





# TSUNAMI HAZARD MAPS OF SOUTHWEST WASHINGTON— MODEL RESULTS FROM A ~2,500-YEAR CASCADIA SUBDUCTION ZONE EARTHQUAKE SCENARIO

---

by Daniel W. Eungard, Corina Forson, Timothy J. Walsh,  
Edison Gica, and Diego Arcas

WASHINGTON  
GEOLOGICAL SURVEY  
Map Series 2018-01  
March 2018 [Revised May 2018]

*This publication has been subject to an iterative technical review process by at least one Survey geologist who is not an author. This publication has also been subject to an iterative review process with Survey editors and cartographers and has been formatted by Survey staff.*



WASHINGTON STATE DEPARTMENT OF  
**NATURAL RESOURCES**  
WASHINGTON GEOLOGICAL SURVEY

## DISCLAIMER

Neither the State of Washington, nor any agency thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise, does not necessarily constitute or imply its endorsement, recommendation, or favoring by the State of Washington or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the State of Washington or any agency thereof.

This map product has been subjected to an iterative internal review process by agency geologists, cartographers, and editors and meets Map Series standards as defined by the Washington Geological Survey.

## INDEMNIFICATION

This item was funded by a National Tsunami Hazard Mitigation Program grant (award no. NA17NWS4670017) to the Washington Geological Survey from the Department of Commerce/National Oceanic and Atmospheric Administration. This does not constitute an endorsement by NOAA. Information about NTHMP is available at <http://nws.weather.gov/nthmp/>.

## WASHINGTON STATE DEPARTMENT OF NATURAL RESOURCES

Hilary S. Franz—*Commissioner of Public Lands*

## WASHINGTON GEOLOGICAL SURVEY

David K. Norman—*State Geologist*  
Timothy J. Walsh—*Assistant State Geologist*  
John P. Bromley—*Assistant State Geologist*

### **Washington State Department of Natural Resources Washington Geological Survey**

*Mailing Address:*  
MS 47007  
Olympia, WA 98504-7007

*Street Address:*  
Natural Resources Bldg, Rm 148  
1111 Washington St SE  
Olympia, WA 98501

*Phone:* 360-902-1450  
*Fax:* 360-902-1785  
*Email:* [geology@dnr.wa.gov](mailto:geology@dnr.wa.gov)  
*Website:* <http://www.dnr.wa.gov/geology>



*Publications and Maps:*  
[www.dnr.wa.gov/programs-and-services/geology/  
publications-and-data/publications-and-maps](http://www.dnr.wa.gov/programs-and-services/geology/publications-and-data/publications-and-maps)

*Washington Geology Library Searchable Catalog:*  
[www.dnr.wa.gov/programs-and-services/geology/  
washington-geology-library](http://www.dnr.wa.gov/programs-and-services/geology/washington-geology-library)

*Suggested Citation:* Eungard, D. W.; Forson, Corina; Walsh, T. J.; Gica, Edison; Arcas, Diego, 2018, Tsunami hazard maps of southwest Washington—Model results from a ~2,500-year Cascadia subduction zone earthquake scenario: Washington Geological Survey Map Series 2018-01, originally published March 2018, 6 sheets, scale 1:48,000, 11 p. text. [[http://www.dnr.wa.gov/publications/ger\\_ms2018-01\\_tsunami\\_hazard\\_southwest\\_washington.zip](http://www.dnr.wa.gov/publications/ger_ms2018-01_tsunami_hazard_southwest_washington.zip)]

*Revision Description:* This revision addresses public comments and presents additional data requested following initial publication in March 2018. Revised text further clarifies inundation depths, timing of wave arrivals, and limitations of the model. Map Sheets 5 and 6 show the full range of inundation depth, approximate first wave arrival times, inundation depths at select locations, and a new diagram depicting terminology used in the publication.

# Contents

Introduction .....	1
Cascadia Subduction Zone .....	3
Recurrence Intervals .....	4
Earthquake Magnitudes and Slip Distributions .....	5
A.D. 1700 Earthquake .....	5
Pre-A.D. 1700 Earthquakes .....	6
Modeling Approach and Results .....	7
Inundation .....	7
Current Speed.....	8
Timing of Tsunami and Initial Water Disturbance .....	8
Limitations of the Model.....	9
Acknowledgments.....	9
References .....	9

## FIGURES

Figure 1. Location map of southwest Washington study area .....	2
Figure 2. Photo of uplifted tsunami deposit at Discovery Bay, WA.....	3
Figure 3. Map of southwest Oregon, showing tsunami deposits and abrupt subsidence locations .....	4
Figure 4. Schematic view of the confluence test for extensive seismic shaking .....	5
Figure 5. L1 splay fault model diagram and map of vertical ground deformation during an M9 Cascadia subduction zone earthquake scenario.....	6
Figure 6. Map of initial deformation from the L1 scenario in southwest Washington .....	7
Figure 7. Modeled tsunami wave amplitude variations for offshore areas near the towns of Ocean Shores and Ocean Park .....	7
Figure 8. Schematic diagram of chronologic events following a CSZ earthquake and tsunami .....	8

## TABLES

Table 1. Published tsunami hazard maps for Washington .....	2
Table 2. Estimates of earthquake recurrence on the Cascadia subduction zone.....	5

## MAP SHEET

Map Sheet 1. Tsunami inundation of southwest Washington— Grays Harbor to northern Willapa Bay
Map Sheet 2. Tsunami inundation of southwest Washington— Willapa Bay to the Columbia River
Map Sheet 3. Tsunami current velocity of southwest Washington— Grays Harbor to northern Willapa Bay
Map Sheet 4. Tsunami current velocity of southwest Washington— Willapa Bay to the Columbia River
Map Sheet 5. Detailed tsunami inundation of southwest Washington— Grays Harbor to northern Willapa Bay
Map Sheet 6. Detailed tsunami inundation of southwest Washington— Willapa Bay to the Columbia River



---

# Tsunami Hazard Maps of Southwest Washington— Model Results from a ~2,500-year Cascadia Subduction Zone Earthquake Scenario

by Daniel W. Eungard<sup>1</sup>, Corina Forson<sup>1</sup>, Timothy J. Walsh<sup>1</sup>, Edison Gica<sup>2</sup>, and Diego Arcas<sup>2</sup>

<sup>1</sup> Washington Geological Survey  
MS 47007  
Olympia, WA 98504-7007

<sup>2</sup> National Oceanic and Atmospheric Administration  
Pacific Marine Environmental Laboratory  
7600 Sand Point Way NE  
Seattle, WA 98115-6349

## ABSTRACT

New finite-difference modeling along the southern Washington coast in the area surrounding Willapa Bay and Grays Harbor uses a simulated magnitude 9 earthquake event with a maximum slip of 88.6 feet (27 meters), inferred to be a ~2,500-year event, or the L1 scenario. This new modeling closely approximates the design requirements in the building code standard for critical facilities, and is more conservative (greater inundation) than previous tsunami modeling. Modeling results indicate that the first tsunami wave will arrive on land along the outer coast 15 to 20 minutes following the earthquake. Inundation depths range from 20 to 60 feet (6–18.2 meters) on the outer coast, decreasing to generally less than 10 feet (3 meters) within Willapa Bay and Grays Harbor. Current velocities from the tsunami waves locally exceed 35 knots, presenting a significant navigational hazard to the maritime community. Tsunami wave inundation is expected to continue over 12 hours and remain hazardous to maritime operations for more than 24 hours after the earthquake. This study is limited in that modeling does not account for tidal effects, liquefaction, or minor topographic changes that would locally modify the impact of tsunami waves. Due to these limitations, this modeling should not be used for site-specific tsunami inundation assessment or for determining effects on the built environment. However, this model is an excellent tool for evacuation and recovery planning.

## INTRODUCTION

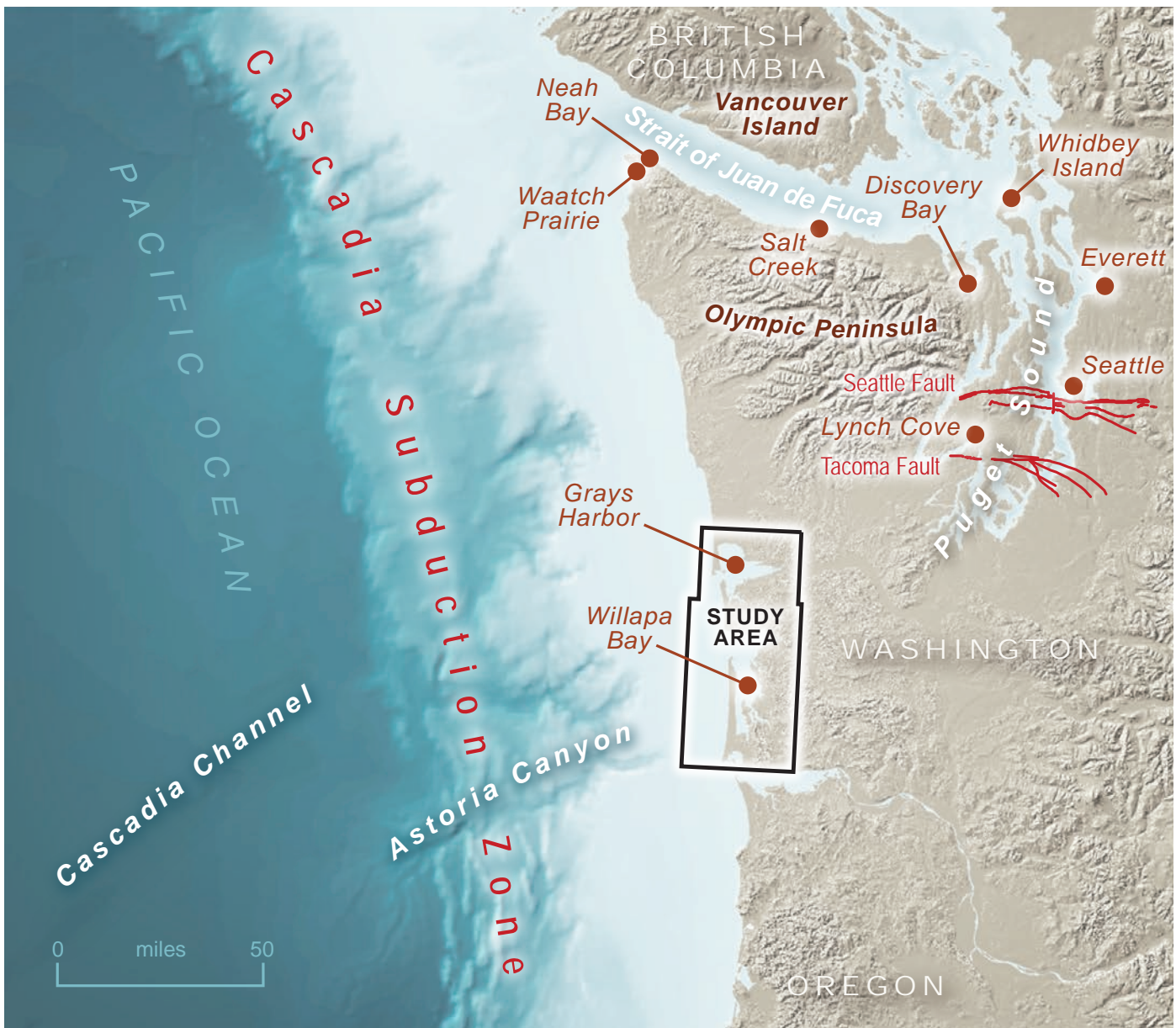
In 1995, Congress directed the National Oceanic and Atmospheric Administration (NOAA) to develop a plan to protect the west coast from tsunamis generated by the nearby Cascadia subduction zone (CSZ). A panel of representatives from NOAA, the Federal Emergency Management Agency (FEMA), the U.S. Geological Survey (USGS) and the five Pacific coast states wrote and submitted the plan to Congress, which created the National Tsunami Hazard Mitigation Program (NTHMP) in October of 1996. The NTHMP is designed to reduce the impact of tsunamis through warning guidance, hazard assessment, education, and mitigation. A key component of the hazard assessment for tsunamis is delineation of areas subject to tsunami inundation. Because local tsunami waves may reach nearby coastal communities within minutes after the earthquake, there will be little or no time to issue formal warnings; evacuation areas and routes will need to be planned well in advance.

These maps (Map Sheets 1–6) depict modeled tsunami inundation and current velocity for the southwestern Washington coast from a CSZ earthquake (Fig. 1); they are part of a series of tsunami inundation maps produced by the Washington Geological Survey, in cooperation with the Washington Emergency Management Division, as a contribution to the NTHMP (Table 1). These maps are produced using computer models of earthquake-generated

tsunamis from nearby seismic sources. The models show tsunami inundation from two main sources in Washington: (1) earthquakes on local crustal faults in Puget Sound (such as the Tacoma or Seattle faults) and (2) CSZ earthquakes.

Previous inundation modeling for this area (Walsh and others, 2000) was for an event on the CSZ using the 1A and 1A with asperity scenarios (Myers and others, 1999; Priest and others, 1997). The 1A scenario was generated prior to the development of any federal or state building code standards for tsunami hazards. For several years, it was the only source of tsunami hazard information for emergency managers in local communities.

More recent studies (Witter and others, 2011) have inferred: (1) higher variability in both the amount of slip and slip distribution from the paleo-tsunami record; and (2) the L1 scenario on the CSZ is a more conservative choice, that is, it is less likely to be exceeded. The L1 source model produces a greater amount of slip—88.6 feet (27 meters) compared to the 1A scenario (62 feet [19 meters]). It also partitions all slip onto a splay fault that intersects the seafloor at a higher angle than the 1A model, which places all slip on the subduction interface. The L1 scenario is estimated to equal or exceed 95 percent of all previously inferred tsunami inundation events produced by a CSZ-sourced

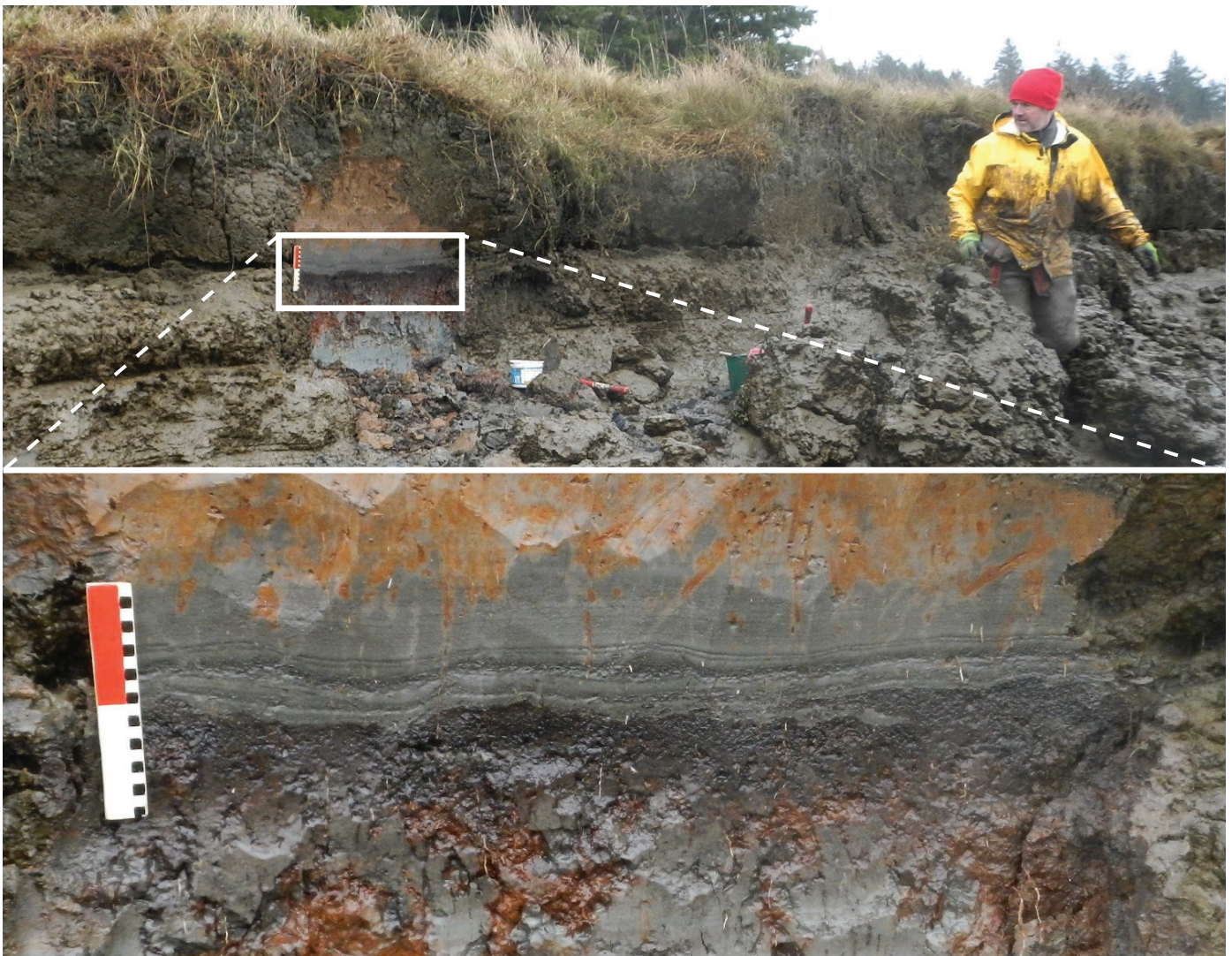


**Figure 1.** Location map of the southwest Washington study area, Cascadia subduction zone, major offshore channels, and major crustal faults discussed in the text.

**Table 1.** Published tsunami hazard maps for Washington. CSZ, Cascadia subduction zone. \* 1A with asperity model incorporates localized areas of offshore uplift.

Location	Reference	Modeled Scenario
San Juan Islands	Walsh and others (2016)	CSZ L1
Everett	Walsh and others (2014)	Seattle Fault
Tacoma	Walsh and others (2009)	Tacoma fault
Anacortes-Whidbey Island	Walsh and others (2005)	CSZ 1A and 1A with asperity*
Bellingham	Walsh and others (2004)	CSZ 1A and 1A with asperity*
Neah Bay	Walsh and others (2003a)	CSZ 1A and 1A with asperity*
Quileute area	Walsh and others (2003b)	CSZ 1A and 1A with asperity*
Seattle	Walsh and others (2003c)	Seattle Fault
Port Angeles	Walsh and others (2002a)	CSZ 1A and 1A with asperity*
Port Townsend	Walsh and others (2002b)	CSZ 1A and 1A with asperity*
southern Washington coast	Walsh and others (2000)	CSZ 1A and 1A with asperity*





**Figure 2.** Photo of uplifted tsunami deposit (sand layer bounded by silty clays) along the Niawiakum River, east of Willapa Bay, WA. Photo by Esther Sumner (University of Southampton). See Figure 8 for a conceptual diagram of earthquake subsidence, tsunami inundation, and sedimentation.

tsunami (Witter and others, 2011). The modeled scenario (L1) earthquake is a close approximation to design requirements for critical facilities in the Washington State building code for seismic hazards. The scenario represents the maximum considered event that a facility may be subjected to during its operational lifetime and serves as a conservative choice for local evacuation planning for tsunami hazards. (See *Earthquake Magnitudes and Slip Distributions* for more information on model scenarios.) Compared to previous 1A modeling, the newer L1 modeling study area extends farther east to include eastern Willapa Bay and includes parts of the mouth of the Columbia River. It also incorporates higher quality elevation data derived from lidar and multibeam bathymetry where available.

## CASCADIA SUBDUCTION ZONE

Research over the last few decades about the occurrence of great earthquakes off the British Columbia, Washington, Oregon, and northern California coastlines and resulting tsunamis (Atwater, 1992; Atwater and others, 1995) has led to concern that locally generated tsunamis will leave little time for response.

Numerous workers have found geologic evidence of tsunami deposits attributed to the CSZ in at least 59 localities from northern California to southern Vancouver Island (Peters and others, 2003). While most of these locations are on the outer coast, inferred CSZ tsunami deposits have been identified along the Strait of Juan de Fuca at Salt Creek (Hutchinson and others, 2013), as far east as Discovery Bay (near Port Townsend) (Fig. 2; Williams and others, 2005), on the west shore of Whidbey Island (Fig. 1; Williams and Hutchison, 2000), and as far south as Lynch Cove at the terminus of Hood Canal (Garrison-Laney, 2017). Heaton and Snavelly (1985) report that Makah stories may tell of a tsunami washing through Waatch Prairie near Cape Flattery (Fig. 1). Ludwin (2002) has found additional stories from native peoples up and down the coast that appear to corroborate this and include apparent references to associated strong ground shaking.

Additionally, high-resolution dendrochronology (Jacoby and others, 1997; Yamaguchi and others, 1997) indicates that the timing of the last CSZ earthquake correlates with historical records of a distant-source tsunami in Japan (Satake and others, 1996) on January 26, A.D. 1700.

## Recurrence Intervals

Estimates of the frequency of occurrence of CSZ earthquakes are derived from several lines of evidence: coastal submergence events, paleo-tsunami deposits (Fig. 2), and offshore turbidite deposits. Great subduction zone earthquakes commonly cause coseismic subsidence (Plafker, 1969; Plafker and Savage, 1970). Where this subsidence occurs in coastal marshes, marsh deposits may be abruptly overlain by estuarine mud, indicating sudden submergence and drowning of upland surfaces (Atwater, 1992). Atwater and Hemphill-Haley (1997) reported six sudden submergence events in Willapa Bay over the last 3,500 years (Table 2). Their data imply an average recurrence interval of about 500–540 years, but individual intervals vary between 100 and 1,300 years.

Researchers working in Oregon have found a somewhat different record farther south. Using marsh stratigraphy and inferred tsunami deposits, Kelsey and others (2002) found a 5,500-year record of 11 earthquake events at Sixes River in southern Oregon (Fig. 3). These records included an abrupt subsidence event not observed on the southern Washington coast. Kelsey and others (2005) examined Bradley Lake on the southern Oregon coast near Bandon and found inferred tsunami

deposits with an average recurrence interval of ~390 years. This discrepancy implies that some tsunamis generated by earthquakes on the CSZ did not produce abrupt subsidence in southern Washington. A possible explanation is that the earthquake did not rupture the entire length of the subduction zone, resulting in a spatially heterogeneous response in the geologic record. Nelson and others (2006) examined the degree of overlap and amount of abrupt subsidence at eight sites along the Oregon and Washington coasts and concluded that rupture lengths (and therefore earthquake magnitudes) varied—ruptures along the northern CSZ are generally long, whereas ruptures along the southern CSZ are more variable in both length and recurrence interval.

Another approach to inferring recurrence intervals is the correlation of turbidites—deposits of sediment gravity flows, or turbidity currents—at the base of the continental shelf. Adams (1990) inferred that turbidite deposits in Cascadia Channel and Astoria Canyon (Fig. 4) were triggered by great earthquakes. If turbidity currents are triggered independently, at different times, and at multiple submarine canyon heads that merge with a main channel, then their deposits should be additive in the main channel. For example, if a channel has three tributaries, each of which has



**Figure 3.** Map of southwest Oregon, showing tsunami deposits and abrupt subsidence locations used by Kelsey and others (2002; 2005) to determine CSZ earthquake recurrence intervals.

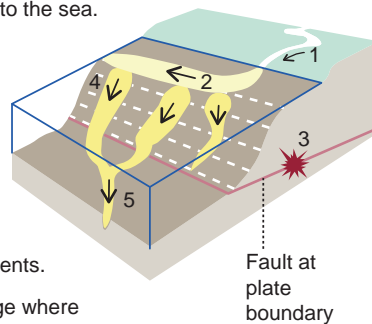
ten independent turbidites, there would be 30 turbidites in the main channel. However, if the turbidites are triggered simultaneously—which would likely be the case if they were initiated by a great earthquake—they should coalesce. In this case, the maximum number of turbidites in the main channel would be no more than the maximum number found in any individual channel. Oregon State University researchers logged 13 turbidites in both Cascadia Channel and Astoria Canyon, from multiple deep-sea cores that were stratigraphically above the Mazama ash (radiocarbon dated at about 6,845 radiocarbon years BP [calibrated to about 7,700 cal yr BP]) (Adams, 1990). These findings suggest that 13 CSZ ruptures occurred since the Mazama ash was deposited. Adams (1990) therefore inferred an average recurrence interval of  $590 \pm 170$  years.

Goldfinger and others (2012) tested Adams' (1990) hypothesis by collecting numerous additional cores in the sea floor along the Cascadia continental margin. Their effort greatly expands the geographic and chronologic range of observation, and increases observation density. Goldfinger and others (2012) inferred from their record of turbidite deposits that the CSZ is segmented, with full-length ruptures having a recurrence interval similar to those estimated by

**Table 2.** Estimates of earthquake recurrence on the Cascadia subduction zone. -- indicates no data.

Events over time interval	Average recurrence interval in years; range if given	Section of CSZ	References	Major evidence
6 submergence events in 3,500 years	500–540 average, 100–300 to 1,000	northern	Atwater and Hemphill-Haley (1997)	submergence events
11 submergence events in 5,500 years	510	southern	Kelsey and others (2002)	marsh stratigraphy and tsunami deposits
13 tsunamis, 17 disturbances in 7,000 years	--	southern	Kelsey and others (2005)	marine incursions and disturbance events in Bradley Lake
--	variable	whole	Nelson and others (2006)	multiple
--	590 ±170	northern	Adams (1990)	turbidites in Astoria Canyon and Cascadia Channel
19 or 20 full-margin turbidites in 10,000 years; 22 turbidites restricted to the south	500–530 average for full-margin rupture; ~240 full-margin plus southern only	whole and partial	Goldfinger and others (2012)	turbidites along Cascadia margin
20 full-margin turbidites in 10,000 years; 3 turbidites on a segment running from northern California to Juan de Fuca Channel; 1 turbidite off Washington and B.C. only	500–530 average for full-margin rupture; ~434 full-margin plus shorter ruptures adjacent to Washington	whole and partial	Goldfinger and others (2017)	turbidites along Cascadia margin

- 1 **River** delivers sediment to the sea.
- 2 **Sediment** settles on the continental shelf.
- 3 **An earthquake** shakes the continental shelf and slope.
- 4 **Shaken sediment** descends submarine canyons as turbidity currents.
- 5 **Turbidity currents** merge where tributaries meet. Resulting deposits are visible in sediment cores.



**Figure 4.** Schematic view of the confluence test for extensive seismic shaking, first used as a guide to fault rupture length by Adams (1990). Adams assumed that extensive shaking enables turbidity currents to descend different submarine channels at the same time, and to merge below channel confluences. Atwater and others (2014), dispute the reliability of this indicator.

Adams (1990) and Atwater and Hemphill-Haley (1997), but with additional partial-length ruptures offshore Oregon and northern California.

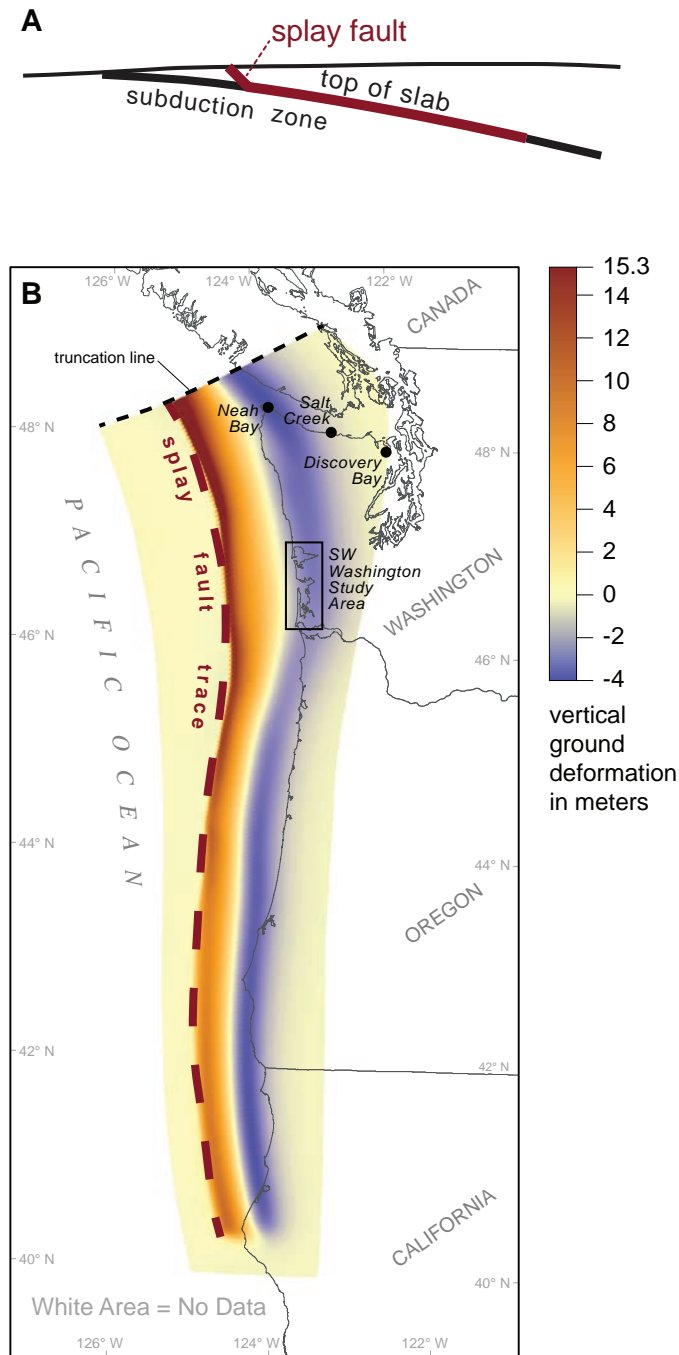
Combining full-length and partial ruptures on the CSZ, Goldfinger and others (2012) estimated a recurrence interval of ~240 years for earthquakes off Oregon and northern California, but still 500–530 years offshore Washington and British Columbia. Earthquakes that rupture only the northern part of the CSZ are also a possibility. Goldfinger and others (2017) revised this chronology slightly, extending several ruptures farther north to include Washington and inferring an additional event offshore Washington and southern British Columbia only. In Discovery Bay and on the northeastern Olympic Peninsula, Williams and others (2005) observed nine muddy sand beds bearing marine diatoms that interrupt a 2,500-year-old sequence of peat deposits beneath a tidal marsh. If all of these are tsunami deposits,

then it is likely that some of them record events that are either not full-length ruptures of the CSZ or come from some other source. The ages of four of these beds, refined by Garrison-Laney and Miller (2017), overlap with known late-Holocene tsunamis generated by full-length ruptures of the CSZ. Diatom assemblages in peat deposits bracketing these four beds do not indicate a concurrent change in elevation at Discovery Bay. This suggests that coseismic subsidence has been negligible as far east as Discovery Bay. However, one inferred tsunami deposit is accompanied by several decimeters of abrupt subsidence, which is interpreted as the result of deformation associated with an upper plate fault (Williams and others, 2005). Other sand sheets in the sequence may represent tsunamis generated by partial ruptures of the CSZ, by upper plate fault earthquakes, or by landslides (Garrison-Laney and Miller, 2017), none of which triggered turbidity currents. This implies that either some CSZ earthquakes do not leave turbidite deposits in Cascadia Channel, or that some deposits were generated by other events such as local earthquakes or landslides. Atwater and others (2014) also questioned whether the absence of turbidites along the northern CSZ necessarily proves the absence of ground shaking, or rather is influenced by differences in sediment supply and in the differences in flow paths down tributary channels. They also questioned some of the correlations among widely spaced sites—used to infer the length of fault rupture—that were used by Goldfinger and others (2012).

## Earthquake Magnitudes and Slip Distributions

### A.D. 1700 EARTHQUAKE

It is believed that the last earthquake on the Cascadia subduction zone was about magnitude ( $M_w$ ) 9.0 (Satake and others, 1996; 2003) in the year A.D. 1700. Satake and others



**Figure 5.** L1 splay fault model diagram (A) and map of vertical ground deformation (B) during a great Cascadia earthquake in the L1 scenario of Witter and others (2011). The northern part of the scenario is truncated south of where the Juan de Fuca plate is beginning to break up into microplates.

(2003) tested various rupture lengths, slip amounts, and observed tsunami wave heights in Japan for the A.D. 1700 event. They estimated that this event had a rupture length of 684 miles (~1,100 kilometers) and 62 feet (19 meters) of coseismic slip on an offshore, full-slip zone with linearly decreasing slip on a down-dip partial-slip zone, suggesting a magnitude of 8.7 to 9.2. They inferred that the most likely magnitude was 9.0 based on the correlation between estimates of coseismic subsidence from paleoseismic studies and the subsidence predicted by their scenario dislocation models.

## PRE-A.D. 1700 EARTHQUAKES

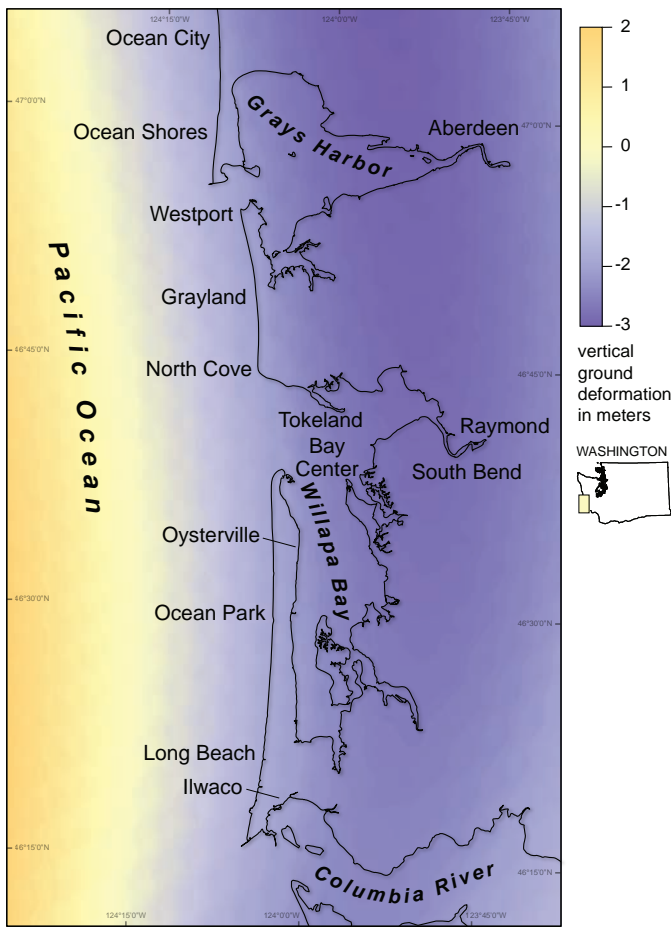
### Partial-Length Rupture Models

The magnitudes and slip distributions of earlier CSZ earthquakes are less well constrained. Inferences of shorter ruptures that affect only the southern part of the CSZ generally imply smaller magnitude earthquakes. Tsunamis from several postulated shorter ruptures limited to the southern part of the CSZ were modeled by Priest and others (2014), who concluded that the tsunamis they generated were significantly smaller in Washington than those generated by full-length ruptures. A partial CSZ rupture restricted to the north was suggested by Goldfinger and others (2013) and Peterson and others (2013). This northern rupture was later confirmed by Goldfinger and others (2017), but supporting paleoseismic data for it is insufficient to generate a tsunami model. These smaller events will not be considered further here.

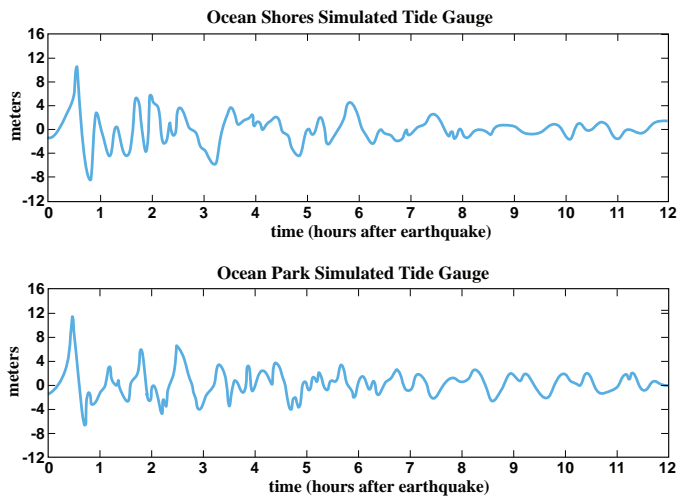
### Full-Length Rupture Models

Witter and others (2012) combined: (1) turbidite data from Goldfinger and others (2012); (2) correlation of inferred tsunami deposits with turbidites in Bradley Lake; and (3) inferred tsunami deposits in the Coquille River estuary at Bandon, Oregon that extend as much as 6.2 miles (10 kilometers) farther inland than the A.D. 1700 tsunami deposits (Witter and others, 2003). They inferred from this that tsunamis generated by the CSZ over the last 10,000 years had been highly variable, with some larger than the one in A.D. 1700. They constructed 15 scenarios of full-length ruptures defining vertical seafloor deformation used to simulate tsunami inundation at Bandon, Oregon. Rupture models include slip partitioned to a splay fault in the accretionary wedge and models that vary the up-dip limit of slip on a buried megathrust fault. Slip estimates were made from several sources. Total turbidite volume was estimated from the thickness averaged over all the paleoseismic records, which Goldfinger and others (2012) correlated to earthquake magnitude. This was combined with estimates of the convergence rate for different segments of the subduction zone multiplied by the time since the previous event to estimate total accumulated strain since the previous event (Witter and others, 2012). Tsunami simulations at Bradley Lake (Witter and others, 2011) and at Bandon (Witter and others, 2012) were compared with the distribution of inferred tsunami deposits there and were broadly compatible with their larger scenarios. They performed numerical simulations of the tsunamis generated by each scenario and evaluated them using a logic tree that ranked model consistency with geophysical and geological data.

Witter and others (2011) concluded that scenario L1—a splay fault model with a maximum slip of 88.6 feet (27 meters) and an average slip of 42.6 feet (13 meters)—produced a tsunami that equaled or exceeded 95 percent of the variability in their simulations (Fig. 5). Other 'L' earthquake scenarios (L2 and L3) have the same amount of slip but somewhat different distributions across the strike of the subduction zone. In other words, the L1 scenario produces tsunamis as big as, or bigger than most other models. Witter and others (2011) also estimated the size of the earthquakes that generated turbidites along the full length of the CSZ. They concluded that three earthquakes in the last ~10,000 years were probably similar to scenario L and only one was larger (table 1 in Witter and others, 2011). The



**Figure 6.** Map of initial ground and seafloor deformation from the L1 scenario in southwest Washington.



**Figure 7.** Modeled tsunami wave (y-axis showing meters) variations over time for offshore areas near the towns of Ocean Shores and Ocean Park (see Map Sheets 1 and 2 for locations).

inter-event times between pairs of inferred L earthquakes are ~1,800 and ~4,600 years. Another way to estimate recurrence frequency is that if three earthquakes in the last 10,000 years are of size L, then these types of events have an average recurrence interval between 2,500 and 5,000 years. If this truly represents 95 percent of the hazard over a 10,000-year period, then scenario L earthquakes have a long recurrence interval and likely are of

a similar probability of occurrence as the International Building Code seismic standard of 2 percent probability of exceedance in 50 years. Colloquially, this scenario is known as a 2,500-year event.

### MODELING APPROACH AND RESULTS

This tsunami inundation model is based on a numerical model of waves generated by a L1 CSZ scenario earthquake as described in Witter and others (2011) and as adapted in Walsh and others (2016). The simulation uses the finite-difference model of Titov and Synolakis (1998), known as the Method of Splitting Tsunami (MOST) model (Titov and González, 1997). The model uses a grid of topographic and bathymetric elevations and calculates a wave elevation and velocity of each cell at specified time intervals to simulate the generation, propagation, and inundation of tsunamis on the coastline of southwestern Washington following a L1-style CSZ earthquake. The model is calculated for mean high water and does not include tidal effects. The modeling for this map was done by the NOAA Center for Tsunami Research at NOAA’s Pacific Marine Environmental Laboratory in Seattle.

The selected scenario is a splay-fault model in which all slip is partitioned into a thrust fault in the accretionary wedge that has an approximate 30° landward dip and the same sense of movement as the megathrust; this results in a much higher, narrower area of uplift than a fault rupture on the megathrust, which dips landward much more shallowly and reaches farther seaward than the splay fault.

The land surface in southwest Washington is modeled to subside substantially during ground shaking (Fig. 6). An average of ~6.6 feet (2 meters) of subsidence immediately following the earthquake may trigger localized flooding prior to or simultaneously with the first tsunami wave arrival. Modeled maximum inundation depths shown on Map Sheets 1, 2, 5, and 6 include this subsidence. The ground elevation of the region will be significantly lower after the earthquake than it is today, and will likely remain so for several generations. Paleoseismic investigations in the region demonstrate tectonic subsidence of 1.64 feet (0.5 meters) to 6.56 feet (2.0 meters) (Atwater, 1987, 1992; Atwater and others, 1995) in past events.

### Inundation

Inundation depth bins on Map Sheets 1 and 2 were selected based on their implications for life safety. These bins are defined as: (1) less than knee high (<2.5 feet; <0.75 meters); (2) knee to head high (2.5 to 6 feet; 0.75–1.8 meters); and (3) above head height (>6 feet; >1.8 meters). These depths approximate the hazard posed to a person if caught within the tsunami zone. At <2.5 feet inundation, survival is likely if steps are taken to avoid the direct force of a wave, such as entering a building, or standing on the leeward side of an obstacle (tree or power pole). From 2.5 to 6 feet inundation, survival is unlikely if caught in the open; however, climbing onto the roof of a single-story structure or entering a structure more than one story tall may improve survivability. At >6 feet inundation, survival is highly unlikely if caught either out in the open or within or on most conventional structures. Fortunately, survival remains highly likely within or on a reinforced and specially-designed building,

such as a vertical evacuation structure. Modeled inundation is also shown using the full range of values on Map Sheets 5 and 6.

Tsunami inundation from this scenario is expected to be extensive, covering most of the low-lying coastal areas in both Pacific and Grays Harbor counties. This study defines the outer coast as the shoreline areas facing the Pacific Ocean, or the westernmost extent of Washington's landmass. These areas will likely be the first affected by the tsunami wave and subject to the greatest inundation. Communities directly on the outer coast should expect 20–60 feet (6–18.2 meters) of on-land inundation. Shorelines within Willapa Bay and Grays Harbor are identified as bay-side. In these areas, tsunami inundation depths are significantly reduced relative to the outer coast shoreline. Bay-side communities along Willapa Bay or Grays Harbor generally should expect 10 feet (3 meters) or less of inundation.

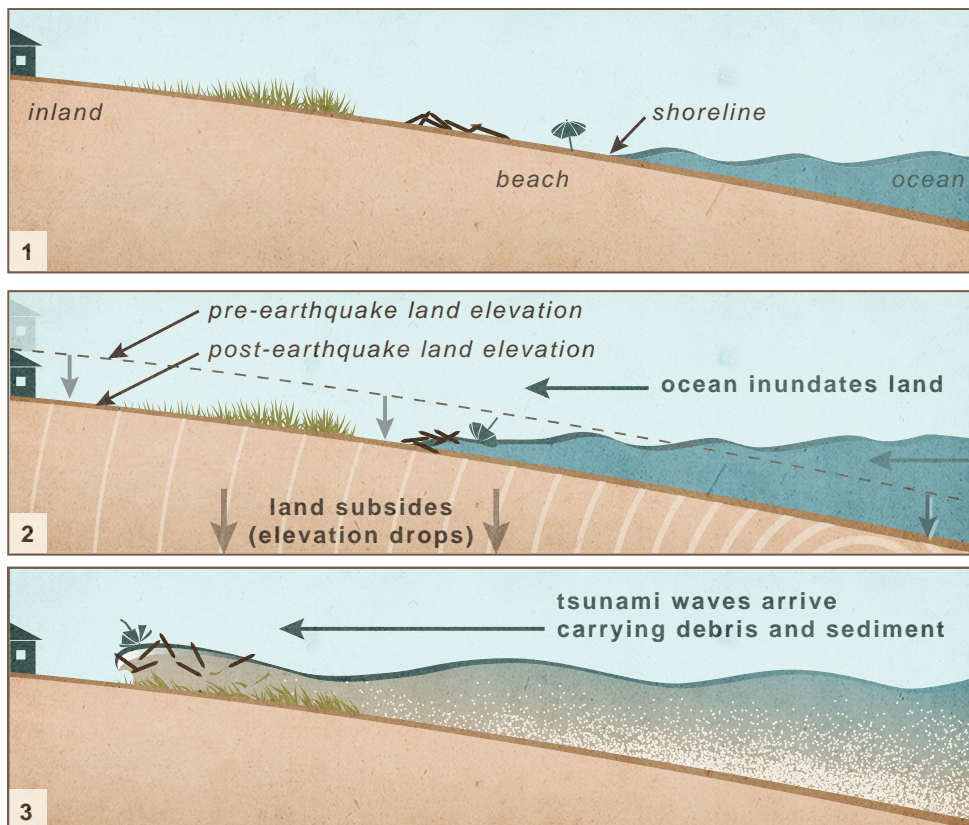
### Current Speed

The modeled current speed (Map Sheets 3 and 4) is shown in four ranges: 0–3 knots, 3–6 knots, 6–9 knots, and greater than 9 knots, following the port damage categorization of Lynett and others (2014). These ranges approximate hazards to ships and docking facilities, representing no expected damage, minor/moderate damage possible, major damage possible, and extreme damage possible, respectively. Modeled current speed locally exceeds 35 knots along the coastline and near the entrances to Willapa Bay and Grays Harbor, where tidal currents are strongest and tsunami-tide interactions are likely to be the most significant.

### Timing of Tsunami and Initial Water Disturbance

Wave arrival times for a given location are estimated from the moment the earthquake begins to the moment the water first rises above high tide (mean high water). For the arrival times shown on Map Sheets 5 and 6, this is not the timing of maximum inundation. Several minutes may transpire between first wave arrival and maximum inundation. Strong earthquake shaking may persist for several minutes, up to five in this scenario, reducing the available time to evacuate to less than the indicated wave arrival times. Figure 7 shows simulated tide gauge records offshore of Ocean Shores and Ocean Park. The initial water disturbance at both locations is a ~6.5 feet (2 meters) rise in sea level due to co-seismic subsidence followed by a wave crest arriving 15 to 20 minutes after the earthquake. Figure 8, a conceptual visualization, demonstrates pre-earthquake conditions, initial subsidence, and tsunami arrival.

Wave crest is defined as the highest offshore peak of the wave, referenced to the tidal datum (mean high water). The first wave crest is expected to be 33.8 feet (10.3 meters) high offshore of Ocean Shores and 36 feet (11 meters) high offshore of Ocean Park. Inundation depth therefore refers to how deep under water any given point on land will be after the tsunami has reached its maximum inundation (see diagram on Map Sheets 5 and 6). Wave crests during the first four hours of inundation are estimated to be >16.4 feet (5 meters), dropping to <16.4 feet (5 meters) within 12 hours following the earthquake. Minor wave bombardment of the coastline will continue for at least 24 hours after the quake, producing minor inundation, generally less than storm surge or tidal effects, but with much stronger currents. These effects



**Figure 8.** Schematic diagram of chronologic events following a CSZ earthquake and tsunami in southwest Washington: (1) Modern-day pre-earthquake topography. Note that the entire coast has slowly uplifted over the last several hundred years to above sea level. (2) The strain on the CSZ plate boundary is released in a sudden large earthquake event, producing severe shaking that lasts for several minutes. During the earthquake event, the land subsides or “drops” causing local flooding of low-lying areas within minutes of the earthquake. (3) Tsunami waves begin to arrive 15–20 minutes following the earthquake; these powerful waves carry sediment and debris onshore and to higher elevations. The inundation continues for 4–24 hours, locally posing a hazard to search, rescue, and recovery efforts. Once the tsunami inundation flood-waters recede, a new shoreline is established many feet higher in elevation than before.

may pose a hazard to maritime operations. For comparison, the January 26, 1700 earthquake along the CSZ produced a tsunami that may have lasted as many as 20 hours there (Satake and others, 2003; Atwater and others, 2005).

## LIMITATIONS OF THE MODEL

Because the characteristics of the tsunami depend on the initial seafloor deformation from the earthquake, which is poorly understood, the largest source of uncertainty is the input earthquake. The earthquake scenario used in this model was selected to approximate the 2 percent probability of exceedance in 50 years (~2,500-year event), but the next earthquake may have a more complex slip distribution than the simplified scenario we used and thus the ensuing tsunami may differ. Witter and others (2011) suggest that the most likely full-length CSZ earthquake will have an average slip of about  $\frac{2}{3}$  of the L1 scenario and therefore generate a smaller tsunami than modeled here.

These model results do not include potential tsunamis from coseismic landslides or ruptures on nearby crustal faults. This modeling does not incorporate localized topographic changes caused by liquefaction, such as settlement or sand-blows. Liquefaction is a site-specific issue and is inappropriate at this map scale. The model also does not include the influences of changes in tides and is referred to mean high water. The tide stage can amplify or reduce the impact of a tsunami on a specific community. For example, the diurnal range (the difference in height between mean higher high water and mean lower low water) is 8.81 feet (2.69 meters) and 8.41 feet (2.56 meters) at the Toke Point and Westport tide gauges respectively. The model also does not include interaction with tidal currents, which can be additive, or if in opposite directions, can steepen the tsunami wave front and cause a breaking wave.

The resolution of the modeling is also limited by the bathymetric and topographic data used to make the elevation grid. Lidar data with 3-ft grid cells along with a 10-meter digital elevation model (DEM) (where lidar was not available) were used to build the topographic grid, but the bathymetric grid in the vicinity of the coastline has grid cells of 33 feet (10 meters) that were generally interpolated from coarser data. The coarser the grid, the fewer small topographic features included that can locally influence the tsunami. The reliability of onshore model results are limited to the extent of high-resolution lidar. In areas where inundation extends beyond the limits of lidar coverage, the model used a 10-meter DEM. In some of the areas covered only with lower-resolution topographic data, inundation is expected to continue beyond the boundary of the lidar coverage, yet inundation may not be represented accurately in the model results. These areas are shown on the map with arrows that point in the direction of expected inundation.

Due to the presence of erroneous high points in the lidar data, small, isolated gaps in inundation exist (for example, the port facilities in East Hoquiam). These points may originate from transient features (log piles, temporary aggregate piles, etc.), mis-classified building or tree-top elevations, or relatively high areas that may not survive the impact of tsunami waves (such as earthen dikes). Additional model irregularities were noted at Porter Point (Map Sheet 2), which should show as inundated

based on land elevation and adjacent inundation depths. In all of these cases, the maps retain these gaps in inundation to remain true to the model results. However, it is highly likely that these small areas will be inundated during a tsunami.

While the modeling can be a useful tool to guide evacuation planning, model uncertainties and insufficient spatial resolution make this modeling unsuitable for site-specific tsunami mitigation planning.

## ACKNOWLEDGMENTS

This project was supported by the National Tsunami Hazards Mitigation Program (NTHMP) in cooperation with Grays Harbor and Pacific Counties, and the Washington Emergency Management Division.

## REFERENCES

- Adams, John, 1990, Paleoseismicity of the Cascadia subduction zone—Evidence from turbidites off the Oregon–Washington margin: *Tectonics*, v. 9, no. 4, p. 569-583.
- Atwater, B. F., 1987, Evidence for great Holocene earthquakes along the outer coast of Washington State: *Science*, v. 236, no. 4804, p. 942-944.
- Atwater, B. F., 1992, Geologic evidence for earthquakes during the past 2,000 years along the Copalis River, southern coastal Washington: *Journal of Geophysical Research*, v. 97, no. B2, p. 1901-1919.
- Atwater, B. F.; Nelson, A. R.; Clague, J. J.; Carver, G. A.; Yamaguchi, D. K.; Bobrowsky, P. T.; Bourgeois, Joanne; Darienzo, M. E.; Grant, W. C.; Hemphill-Haley, Eileen; Kelsey, H. M.; Jacoby, G. C.; Nishenko, S. P.; Palmer, S. P.; Peterson, C. D.; Reinhart, M. A., 1995, Summary of coastal geologic evidence for past great earthquakes at the Cascadia subduction zone: *Earthquake Spectra*, v. 11, no. 1, p. 1-18.
- Atwater, B. F.; Hemphill-Haley, Eileen, 1997, Recurrence intervals for great earthquakes of the past 3,500 years at northeastern Willapa Bay, Washington: U.S. Geological Survey Professional Paper 1576, 108 p. [<https://pubs.er.usgs.gov/publication/pp1576>]
- Atwater, B. F.; Musumi-Rokkaku, Satoko; Satake, Kenji; Tsuji, Yoshinobu; Ueda, Kazue; Yamaguchi, D. K., 2005, The orphan tsunami of 1700—Japanese clues to a parent earthquake in North America: University of Washington Press and U.S. Geological Survey Professional Paper 1707, 133 p. [[https://pubs.usgs.gov/pp/pp1707/pp1707\\_front.pdf](https://pubs.usgs.gov/pp/pp1707/pp1707_front.pdf)]
- Atwater, B. F.; Carson, R. C.; Griggs, G. B.; Johnson, H. P.; Salmi, M. S., 2014, Rethinking turbidite paleoseismology along the Cascadia subduction zone: *Geology*, v. 42, no. 9, p. 827-830.
- Garrison-Laney, C. E., 2017, Tsunamis and sea levels of the past millennium in Puget Sound, Washington: University of Washington Doctor of Philosophy thesis, 166 p.
- Garrison-Laney, C. E.; Miller, I., 2017, Tsunamis in the Salish Sea: Recurrence, sources, hazards, *In* Haugerud, R. A.; Kelsey, H. M., 2017, From the Puget Lowland to east of the Cascade Range—Geologic excursions in the Pacific Northwest: Geological Society of America Field Trip Guide v. 49, p. 67-78.
- Goldfinger, Chris; Nelson, C. H.; Morey, A. E.; Johnson, J. E.; Patton, J. R.; Karabanov, Eugene; Gutierrez-Pastor, Julia; Eriksson, A. T.; Gracia, Eulalia; Dunhill, Gita; Enkin, R. J.; Dallimore, Audrey; Vallier, Tracy, 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., 64 figures. [<https://pubs.usgs.gov/pp/pp1661f/>]

- Goldfinger, C.; Morey, A. E.; Black, B.; Beeson, J.; Nelson, C. H.; Patton, J., 2013, Spatially limited mud turbidites on the Cascadia margin: segmented earthquake ruptures?: *Natural Hazards and Earth System Sciences*, v. 13, no. 8, p. 2109-2146.
- Goldfinger, C.; Galer, S.; Beeson, J.; Hamilton, T.; Black, B.; Romsos, C.; Patton, J.; Nelson, C. H.; Hausmann, R.; 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.
- Heaton, T. H.; Snavely, P. D., Jr., 1985, Possible tsunami along the northwestern coast of the United States inferred from Indian traditions: *Seismological Society of America Bulletin*, v. 75, no. 5, p. 1455-1460.
- Hutchinson, Ian; Peterson, C. D.; Sterling, S. L., 2013, Late Holocene tsunami deposits at Salt Creek, Washington, USA: *Science of Tsunami Hazards*, v. 32, p. 221-235.
- Jacoby, G. C.; Bunker, D. E.; Benson, B. E., 1997, Tree-ring evidence for an A.D. 1700 Cascadia earthquake in Washington and northern Oregon: *Geology*, v. 25, no. 11, p. 999-1002.
- Kelsey, H. M.; Nelson, A. R.; Hemphill-Haley, Eileen; Witter, R. C., 2005, Tsunami history of an Oregon coastal lake reveals a 4,600 yr record of great earthquakes on the Cascadia subduction zone: *Geological Society of America*, v. 117, no. 7-8, p. 1009-1032.
- Kelsey, H. M.; Witter, R. C.; Hemphill-Haley, Eileen, 2002, Plate-boundary earthquakes and tsunamis of the past 5,500 yr, Sixes River estuary, southern Oregon: *Geological Society of America Bulletin*, v. 114, no. 3, p. 298-314.
- Ludwin, R. S., 2002, Cascadia megathrust earthquakes in Pacific Northwest Indian myths and legends: *TsuInfo Alert*, v. 4, no. 2, p. 6-10. [[https://www.dnr.wa.gov/publications/ger\\_tsuinfo\\_2002\\_v4\\_no2.pdf](https://www.dnr.wa.gov/publications/ger_tsuinfo_2002_v4_no2.pdf)]
- Lynett, P. J.; Borrero, Jose; Son, Sangyoung; Wilson, Rick; Miller, Kevin, 2014, Assessment of the tsunami-induced current hazard, *Geophysical Research Letters*, v. 41, iss. 6, p. 2048-2055.
- Myers, E. P., III; Baptista, A. M.; Priest, G. R., 1999, Finite element modeling of potential Cascadia subduction zone tsunamis: *Science of Tsunami Hazards*, v. 17, no. 1, p. 3-18.
- Nelson, A. R.; Kelsey, H. M.; Witter, R. C., 2006, Great earthquakes of variable magnitude at the Cascadia subduction zone: *Quaternary Research*, v. 65, no. 3, p. 354-365.
- Peters, Robert; Jaffe, B. E.; Gelfenbaum, Guy; Peterson, C. D., 2003, Cascadia tsunami deposit database: U.S. Geological Survey Open-File Report 03-13, 25 p. [accessed May 6, 2004 at <http://geopubs.wr.usgs.gov/open-file/of03-13/>]
- Peterson, C. D.; Cruikshank, K. M.; Darienzo, M. E.; Wessen, G. C.; Butler, V. L.; Sterling, S. L., 2013, Coseismic subsidence and paleotsunami run-up records from latest Holocene deposits in the Waatch Valley, Neah Bay, northwest Washington, U.S.A.: Links to great earthquakes in the northern Cascadia margin: *Journal of Coastal Research*, v. 29, no. 1, p. 157-172.
- Plafker, George, 1969, Tectonics of the March 27, 1964, Alaska earthquake: U.S. Geological Survey Professional Paper 543-1, 74 p., 2 sheets, scales 1:2,000,000 and 1:500,000. [<https://pubs.usgs.gov/pp/0543i/>].
- Plafker, George; Savage, J. C., 1970, Mechanism of the Chilean earthquakes of May 21 and 22, 1960: *Geological Society of America Bulletin*, v. 81, no. 4, p. 1001-1030.
- Priest, G. R.; Myers, E. P., III; Baptista, A. M.; Fleuck, Paul; Wang, Kelin; Kamphaus, R. A.; Peterson, C. D., 1997, Cascadia subduction zone tsunamis—Hazard mapping at Yaquina Bay, Oregon: Oregon Department of Geology and Mineral Industries Open-File Report O-97-34, 144 p. [<http://www.oregongeology.org/pubs/ofr/O-97-34.pdf>]
- Priest, G. R.; Zhang, Yinglong; Witter, R. C.; Wang, Kelin; Goldfinger, Chris; Stimely, Laura, 2014, Tsunami impact to Washington and northern Oregon from segment ruptures on the southern Cascadia subduction zone: *Natural Hazards*, v. 72, no. 2, p. 849-870.
- Satake, Kenji; Shimazaki, Kunihiko; Tsuji, Yoshinobu; Ueda, Kazue, 1996, Time and size of a giant earthquake in Cascadia inferred from Japanese tsunami records of January 1700: *Nature*, v. 379, no. 6562, p. 246-249.
- Satake, Kenji; Wang, Kelin; Atwater, B. F., 2003, Fault slip and seismic moment of the 1700 Cascadia earthquake inferred from Japanese tsunami description: *Journal of Geophysical Research*, v. 108, no. B11, 2535.
- Titov, V. V.; González, F. I., 1997, Implementation and testing of the Method of Splitting Tsunami (MOST) model: NOAA Technical Memorandum ERL PMEL-112 (PB98-122773), 11 p.
- Titov, V. V.; Synolakis, C. E., 1998, Numerical modeling of tidal wave runup: *Journal of Waterway, Port, Coastal and Ocean Engineering*, v. 124, no. 4, p. 157-171.
- Walsh, T. J.; Caruthers, C. G.; Heinitz, A. C.; Myers, E. P., III; Baptista, A. M.; Erdakos, G. B.; Kamphaus, R. A., 2000, Tsunami hazard map of the southern Washington coast—Modeled tsunami inundation from a Cascadia subduction zone earthquake: Washington Division of Geology and Earth Resources Geologic Map GM-49, 1 sheet, scale 1:100,000, with 12 p. text. [[http://www.dnr.wa.gov/publications/ger\\_gm49\\_tsunami\\_hazard\\_southern\\_coast.zip](http://www.dnr.wa.gov/publications/ger_gm49_tsunami_hazard_southern_coast.zip)]
- Walsh, T. J.; Myers, E. P., III; Baptista, A. M., 2002a, Tsunami inundation map of the Port Angeles, Washington area: Washington Division of Geology and Earth Resources Open File Report 2002-1, 1 sheet, scale 1:24,000. [[http://www.dnr.wa.gov/publications/ger\\_ofr2002-1\\_tsunami\\_hazard\\_portangeles.pdf](http://www.dnr.wa.gov/publications/ger_ofr2002-1_tsunami_hazard_portangeles.pdf)]
- Walsh, T. J.; Myers, E. P., III; Baptista, A. M., 2002b, Tsunami inundation map of the Port Townsend, Washington area: Washington Division of Geology and Earth Resources Open File Report 2002-2, 1 sheet, scale 1:24,000. [[http://www.dnr.wa.gov/publications/ger\\_ofr2002-2\\_tsunami\\_hazard\\_porttownsend.pdf](http://www.dnr.wa.gov/publications/ger_ofr2002-2_tsunami_hazard_porttownsend.pdf)]
- Walsh, T. J.; Myers, E. P., III; Baptista, A. M., 2003a, Tsunami inundation map of the Neah Bay, Washington, area: Washington Division of Geology and Earth Resources Open File Report 2003-2, 1 sheet, scale 1:24,000. [[http://www.dnr.wa.gov/publications/ger\\_ofr2003-2\\_tsunami\\_hazard\\_neahbay.pdf](http://www.dnr.wa.gov/publications/ger_ofr2003-2_tsunami_hazard_neahbay.pdf)]
- Walsh, T. J.; Myers, E. P., III; Baptista, A. M., 2003b, Tsunami inundation map of the Quileute, Washington, area: Washington Division of Geology and Earth Resources Open File Report 2003-1, 1 sheet, scale 1:24,000. [[http://www.dnr.wa.gov/publications/ger\\_ofr2003-1\\_tsunami\\_hazard\\_quileute.pdf](http://www.dnr.wa.gov/publications/ger_ofr2003-1_tsunami_hazard_quileute.pdf)]
- Walsh, T. J.; Titov, V. V.; Venturato, A. J.; Mofjeld, H. O.; González, F. I., 2003c, Tsunami hazard map of the Elliott Bay area, Seattle, Washington—Modeled tsunami inundation from a Seattle Fault earthquake: Washington Division of Geology and Earth Resources Open File Report 2003-14, 1 sheet, scale 1:50,000. [[http://www.dnr.wa.gov/publications/ger\\_ofr2003-14\\_tsunami\\_hazard\\_elliottbay.pdf](http://www.dnr.wa.gov/publications/ger_ofr2003-14_tsunami_hazard_elliottbay.pdf)]
- Walsh, T. J.; Titov, V. V.; Venturato, A. J.; Mofjeld, H. O.; González, F. I., 2004, Tsunami hazard map of the Bellingham area, Washington—Modeled tsunami inundation from a Cascadia subduction zone earthquake: Washington Division of Geology and Earth Resources Open File Report 2004-15, 1 sheet, scale 1:50,000. [[http://www.dnr.wa.gov/publications/ger\\_ofr2004-15\\_tsunami\\_hazard\\_bellingham.pdf](http://www.dnr.wa.gov/publications/ger_ofr2004-15_tsunami_hazard_bellingham.pdf)]
- Walsh, T. J.; Titov, V. V.; Venturato, A. J.; Mofjeld, H. O.; González, F. I., 2005, Tsunami hazard map of the Anacortes-Whidbey Island area, Washington—Modeled tsunami inundation from a Cascadia subduction zone earthquake: Washington Division of Geology and Earth Resources Open File Report 2005-1, 1 sheet, scale 1:62,500. [[http://www.dnr.wa.gov/publications/ger\\_ofr2005-1\\_tsunami\\_hazard\\_anacortes\\_whidbey.pdf](http://www.dnr.wa.gov/publications/ger_ofr2005-1_tsunami_hazard_anacortes_whidbey.pdf)]



- Walsh, T. J.; Arcas, Diego; Venturato, A. J.; Titov, V. V.; Mofjeld, H. O.; Chamberlin, C. C.; González, F. I., 2009, Tsunami hazard map of Tacoma, Washington—Model results for Seattle fault and Tacoma fault earthquake tsunamis: Washington Division of Geology and Earth Resources Open File Report 2009-9, 1 sheet, scale 1:24,000. [[http://www.dnr.wa.gov/publications/ger\\_ofr2009-9\\_tsunami\\_hazard\\_tacoma.pdf](http://www.dnr.wa.gov/publications/ger_ofr2009-9_tsunami_hazard_tacoma.pdf)]
- Walsh, T. J.; Arcas, Diego; Titov, V. V.; Chamberlin, C. C., 2014, Tsunami hazard map of Everett, Washington: Model results for magnitude 7.3 and 6.7 Seattle fault earthquakes: Washington Division of Geology and Earth Resources Open File Report 2014-03, 1 plate, scale 1:32,000. [[http://www.dnr.wa.gov/publications/ger\\_ofr2014-03\\_tsunami\\_hazard\\_everett.pdf](http://www.dnr.wa.gov/publications/ger_ofr2014-03_tsunami_hazard_everett.pdf)]
- Walsh, T. J.; Gica, Edison; Arcas, Diego; Titov, V. V.; Eungard, D. W., 2016, Tsunami hazard maps of the San Juan Islands, Washington—Model results from a Cascadia subduction zone earthquake scenario: Washington Division of Geology and Earth Resources Map Series 2016-01, 4 sheets, scale 1:24,000 and 1:48,000, 9 p. text. [[http://www.dnr.wa.gov/publications/ger\\_ms2016-01\\_tsunami\\_hazard\\_san\\_juan\\_islands.zip](http://www.dnr.wa.gov/publications/ger_ms2016-01_tsunami_hazard_san_juan_islands.zip)]
- Williams, H. F. L.; Hutchinson, Ian, 2000, Stratigraphic and microfossil evidence for late Holocene tsunamis at Swantown Marsh, Whidbey Island, Washington: *Quaternary Research*, v. 54, no. 2, p. 218-227.
- Williams, H. F. L.; Hutchinson, Ian; 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.; Kelsey, H. M.; and Hemphill-Haley, E., 2003, Great Cascadia earthquakes and tsunamis of the past 6,700 years, Coquille River estuary, southern coastal Oregon: *Geological Society of America Bulletin*, v. 115, no. 10, p. 1289–1306.
- Witter, R. C.; Zhang, Yinglong; Wang, Kelin; Priest, G. R.; Goldfinger, Chris; Stimely, L. L.; English, J.T.; Ferro, P. A., 2011, Simulating tsunami inundation at Bandon, Coos County, Oregon, using hypothetical Cascadia and Alaska earthquake scenarios: Oregon Department of Geology and Mineral Industries Special Paper 43, 57 p. [<http://www.oregongeology.org/pubs/sp/p-SP-43.htm>]
- Witter, R. C.; Zhang, Yinglong; Wang, Kelin; Goldfinger, Chris; Priest, G. R.; Allan, J. C., 2012, Coseismic slip on the southern Cascadia megathrust implied by tsunami deposits in an Oregon lake and earthquake-triggered marine turbidites: *Journal of Geophysical Research*, v.117, no. B10303, 17 p.
- Yamaguchi, D. K.; Atwater, B. F.; Bunker, D. E.; Benson, B. E.; Reid, M. S., 1997, Tree-ring dating the 1700 Cascadia earthquake: *Nature*, v. 389, p. 922-923.