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NOAA TIME Center
Pacific Marine Environmental Laboratory
Seattle, Washington

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Tsunami Hazard Map of the Anacortes–Whidbey Island Area, Washington: Modeled Tsunami Inundation from a Cascadia Subduction Zone Earthquake

by

Timothy J. Walsh[1], Vasily V. Titov[2], Angie J. Venturato[2], Harold O. Mofjeld[2], and Frank I. Gonzalez[2]

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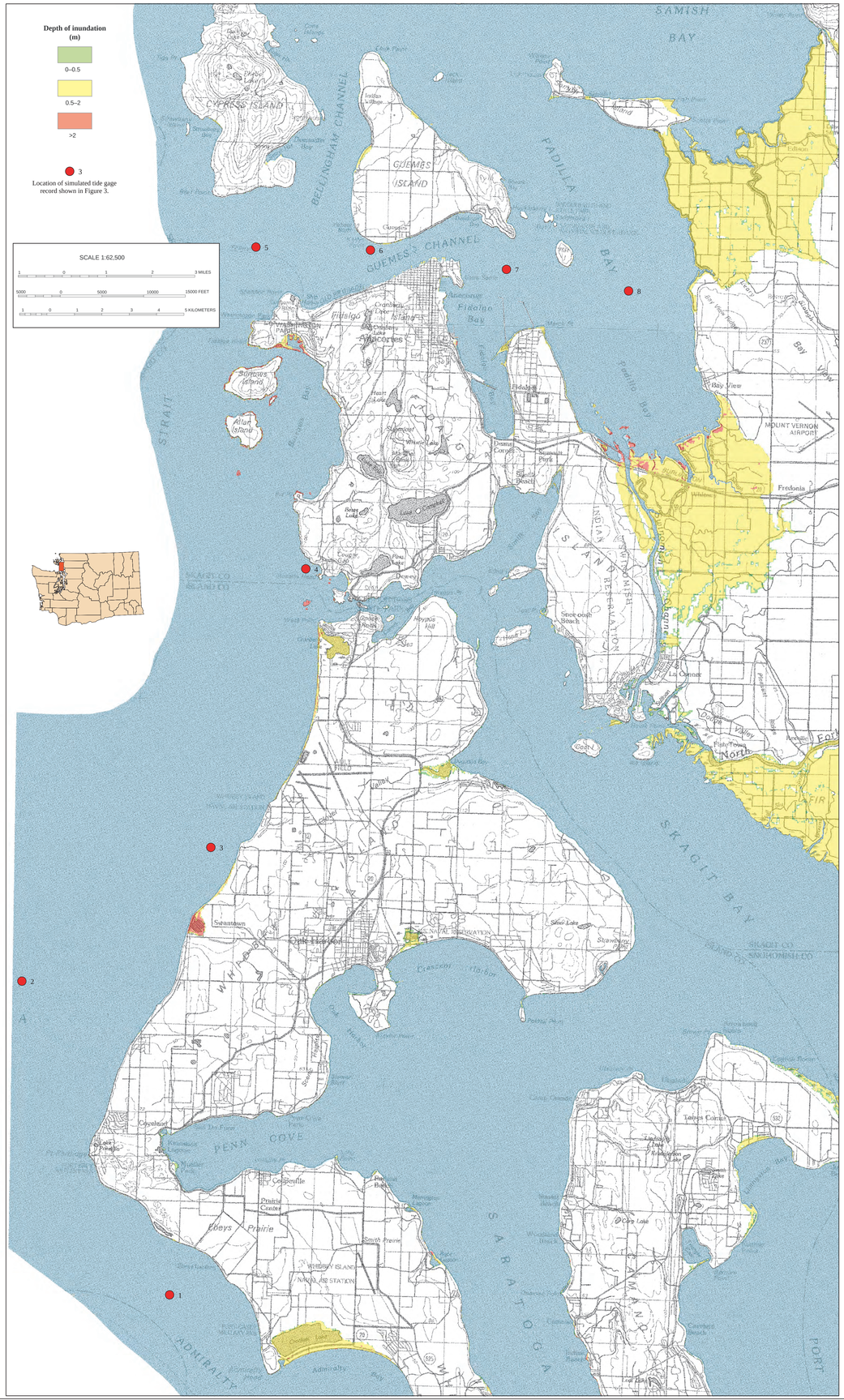
[1] Washington Division of Geology and Earth Resources, PO Box 47007, Olympia, WA 98504-7007, tim.walsh@wadnr.gov
[2] National Oceanic and Atmospheric Administration, Pacific Marine Environmental Laboratory, 7600 Sand Point Way NE, Seattle, WA 98115-6349
Vasily.Titov@noaa.gov, Angie.J.Venturato@noaa.gov, Harold.Mofjeld@noaa.gov, Frank.I.Gonzalez@noaa.gov



INTRODUCTION

In 1995, Congress directed the National Oceanic and Atmospheric Administration (NOAA) to develop a plan to protect the West Coast from locally generated tsunamis. 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 the plan and submitted it to Congress, which created the National Tsunami Hazard Mitigation Program (NTHMP) in October of 1996. The National Tsunami Hazard Mitigation Program is designed to reduce the impact of tsunamis through warning guidance, hazard assessment, and mitigation. A key component of the hazard assessment for tsunamis is delineation of areas subject to tsunami inundation. Since local tsunami waves may reach nearby coastal communities within minutes of the earthquake, there will be little or no time to issue formal warnings. Consequently, evacuation areas and routes need to be planned well in advance.

This map is one of a series of tsunami inundation maps produced by the Washington Department of Natural Resources, Division of Geology and Earth Resources, in cooperation with the Washington Emergency Management Division as a contribution of the National Tsunami Hazard Mitigation Program (Walsh and others, 2004; 2003a,b,c; 2002a,b; 2000). These maps are produced using computer models of earthquake-generated tsunamis from nearby seismic sources. The modeling for this map for a scenario earthquake on the Cascadia subduction zone was done by the Center for the Tsunami Inundation Mapping Efforts (TIME) at NOAA's Pacific Marine Environmental Laboratory in Seattle.

CASCADIA SUBDUCTION ZONE

Recent research about the occurrence of great earthquakes off the Washington, Oregon, and northern California coastlines and resulting tsunamis (Atwater, 1992; Atwater and others, 1995) has led to concern about locally generated tsunamis that will leave little time for response. Numerous workers have found geologic evidence of tsunami deposits attributed to the Cascadia subduction zone (CSZ) in at least 59 localities from northern California to southern Vancouver Island (Peters and others, 2003). While most of these are on the outer coast, inferred tsunami deposits have been identified as far east as Discovery Bay, just west of Port Townsend (Williams and others, 2002), and on the west shore of Whidbey Island (Williams and Hutchison, 2000). Heaton and Snavely (1985) report that Makah stories may reflect a tsunami washing through Waatch Prairie near Cape Flattery, and Ludwin (2002) has found additional stories from native peoples up and down the coast that appear to corroborate this interpretation and also include apparent references to associated strong ground shaking.

Additionally, correlation of the timing of the last CSZ earthquake by high-resolution dendrochronology (Jacoby and others, 1997; Yamaguchi and others, 1997) to Japanese historical records of a distant-source tsunami (Satake and others, 1996) demonstrate that it almost certainly came from the CSZ. This tsunami may have lasted as much as 20 hours in Japan and caused a shipwreck about 100 km north of Tokyo in A.D. 1700 (Atwater and Satake, 2003).

The frequency of occurrence of Cascadia subduction zone earthquakes ranges from a few centuries to a millennium, averaging about 500 to 540 years (Atwater and Hemphill-Haley, 1997). It is believed that the last earthquake on the Cascadia subduction zone was about magnitude (M_w) 9 (Satake and others, 1996, 2003). It is not known, however, if that is a characteristic magnitude for this fault.

INUNDATION MODELING

The tsunami inundation is based on a computer model of waves generated by a scenario earthquake. The earthquake scenario adopted for this study was developed by Priest and others (1997) and designated Scenario 1A (also see Myers and others, 1999). It was one of a number scenarios they compared to paleoseismic data and was found to be the best fit for the A.D. 1700 event. This scenario has been the basis for tsunami inundation modeling for the other maps produced by the NTHMP in both Oregon and Washington, based on a CSZ event. The land surface along the coast is modeled to subside during ground shaking by about 1 to 2 meters (Fig. 1), which is consistent with some paleoseismologic investigations and also matches thermal constraints of Hyndman and Wang (1993). This earthquake is a magnitude (M_w) 9.1 event with a rupture length of 1050 km and a rupture width of 70 km. Satake and others (2003) have recently calculated a very similar magnitude and rupture dimension from an inversion of tsunami wave data from the A.D. 1700 event.

The model used is the finite difference model of Titov and Synolakis (1998), also known as the Method of Splitting Tsunami (MOST) model (Titov and Gonzalez, 1997). It uses a grid of topographic and bathymetric elevations and calculates a wave elevation and velocity at each grid point at specified time intervals to simulate the generation, propagation, and inundation of tsunamis down the Strait of Juan de Fuca and into the Anacortes–Whidbey Island area. Details of the topographic and bathymetric data are in Venturato and others (in press).

These models do not include potential tsunamis from landslides or nearby crustal faults, which are generally not well enough understood to be modeled. Apparently locally generated tsunami deposits have been found on Whidbey Island (Williams and Hutchinson, 2000; Atwater and Moore, 1992); in Discovery Bay, southwest of Port Townsend (Williams and others, 2002); in the Snohomish delta near Everett (Bourgeois and Johnson, 2001); and at West Point near Seattle (Atwater and Moore, 1992). Gonzalez (2003) summarizes the evidence for tsunamis generated within the Puget Lowland by local earthquakes and landslides and estimates their probabilities.

RESULTS

The computed tsunami inundation is shown on the map in three color-coded depth ranges: 0–0.5 m, 0.5–2 m, and greater than 2 m. These depth ranges were chosen because they are approximately knee-high or less, knee-high to head-high, and more than head-high and so approximately represent the degree of hazard for life safety. The greatest tsunami flooding is expected to occur at Swantown Marsh on Whidbey Island and on the southern shores of Padilla Bay. Elsewhere, tsunami flooding is expected only in the immediate vicinity of the shoreline where evacuation to higher ground would be an easy matter. Large areas of inundation occur in areas of low topography surrounding Samish Bay, Padilla Bay, and the Swinomish Channel. Though not part of the modeling study, inundation also occurs within the vicinity of Fir Island. These areas are protected by dikes that were not resolved in the grid used for the modeling, but the height of the dikes suggests they would be overtopped by the modeled tsunami and so inundation shown there is probably appropriate (Venturato and others, 2004).

Current velocities (Fig. 2) are shown in three zones—less than 1.5 m/s (~3 mph), which is the current speed at which it would be difficult to stand; 1.5–5 m/s, and greater than 5 m/s, which is a modest running pace. Within this zone, computed velocities locally exceed 20 m/s (~40 mph) in confined channels.

Figure 3 shows simulated tide gage records at eight locations. These records show fluctuations of water surface elevation and also the time history of the waves. The initial water disturbance is a trough or drop in sea level of about a meter at about 1½ hours after the earthquake at the westernmost end of Whidbey Island and about half an hour later in the narrow channels to the north. The first crest or rise in sea level arrives between 2 and 2½ hours after the earthquake, again earlier at Whidbey Island and later in Bellingham and Guemes Channels and at Padilla Bay. At about 2½ hours after the earthquake, another trough of about a meter occurs in the south, but water piles up in Padilla Bay and the crest remains for two cycles, indicating a prolonged period of flooding. This is visually displayed in Figure 4, which shows screen shots of an animation of the tsunami troughs and crests coming eastward in the Strait of Juan de Fuca into the Fidalgo and Whidbey Island area.

LIMITATIONS OF THE MAP

Because the nature of the tsunami depends on the initial seafloor deformation caused by the earthquake, which is poorly understood, the largest source of uncertainty is the input earthquake. The earthquake scenario used in this modeling was selected for consistency with the paleoseismic and historical constraints, but the next CSZ earthquake may be substantially different.

Another significant limitation is that the resolution of the modeling is no greater or more accurate than the bathymetric and topographic data used. Topographic mapping with a 10-ft contour was available from the City of Anacortes, but elsewhere 10-m DEMs, which are interpolated from 20-ft contour data, were used.

The model run is referenced to mean high water and does not include the influences of changes in tides. The tide stage and tidal currents can amplify or reduce the impact of a tsunami on a specific community. In Padilla Bay, the mean spring tide range is about 8½ ft and can be as much as about 13 ft (NOAA, accessed at http://co-ops.nos.noaa.gov/co-ops.html, July 28, 2004). 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.

ACKNOWLEDGMENTS

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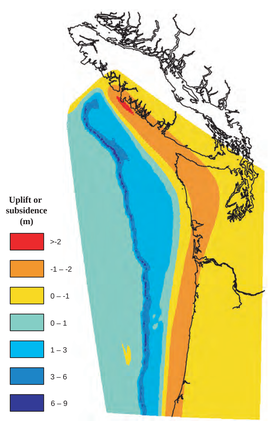

Figure 1. Map of uplift and subsidence for earthquake scenario (1A) used to model the initial condition for the tsunami simulation.

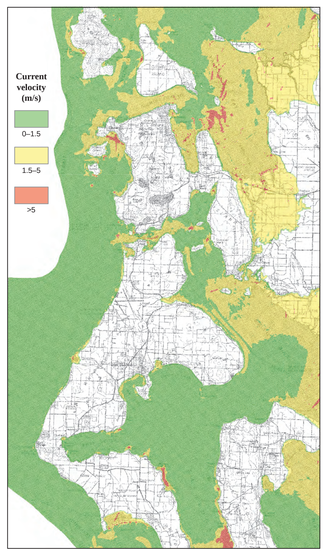

Figure 2. Computed current velocity zones. Note that velocities are highest along the shoreline and in narrow channels. One m/s is about 2.2 mph.

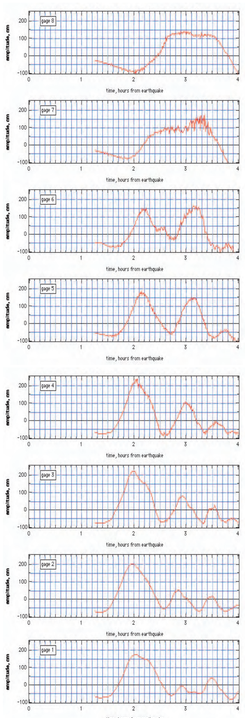

Figure 3. Time histories (simulated tide gages) at eight locations noted on map. Note that the first wave crest is not projected to reach the area until about 2 hours after the earthquake.

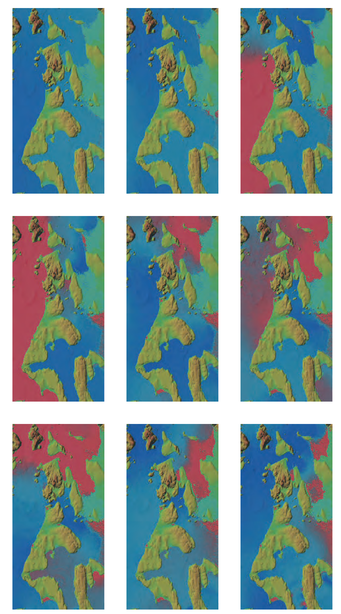

Figure 4. Screen shots of animation of tsunami arriving in the Anacortes–Whidbey Island area. Red areas are crests, blue are troughs. From left to right and top to bottom, frames shown are taken at 20-minute intervals from the time the tsunami arrives in the area at about 2 hours and 15 minutes after the scenario earthquake until the second crest has receded from Whidbey Island nearly 4 hours after the earthquake.

The phenomenon we call "tsunami" (soo-NAH-mee) is a series of traveling ocean waves of extremely long length generated primarily by earthquakes occurring below or near the ocean floor. Underwater volcanic eruptions and landslides can also generate tsunamis. In the deep ocean, the tsunami waves propagate across the deep ocean with a speed exceeding 800 km/hr (~500 mi/hr), and a wave height of only a few tens of centimeters (1 ft) or less. Tsunami waves are distinguished from ordinary ocean waves by their great length between wave crests, often exceeding a 100 km (60 mi) or more in the deep ocean, and by the time between these crests, ranging from 10 minutes to an hour.

As they reach the shallow waters of the coast, the waves slow down and the water can pile up into a wall of destruction tens of meters (30 ft) or more in height. The effect can be amplified where a bay, harbor or lagoon funnels the wave as it moves inland. Large tsunamis have been known to rise over 30 m (100 ft). Even a tsunami 3 to 6 m high can be very destructive and cause many deaths and injuries.

From *Tsunamis—The Great Waves*
by the U.S. Department of Commerce,
National Oceanic and Atmospheric Administration,
National Weather Service,
Intergovernmental Oceanographic Commission,
and International Tsunami Information Center

Accessed at www.prh.noaa.gov/pr/hq/library/pubs/great_waves/great_waves_en_2002.pdf on 7/27/04