

Tsunamis in the Salish Sea: Recurrence, sources, hazards

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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 radio-carbon 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)

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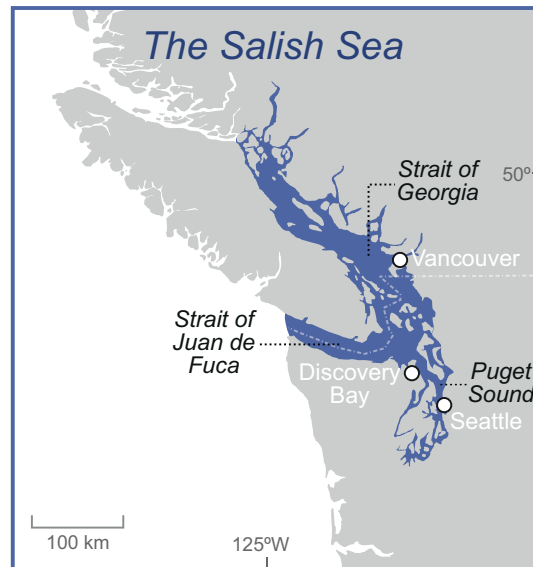
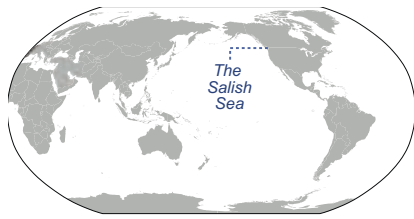


Figure 1. Location and area of the Salish Sea.

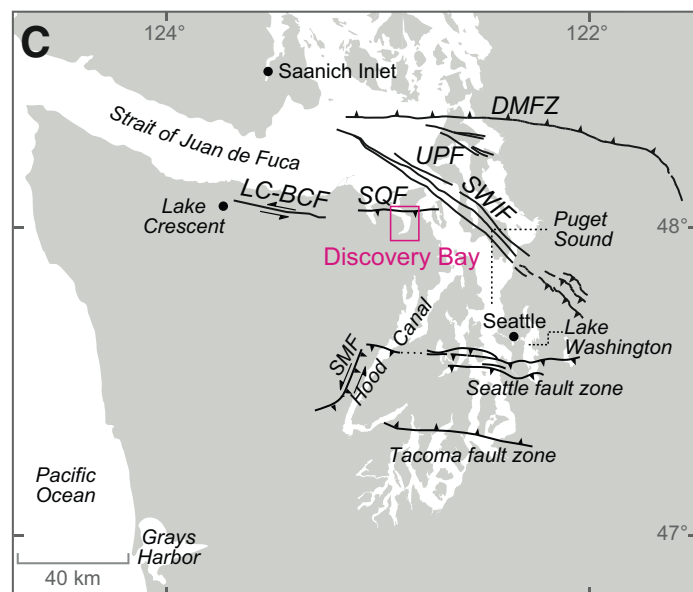
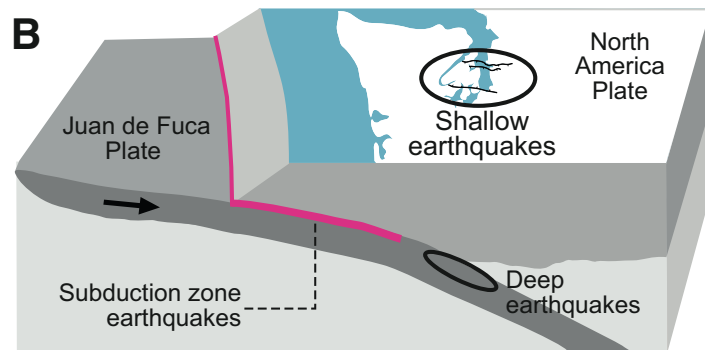
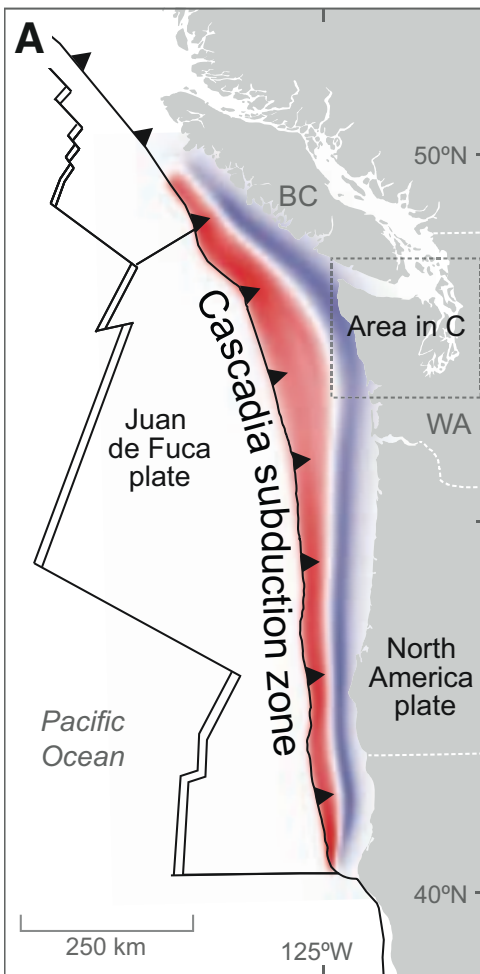


Figure 2.

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

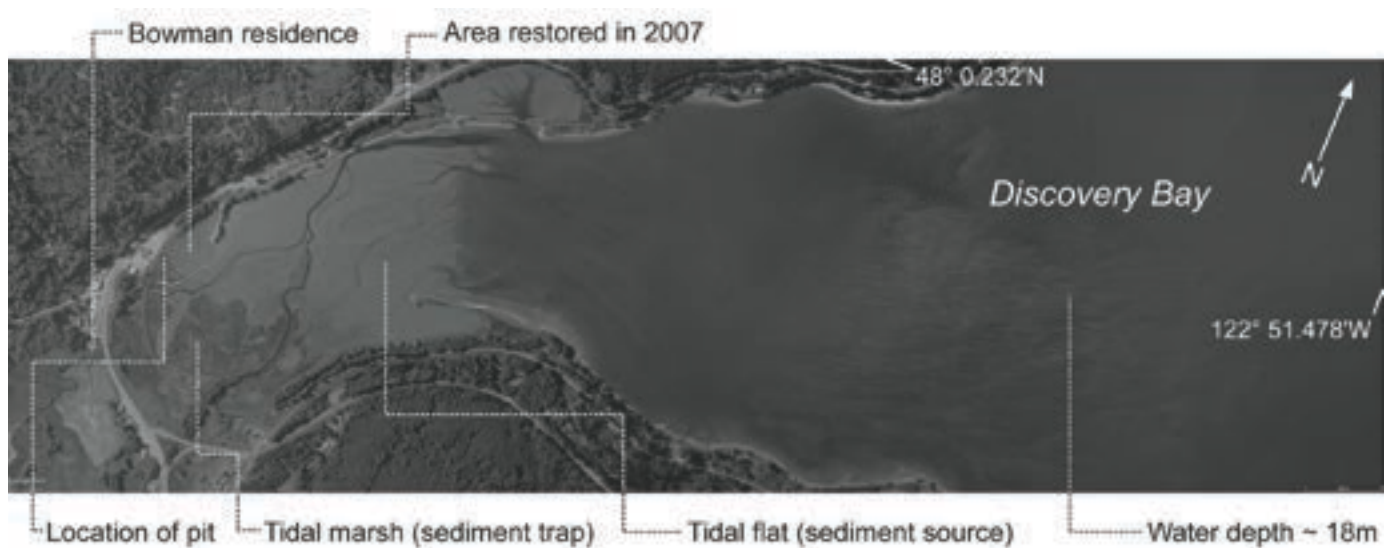


Figure 3. Google Earth image of Discovery Bay from 2009, showing the 2007 marsh restoration area, location of tidal flat source of tsunami deposit sediments, and tidal marsh areas. The Bowman residence was flooded in 1964 by the Alaska earthquake tsunami.

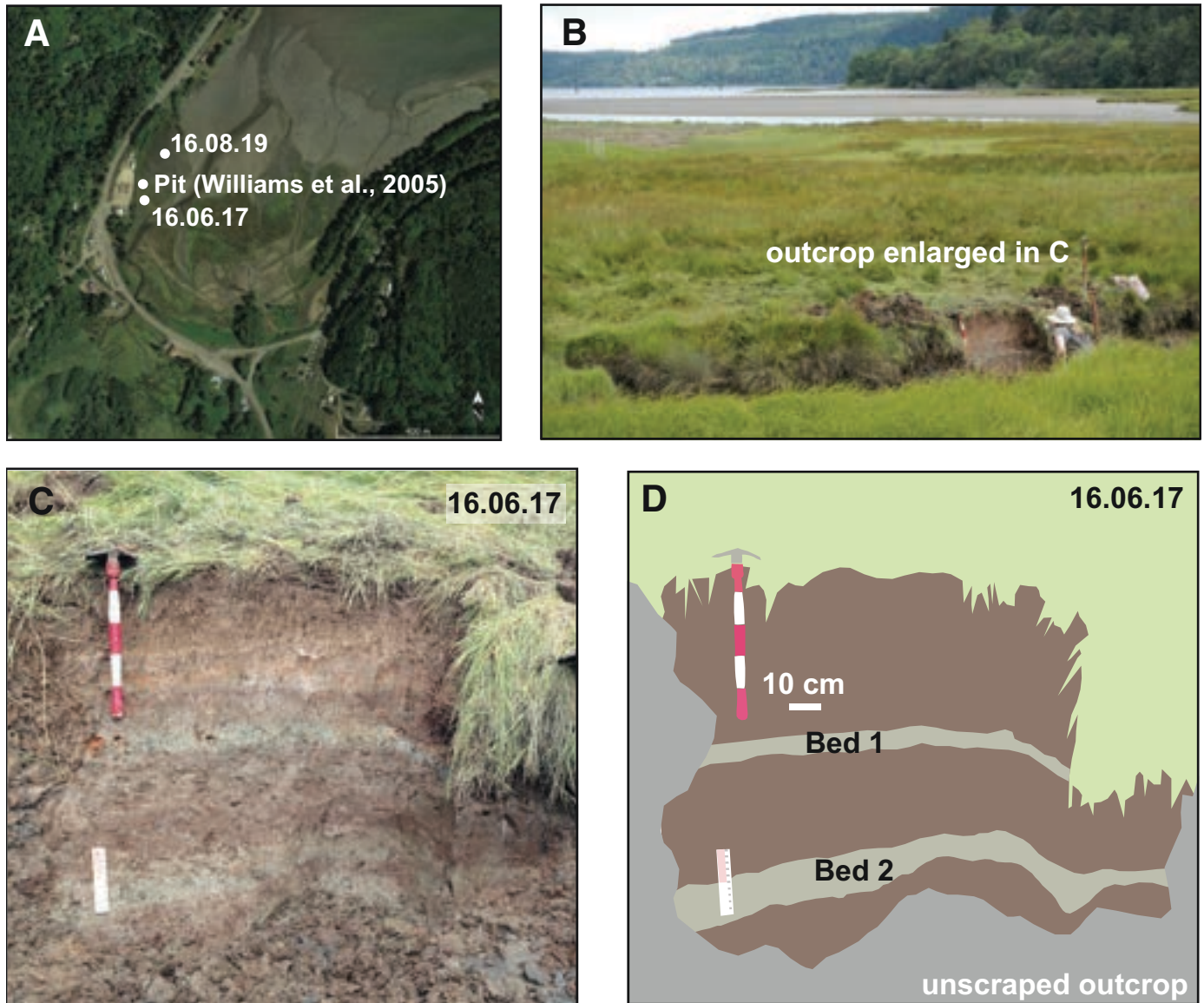


Figure 4. (A) Discovery Bay field sites, (B) overview of outcrop 16.06.17 looking to the northeast with exposed tidal flat in the background, (C) close-up of outcrop 16.06.17 showing beds 1 and 2, and (D) interpretation of outcrop 16.06.07. Bed 1 is probably from the 1700 A.D. Cascadia tsunami. Each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

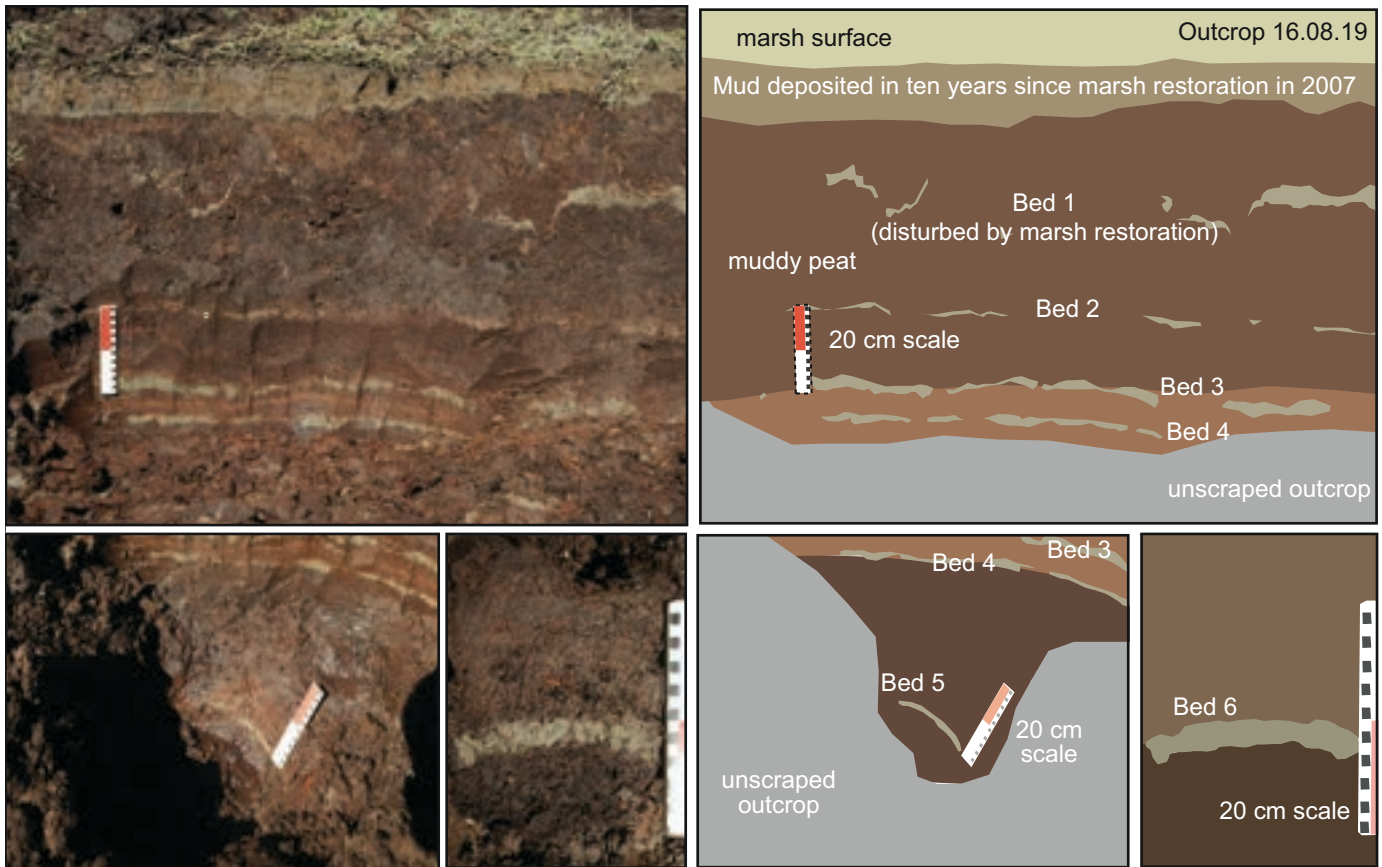


Figure 5. Outcrop of beds 1–6 tsunami deposits at Discovery Bay, and layer of mud that has aggraded on the marsh surface since it was restored in 2007. Photographs on left, annotation on right. Scale bar in each panel is 20 cm. Outcrop is at location 16.08.19 in Figure 4A.

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

tral 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

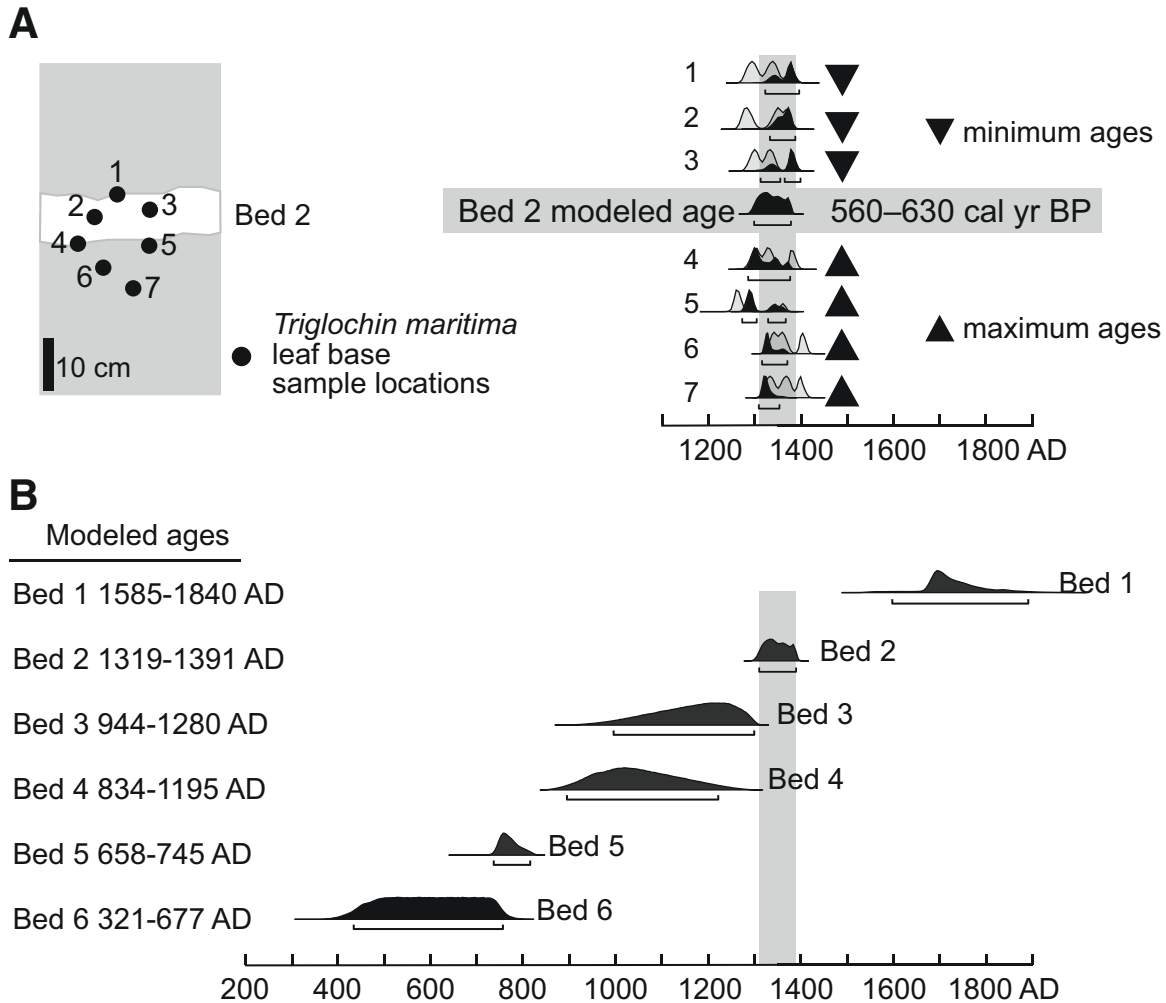


Figure 6. Radiocarbon dating at Discovery Bay. (A) Stratigraphic positions of radiocarbon samples of leaf bases of the marsh plant *Triglochin maritima* indicated by black dots (composite of two different outcrops) with respect to bed 2. *Triglochin maritima* leaf bases grow at or near the marsh surface, 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. 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 (Darienzone, 1991; Darienzone 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.

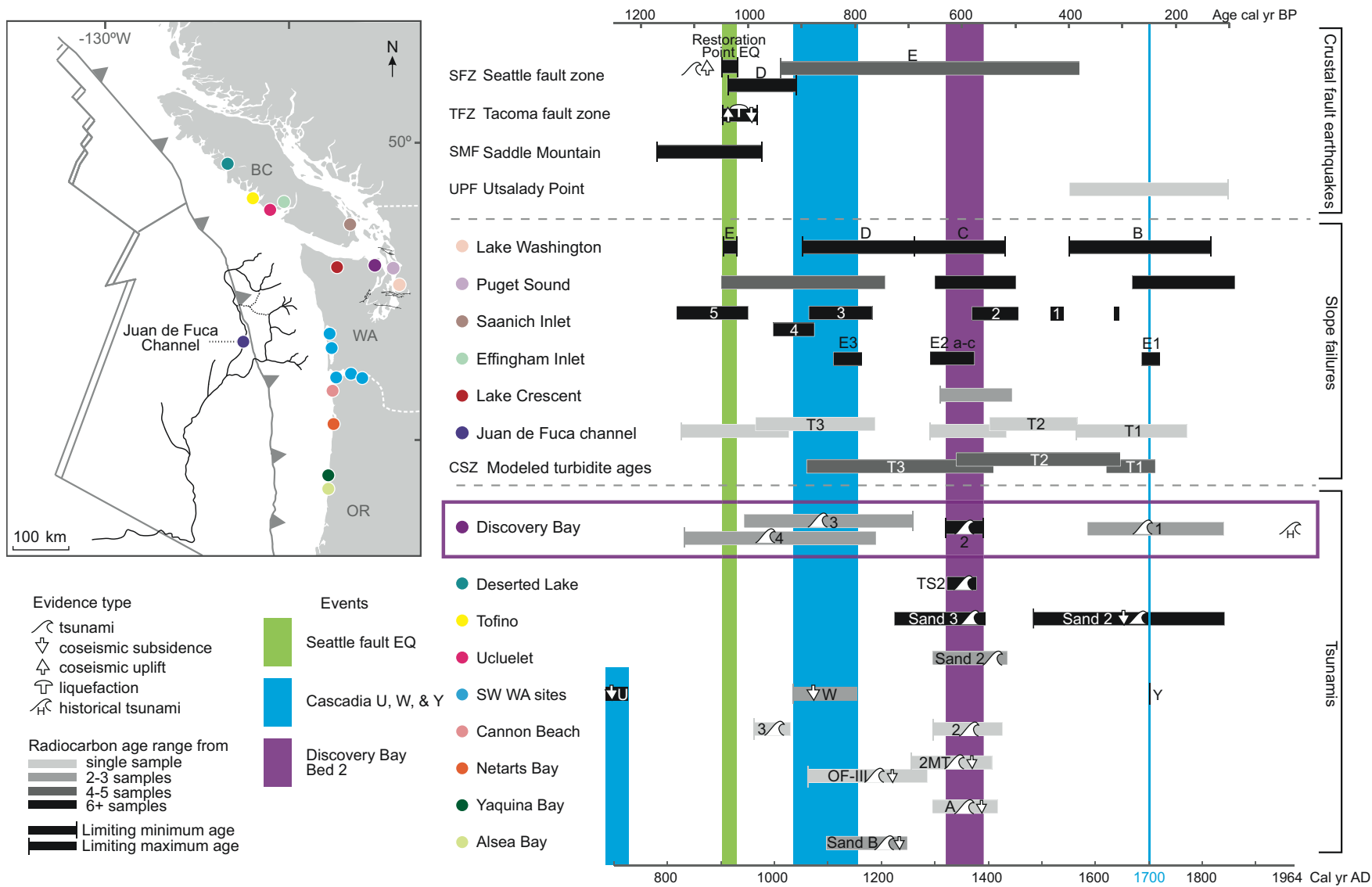


Figure 7.

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 earth-

quake 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 sloggng 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

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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 Quileuse 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.



Discovery Bay Alaska source Mw = 9.2

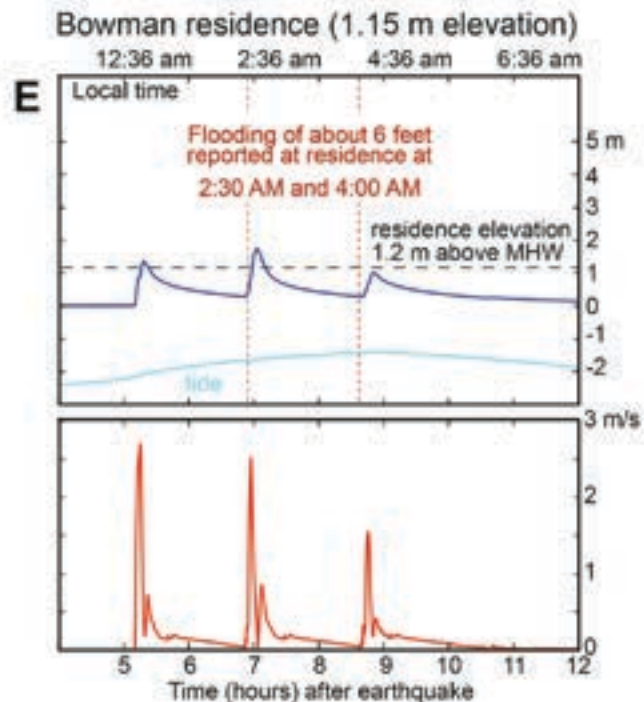
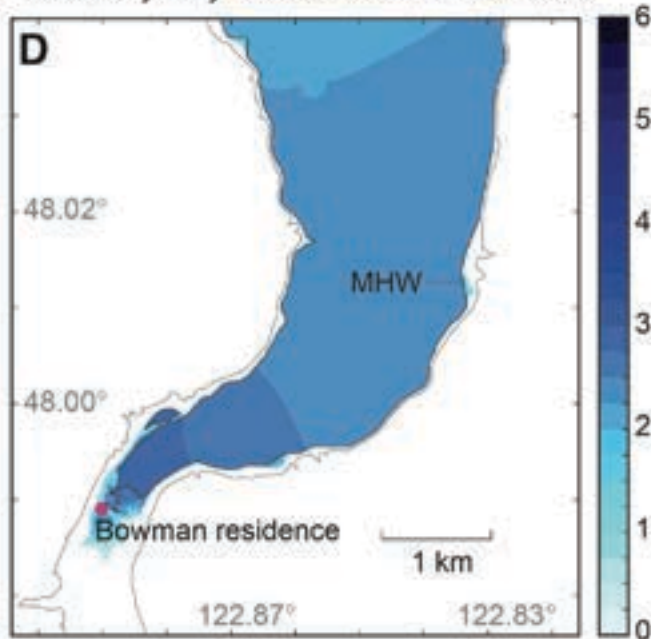


Figure 9.

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-21 of Williams et al. (2005).

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

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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.

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