293:TDBTMO>2.3.CO;2.

Clawpack Development Team, 2015, Clawpack Software, https://depts.washington.edu/clawpack/geoclaw/.

Creager, K., and Xu, Q., 2002, The 2001 Mw 6.8 Nisqually earthquake and its aftershocks: Eos (Transactions, American Geophysical Union), v. 83, no. 47, p. F1074.

Darienzo, M., 1991, Late Holocene paleoseismicity along the northern Oregon coast [Diss.]: Portland, Oregon, Portland State University, ProQuest Dissertations Publishing, Paper 1147, http://citeseerx.ist.psu.edu, 167 p.

Darienzo, M.E., Peterson, C.D., and Clough, C., 1994, Stratigraphic evidence for great subduction-zone earthquakes at four estuaries in northern Oregon, U.S.A.: Journal of Coastal Research, v. 10, no. 4, p. 850–876.

Enkin, R.J., Dallimore, A., Baker, J.R., Southon, J., and Ivanochko, T., 2013, A new high-resolution radiocarbon Bayesian age model of the Holocene and Late Pleistocene from core MD02-2494 and others, Effingham Inlet, British Columbia, Canada; with an application to the paleoseismic event chronology of the Cascadia Subduction Zone: Canadian Journal of Earth Sciences, v. 50, no. 7, p. 746–760, doi:10.1139/cjes-2012-0150.

Goldfinger, C., Nelson, C.H., Morey, A.E., Johnson, J.E., Patton, J.R., Karabanov, E., Gutiérrez-Pastor, J., Eriksson, A.T., Gràcia, E., Dunhill, G., Enkin, R.J., Dallimore, A., and Vallier, T., 2012, Turbidite Event History—Methods and Implications for Holocene Paleoseismicity of the Cascadia Subduction Zone: U.S. Geological Survey Professional Paper 1661-F, 170 p.; online at https://pubs.usgs.gov/pp/pp1661f/.

Goldfinger, C., Galer, S., Beeson, J., Hamilton, T., Black, B., Romsos, C., Patton, J., Nelson, C.H., Hausmann, R., and Morey, A., 2017, The importance of site selection, sediment supply, and hydrodynamics: A case study of submarine paleoseismology on the northern Cascadia margin, Washington, USA: Marine Geology, v. 384, p. 4–16, 17, 25–46.

González, F.I., Geist, E.L., Jaffe, B., Kânoğlu, U., Mofjeld, H., Synolakis, C.E., Titov, V.V., Arcas, D., Bellomo, D., Carlton, D., Homing, T., Johnson, J., Newman, J., Parsons, T., Peters, R., Peterson, C., Priest, G., Venturato, A., Weber, J., Wong, F., and Yalciner, A., 2009, Probabilistic tsunami hazard assessment at Seaside, Oregon, for near- and far-field seismic sources: Journal of Geophysical Research: Oceans, v. 114, C11023, doi:10.1029/2008JC005132.

González, F., LeVeque, R., Adams, L., Goldfinger, C., Priest, G., and Wang, K., 2014, Probabilistic Tsunami Hazard Assessment (PTHA) for Crescent City, CA: Final Report, September 11, 2014; funded by BakerAECOM, 101 p.

Graehl, N., Kelsey, H., Witter, R., Hemphill-Haley, E., and Engelhart, S., 2015, Stratigraphic and microfossil evidence for a 4500-year history of Cascadia subduction zone earthquakes and tsunamis at Yaquina River estuary, Oregon, USA: Geological Society of America Bulletin, v. 127, no. 1–2, p. 211–226, doi:10.1130/B31074.1.

Hutchinson, I., and Clague, J., 2017, Were they all giants? Perspectives on late Holocene plate-boundary earthquakes at the northern end of the Cascadia subduction zone: Quaternary Science Reviews, v. 169, p. 29–49.

Johnson, S.Y., Nelson, A.R., Personius, S.F., Wells, R.E., Kelsey, H.M., Sherrod, B.L., Okumura, K., Koehler, R., Witter, R.C., Bradley, L.-A., and Harding, D.J., 2004, Evidence for late Holocene earthquakes on the Utsalady Point fault, northern Puget Lowland, Washington: Bulletin of the Seismological Society of America, v. 94, no. 6, p. 2299–2316, doi:10.1785/0120040050.

Karlin, R.E., Holmes, M., Abella, S.E.B., and Sylwester, R., 2004, Holocene landslides and a 3500-year record of Pacific Northwest earthquakes from sediments in Lake Washington: Geological Society of America Bulletin, v. 116, no. 1–2, p. 94–108, doi:10.1130/B25158.1.

Lander, J.F., Lockridge, P.A., and Kozuch, M.J., 1993, Tsunamis Affecting the West Coast of the United States, 1806–1992: Boulder, Colorado, U.S. Dept. of Commerce, National Oceanic and Atmospheric Administration, National Environmental Satellite, Data, and Information Service, National Geophysical Data Center, 242 p.

LeVeque, R.J., George, D.L., and Berger, M.J., 2011, Tsunami modelling with adaptively refined finite volume methods: Acta Numerica, v. 20, p. 211–289, doi:10.1017/S0962492911000043.

Ludwin, R.S., Slemmons, D.B., Engdahl, E.R., Zoback, M.D., Blackwell, D.D., Weaver, C.S., and Crosson, R.S., 1991, Seismicity of Washington and Oregon, *in* Slemmons, D., Burton, D., Engdahl, E.R., Zoback, M.D., and Blackwell, D.D., eds., Neotectonics of North America: Boulder, Colorado, Geological Society of America, Decade Map Volume to Accompany the Neotectonic Maps, Part of the Continent-Scale Maps of North America 1, p. 77–97, doi:10.1130/DNAG-CSMS-NEO.77.

Nelson, A.R., Kelsey, H.M., and Witter, R.C., 2006, Great earthquakes of variable magnitude at the Cascadia subduction zone: Quaternary Research, v. 65, no. 3, p. 354, doi:10.1016/j.yqres.2006.02.009.

Nelson, A.R., Personius, S.F., Buck, J., Bradley, L.-A., Wells, R.E., and Schermer, E.R., 2007, Field and Laboratory Data from an Earthquake History Study of Scarps of the Lake Creek–Boundary Creek Fault between the Elwha River and Siebert Creek, Clallam County, Washington: U.S. Geological Survey Scientific Investigations Map 2961, 2 sheets.

Nelson, A.R., Sawai, Y., Jennings, A.E., Bradley, L.-A., Gerson, L., Sherrod, B.L., Sabean, J., and Horton, B.P., 2008, Great-earthquake paleogeodesy and tsunamis of the past 2000 years at Alsea Bay, central Oregon coast, USA: Quaternary Science Reviews, v. 27, no. 7–8, p. 747–768, doi:10.1016/j.quascirev.2008.01.001.

Nelson, A.R., Personius, S.F., Sherrod, B.L., Kelsey, H.M., Johnson, S.Y., Bradley, L., and Wells, R.E., 2014, Diverse rupture modes for surface-deforming upper plate earthquakes in the southern Puget Lowland of Washington State: Geosphere, v. 10, no. 4, p. 769–796, doi:10.1130/GES00967.1.

Okada, R., 1985, Surface deformation due to shear and tensile faults in a half-space: Bulletin of the Seismological Society of America, v. 75, p. 1135–1154.

Pollen, A., 2016, The sedimentary record of past earthquakes identified in Holocene sediments of Lake Crescent, Washington [M.S. thesis]: North Carolina State University, 79 p., online at http://www.lib.ncsu.edu/resolver/1840.16/11366.

Port Townsend Leader, 1964 (2 April), Tidal wave alerts received by various agencies here, v. 76, no. 14, p. 1.

Reimer, P.J., Bard, E., Bayliss, A., and Beck, J.W., 2013, IntCal13 and Marine13 radiocarbon age calibration curves 0–50,000 years cal BP: Radiocarbon, v. 55, no. 4, p. 1869–1887, doi:10.2458/azu_js_rc.55.16947.

Shennan, I., Long, A.J., Rutherford, M.M., Innes, J.B., Green, F.M., and Walker, K.J., 1998, Tidal marsh stratigraphy, sea-level change and large earthquakes—II: Submergence events during the last 3,500 years at Netarts Bay, Oregon, USA: Quaternary Science Reviews, v. 17, no. 4–5, p. 365–393, doi:10.1016/S0277-3791(97)00055-3.

Sherrod, B.L., 2001, Evidence for earthquake-induced subsidence about 1100 yr ago in coastal marshes of southern Puget Sound, Washington: Geological Society of America Bulletin, v. 113, no. 10, p. 1299–1311, doi:10.1130/0016-7606(2001)113<1299:EFEISA>2.0.CO;2.

Sherrod, B.L., Brocher, T.M., Weaver, C.S., Bucknam, R.C., Blakely, R.J., Kelsey, H.M., Nelson, A.R., and Haugerud, R., 2004, Holocene fault scarps near Tacoma, Washington, USA: Geology, v. 32, no. 1, p. 9–12, doi:10.1130/G19914.1.

Smith, S., 2012, Controls on Large and Very Large Submarine Landslides in Puget Sound, WA, USA [Diss.:]: Reno, Nevada, University of Nevada, Reno, 151 p., available through ProQuest Dissertations Publishing.

Tsunami Pilot Study Working Group, 2006, Seaside, Oregon Tsunami Pilot Study—Modernization of FEMA Flood Hazard Maps: National Oceanic and Atmospheric Administration OAR Special Report, NOAA/OAR/PMEL, Seattle, Washington, 94 p. + 7 appendices.

Williams, H.F.L., Hutchinson, I., and Nelson, A.R., 2005, Multiple sources for late-Holocene tsunamis at Discovery Bay, Washington State, USA: The Holocene, v. 15, no. 1, p. 60–73.

Witter, R.C., Peterson, C.D., Cruikshank, K.M., Hemphill-Haley, E., Schlichting, R.B., and Allan, J.C., 2008, Prehistoric Cascadia Tsunami Inundation and Runup at Cannon Beach, Clatsop County, Oregon: State of Oregon, Department of Geology and Mineral Industries, Open-File Report O-08-12, 36 p. + appendix.

Yamaguchi, D.K., Atwater, B.F., Bunker, D.E., Benson, B.E., and Reid, M.S., 1997, Tree-ring dating the 1700 Cascadia earthquake: Nature, v. 389, no. 6654, p. 922–923, doi:10.1038/40048.

Manuscript Accepted by the Society 20 July 2017

Printed in the USA