Testing Crustal Fault Tsunami Sources in the Salish Sea: Comparing Modeled Inundation With the Geologic Record at Discovery Bay, WA

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1. Abstract

Crustal faults across the Salish Sea are capable of producing M7+ earthquakes and hazardous tsunamis in Puget Sound and the Strait of Georgia. A better understanding of the history of Salish Sea tsunamis and their sources will improve tsunami hazard assessments in Washington state and British Columbia. The Seattle and Tacoma faults are well-studied tsunami sources, but other Salish Sea crustal faults are just starting to be evaluated for their tsunami hazard. One way to advance our understanding of crustal fault tsunami hazards is to compare modeled tsunami inundation from various sources with geologic evidence for past tsunamis. The tidal marsh at Discovery Bay, Washington, is an excellent geologic recorder of past tsunamis because of its wave-amplifying funnel-shaped morphology, an abundant sediment supply, and a terminal tidal marsh that has preserved tsunami deposits in the marsh stratigraphy. With at least 10 tsunami deposits of thicknesses between 2-10 cm thick, and at least 6 thinner layers under 1 cm thick spanning the last ~3,000 years, the deposits at Discovery Bay likely represent not only tsunamis generated by the Cascadia subduction zone, but also those generated by crustal faults, landslides, or tsunamis from other Pacific subduction zones. To better understand potential crustal fault sources of Discovery Bay tsunami deposits, we test high-resolution tsunami inundation models of the Skipjack Island, Darrington-Devils Mountain, South Whidbey Island, Seattle, and Tacoma fault zones. We also test tsunami inundation models of the 1700 C.E. Cascadia subduction zone and 1964 Great Alaskan earthquake tsunamis, both of which have probable deposits at Discovery Bay. Some of the crustal fault sources we tested appear to be more likely to cause flooding at Discovery Bay than others and may be the sources for deposits whose ages do not align with known Cascadia earthquakes.

2. Study location

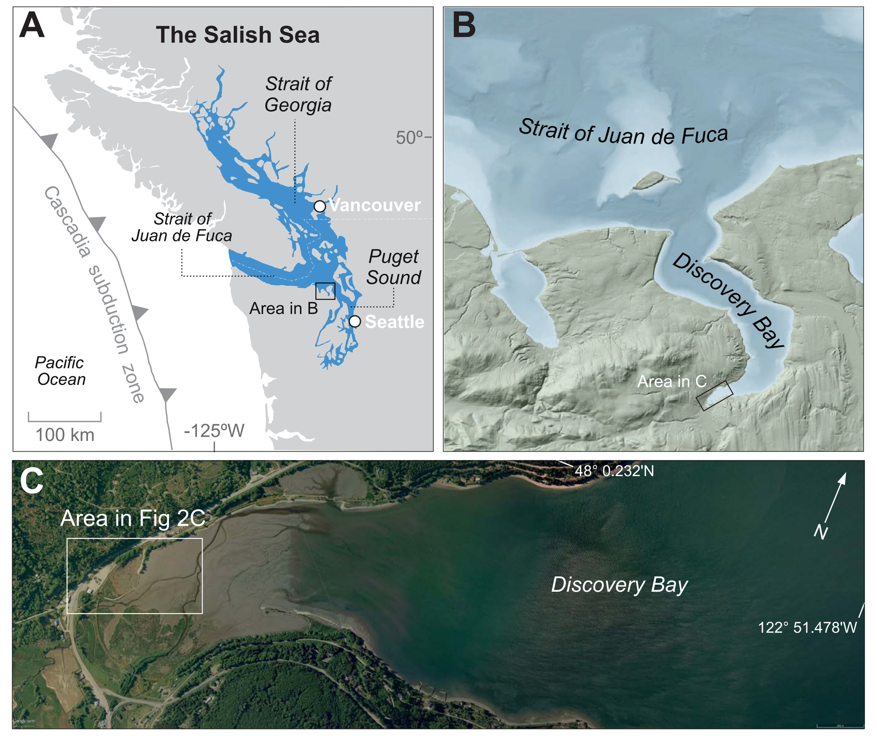


Figure 1. Tsunami deposit study area in the Salish Sea. A. The study area (black box) along the Strait of Juan de Fuca and location relative to the Cascadia subduction zone. B. The entrance to Discovery Bay from the Strait of de Fuca, showing the tapering shape of the bay that amplifies tsunami waves. C. An ample sediment source and tidal marsh at the head of the bay serves as a sediment source and depositional environment for tsunami deposits.

3. Discovery Bay–at least ten tsunami deposits in 3,000 years

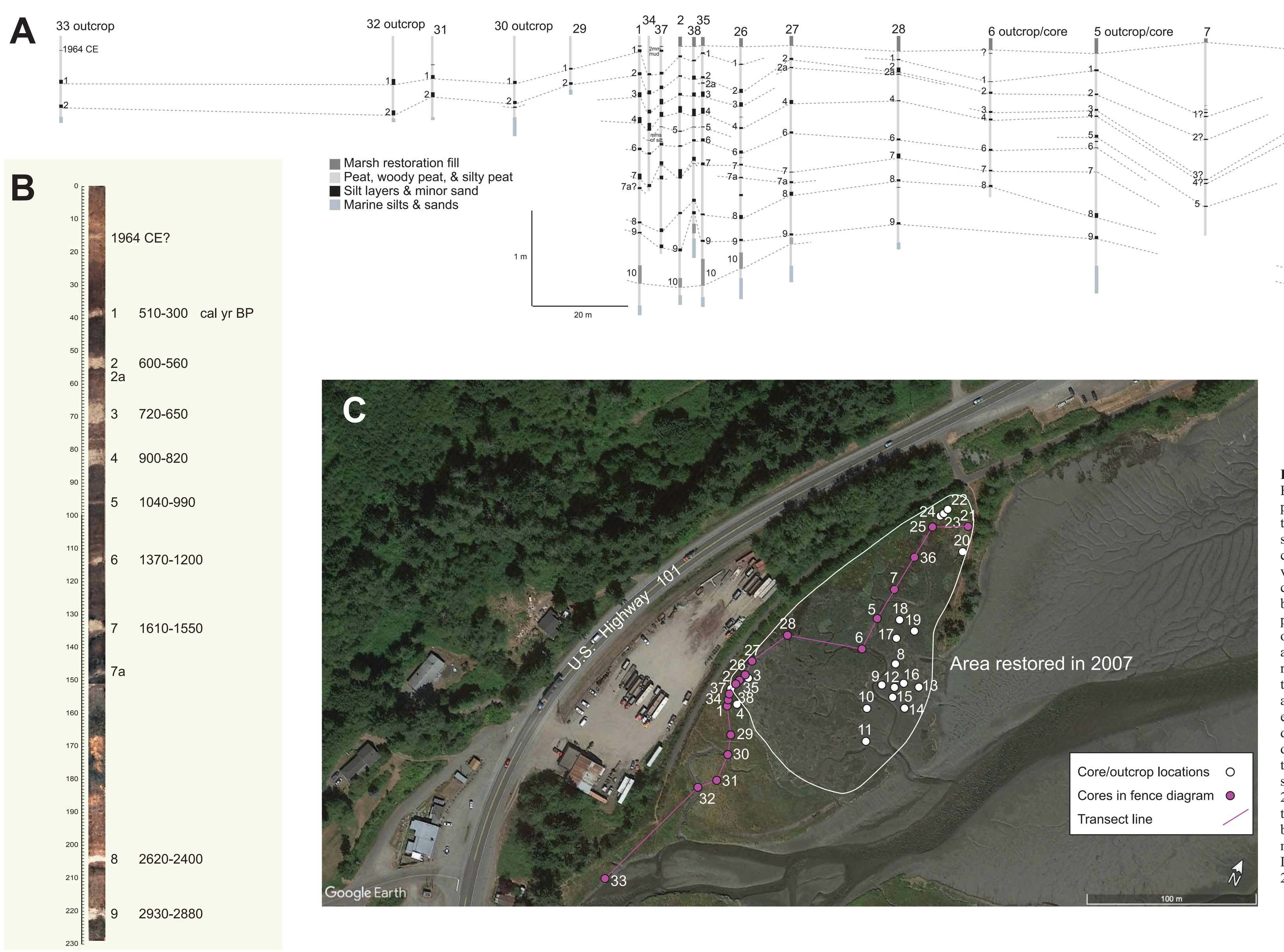


Figure 2. Tsunami deposits from Discovery Bay. **A**. Fence diagram showing stratigraphy and distribution of Discovery Bay tsunami deposits (in black) in tidal marsh sediments. Deposits mapped from 36 2.5 cm diameter cores, two 7.6 cm diameter vibracores (Locations 37 and 38), and 5 channel bank exposures. Correlations between tsunami deposits based on deposit properties, depths, and ages. **B**. Photograph of vibracore from Location 37 in with average modeled ages from a set of 45 radiocarbon samples. Figure 3 shows additional information about age models used and potential correlations with regional earthquake, tsunami, and turbidite evidence. **C**. Core locations used in the fence diagram in A (Google Earth image). Locations used in the fence diagram in A are shown by the transect line in magenta. In 2007, clearing and restoration of an area of the marsh (white outline on map) that had been previously diked allowed access to marsh deposits not available to earlier Discovery Bay researchers (Williams et al. 2005).

4. Tsunami deposit ages and potential sources

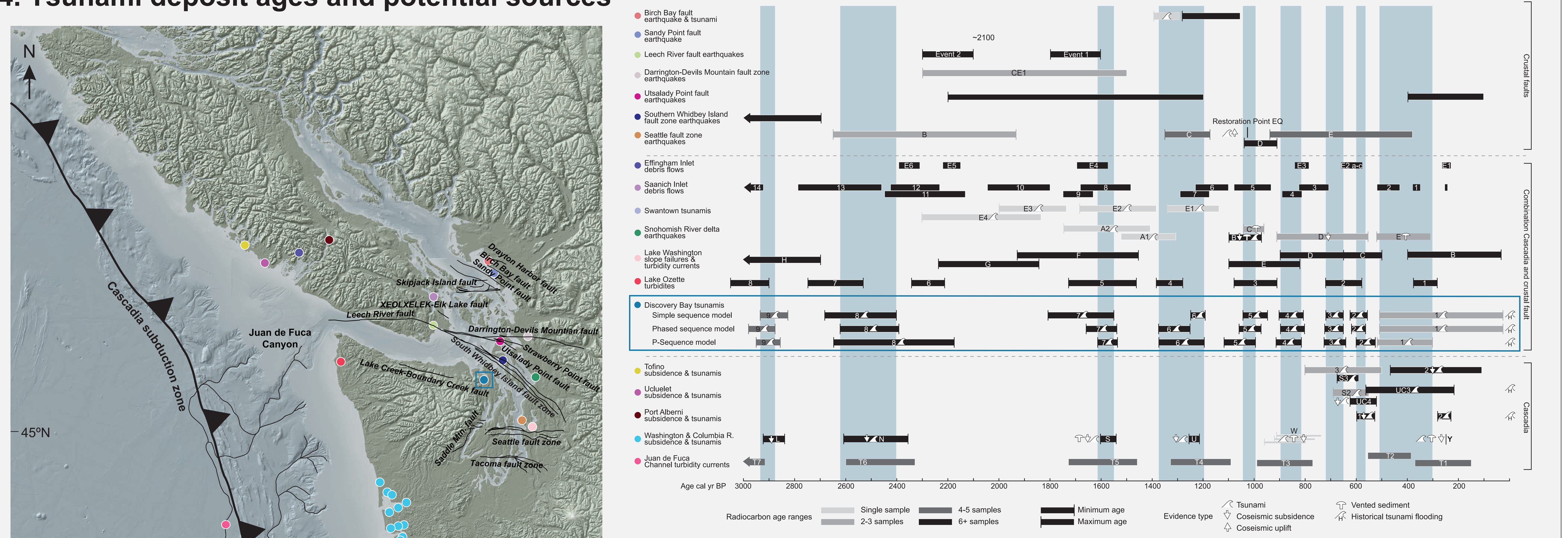


Figure 3. Comparison of radiocarbon ages of Discovery Bay tsunami deposits (location and ages bounded by blue box above) with evidence for earthquakes, tsunamis, and turbidites from other regional sources. Discovery Bay ages from three different models are plotted, a simple sequence model on top, a phased sequence model in the middle, and a P-Sequence model on the bottom. Vertical blue shading corresponds to the areas of agreement between the three age models for each tsunami deposit. Ages from other locations grouped by source type. At the top, sites that record earthquakes and tsunamis from intraplate (crustal) faults; in the center, sites that likely record both Cascadia subduction zone earthquakes and crustal fault earthquakes, and their secondary effects; at the bottom of the plot, sites that record Cascadia earthquakes. Colored dots on the map correspond to colored dots next to place names. Symbols under "Evidence type" indicate type of evidence shown on age plots. Horizontal age range bars are shaded to reflect the number of samples used to determine the age, and are bracketed as minimum or maximum ages where known. Ages plotted and references: Birch Bay and Sandy Point faults (Kelsey et al., 2012); Darrington-Devils Mountain fault (Personius et al., 2014); Utsalady Point (Johnson et al., 2004b); South Whidbey Island fault zone (Kelsey et al., 2004); Seattle fault zone (Atwater and Moore, 1992; Bucknam et al., 1992; Atwater, 1999; Nelson et al., 2014; Black et al., 2023); Effingham Inlet (Enkin et al., 2013); Saanich Inlet (Blais-Stevens et al., 2011); Swantown (Williams and Hutchinson, 2000); Snohomish River delta (Bourgeois and Johnson, 2001); Lake Washington (Karlin et al., 2004); Lake Ozette (Brothers et al., in review); Discovery Bay (Williams et al., 2005; Garrison-Laney, 2017; Garrison-Laney and Miller, 2017); Tofino (Clague and Bobrowsky, 1994a; Clague and Bobrowsky, 1994b; Hughes et al., 2002; Tanigawa et al., 2022); Ucluelet Sand 2, (Clague and Bobrowsky, 1994a, 1994b); Port Alberni (Clague et al., 1994; Clague and Bobrowsky, 1994a; Clague and Bobrowsky, 1994b; Riou, 2024); WA coast (Atwater, 1987; Atwater and Hemphill-Haley, 1997; Atwater et al., 2004; event W shrub Atwater and Griggs, 2012); Juan de Fuca channel turbidites from cores M9907-11/12 (Goldfinger et al., 2012; 1964 Alaska tsunami flooding (Seattle Daily Times, 1964; Port Townsend Leader, 1964).

5. Modeling Salish Sea crustal fault tsunami sources

We tested different tsunami sources for their potential to make tsunami deposits at Discovery Bay. We simulated three crustal faults in northern Puget Sound: the Skipjack Island fault zone (an M7.3 earthquake; Caston, 2018; Greene et al., 2018), the Darrington-Devils Hill fault zone (an M7.5 earthquake; Barrie and Greene, 2018), and the South Whidbey Island fault zone (an M7.4 earthquake; Peterson et al., 2014). We also modeled tsunamis generated by southern Puget Sound crustal faults, though the geometry of the waterways makes them less likely sources for Discovery Bay deposits. We modeled the Seattle fault zone (an M7.2 earthquake; Venturato et al, 2007; Dolcimascolo et al., 2022), and the Tacoma Fault Zone (an M6.9 earthquake; Venturato et al, 2007). From previous modeling (Garrison-Laney, 2017; Garrison-Laney and Miller, 2017; Dolcimascolo et al., 2022), Cascadia subduction zone and Alaska-Aleutian subduction zone tsunamis are large enough to be potential sources of tsunami deposits at Discovery Bay. We modeled tsunami inundation from the Cascadia and Alaska-Aleutian subduction zones. For Cascadia we tested a trench-breaking rupture model by Wang et al. (2013) with an improved megathrust geometry by Gao et al. (2018). The Alaska source earthquake is a hypothetical model of the 1964 M9.2 Alaska earthquake with~ 17 m uniform slip over the rupture area made by the NOAA Center for Tsunami Research. The deformation models for each of these sources are shown in Figure 4 below.

We conducted all model simulations using the tsunami code of "Method of Splitting Tsunamis" (MOST). The MOST model is a suite of integrated numerical codes capable of simulating tsunami generation, transoceanic propagation, and its subsequent inundation in the coastal area (Titov et al., 2016). The model is a finite-difference approximation of the characteristics form of the shallow-water-wave equations using the splitting method. In MOST, the co-seismic vertical disturbance of the ocean floor because of earthquake faulting computed from elastic theory, for example Okada (1985), is assumed to be instantaneously transferred to the ocean surface. For inundation modeling, MOST uses nested computational grids to telescope down to the high-resolution area of interests for inundation computation. In the present study, we employ two different sets of telescoped grids for tsunamis generated by the subduction zone earthquakes and by crustal faults due to different scales of tsunami propagation distance. In both grid systems we apply the same grid coverage and high spatial resolution, 5 m, for the entire Discovery Bay to investigate the tsunami wave dynamics at our study site. The vertical datum of our model grids is the Mean High Water (MHW) following the model grids developed by the National Center for Environmental Center (NCEI). MOST employs a uniform Manning's friction coefficient, 0.03, throughout all the grids.

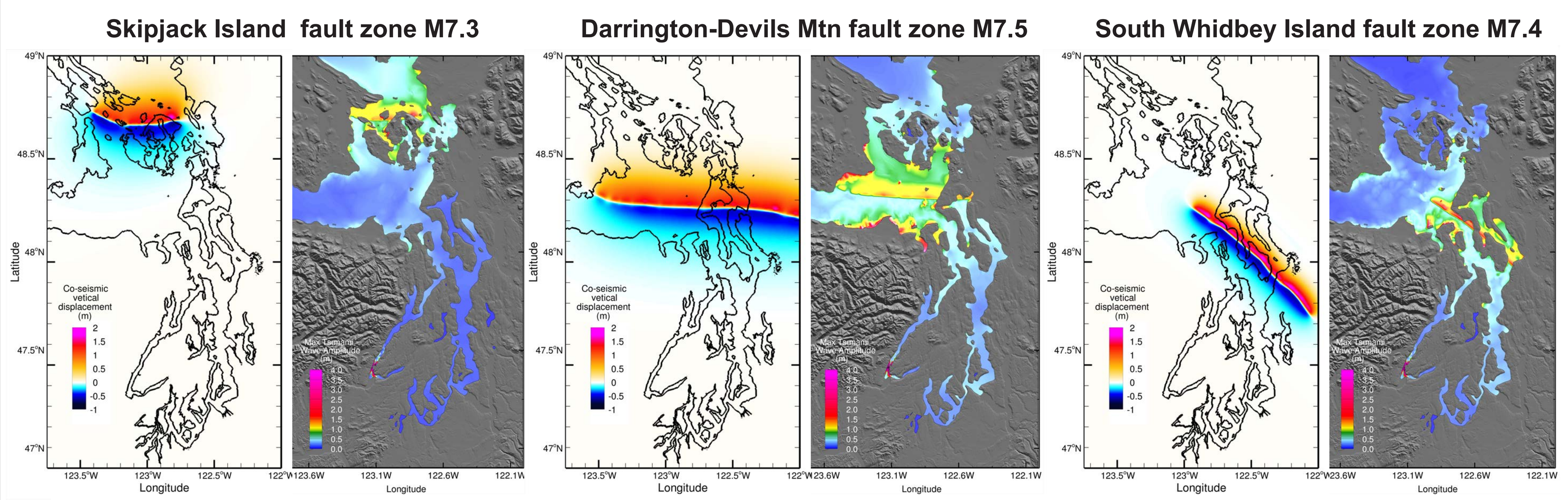
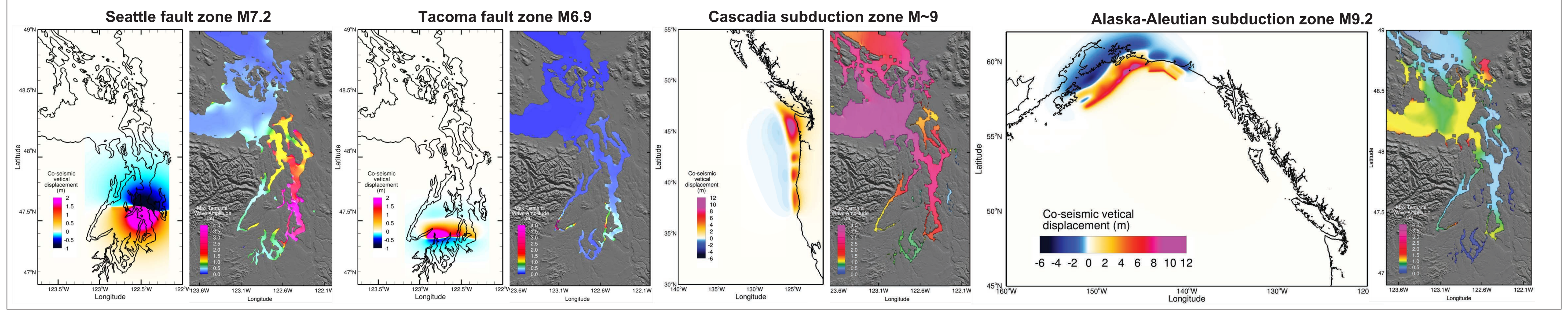


Figure 4. The potential tsunami sources tested for inundation at Discovery Bay. The paired plots for each source shows fault deformation models (vertical displacement) on the left and corresponding maximum modeled tsunami amplitudes in Puget Sound on the right. Figure 5 zooms in on Discovery Bay for each of these sources. The ages, where available, for earthquake, tsunami, and turbidite events for each of these sources are plotted in Figure 3. Google Earth image showing location of Discovery Bay and Puget Sound region cities (right).



6. Crustal Fault Inundation at Discovery Bay

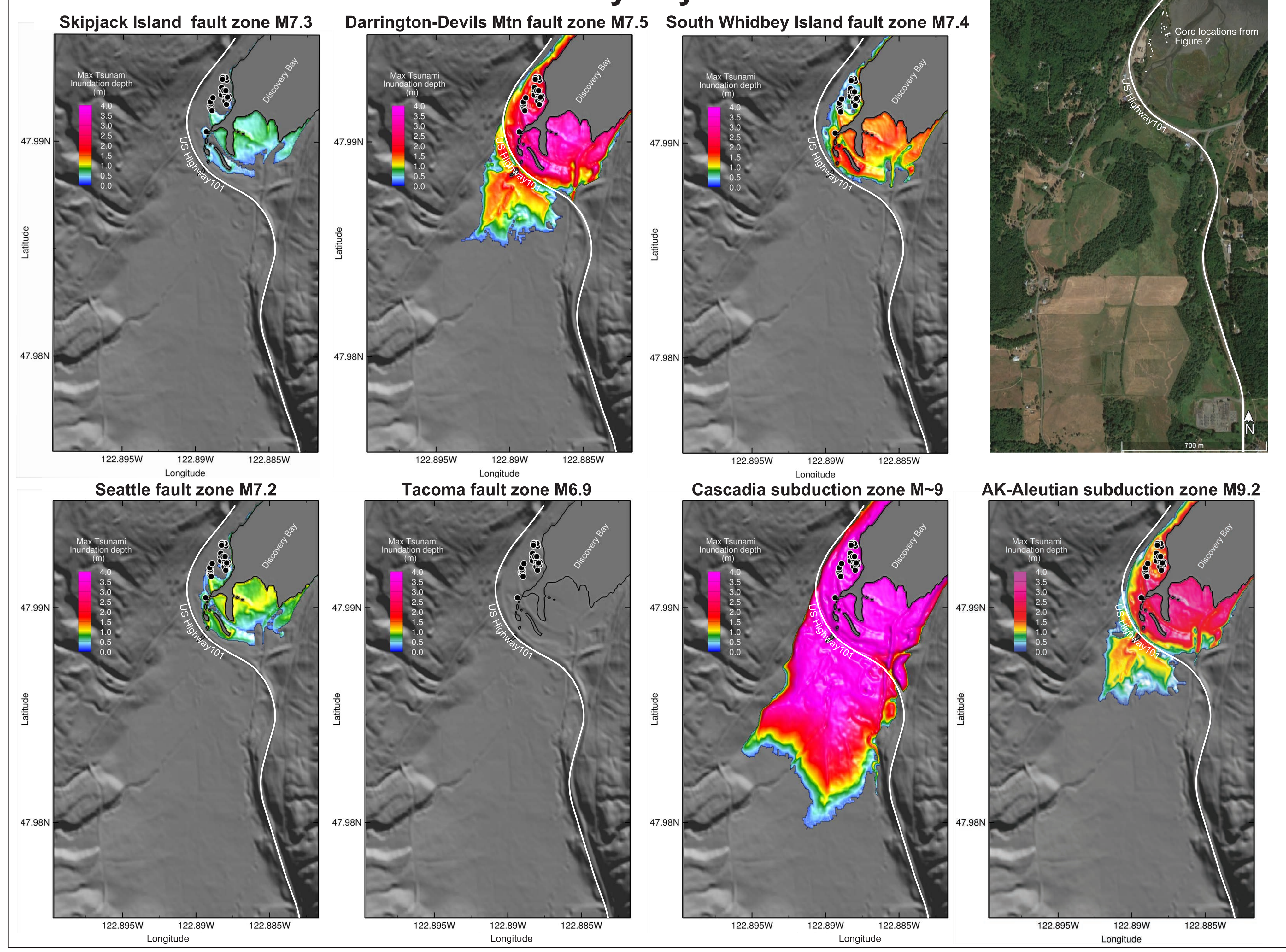


Figure 5. Maximum computed tsunami inundation depths at Discovery Bay at 5 m resolution for each tested source. The colored inundation area heights (in m) correspond to the values in the scale bar. The black dots are the core locations in Figure 2. These models were run at modernMean High Water (MHW), and are therefore not reproductions of prehistoric tsunami events when sea levels were lower than present day MHW. However, these results can be used as a starting point for identifying sources most likely to make deposits to be modeled at appropriate sea level. Two crustal fault sources that appear to be most likely to leave behind tsunami deposits are the Darrington-Devils Mountain fault zone and the South Whidbey Island fault zone. In addition, tsunamis generated by either full margin Cascadia subduction zone, or partial ruptures near the latitude of the Strait of Juan de Fuca are appear highly likely leave tsunami deposits at Discovery Bay. (Right) Google Earth image of the modeled area, head of Discovery Bay.

7. Conclusions

Discovery Bay has the most tsunami deposits of any other location in Washington state, with a record that spans the last 3,000 years. Discovery Bay's tapering morphology, sediment source, and tidal marsh make it an excellent geologic recorder of tsunamis. At least ten tsunami deposits of thickness 1 cm or greater are represented in the thickest part of the marsh section, in addition to several thinner discontinuous layers.

Cascadia tsunami deposits are apparently well-represented at Discovery Bay. The ages of Discovery Bay's Beds 1, 4, 6, 7, 8, and 9 align well with Cascadia earthquakes Y (1700 CE), W, U, S, N, and L from southwest Washington, respectively (Atwater and Hemphill-Haley, 1997). However, three tsunami deposits at Discovery Bay do not align with known Cascadia earthquake ages from southwest Washington: Beds 2, 3, and 5.

Bed 2 (~ 580 yr BP) may represent a hypothesized Cascadia rupture limited to the northern part of the subduction zone (Garrison-Laney, 2017), supported by similar-aged evidence from the region including tsunami deposits and coseismic subsidence from Port Alberni, Tofino, and Ucluelet on Vancouver Island (Clague and Bobrowsky, 1994a & 1994b; Tanagawa et al., 2022; and Riou, 2024), submarine debris flows from Effingham inlet (Enkin et al., 2013), and potentially by lake turbidite 2 from Ozette Lake (Brothers et al., in preparation). Bed 3 has no obvious correlative seismic evidence in the region, with the possible exception of turbidite 2 from Ozette Lake (Brothers et al., in preparation).

Discovery Bay Bed 5 is a thin, patchy deposit with an age range that overlaps with the age of the Seattle/Saddle Mountain fault earthquake(s) of 923-924 CE (Black et al., 2023); subsidence, vented sediments, and a tsunami deposit at the attributed to the Seattle fault at the Snohomish River delta (Bourgeois and Johnson, 2001); slumps in Lake Washington (Karlin et al., 2004); Saanich Inlet debris flows (Blais-Stevens et al., 2011); and Ozette Lake turbidite 3 (Brothers et al., in preparation). Discovery Bay's thin patchy Bed 5 may represent the Seattle fault tsunami, which would have lost much of its energy by the time it traveled north, and turned sharply into Discovery Bay.

The thin and discontinuous tsunami deposits at Discovery Bay, may also represent tsunamis from other subduction zones. A patchy deposit up to 0.5 cm thick in the upper 20 cm of the section may be from the 1964 Great Alaskan Earthquake tsunami, which caused flooding of a residence at the head of the bay (Seattle Daily Times, 1964; Port Townsend Leader, 1964). Either Bed 2, 3, or 5, or any of the multiple thinner deposits may also be the result of landslide-generated tsunamis.

Of the tsunami sources tested for inundation at Discovery Bay, the ones with the most significant inundation at Discovery Bay are the Darrington-Devils Mountain fault M7.5 source, the South Whidbey Island fault M7.4 source, a Cascadia M9 source, and an Alaska-Aleutian subduction zone M9 source. The Seattle fault M7.2 source only causes slight inundation of the marsh at Discovery Bay, but its age is a reasonable match for Bed 5. Of the sources that cause the most inundation at Discovery Bay, none, with the exception of the Seattle fault, have known earthquakes that fall within the modeled age ranges of the deposits. Further modeling of crustal fault sources, distant tsunami sources, and submarine landslides at past lower sea levels would help to narrow potential candidates sources for Bed 3 and 5 at Discovery Bay.

References

Acknowledgments

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