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著者	Koshimura Shunichi, Mofjeld Harold O., Gonzalez Frank I., Moore Andrew L.
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Modeling the 1100 bp paleotsunami in Puget Sound, Washington

Shunichi Koshimura
Disaster Reduction and Human Renovation Institution, Kobe, Japan

Harold O. Mofjeld and Frank I. González
NOAA/Pacific Marine Environmental Laboratory, Seattle, Washington, USA

Andrew L. Moore
Department of Geology, Kent State University, Kent, Ohio, USA

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[1] Recent paleoseismic and geologic studies indicate that a tsunami occurred 1100 years ago in Puget Sound. This study aims to reproduce and validate the model tsunami, using a finite difference model based on nonlinear shallow water theory and abathymetry/topography computational grid that takes into account the 1-meter rise in sea level that has occurred in the region during the past 1100 years. Estimates of tsunami height, the extent of inundation, and the current velocity pattern are provided at the northern head of Cultus Bay, Whidbey Island, where paleotsunami sand deposits have been found. The model demonstrates that a tsunami generated when the background water level was at mean high water or above could have surged across the then-existing coastal marsh, penetrated the full length of the shallow bay, and deposited the observed sand layers. *INDEX TERMS:* 4564 Oceanography: Physical: Tsunamis and storm surges; 4255 Oceanography: General: Numerical modeling; 7221 Seismology: Paleoseismology; 4560 Oceanography: Physical: Surface waves and tides (1255); 9350 Information Related to Geographic Region: North America. **Citation:** Koshimura, S., H. O. Mofjeld, F. I. González, and A. L. Moore, Modeling the 1100 bp paleotsunami in Puget Sound, Washington, *Geophys. Res. Lett.*, *29*(20), 1948, doi:10.1029/2002GL015170, 2002.

1. Introduction

[2] Paleoseismic studies in the Puget Lowland of Western Washington State demonstrate that a strong shallow crustal earthquake occurred in this region about 1100 years ago. This earthquake occurred on the Seattle Fault, a zone of thrust or reverse faults that cross Puget Sound between Seattle and Bremerton [*Johnson et al.*, 1999] with a magnitude estimated at 7 or larger [*Bucknam et al.*, 1992]. Based on the distribution of exposed bedrock 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 abrupt uplift and subsidence occurred main lyat Restoration Point (7 m), Alki Point (4 m), and West Point (−1 m), and no surface displacement was observed at Winslow.

[3] A tsunami in Puget Sound is believed to have accompanied this earthquake. *Atwater and Moore* [1992] have interpreted sandlayers found at West Point and Cultus Bay as tsunami deposits. This evidence was especially well-preserved at Cultus Bay, which opens southward at the southern end of Whidbey Island, 40 km northof Seattle. *Holmes and Dinkelman* [1993] and *Walters and Takagi* [1996] have simulated this tsunami using numerical models-with coarse grid bathymetry (500 m and 200–1000 m, respectively).Each used a model without inundation on land and highly simplified d is placement models for the 1100 bp earthquake. *Walters and Takagi* [1996] found that a significant tsunami would reach Cultus Bay 20 minutes after the earthquake, while *Holmes and Dinkelman* [1993] found maximum wave heights in their model of 6 m at West Point, Seattle, and 2–5 m at Cultus Bay. However, the limitations of these models lead to the conclusion that the details of the tsunami's generation and the inundation at Cultus Bay are still not well determined. These shortcomings are addressed in the present study, and we provide improved estimates of tsunami height, the extent of the inundation zone and current velocity patterns for sites where geological evidence was found. We also place limits on what the background tide and sea level must have been during the tsunami.

2. Geological Evidence for the Tsunami

[4] According to *Atwater and Moore* [1992], the tsunami deposited a sand sheet 1 to 15 cm thick within a prehistoric coastal marsh at the northwestern head of Cultus Bay. The deposit rises from east to west through an area of approximately 150 m by 300 m, which was sampled by numerous auger borings and observations recorded in existing trenches, and the deposit finally pinches out 3.9 m above present mean lower low water, i.e., 1.9 m above present mean sea level (MSL). This means that the tsunami surged up at least to this level 1100 years ago. *Atwater and Moore* [1992] reported that the grain size of the sand observed along the line of auger borings at Cultus Bay varies from 0.09 to 0.07 mm. *Atwater and Moore* [1992] found that the sand fines from east to west and concluded that a westward current during the run-up produced the sand deposit. In over 200 meters of continuous exposure, the lack of sedimentary structures associated with bed load suggests that the sand was carried in suspension by the tsunami and the lack of multiple graded beds suggests that the sand sheet was deposited in a single pulse of sedimentation.

3. Earthquake Scenario

[5] Based on seismic reflection data, *Pratt et al.* [1997] interpreted the Seattle Fault as a thrust fault dipping south-

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Table 1. Dimension of the Fault and Source Parameters for the Present Scenario

Shallow Segments (≤5.5 km)				Deep Segments (≥5.5 km)			
n	L (km)	W (km)	D (m)	n	L (km)	W (km)	D (m)
1	15.2	6.0	4.0	1	15.2	38.0	2.0
2	6.3	6.0	6.0	2	6.3	38.0	4.0
3	8.9	6.0	8.0	3	8.9	38.0	6.0
4	3.2	6.0	8.0	4	3.2	38.0	6.0
5	11.5	6.0	6.0	5	11.5	38.0	4.0
6	14.9	6.0	4.0	6	14.9	38.0	2.0

n indicates the index of fault segments, which increases from west to east along the strike direction. L is the strike length of each fault segment, W is the downdip width, and D is the fault displacement.

ward at an angle of about 20° steepening to 45° near the surface, within a total rupture area of 4420 km^2, and concluded that the fault could generate a M_w =7.6 to 7.7 earthquake. Details of the rupture that occurred 1100 years ago are uncertain; therefore, we modified the hypothesis of *Pratt et al.* [1997] to develop a scenario that provided a reasonable match to coseismic displacement estimates based on geologic evidence. Thus, we divided the fault rupture area into 12 segments, according to the structure inferred by *Pratt et al.* [1997] and *Johnson et al.* [1999]. Six segments form the shallow (≤5.5 km) and steeper-dipping (60°) portion of the fault, while six segments directly underneath these form the deeper (≥5.5 km)and less-steeply dipping (25°) portion.

[6] The total length of the fault (Table 1) is 60 km with a combined width of 44 km. Values of D, the sub-surface slip on each segment, were adjusted to provide computed surface displacements [*Okada*, 1985] that are reasonably consistent with those inferred from the geological evidence. The computed uplifts (Figure 1) are 5.3 m at Restoration Point and 4.2 m at Alki Point, in reasonable agreement with geological evidence of 7 m and 4 m uplift, respectively. The computed subsidence at West Point is only 0.22 m, slightly less than the observed 1 m value.

[7] The resulting total seismic moment for this seismic source model is calculated to be $M_0 = 2.91 \times 10^{20}$ Nm from Equation (1), where μ is the shear modulus equal to 3.0×10^{10} N/m^2. This value corresponds to an earthquake of magnitude M_w = 7.6, as given by the relationship of Equation (2) [*Kanamori*, 1977]. The average amount of sub-surface fault displacement D_A is 3.67 m, and is compatible with the empirical relationship between the magnitude and the fault displacement obtained by *Wells and Coppersmith* [1994].

$$M_0 = \sum_{k=1}^{12} \mu W_k L_k D_k \qquad (1)$$

$$1.5M_w = \log M_0 - 9.1 \qquad (2)$$

4. Numerical Model

[8] We use the TUNAMI-N2 model [*Imamura*, 1996] to simulate the tsunami propagation and coastal inundation in Puget Sound. This model is based on a set of non-linear shallow water equations with bottom friction in the form of Manning's formula, with coefficient n = 0.025; the equations are discretized by the leap-frog finite difference scheme applied over the computational domain shown in Figure 1 (b), with corner coordinates (47.2°N, 123.0°W) and (48.0°N, 122.1°W). As the initial condition, we assume instantaneous displacement of the sea surface identical to the vertical sea floor displacement shown in Figure 1 (b).

[9] The digital bathymetry/topography data were provided by the PRISM (Puget Sound Regional Synthesis Model) Program [*Finlayson et al.*, 2001], which compiled the data from USGS digital elevation models and NOS GODAS bathymetry. The original grid spacing of this data is 30 m, and the datum for the elevation is based on NGVD29. We retained 30 m spacing in the smaller rectangle enclosing Cultus Bay (Figure 1 (b)) but decimated the rest of the grid to a coarser 90 m spacing.

[10] *Eronen et al.* [1987] collected a core from the northern Puget Lowland and investigated relative sea level change during the past 6000 years. Their result shows that

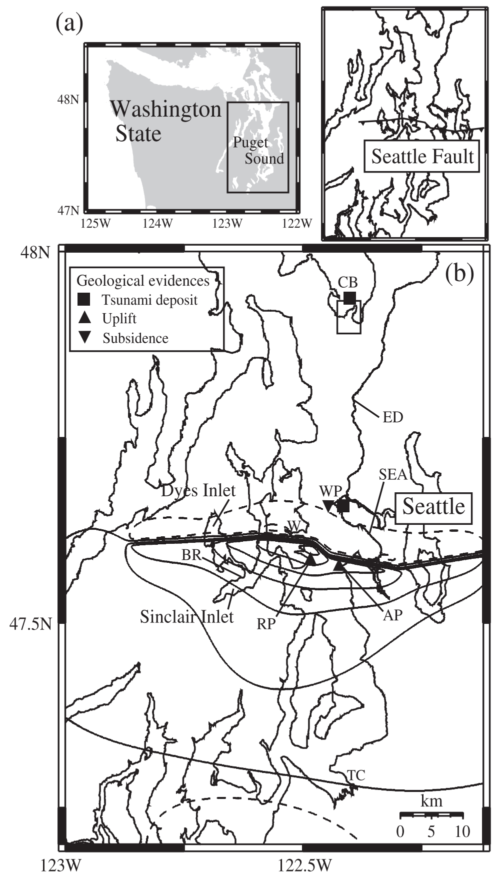

Figure 1. (a) Inferred structure of the Seattle Fault [*Johnson et al.*, 1999]. (b) Computed coseismic deformation of the earthquake about 1100 years ago. The contour intervals are 1 m for uplift (solid line) and 0.25 m for subsidence (dashed line). Abbreviations as follows: CB = Cultus Bay, ED = Edmonds, SEA = Seattle Waterfront, WP = West Point, W = Winslow, AP = Alki Point, RP = Restoration Point, BR = Bremerton and TC = Tacoma. The square at Cultus Bay indicates the computational domain with high resolution data (30 m grid).

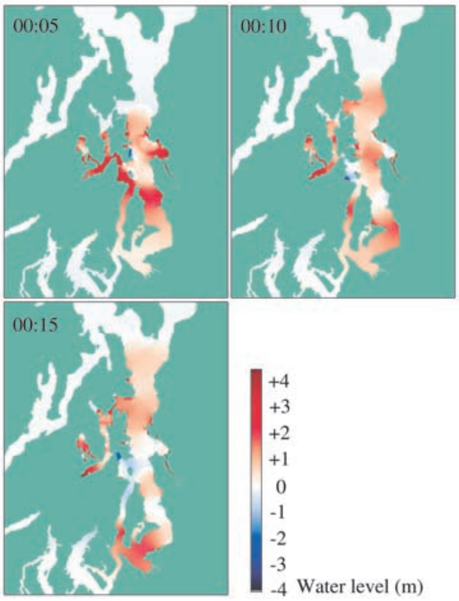

Figure 2. Snapshots of computed tsunamis propagating within central Puget Sound at 5-minute intervals.

1000 bp sea level was approximately 1 m below its present position. Thus we assume that mean sea level (MSL) at the time of the earthquake was 1 m below the present value, relative to the land, and have adjusted the bathymetry/topography grid accordingly. The tidal range within Puget Sound is approximately 3 m and mean high water (MHW) is 1.2 m above MSL in the vicinity of Cultus Bay [*NOS*, 2001]. The effect of these changes in background water level can be significant; therefore, two separate model simulations were conducted for tide stages corresponding to MSL and MHW.

5. Results and Discussion

[11] The background water level is Late Holocene MSL. As shown in the Figure 2, the tsunami propagates toward both north and south from the source region. Figure 3 illustrates the computed tsunami waveforms at Edmonds, the Seattle Waterfront, Bremerton and Tacoma. Since the Seattle Waterfront is within the tsunami source region, a tsunami more than 3 m high strikes and inundates this area within 3 minutes after the earthquake, with clear potential to cause significant damage.

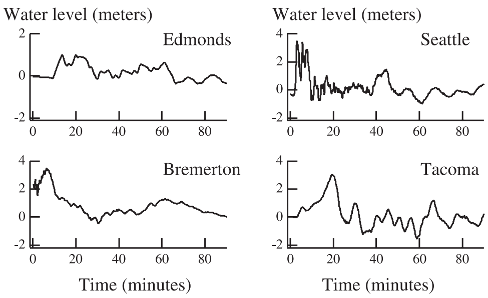

Figure 3. Computed tsunami waveforms at Edmonds, Seattle, Bremerton, and Tacoma. See Figure 1 for the locations of these sites in Puget Sound.

[12] Figure 4 shows the maximum extent of tsunami inundation and the time series of water levels for MSL and MHW. With the background water level at MSL, the tsunami could not reach the marsh at the head of Cultus Bay to deposit a substantial sand layer. At MHW, however, the tsunami inundation reaches the level of the observed deposit. Figure 5 shows snapshots of the computed current velocity patterns within Cultus Bay at 2-minute intervals, when the background water level is set to MHW. The first wave reaches the mouth of the bay in 20 minutes, then surges northward toward the head of the bay. The tsunami current velocity at the head of the bay is estimated to be more than 3 m/s. *Southard and Boguchwal* [1990] showed that the sand with 0.1 to 0.14 mm diameter would be suspended at 80–90 cm/s flow for the flow depth of 1 m. The water depth at the bottom of Cultus Bay is approximately 1–2 m. Thus it is likely that the sand on the bottom of the shallow swash zone of Cultus Bay could be easily suspended by the modeled current to be deposited on the marsh.

[13] The inundation simulated in the present model does not extend across the full tsunami deposit area excavated by *Atwater and Moore* [1992]. One possible reason is that the topography and near shore bathymetry used in the present model are based on recent surveys that may not accurately

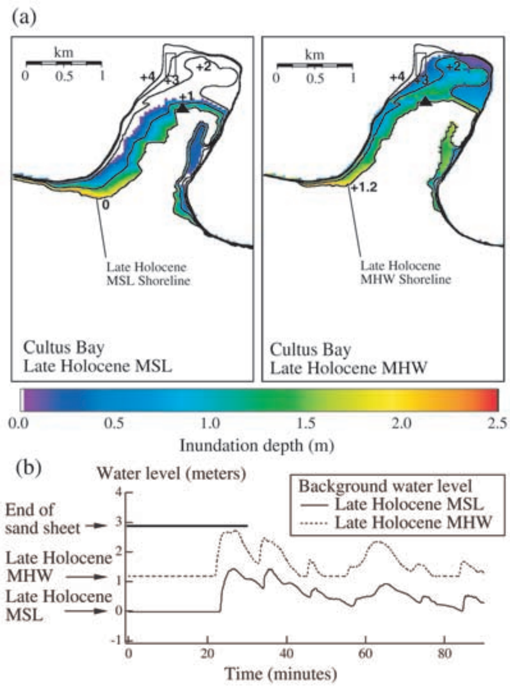

Figure 4. (a) Extent of computed tsunami inundation zone within Cultus Bay based on each background water level. Solid line in each figure is the contour of land elevation in meter, including the shoreline at each tidal stage. The datum of the contours is Late Holocene (1100 bp) MSL. The square indicates the excavated area for tsunami deposit by *Atwater and Moore* [1992]. Black triangle is the point to output the computed tsunami waveforms. (b) Computed tsunami waveforms at the western head of Cultus Bay.

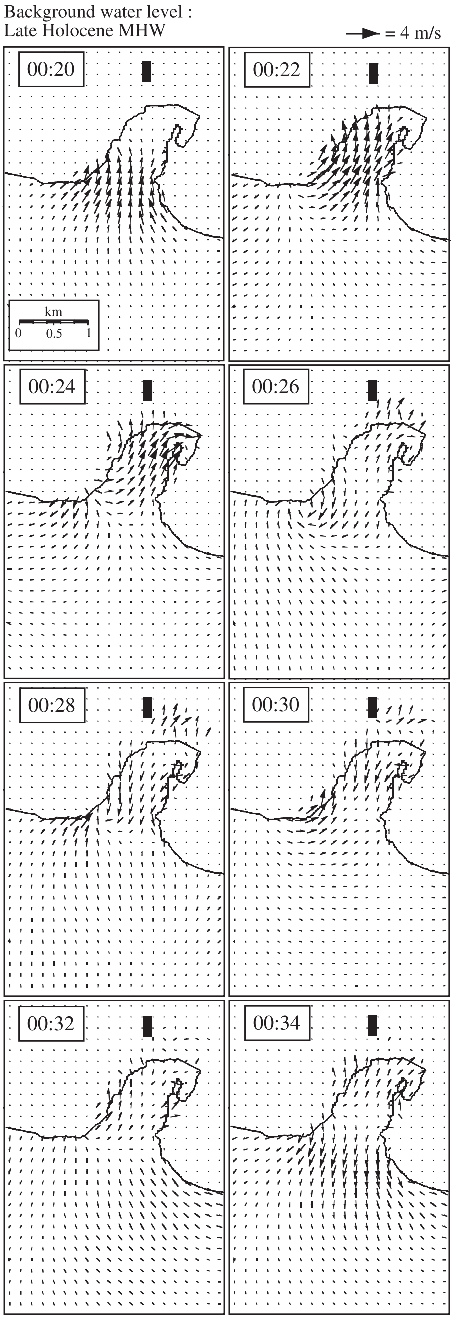

Figure 5. Snapshots of computed current velocity patterns within Cultus Bay at 2 minute intervals. Black square is the area excavated by *Atwater and Moore* [1992] that contained the tsunami deposit.

reflect conditions 1100 years ago. For example, a west-trending upward slope has been created in the excavated area by peat layers over the tsunami sand deposits since the time of the earthquake [*Atwater and Moore*, 1992]. This post tsunami peat layer was not removed from the topography data in the present model, and may therefore prevent the modeled tsunami from penetrating farther westward across the excavated area, as the actual tsunami may have done so. However, we feel the results support their interpretation of the event, given the inherent uncertainties, and conclude that a tsunami could have been generated by the 1100 bp Puget Sound earthquake at a tidal stage at or above MHW, and could have subsequently penetrated the coastal marsh at the head of Cultus Bay and deposited the observed sand layers. This study also suggests that further tsunami modeling studies using shallow crustal faults as the source scenarios may spread additional light on the tsunami hazard in Puget Sound.

[14] **Acknowledgments.** We thank David Finlayson of University of Washington for his effort in the creation of a high resolution Puget Sound bathymetry and topography database. The study was funded in part by the U.S. National Tsunami Hazard Mitigation Program to develop tsunami inundation maps for at-risk U.S. coastal communities. Preliminary results of this study were presented at ITS 2001. PMEL Contribution 2444.

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S. Koshimura, Disaster Reduction and Human Renovation Institution, 1-5-2 Wakinohama Kaigan-Dori, Chuo-Ku, Kobe 651-0073, Japan. (koshimuras@dri.ne.jp)

H. O. Mofjeld and F. I. González, NOAA/Pacific Marine Environmental Laboratory, 7600 Sand Point Way NE, Seattle, WA 98115-6349, USA. (mofjeld@pmel.noaa.gov; gonzalez@pmel.noaa.gov)

A. L. Moore, Department of Geology, Kent State University, Kent, OH 44242, USA. (amoore5@kent.edu)