TSUNAMI HAZARD MAP OF THE SOUTHERN WASHINGTON COAST:

Modeled Tsunami Inundation from a Cascadia Subduction Zone Earthquake

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by Timothy J. Walsh,
Charles G. Caruthers,
Anne C. Heinitz,
Edward P. Myers III,
Antonio M. Baptista,
Garnet B. Erdakos, and
Robert A. Kamphaus

WASHINGTON
DIVISION OF GEOLOGY
AND EARTH RESOURCES

Geologic Map GM-49
October 2000

This map is intended for use as an emergency management guide only and is not of sufficient resolution to be used for site-specific planning.

WASHINGTON STATE DEPARTMENT OF
Natural Resources
Jennifer M. Belcher - Commissioner of Public Lands

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Tsunami Hazard Map of the Southern Washington Coast: Modeled Tsunami Inundation from a Cascadia Subduction Zone Earthquake

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INTRODUCTION

Recent research about the potential for a great earthquake off the Washington, Oregon, and northern California coastlines (Atwater and others, 1995) has led to concerns about the effect of a local tsunami generated by this earthquake zone. In addition, the 1992 Petrolia earthquake did generate a small tsunami that was observed at Crescent City, California. Since local tsunami waves may reach nearby coastal communities within minutes of the earthquake, there would be little or no time to issue formal warnings; evacuation areas and routes will need to be planned well in advance. Previous workers (Hebenstreit and Murty, 1989; Preuss and Hebenstreit, 1998) have modeled potential tsunamis in parts of Washington and provided mitigation guidance to some coastal communities. Substantial advances in both computer modeling and understanding the Cascadia subduction zone hazards permit more comprehensive mapping of tsunami inundation potential. This map was prepared as part of the National Tsunami Hazard Mitigation Program (NTHMP) to aid local governments in designing evacuation plans for areas at risk from potentially damaging tsunamis.

MAP DESIGN

The landward limit of tsunami inundation is based on a computer model of waves generated by two different scenario earthquakes on the Cascadia subduction zone. The model used was a finite element model called ADCIRC, which was modified by Antonio Baptista and Edward P. Myers III of the Oregon Graduate Institute of Science and Technology (OGI) and adapted for modeling earthquake deformation and the resulting tsunami. The model uses a grid of variable spacing to allow for an increase in resolution where needed. It calculates a wave elevation and velocity for each point of the grid at specified time intervals for a period of eight hours from the time of the earthquake. Myers and others (1999) and Priest and others (1997) tested several earthquake scenarios in earlier simulations using this model that differ in the distribution of fault slip in locked and transition zones and in the placement of critical temperatures along the fault.

The earthquake scenarios adopted for this study were Scenario 1A (Myers and others, 1999; Priest and others, 1997) and Scenario 1A with an asperity offshore of Washington (Fig. 1), which appear to fit the available paleoseismic evidence reasonably well. The earthquake is a magnitude (M_W) 9.1 Cascadia subduction zone (CSZ) event with a rupture length of 650 mi (1,050 km) and a rupture width of 45 mi (70 km). The asperity is an area of locally greater fault slip, or displacement along the fault plane, that generates a higher uplift of about 20 ft (6 m), offshore of northern Washington. The land surface along the coast was modeled to subside by about 5 ft (1.0–1.5 m) (Fig. 1) during ground shaking, which is consistent with some paleoseismologic investigations. (See Priest and others, 1997, for a complete discussion.) This scenario has been adopted for tsunami inundation mapping in Oregon as well.

Scenario 1A is shown on the accompanying hazard map as “Areas inundated by a moderately high runup from the modeled Cascadia subduction zone tsunami” and Scenario 1A with asperity is mapped as the worst-case “Additional areas inundated by a high runup from the modeled Cascadia subduction zone tsunami”. The modeled lines were smoothed to compensate for resolution limitations and, in some instances, to place the inundation limit at nearby logical topographic boundaries.

The model runs did not include the influences of changes in tides but used a tide height of 4 ft (1.2 m). The tide stage and tidal currents can amplify or reduce the impact of a tsunami on a specific community.

TIME HISTORIES

The arrival time and duration of flooding are key factors to be considered in evacuation strategies. We show time histories of the modeled waves at twelve localities (Fig. 2) (shown on the map as numbers within circles) immediately offshore of key communities. These time histories give the change in water surface elevation with time for 8 hours of modeling. Negative elevations are wave troughs, or times when water is flowing out to sea. Positive elevations are wave crests. Note that for locations on the outer coast, the first wave crest is generally predicted to arrive at between 30 and 60 minutes after the earth-

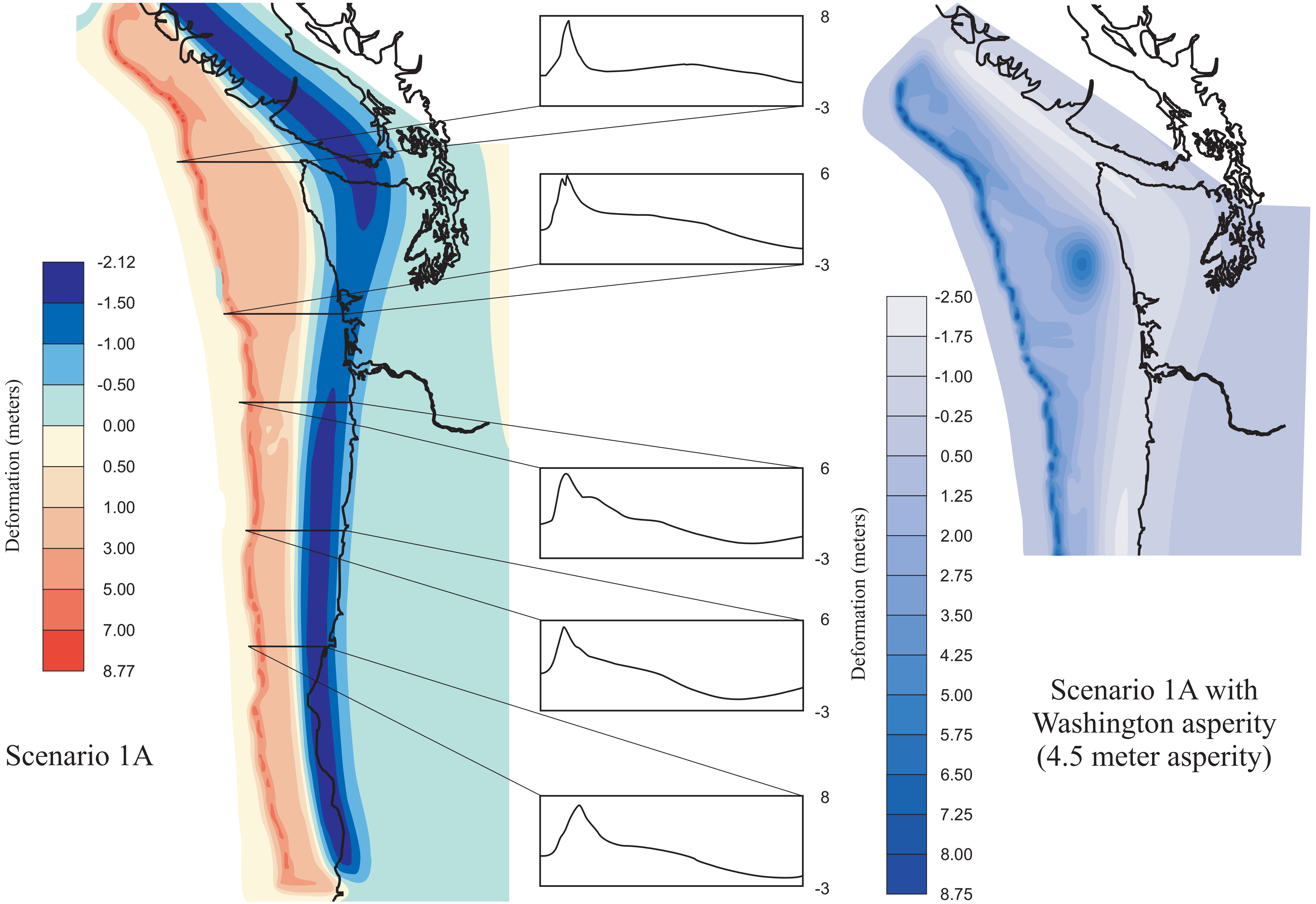
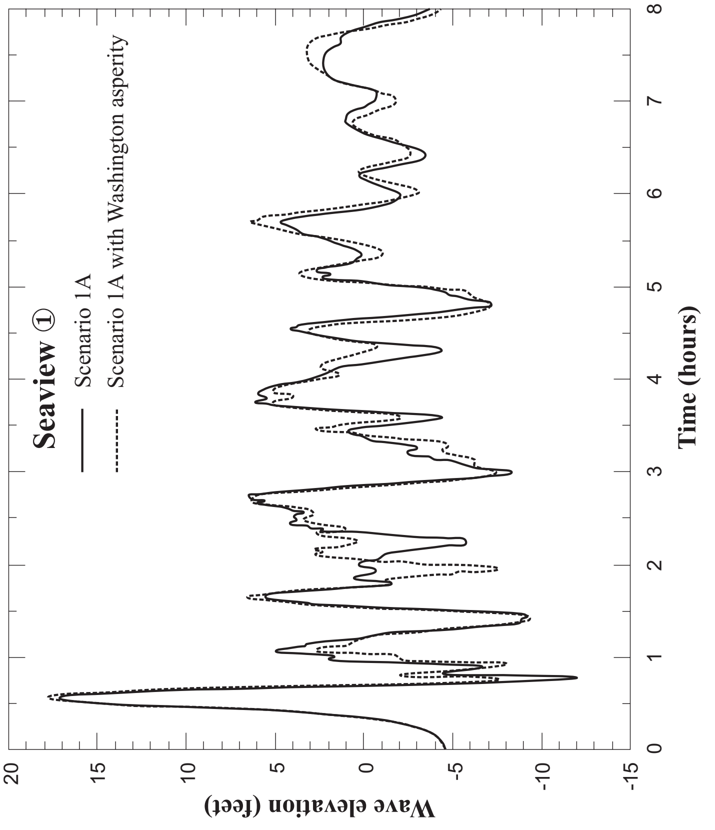
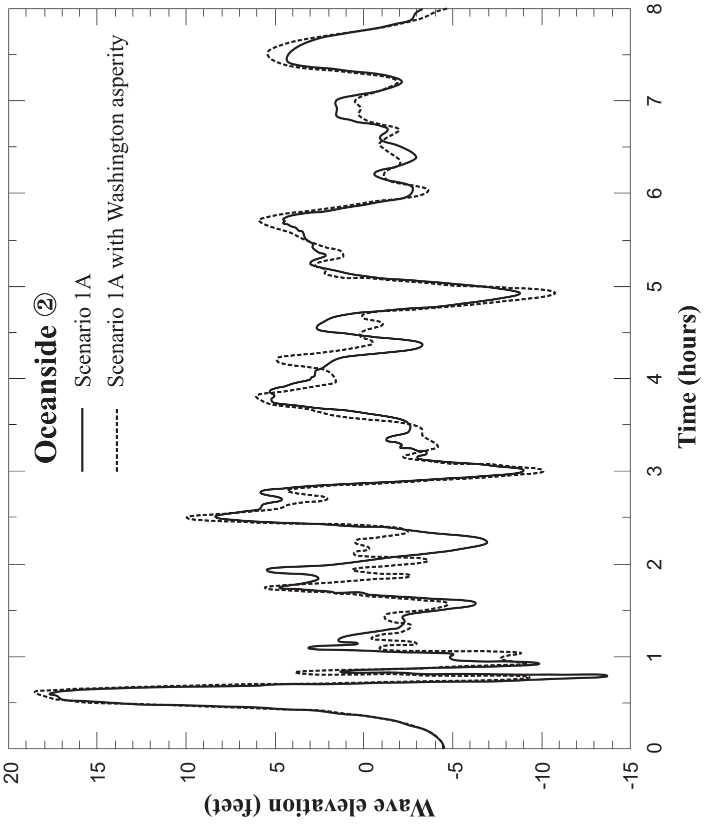
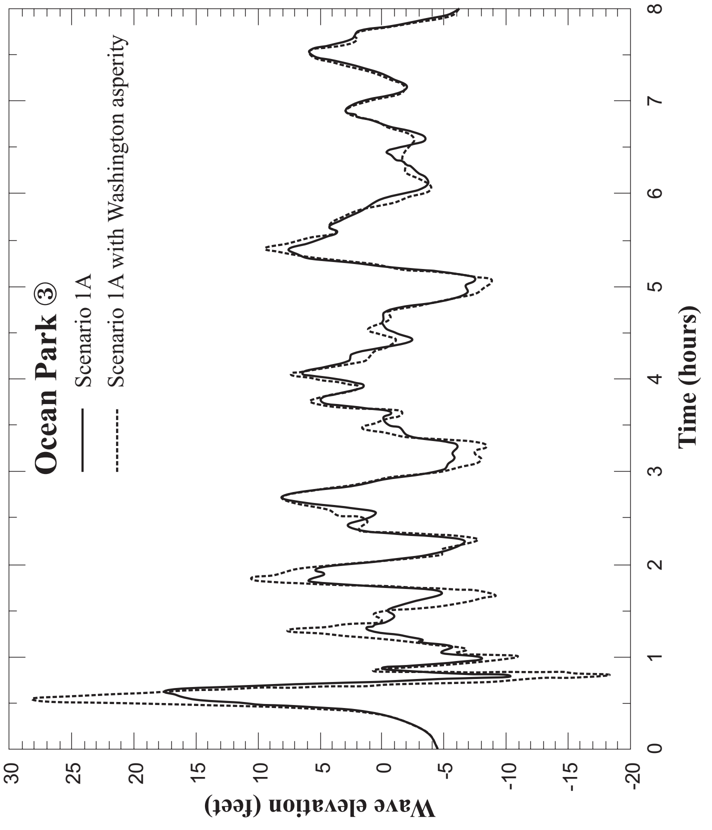


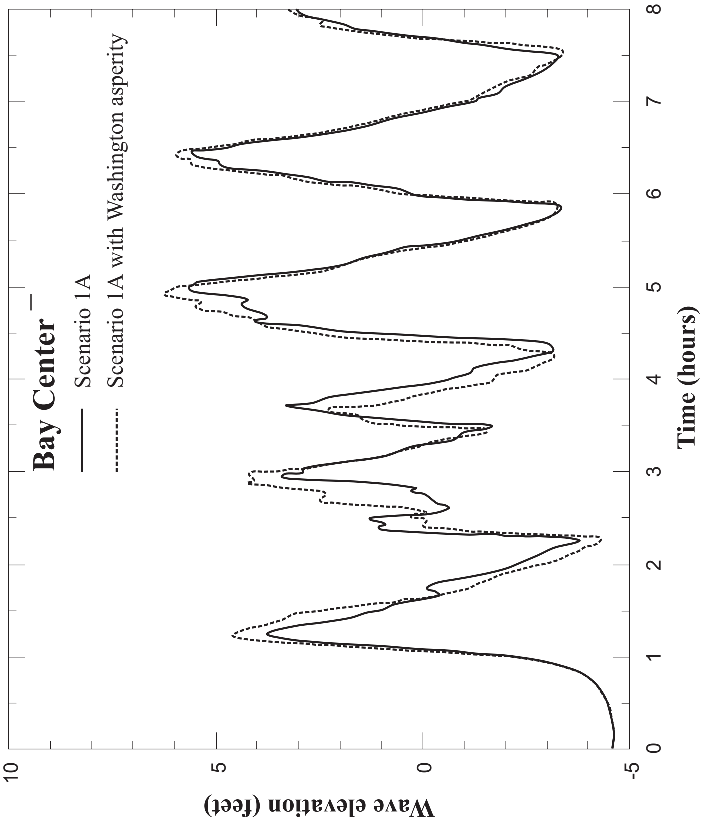
Figure 1. Map of fault uplift and subsidence showing Scenario 1A and Scenario 1A with 4.5-meter Washington asperity added. Scenario 1A shows time histories of modeled waves at various locations along the coast.

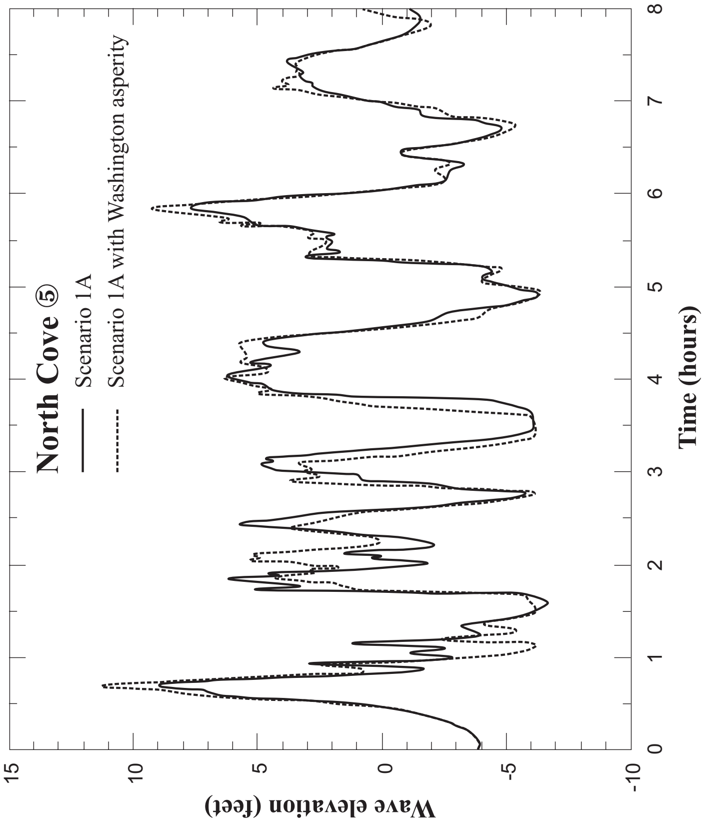
Figure 2. *(next three pages)* Time histories of the modeled waves at twelve localities immediately offshore of key communities, identified by community name and map number (in circle). These time histories give the change in water surface elevation with time for 8 hours of modeling.

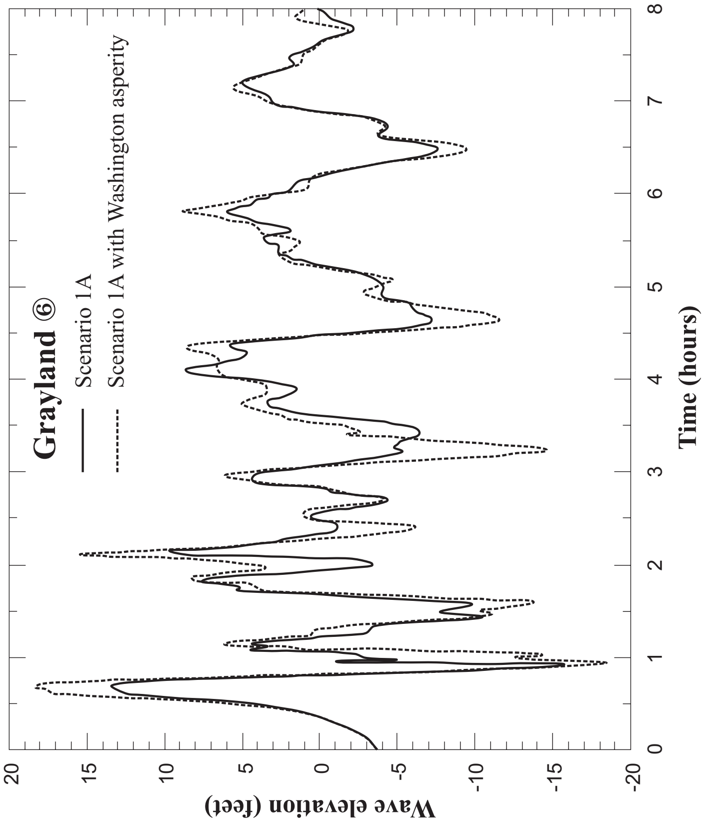

Seaview ①
Scenario 1A
Scenario 1A with Washington asperity
Wave elevation (feet)
20
15
10
5
0
-5
-10
-15
Time (hours)
0
1
2
3
4
5
6
7
8

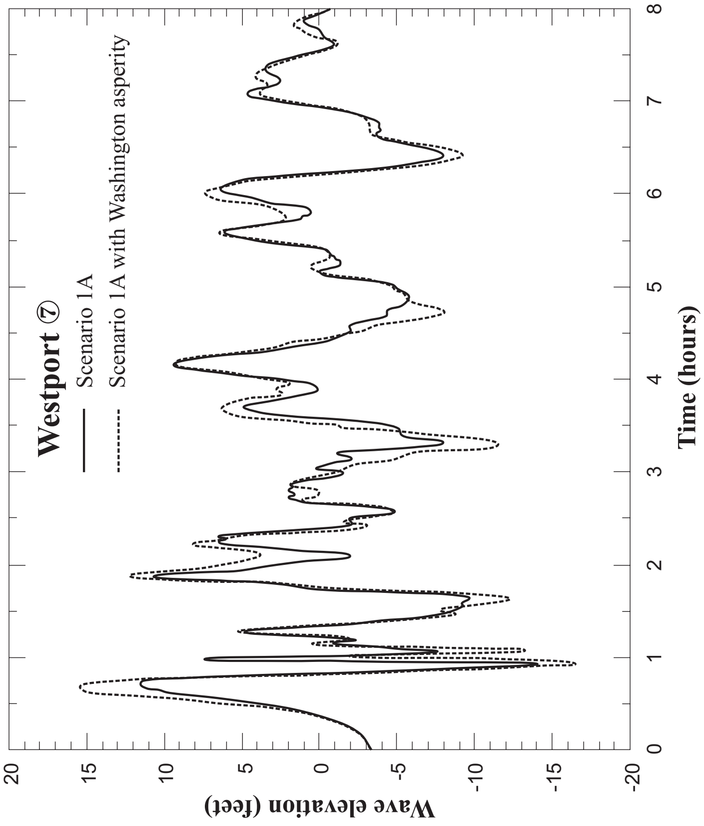

Oceanside ②
Scenario 1A
Scenario 1A with Washington asperity
Wave elevation (feet)
20
15
10
5
0
-5
-10
-15
Time (hours)
0
1
2
3
4
5
6
7
8

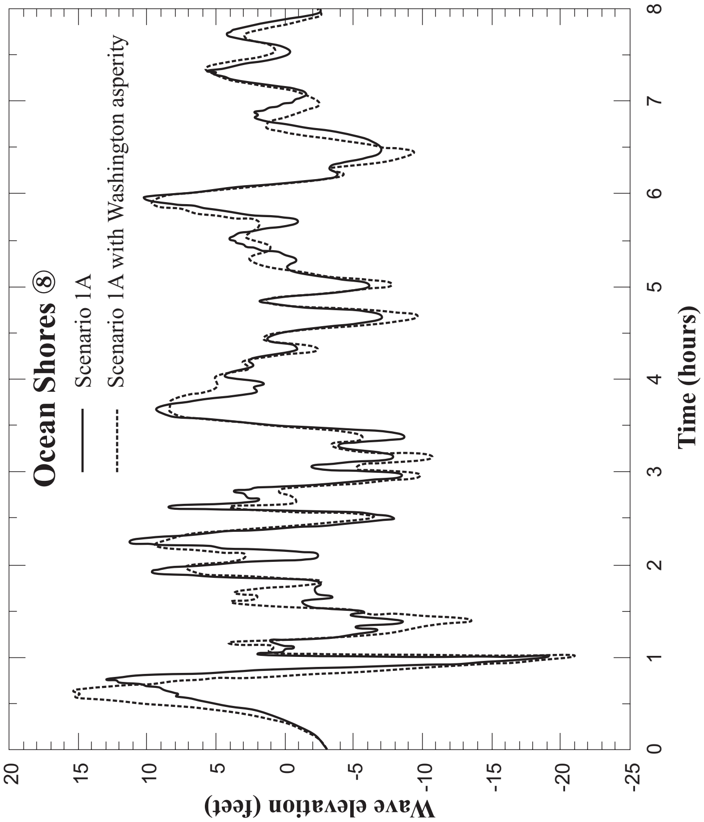

Ocean Park ③
Scenario 1A
Scenario 1A with Washington asperity
Wave elevation (feet)
30
25
20
15
10
5
0
-5
-10
-15
-20
Time (hours)
0
1
2
3
4
5
6
7
8

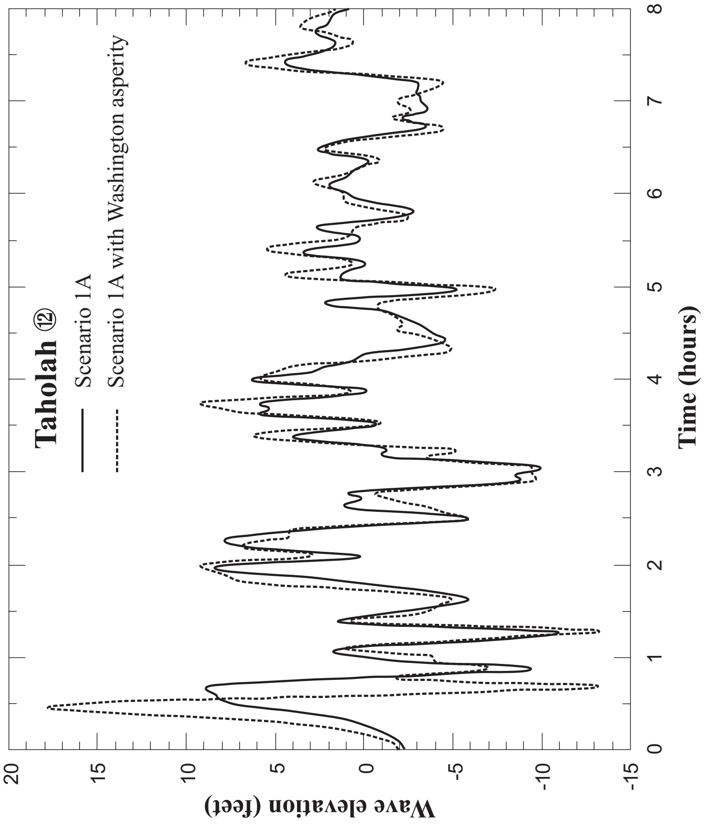

Bay Center ¯
Scenario 1A
Scenario 1A with Washington asperity
Wave elevation (feet)
10
5
0
-5
Time (hours)
0
1
2
3
4
5
6
7
8

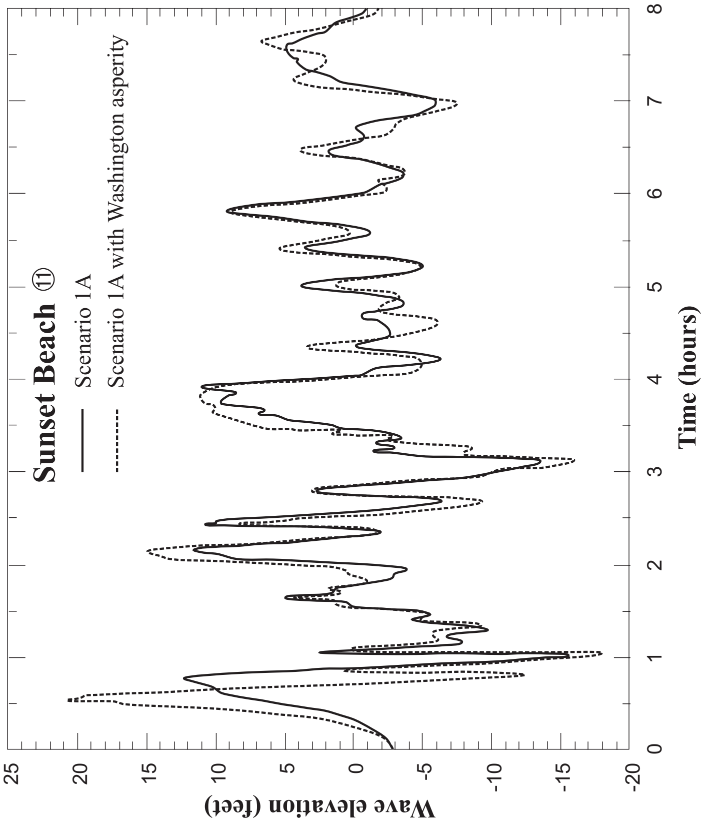

North Cove ⑤
Scenario 1A
Scenario 1A with Washington asperity
Wave elevation (feet)
15
10
5
0
-5
-10
Time (hours)
0
1
2
3
4
5
6
7
8

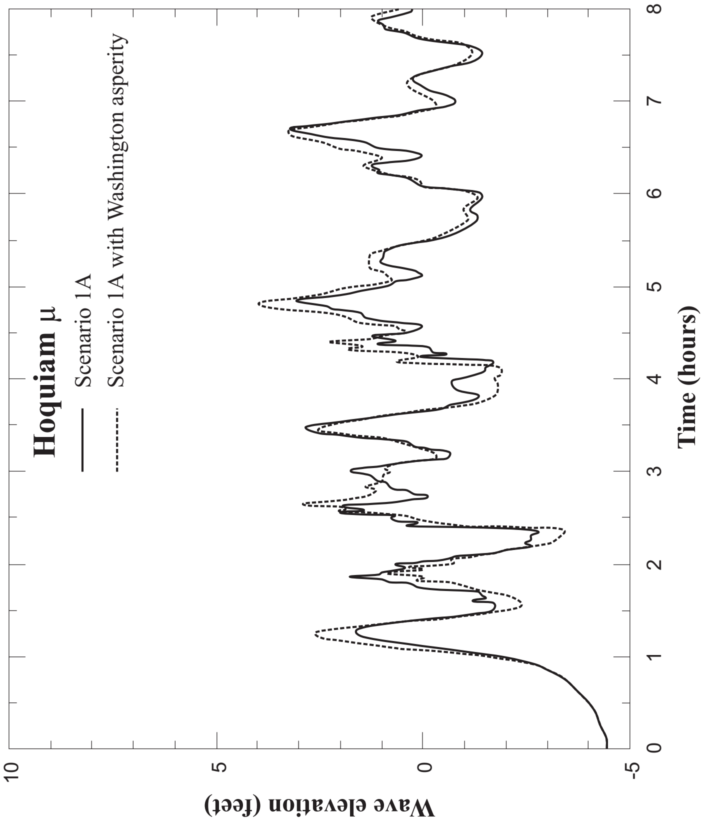

Grayland ⑥
Scenario 1A
Scenario 1A with Washington asperity
Wave elevation (feet)
20
15
10
5
0
-5
-10
-15
-20
Time (hours)
0
1
2
3
4
5
6
7
8


Westport ⑦
Scenario 1A
Scenario 1A with Washington asperity
Wave elevation (feet)
20
15
10
5
0
-5
-10
-15
-20
Time (hours)
0
1
2
3
4
5
6
7
8


Ocean Shores ⑧
Scenario 1A
Scenario 1A with Washington asperity
Wave elevation (feet)
20
15
10
5
0
-5
-10
-15
-20
-25
Time (hours)
0
1
2
3
4
5
6
7
8


Taholah ⑫
Scenario 1A
Scenario 1A with Washington asperity
Wave elevation (feet)
Time (hours)
20
15
10
5
0
-5
-10
-15
0
1
2
3
4
5
6
7
8


Sunset Beach ⑪
Scenario 1A
Scenario 1A with Washington asperity
Wave elevation (feet)
Time (hours)
25
20
15
10
5
0
-5
-10
-15
-20
0
1
2
3
4
5
6
7
8


Hoquiam μ
Scenario 1A
Scenario 1A with Washington asperity
Wave elevation (feet)
Time (hours)
10
5
0
-5
0
1
2
3
4
5
6
7
8

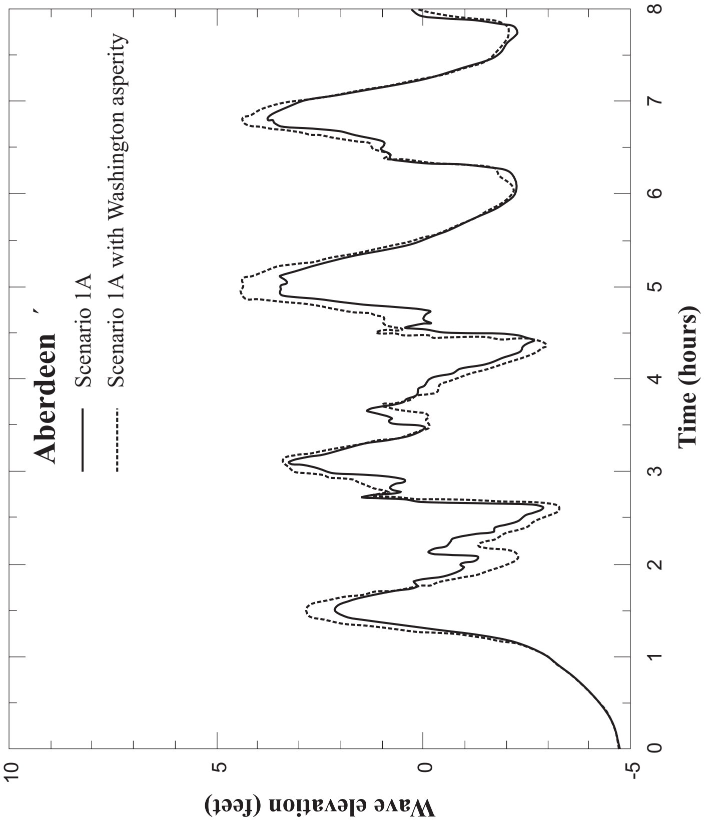

Aberdeen ´
Scenario 1A
Scenario 1A with Washington asperity
Wave elevation (feet)
Time (hours)
10
5
0
-5
0
1
2
3
4
5
6
7
8

Table 1. Observations of the 1964 tsunami on the Washington coast. Height is height of highest wave; MLW, mean low water; MSL, mean sea level. Estimated damage is in 1964 dollars (from Hogan and others, 1964; Wilson and Torum, 1972; and newspaper accounts)

Location	Map no.	Height (ft) above tide	Height (ft) above MLW	Height (ft) above MSL	Estimated damage	Type of damage	Photo
Coast Guard Station, Cape Disappointment	1	5.7	11.9	8.3		None	
Town of Ilwaco	2	4.5	10.7	7.1		Minor damage	
Town of Seaview	3	12.5	19.5	14.8		None	
Ocean Shores	4	9.7	18.1	13.3		Deposition of debris on streets near Central Motel Office. Debris on streets and yards in vicinity of break in sand dune dike about ¾ mile south of motel	
State Highway 109, Copalis River Bridge	5					Loss of one four-pile timber bent and two timber spans near the bridge center and one piling in a four-pile timber bent.	9-1-A; Fig.3
Town of Copalis, Copalis River	6				$5,000	Damage to buildings	
State Hwy 109 at Boone Creek	7				$5,000	Erosion of 80 ft (24 m) of shoulder and deposition of debris on highway.	8-4-A
Iron Springs Resort	7				$500	Foundation and water damage to one house and deposition of debris in yard.	
State Highway 109, Joe Creek Bridge	8				$75,000	Loss of five-pile bent, damage to two pile bents (loss of three pilings), and loss of two 20-ft (6.1-m) reinforced concrete spans.	8-3-A; Fig. 4
Town of Pacific Beach	9	12–14 (est.)			$12,000	Medium-sized house lifted off the foundation and partly torn apart; total loss. Several sheds moved off foundations. A second building partly damaged. Yards eroded and covered with debris.	8-2-A; Fig. 5
Town of Moclips	10	11.1	19.7	14.9	$6,000	Damage to ocean side of buildings by floating logs; one building moved off foundation. Timber pile bulkheads and fills extensively damaged. Water over some floors from 6 in. to several feet. Heavy debris scattered over yards.	8-1-A, B,C; Figs. 6,7,8
State Highway 109, Wreck Creek Bridge	11	14.9	23.5	18.83	$500	Erosion of fill at bridge approach: debris on bridge deck and nearby highway.	7-1-A
Taholah	12	2.4	11.0	6.3	$1,000	Loss of several skiffs and fish nets in inlet at mouth of Quinault River.	
Mouth of Hoh River		1.7	10.1	5.6		None	
La Push		5.3	13.7	9.3		Several boats and a floating dock broke loose from moorings.	
U.S. Highway 101, Bone River Bridge	13					Pilings damaged when the Moore cannery building was lifted off its foundation and washed against the south approach of the Highway 101 bridge over the Bone River	
Raymond docks		3.5–4 (est.)				None	

quake, whereas within Willapa Bay and Grays Harbor, the first crest is not expected to arrive for more than an hour. In all of the time histories, the first arrival is a wave trough, which, if correct, implies that flooding is delayed by a few tens of minutes. However, significant flooding can occur before the first crest arrives because a CSZ earthquake is expected to lower the ground surface along the coast. Flooding of areas less than about 6 ft (1.8 m) above tide stage is expected immediately, rendering evacuation time even shorter. Maximum flooding depth and extent will depend on tide height at the time of tsunami arrival.

OTHER DATA SHOWN ON MAP

Paleotsunami Data

A substantial body of evidence suggests that the Cascadia subduction zone (CSZ) has produced large earthquakes and consequent tsunamis (Atwater and others, 1995) in the past. Large subduction zone earthquakes elsewhere (Chile in 1960; Alaska in 1964) have resulted in coseismic subsidence over significant areas. Where these areas are near sea level, subsidence causes abrupt submergence and sometimes inundation by tsunamis. In the geologic record, this phenomenon is most readily recognized where marshes that received little or no sand supply are inundated by a wave that deposits a sheet of sand. Radiocarbon dating permits assignment of approximate ages to these events. This kind of evidence suggests that the most recent CSZ earthquake was about 300 years ago (Atwater and others, 1995, and references therein).

Recent work by Satake and others (1996) found records for a large tsunami in Japan that was not associated with an earthquake there. From the distribution of wave heights, they concluded that the tsunami probably originated in North or South America and was generated by an earthquake of about magnitude 9. Because historical records in South America would have included an earthquake that large, but do not, they concluded that the tsunami in Japan was most likely generated by a magnitude 9 earthquake on the CSZ on January 26, 1700. Subsequent dating of trees inferred to have been killed by a CSZ earthquake confirmed the occurrence of a large earthquake in the winter of 1699/1700 (Jacoby and others, 1997; Yamaguchi and others, 1997), strongly supporting Satake and others' inference that the CSZ was the source of this tsunami.

Because it is the most recent large CSZ event, geologic evidence of the A.D. 1700 earthquake is the most abundantly preserved. A number of geologists have been searching for evidence of sudden coseismic submergence and consequent inundation by sand-laden water. This map shows three sets of such data.

Mary Ann Reinhart (GeoEngineers, written commun., 1999) has identified marsh surfaces that she infers to have subsided coseismically during the A.D. 1700 event. Where these marsh deposits are overlain by inferred tsunami sand, our map shows a filled blue circle. Where the subsided marsh surface had no sand on top of it, the map shows an open blue circle.

Schlichting and Peterson (1998) and Schlichting (2000) have cored peat deposits from fresh-water lakes on the Grayland plains and the Long Beach peninsula. They have found evidence of tsunami inundation from both the A.D. 1700 event (inferred) and from an earlier event about 1,300 years ago. The A.D. 1700 sites are shown on the map as blue crosses. The data are preliminary as of this writing, but they imply that the tsunami 1,300 years ago (not shown on map) was more extensive than the one in A.D. 1700.

Also within the map area are three archaeological sites that show evidence of abandonment about 300 years ago that is attributed to the A.D. 1700 earthquake (Atwater, 1992; Atwater and Hemphill-Haley, 1997). Where these sites have evidence of an inferred tsunami (a sand sheet directly overlying the cultural material), they are shown as an inverted blue triangle topped by a horizontal line; where evidence of tsunami is lacking (near South Bend) the

Figure 3. Photo 9-1-A. Two spans lost and timber bent. Two other 20-foot spans are shown considerably deflected. Map location 5.

Figure 4. Photo 8-3-A. Two spans of bridge and middle pile bent lost. Pile bents on each side damaged, right side has been deflected from original position. Map location 8.

Figure 5. Photo 8-2-A. Portion of house completely torn from main part. Entire house was moved northwest 40 ft (12.2 m) from foundation. Map location 9.

site is shown as an inverted blue triangle without the horizontal line.

These data are shown because they illustrate the minimum extent of the A.D. 1700 tsunami. They do not, however, show the maximum extent. Lack of evidence for a tsunami does not imply that a tsunami did not inundate the locality, but only that there is not a record of one. This could be because the tsunami did not inundate the site, because the site was inundated by water that did not leave a sand deposit, or because sand was deposited but not preserved.

Another distinction to be made is that a tsunami's characteristics depend on bathymetry, topography, and tide stage. The model was run with modern topography and bathymetry that included the effects of cultural features that have influenced deposition, such as dams on the Columbia River; jetties on the Columbia and at the mouth of Grays Harbor that intercept sediment and increase currents at bay mouths, altering the bathymetry; road building on and excavation of the dunes protecting the coastline; and the introduction of European beach grass that traps sand and enlarges the dunes. The bathymetry and topography at A.D. 1700 can only be inferred.

The tide stage at the time of that tsunami may also have been significantly different. Mofjeld and others (1997) estimated that the A.D. 1700 tsunami may have occurred at a low neap tide, perhaps 7 or 8 ft (2.1–2.4 m) lower than the tide stage modeled. The overall differences between that tsunami and the ones modeled here are unknown.

Figure 6. Photo 8-1-A showing drift line. Slough in back of house with debris scattered showing evidence of backwater. Map location 10.

Figure 7. Photo 8-1-B showing windows broken, siding torn off, and drift logs scattered in back yard. Map location 10.

Historic Tsunami Data

The tsunami following the March 27, 1964, Alaskan earthquake was the largest and best recorded historical tsunami on the southern Washington coast. Unpublished observations and measurements of maximum inundation made by Hogan and others (1964) and later published in the account of the Alaskan earthquake (Wilson and Torum, 1972) are listed in Table 1. Some of Hogan and others' photos are reproduced here as Figures 3 through 8 with the original captions. The locations of their observations are shown as numbered blue diamonds on the map and are keyed to 'Map no.' column in Table 1. Newspaper reports provided additional damage estimates and approximate inundation elevations.

The observations of Hogan and others (1964) were limited to the outer coast. We searched newspaper records for additional tsunami observations, particularly within Grays Harbor and Willapa Bay. At Aberdeen, three log rafts of the Saginaw Shingle Co. broke up and had to be cleared by tug (*Aberdeen Daily World*, March 28, 1964), but no tsunami damage was reported within Grays Harbor. There was, however, a seiche in the Aberdeen city reservoir that overtopped the reservoir's walls, washing gravel into the nearby neighborhood (*Aberdeen Daily World*, March 28, 1964). At Westport at the entrance to Grays Harbor, the maximum wave height was reported to be about 5 ft (1.5 m) (*Twin Harbors Press*, April 2, 1964).

In Willapa Bay, the greatest damage occurred in the northern part of the bay. Strong currents scoured into oyster beds, in some cases transporting oysters more than a half mile (0.8 km), and in others, burying oyster beds with sand transported from the spits at the entrance to the bay (*Raymond Herald*, April 2, 1964). Highway 101 was damaged when the Moore Cannery building was lifted from its foundation and washed against the south approach of the bridge over the Bone River. One piling and all its supports were washed away, causing the bridge to be restricted to one lane until repairs could be made (*Raymond Herald*, April 2, 1964).

John Shulene, a retired science teacher and volunteer with the U.S. Geological Survey (USGS), interviewed residents in the Willapa Bay area, who provided additional information on the behavior of this tsunami within Willapa Bay. The most destructive part of the 1964 Alaska tsunami, near Raymond and South Bend, hit about 12 hours after the first waves reached Washington.

The story came independently from Ed Norman, Bill Campbell, and Ed Triplett. As the surges began, Norman and Campbell were working at the Port Dock (the port facility a little more than 1 mi (1.6 km) downstream from U.S. 101), while Triplett was in a tug tethered to a log ship that was moving seaward another mile or two downstream.

All three men recounted a swift series of daytime, probably late-morning or mid-day surges on the day after the 1964 earthquake. The surges, both up and down the river, broke up log rafts and threatened boats on the river.

All testified noticing no sign of damage—to the rafts or to anything else along the Willapa River—from earlier waves in the tsunami. All further stated that the surges took them by surprise. None of the men recalled receiving warning that the earthquake might cause a tsunami in Washington.

There was also agreement that the surges happened at a tide that was neither extremely high nor extremely low. (In Washington, the 1964 tsunami began at high tide. If the surges noticed by the men occurred in mid-morning, they came in shortly before low tide.)

Campbell estimated that the first big withdrawal caused the water level to drop 6 to 8 ft (1.8–2.4 m). He based this estimate on the temporary grounding of a tug that had been afloat on the north side of the river, opposite the Port Dock. According to Campbell, this tug had a draft of about 6 ft (1.8 m). Campbell recalled that Harry Nielson (now deceased) jumped off the grounded tug and scrambled up to the Westport highway, and that Nielson barely got back on the tug as the current reversed. He also recalled the snapping of two ½-in. (13-mm) nylon lines that had tied a 550-ft (168-m) log ship to the Port Dock.

Campbell and Triplett both stated that the broken-up log rafts contained Douglas fir 3 to 6 ft (0.9–1.8 m) in diameter. According to Campbell, the surges "snapped the tailsticks"—the chained logs at the squared-off stern.

Campbell had the clearest recollection of the event. He said that where he was, the peak currents were probably at least 10 to 12 knots—certainly faster than someone could run for any length of time. Triplett didn't remember much about currents, except that he was impressed by how quickly the mud flats drained into the navigation channel and then returned. He did say that he was on a 70-ft (21-m) boat at the time, so the currents would be less obvious than had he been in a small boat.

The same late waves probably came to Bay Center. Shulene's source there was Sam Pickernell (b. 1928), interviewed July 11, 2000. The morning after the earthquake, Pickernell was out crabbing. Around that time there was a series of surges, about 10 minutes apart, that lasted a total of a half hour or 45 minutes. The surges emptied the sloughs, made buoys move in an unusual way, and rolled oysters onto the shore. In Bay Center, people watched from the bridge near the cemetery.

Figure 8. Photo 8-1-C showing erosion of bank and damage to bulkhead. Map location 10.

LIMITATIONS OF THE MAP

Sources of error are discussed in detail in Priest and others (1997). Because the nature of the tsunami depends on the initial deformation of the earthquake, which is poorly understood, the largest source of uncertainty is the input earthquake. The earthquake scenarios used in this modeling appear to reasonably honor the paleoseismic constraints, but the next CSZ earthquake may be substantially different from these. Scenario 1A (with asperity) is considered a worst-case scenario (at least for the southern Washington coast), but some scenarios tested by Priest and others (1997) locally showed larger tsunamis.

Another significant limitation is that the resolution of the modeling is no greater or more accurate than the bathymetric and topographic data used. Horizontal resolution errors can be up to 165 ft (50 m). The vertical resolution is not well constrained but errors are probably on the order of 7 to 20 ft (2.1–6.1 m). This means that, while the modeling can be a useful tool to guide evacuation planning, it is not of sufficient resolution to be useful for land-use planning.

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