Simulation of paleotsunamis in Puget Sound, Washington

Shunichi Koshimura[1], Andrew L. Moore[2], and Harold O. Mofjeld[1]

[1]***NOAA/Pacific Marine Environmental Laboratory, Seattle, Washington, U.S.A.***
[2]***Disaster Control Research Center, Tohoku University, Aoba, Sendai, Japan***

Abstract. This study aims to reproduce the tsunami that occurred 1100 years ago in Puget Sound reported by recent paleoseismological studies, using a finite difference model based on nonlinear shallow water theory. The study refines the estimates of run-up height, flow depth, and current velocity at these sites made by Moore (1993) and Dinkelman and Holmes (1993), using a high-resolution model that explicitly allows for coastal flooding and drying. The model is also used to estimate the spatial patterns of tsunami propagation and coastal inundation throughout Puget Sound for this earthquake scenario. When combined with existing field observations of paleotsunamis and ground movement, the simulations will help to constrain the earthquake mechanism. They will also help guide the search for additional geological evidence of this event.

1. Introduction

The Puget Lowland of western Washington State is subject to a number of earthquake hazards. The most recent one was the M 6.8 Nisqually earthquake on 28 February 2001. The Juan de Fuca Plate is subducting beneath the North American continental plate. This subduction process is believed to be the cause of earthquakes within the North American crust and the interface between the plates. Deep earthquakes, so called Benioff Zone earthquakes, are caused within the subducting oceanic plate as it bends beneath the continental plate. Most of the historical earthquakes with magnitudes greater than 6 have occurred in the Benioff Zone.

However, paleoseismic studies in the Puget Lowland of western Washington demonstrate that a strong shallow earthquake occurred in this region about 1100 years ago. This earthquake occurred on the Seattle Fault, a zone of thrust or reverse faults which cross Puget Sound between Seattle and Bremerton (Johnson *et al.*, 1999) and the magnitude is estimated to be 7 or larger (Bucknam *et al.*, 1992). Based on the distribution of exposed bedrock, anomalies in the earth's magnetic and gravity fields, and seismic-reflection data, Johnson *et al.* (1999) inferred that the Seattle Fault forms a west-trending zone of three or more south dipping reverse faults. Bucknam *et al.* (1992) reported that a 5- to 7-m uplift occurred abruptly between Dyes Inlet and the Duwamish River in Seattle during the earthquake of 1000–1100 years ago. Figure 1 shows a map of one of the structures in the Seattle Fault zone inferred by Johnson *et al.* (1999) and geological evidences reported by Bucknam *et al.* (1992).

A tsunami in Puget Sound was accompanied by this earthquake. Atwater and Moore (1992) found the evidence in terms of tsunamigenic sand deposits, a sand sheet deposited during tsunami run-up on the land, at two sites north

[1]Pacific Marine Environmental Laboratory, NOAA, 7600 Sand Point Way NE, Bldg. 3, Seattle, WA 98115-6349, U.S.A. (koshi@pmel.noaa.gov, mofjeld@pmel.noaa.gov)

[2]Disaster Control Research Center, School of Engineering, Tohoku University, Aoba 06, Sendai 980-8579, Japan (moore@tsunami2.civil.tohoku.ac.jp)

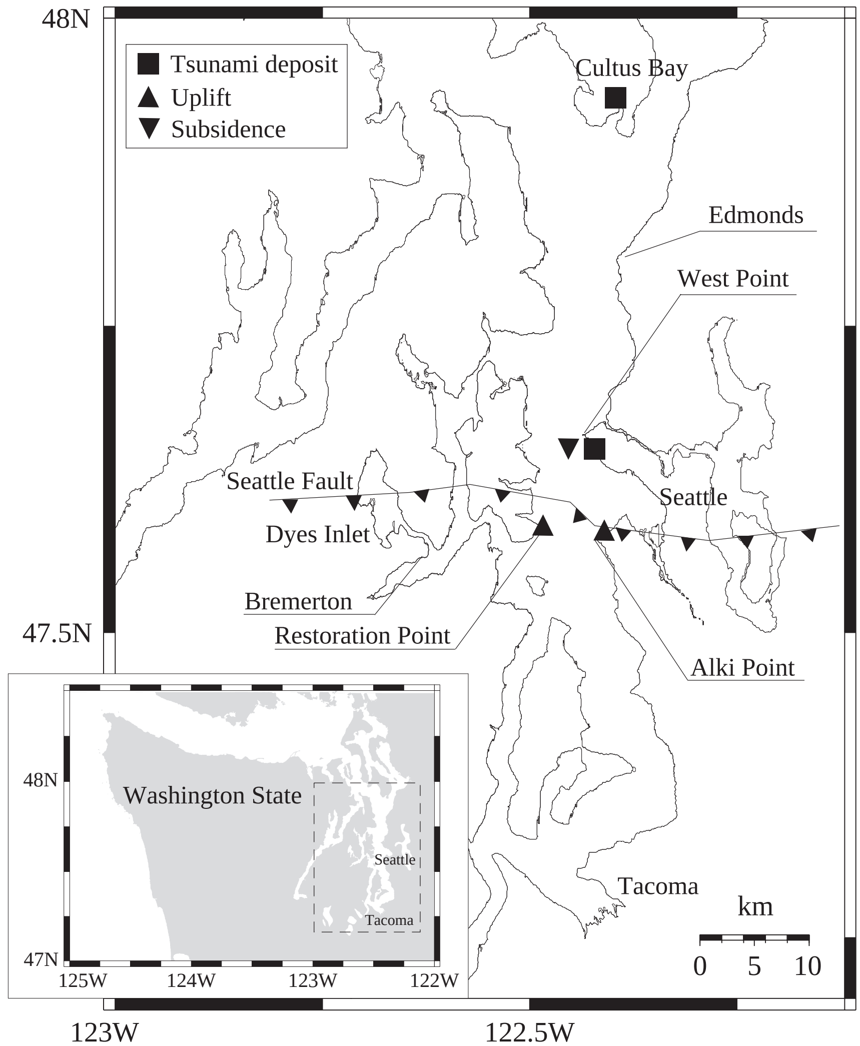

Figure 1: Inferred structure of the Seattle Fault and geological evidence suggesting the occurrence of the earthquake and accompanied tsunamis about 1100 years ago.

of Seattle Fault (see Fig. 1). Holmes and Dinkelman (1993) attempted to simulate this tsunami by constructing a simple tectonic impulse model as the initial condition of the numerical modeling of tsunamis. Based on the modeling results, they concluded that maximum wave heights were 6 m at West Point, Seattle, and 2–5 m at Cultus Bay at the southern end of Whidbey Island, where the tsunami deposits were found. However, their models were based on a relatively coarse 500 m grid of Puget Sound bathymetry and did not include the estimates of tsunami run-up on dry land.

This study aims to reproduce the tsunami that occurred about 1100 years ago in Puget Sound, using a conventional finite difference model based on the non-linear shallow water theory. The model refines the estimates of run-up height, flow depth, and current velocity where the tsunamigenic evidence was found. Considering the possibility of the occurrence of this type of shallow crustal earthquake within the Puget Lowland, the model is also used to estimate the tsunami hazard impact to local communities throughout Puget Sound in terms of the spatial patterns of tsunami propagation and coastal inundation.

We use the evidence at Cultus Bay to compare with the results of tsunami inundation modeling. We believe that Cultus Bay was not included within the seismic deformation area during the Seattle Fault earthquake 1100 years ago. It makes the problem simpler not to consider the interaction of local subsidence and relative sea level change during 1000 years.

2. Tsunamigenic Evidence

2.1 Cultus Bay

According to Atwater and Moore (1992), the tsunami deposit at Cultus Bay forms a sand sheet of 1 to 15 cm thick within the historical tidal marsh at the western head of the bay. The deposit climbs through the excavated area of 150 m by 300 m from east to west and finally pinches out 4.5 m above the present MLLW. This means that the tsunami surged up to at least this level during the process of tsunami run-up on the marsh. Moore (2001) analyzed the grain size trends in the deposit and found that the sand fines from the east to the west. Based on this result, he concluded that a westward current occuring during the tsunami run-up on the marsh produced the sand deposit.

2.2 West Point

The tsunami deposit at West Point was found between the strata of historical tidal marsh and overlain tidal flat deposits (Atwater and Moore, 1992). Considering the structure of the Seattle Fault zone interpreted as reverse faults dipping southward, it can be inferred that the land at West Point subsided abruptly during the earthquake. Atwater and Moore excavated this area and concluded that the tsunami surged on the subsided historical tidal marsh to deposit the sand, then the deposit was overlain by the tidal flat deposits. From the thickness of the tidal flat deposits, they inferred that the amount of subsidence was 1 m.

3. Earthquake Scenario

Based on seismic reflection data collected from the Puget Lowland, Pratt *et al.* (1997) interpreted the Seattle Fault as a thrust fault dipping southward at angle of about 20° and steepening to 45° in the near surface, within the total rupture area of 4420 km^2. They also concluded that the rupture of the fault could generate a $M_w = 7.6$ to 7.7 earthquake. Since the structure of the Seattle Fault is still uncertain, we modified the hypothesis of Pratt *et al.* (1997) to get a better match to the geological evidence for the event that occurred about 1100 years ago.

Assuming a rupture area of 60 km by 44 km and an earthquake of $M_w = 7.6$, we divide this area shown in Fig. 1 into 12 segments to fit the

Table 1: Dimension of the fault and source parameters.

	Shallower fault	**Deeper fault**
L	60.0 km	60.0 km
W	6.0 km	38.0 km
D_A	6.0 m	4.0 m
Dip	60°	25°

recent interpretation of the Seattle Fault proposed by Johnson *et al.* (1999). Table 1 shows the dimensions of the fault and source parameters used for the estimate of the seismic deformation. L is the total strike length of the fault, W is downdip width of the fault and D_A is the average fault displacement. We determined dip angles of 25° for the deeper fault plane (≥5.5 km) and 60° for the shallower fault plane (≤5.5 km). The average amount of slip is determined to be 4.27 m, 6 m on the shallower fault and 4 m on the deeper fault. The empirical relationships between moment magnitude M_w, maximum displacement D_M, and average displacement D_A are obtained by Wells and Coppersmith (1994) as (1) and (2). Using these relationships, we obtain the empirical values in terms of D_M and D_A for the earthquake of $M_w = 7.6$ as $D_M = 5.9$ m and $D_A = 2.8$ m. Strike angle of each segment is determined by the inferred structure of Fig. 1.

$$\log D_M = -5.46 + 0.82\ M_w \tag{1}$$

$$\log D_A = -4.80 + 0.69\ M_w \tag{2}$$

Figure 2 shows the computed vertical seismic deformation of the land and sea bottom within the Puget Lowland. The contour intervals are 1 m for uplift (solid line) and 0.5 m for subsidence (dashed line). These static fault displacements are computed by the theory of Okada (1985). The computed seismic uplifts are 4 m at Restoration Point and 4 m at Alki Point, while the geological evidence indicates 7 m at Restoration Point and 4 m at Alki Point. The computed subsidence is 0.2 m at West Point, while the evidence shows 1 m. The computed results are consistent with this evidence, although they are slightly underestimated.

4. Bathymetry and Topography

4.1 Digital elevation data in Puget Sound

For the modeling of tsunamis, we use the digital elevation data which is provided by PRISM (Puget Sound Regional Synthesis Model). The data were compiled from USGS digital elevation models and NOS GODAS Bathymetry. The original grid size is 30 m and the datum for the elevation is based on NAVD29. We focus on an area of (47.2°N, 123.0°W)–(48.0°N, 122.1°W) as a computational domain (see Fig. 1). For the computation of tsunamis within a broad area of Puget Sound, we resampled the original grid to create a 90 m

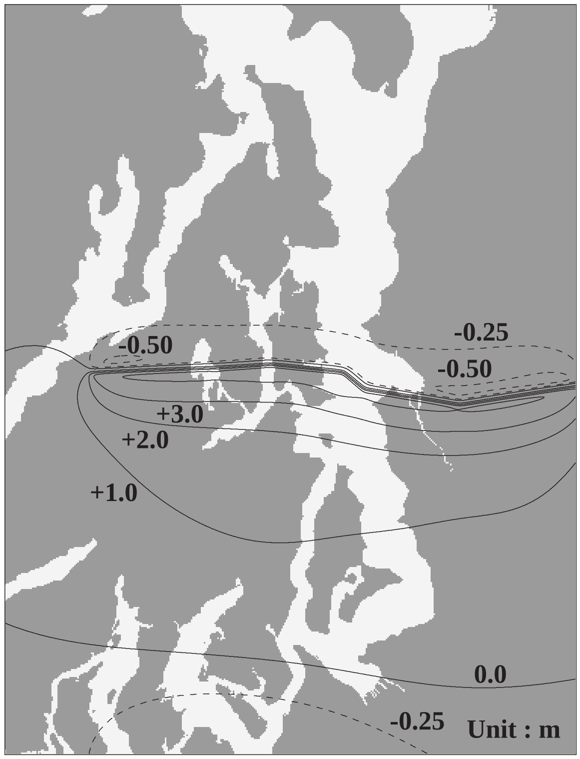

Figure 2: Computed seismic deformation according to the present scenario for the Seattle Fault earthquake about 1100 years ago.

grid. For the inundation modeling within Cultus Bay, we use the original 30 m grid, constructing a nested grid system with 90 m data.

4.2 Reproduction of Holocene sea level

In order to reproduce the tsunami of about 1100 years ago, the present bathy/topo data should be adjusted to that epoch. Eronen *et al.* (1987) collected a core from the northern Puget Lowland and investigated relative sea level change during the past 6000 years. Their results show that the sea level of 1000 years ago was approximately 1 m below its present position. Thus, we assume that the MSL at the time of the earthquake was 1 m below the present value and adjusted the bathy/topo data to it.

5. Numerical Model

We used the TUNAMI-N2 model (Imamura, 1995) for modeling propagation and coastal inundation of tsunamis in Puget Sound. In this model, a set of non-linear shallow water equations with bottom friction term are discretized by the leap-frog finite difference scheme. This model is widely used to simulate tsunami propagation and inundation on a dry land.

We assume that seismic deformation of the sea floor pushes up the overlying water instantaneously and use the feature shown in Fig. 2 as the initial condition for the tsunami inundation modeling.

6. Modeling Results

6.1 Tsunami propagation within Puget Sound

Figure 3 shows the computed tsunami waveforms at Edmonds which is 20 km north of Seattle, the Seattle waterfront (the head of Elliott Bay), Bremerton, and Tacoma. Here, we discuss the tsunami propagation pattern within Puget Sound. Figure 4 shows snapshots of computed tsunamis at three time steps, 5, 10, and 15 min after the generation. As shown in Fig. 4, the tsunami splits and propagates from the source region to the north and south. We should focus on two aspects impacted by the tsunami: Elliott Bay and Sinclair Inlet.

Since Elliott Bay is within the tsunami source region, the tsunami more than 4 m high strikes and inundates the Seattle waterfront areas within 5 min after the earthquake. Also, because of the directivity of tsunami energy from the source, which is evident in Fig. 2, a more than 5 m tsunami strikes the northern shore of Elliott Bay in only 2.5 min.

Another example is tsunamis propagating within Sinclair Inlet, which is located 20 km west of Elliott Bay. We can see the tsunami concentrates toward the southern tip of the inlet. High inundation flows can be expected in this region. Local sea bottom deformation at Bremerton yields more than 2 m uplift of water at the moment of the earthquake, creating a tsunami that recedes rapidly. Note that there is a naval shipyard in Bremerton and the impact on ships or boats are subject to the strong current induced by this tsunami.

6.2 Coastal inundation in the populated region

Next, we discuss coastal inundation in the populated region within central Puget Sound. Figure 5 shows the distribution of maximum inundation depths within the tsunami source region. The gray solid line in the figure indicates the shoreline after the earthquake. Inundation depth is measured from the local ground to the surface of surging water. The dark color indicates high inundation depths. Along the coast of Sinclair Inlet, the tsunami inundates several hundred meters inland from the shoreline with a depth of more than 2 m. Especially, at the southern tip of Sinclair Inlet, the tsunami yields almost 1 km inland inundation from the shore line with a depth of 4 m at the shore. At the northern shore of Dyes Inlet, the inundation flow was also 4 m deep over the Clear Creek delta. These results will help the search for additional geological evidence of this event. The Seattle waterfront area, which is developed along the narrow area of Elliott Bay, experiences inundation depths of 1–2 m.

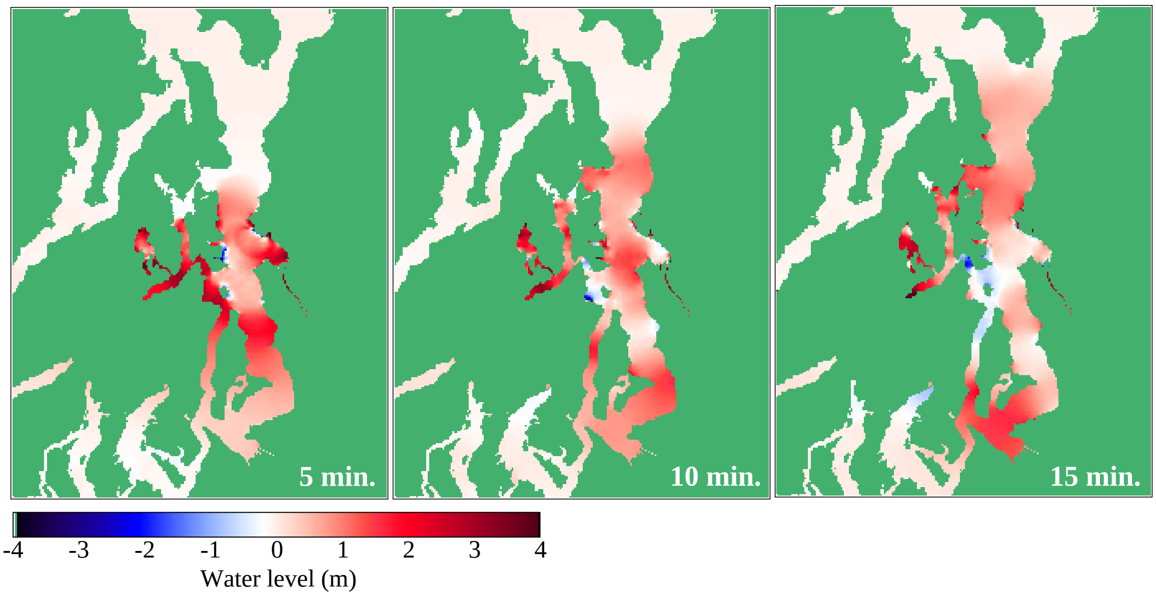

Figure 3: Snapshots of computed tsunamis propagating within Puget Sound.

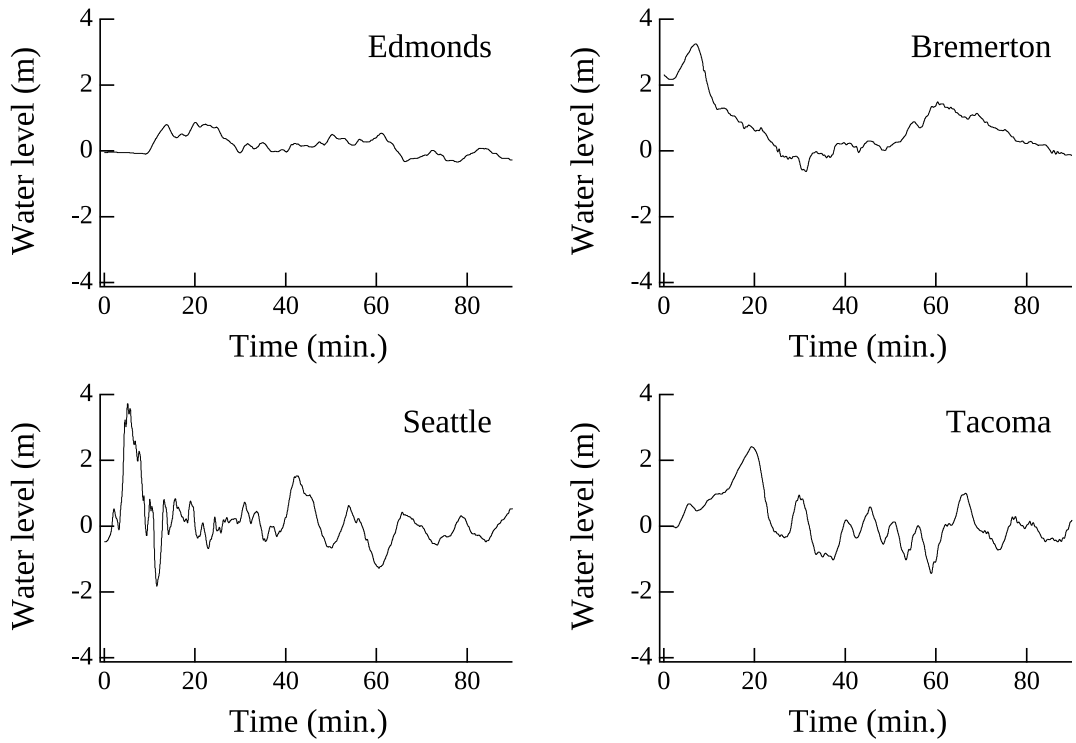

Figure 4: Computed tsunami waveforms at Edmonds, Seattle, Bremerton, and Tacoma.

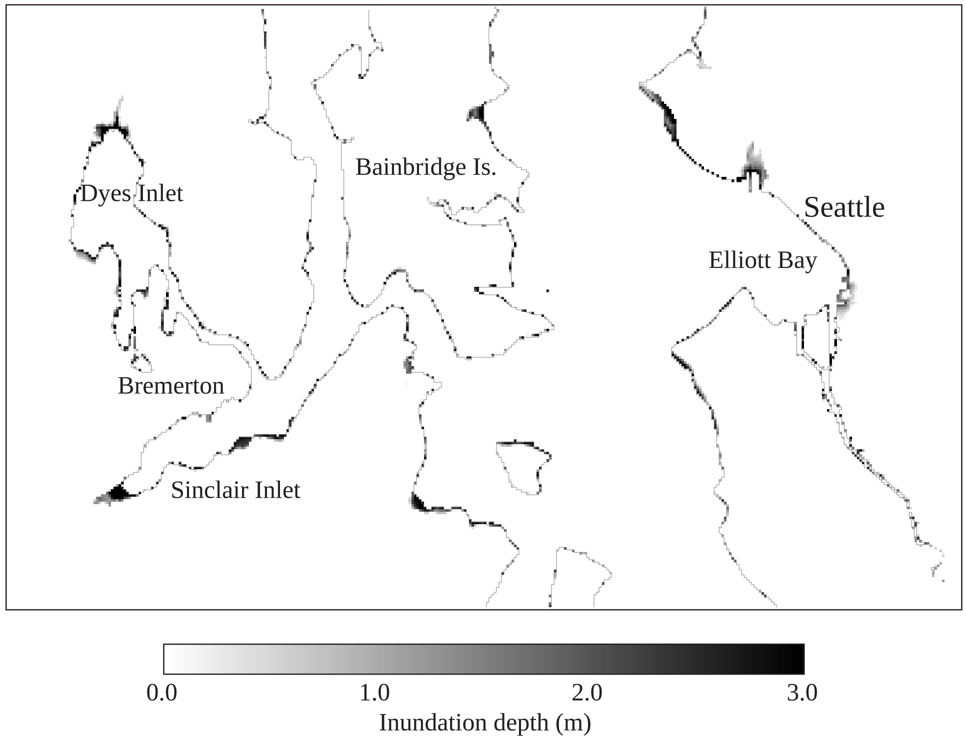

Figure 5: Distribution of maximum inundation depths within the populated region.

6.3 Tsunami run-up process in Cultus Bay

Cultus Bay opens southward at the southern tip of Whidbey Island, 40 km north of Seattle. Figure 6 shows the aerial photo of present day Cultus Bay. Atwater and Moore (1992) excavated an area of 150 m by 300 m, which was centered approximately 800 m inland from the present shoreline of the western head of the bay, and found a tsunami deposit in the historical tidal marsh.

As shown in Fig. 7, we computed the tsunami waveforms at the shoreline of the western head of the bay, just in front of the excavated area (see Fig. 6 for the location of the model site). The inland limit of the tsunami deposit is estimated to be at the level of 4.5 m above the present MLLW, which corresponds to 3.5 m above the 1100 year-old MSL (the present MSL is 2 m above the present MLLW). The results are obtained at two tidal stages. One is the case of mean tide, which is 1 m below the present. Another is the case of high tide (mean high water), 1.3 m above the mean tide level. We estimated the high tide level from the present tidal range within Puget Sound, which is demonstrated as approximately 3 m. The result assuming mean tide is not enough to yield the inundation on the marsh, because the tides could not reach the head of the Bay. However, when the tide is higher and increases the water depth within the bay, we have a situation which makes a tsunami easier to inundate the land. The computed tsunami, assuming high tide, barely reaches the level of the inland limit of tsunami deposit.

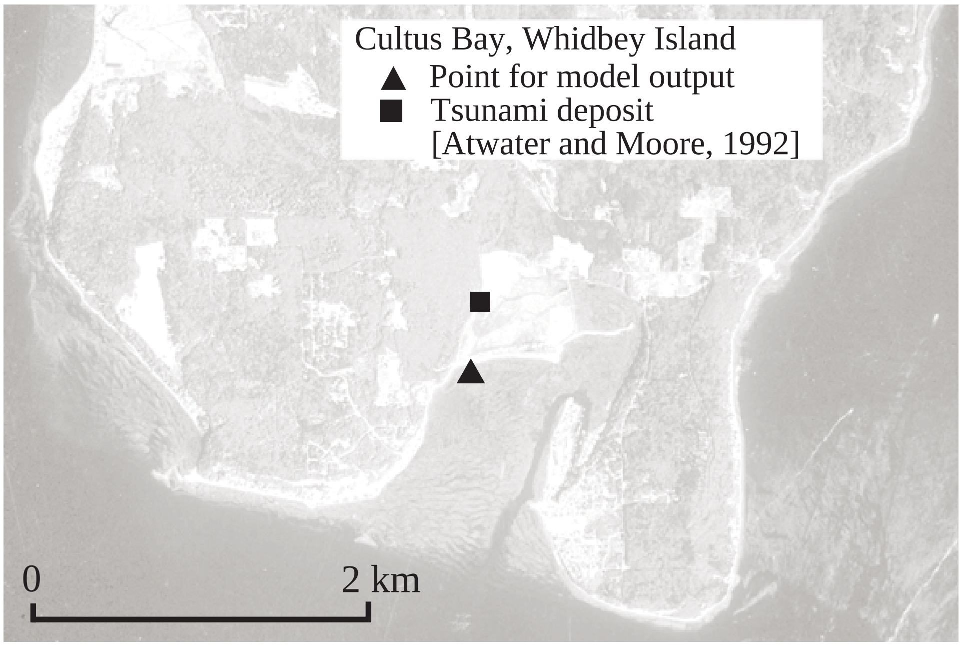

Figure 6: Aerial photo of present Cultus Bay.

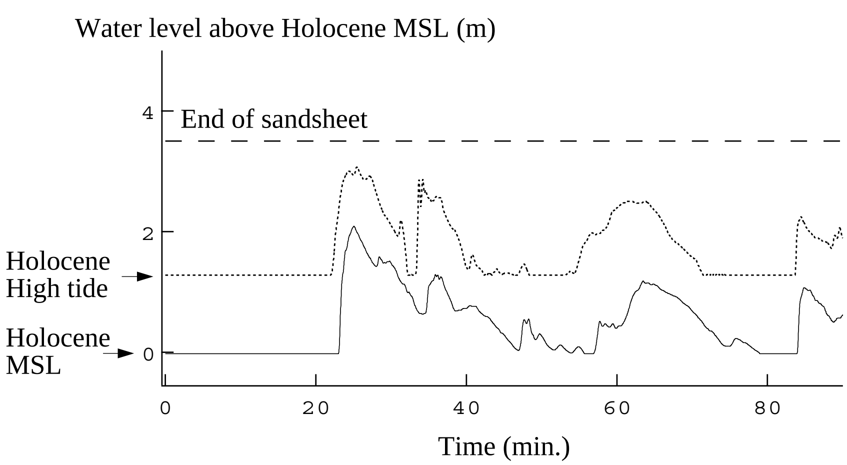

Figure 7: Computed tsunami waveforms at the western head of Cultus Bay.

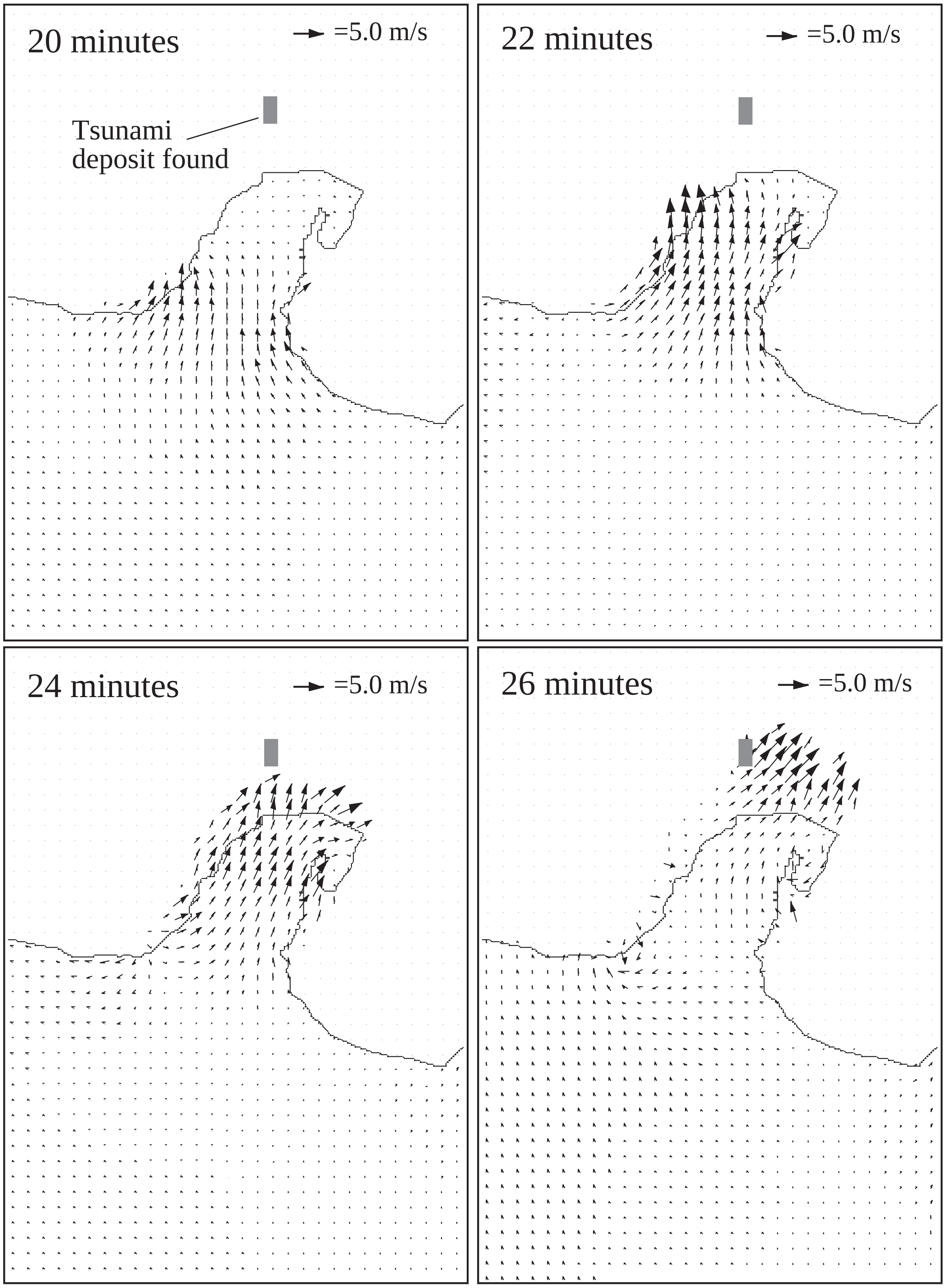

Figure 8: Snapshots of computed current field in Cultus Bay.

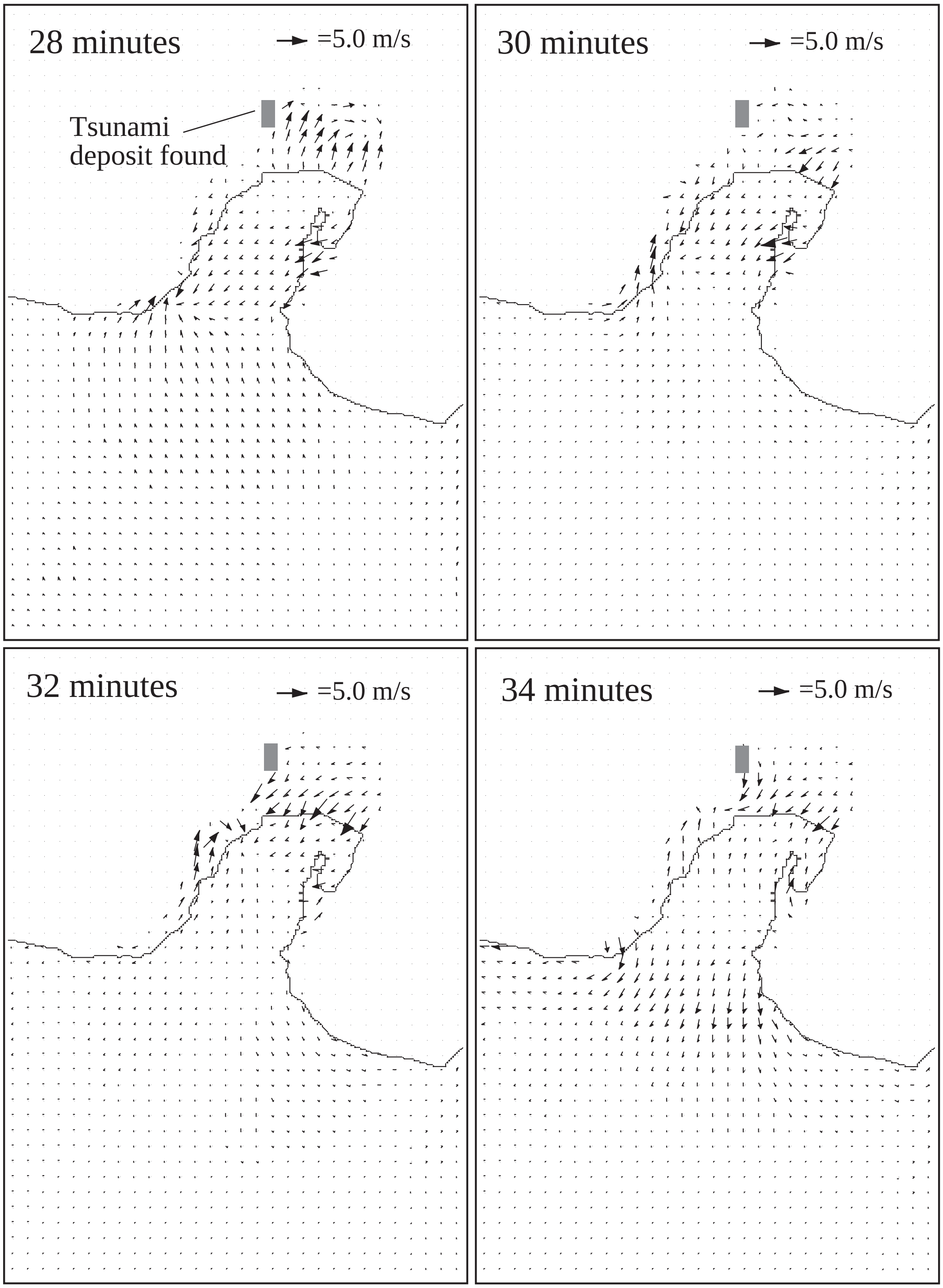

Figure 8: (continued)

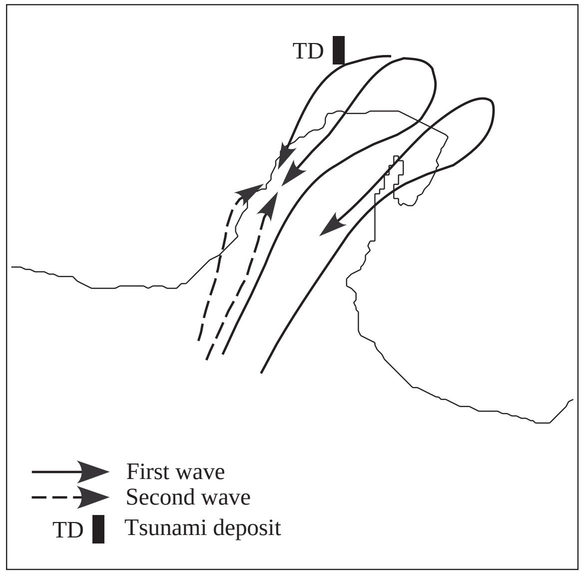

Figure 9: Overview of inundation process at the head of Cultus Bay.

Figure 8 shows snapshots of currents within Cultus Bay at 2-min intervals. The excavated area by Atwater and Moore (1992) is marked in each figure. The results are obtained from the computation assuming the late Holocene high tide. The first wave from the source region reaches the mouth of the bay in 20 minutes, then surges toward the head of the bay. The velocity of tsunami current at the head of Cultus Bay is estimated to be up to 5 m/s. After inundating the tidal marsh, backwash current is shown in the snapshot of 30 min. This backwash current is going south-westward at the south of the area, where a tsunami deposit was found and collides with the second wave at the western head. The flow in the present model does not inundate the excavated area. The present topography of the excavated area is a result of overlying marsh peat above the tsunami deposit, forming a westward slope (Atwater and Moore, 1992). Since the topography data in this model is obtained from the present DEM, this does not well reproduce the late Holocene topography. This is a reason for underestimated inundation within the marsh. Figure 9 shows an overview of tsunami inundation process within Cultus Bay. From these results, we infer that the tsunami surged northward over the marsh, then turned into a backwash current flowing southwestward, which formed the final deposition of sediment on the marsh.

7. Concluding Remarks

We reproduced the tsunami which was generated by the Seattle Fault earthquake about 1100 years ago, using the numerical model for tsunami propagation and inundation. The modeling results show that hazardous inundation can occur through this type of shallow crustal earthquake. The maximum wave heights are estimated to be more than 4 m at Seattle, 3 m at Bremerton, and more than 2 m at Tacoma. Inundation modeling results suggest that the southern tip of Sinclair Inlet and northern tip of Dyes Inlet may contain additional evidence for this event.

We also carried out the inundation modeling at Cultus Bay with high-resolution bathymetry/topography grids and compared the results with the geological evidence obtained by Atwater and Moore (1992). The result, assuming the late Holocene high tide, demonstrates that this tsunami had the potential to deposit the sand at the marsh of Cultus Bay. It can be inferred that the southwestward current at the western head of the bay formed the final deposition of sediment on the marsh.

Acknowledgments. We thank David Finlayson of the University of Washington and scientists working on PRISM for their efforts in creating high resolution bathymetry and topography data of Puget Sound.

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