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WASHINGTON DIVISION OF GEOLOGY AND EARTH RESOURCES
OPEN FILE REPORT 2014-03
Tsunami Hazard Map of Everett, Washington
December 2014

Tsunami Hazard Map of Everett, Washington:
Model Results for Magnitude 7.3 and 6.7 Seattle Fault Earthquakes

by

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M_W 7.3

Modeled Inundation

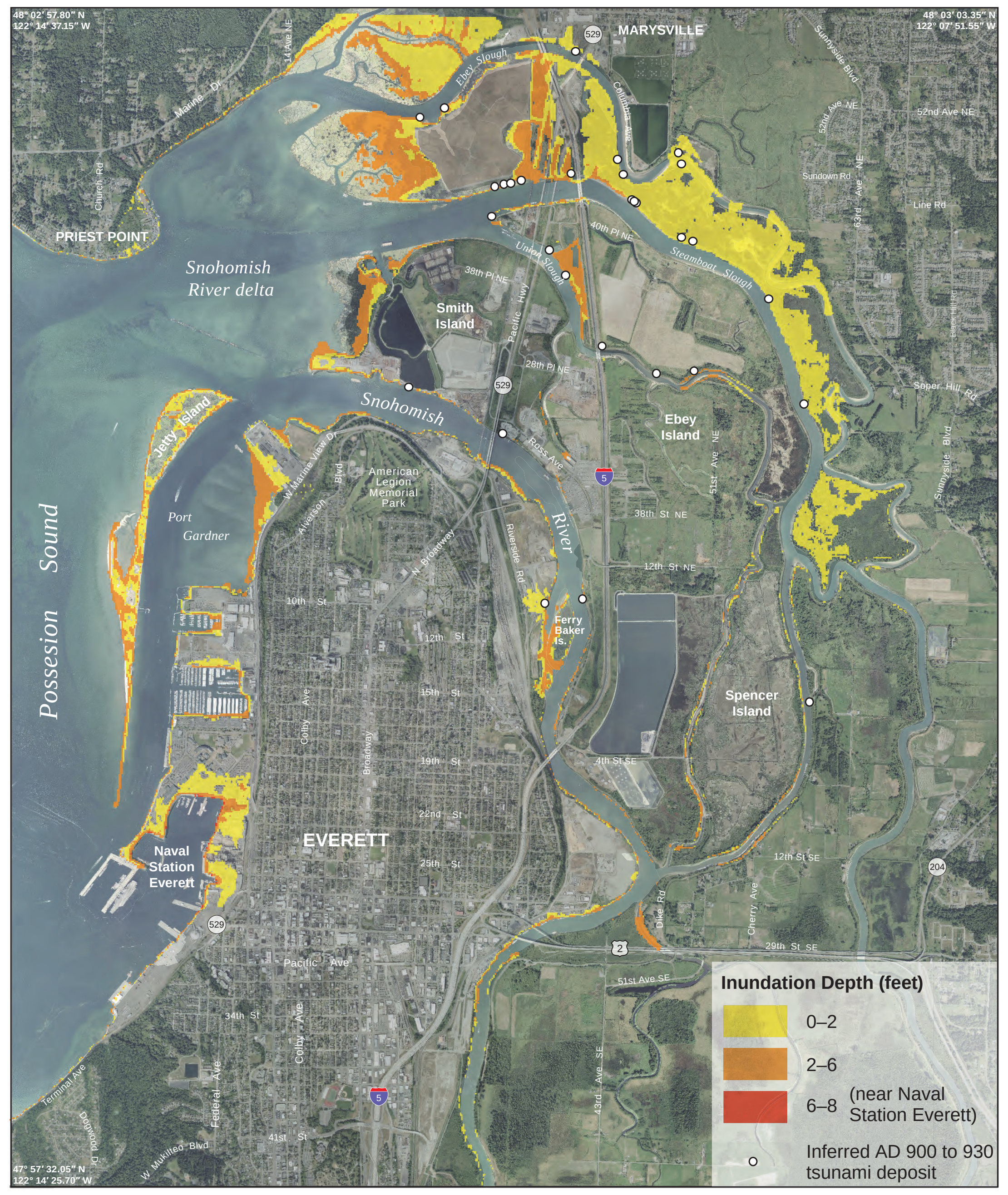

Figure 1

Maximum Current

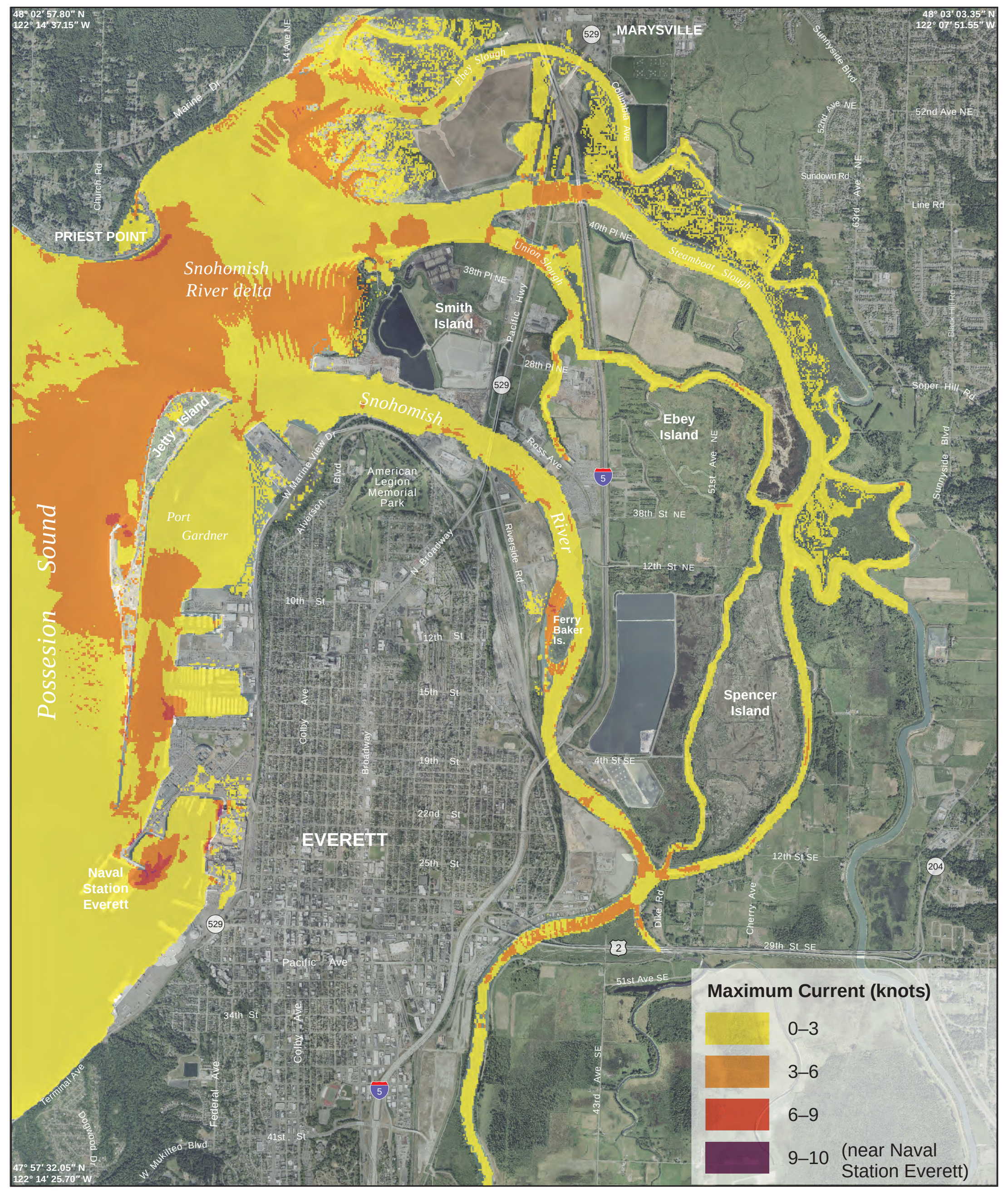

Figure 2

M_W 6.7

Modeled Inundation

Figure 3

Maximum Current

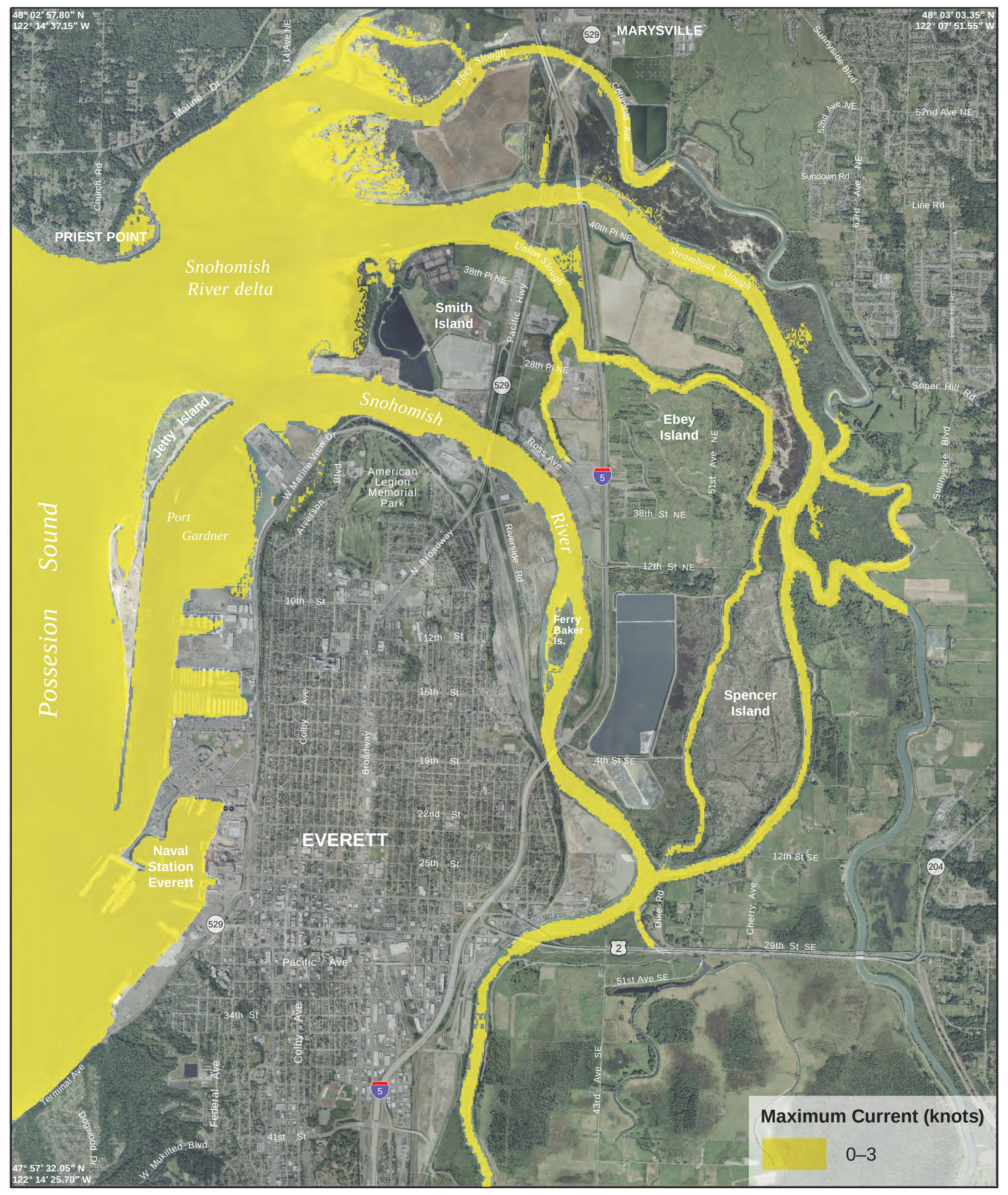

Figure 4

SCALE 1:32,000

1 0.5 0 1 mile

1 0.5 0 1 kilometer

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, 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 1996. The NTHMP is a program 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. These maps are produced using computer models of earthquake-generated tsunamis from nearby seismic sources. The modeling for this map was performed by the NOAA Center for Tsunami Research (NCTR) at NOAA's Pacific Marine Environmental Laboratory (PMEL) in Seattle and the results are shown in Figures 1 through 4.

This map is part of a series of tsunami inundation maps produced by the Washington Division of Geology and Earth Resources (WADGER), in cooperation with the Washington Emergency Management Division (WAEMD), as a contribution to the NTHMP. Completed maps are the southern Washington coast (Walsh and others, 2000), Port Angeles (Walsh and others, 2002a), Port Townsend (Walsh and others, 2002b), Neah Bay (Walsh and others, 2003a), Quileute area (Walsh and others, 2003b), Seattle (Walsh and others, 2003c), Bellingham (Walsh and others, 2004), Anacortes–Whidbey Island (Walsh and others, 2005), and Tacoma (Walsh and others, 2009).

PALEOSEISMOLOGY OF THE SEATTLE FAULT

Geographic features now known to be associated with the Seattle fault have been noted for many years. In his journal entry for May 29, 1792, Vancouver (1798) noted that the fault-uplifted and wavecut bedrock platform at Restoration Point on Bainbridge Island "did not possess that beautiful variety of landscape, being an almost impenetrable wilderness of lofty trees" that characterized the rest of his explorations in Puget Sound. Kimball (1897) also noted the uplifted wavecut platform at Restoration Point, measured its height, and identified the marine fossils found there. He also described the Newcastle Hills, part of the hanging wall of the fault, as a 'postglacial eruption'. Daneš and others (1965) interpreted the large gravity and magnetic anomalies through central Puget Sound, and an associated abrupt change in sedimentary section thickness, as an active fault with about 11 km of displacement. Rogers (1970) collected additional gravity and magnetic data across the structure and named it the Seattle–Bremerton fault. Gower (1978) demonstrated that the uplift at Restoration Point was Holocene in age and Bucknam and others (1992) showed that an earthquake produced 7 m of uplift on the fault about 1000 years ago (Sherrod and others, 2000), probably between AD 900 and 930 (Atwater, 1999), and hereafter referred to as the AD 900 to 930 event.

In 1996, the first of a series of lidar (Light Detection and Ranging) surveys was flown over Bainbridge Island. This and subsequent lidar missions have enabled scientists to accurately locate expressions of the Seattle fault in a number of places and to site paleoseismic trenches across those faults in order to determine fault age and potential recurrence intervals (Bucknam and others, 1999; Nelson and others, 2002). At about the same time, the USGS began several large-scale geophysical studies. An aeromagnetic study of the Puget Sound (Blakely and others, 1999, 2002) enabled more accurate location of the fault along its entire length. Seismic studies, such as SHIPS (Seismic Hazards Investigations in Puget Sound; Brocher and others, 2001) and other geophysical studies in Puget Sound, have greatly increased the understanding of the fault at depth (Pratt and others, 1997; Johnson and others, 1999; ten Brink and others, 2002; Brocher and others, 2004). Later, ten Brink and others (2006) evaluated existing fault models by using uplifted shorelines and concluded that the best-fitting model geometry is a south-dipping reverse fault with a shallow roof ramp consisting of at least two back thrusts. Kelsey and others (2008) suggested that some of the scarps that have been trenched in central Puget Sound were generated by bedding-plane slip on reverse faults—which can rupture independently of the master Seattle fault—and they proposed that the Seattle fault zone is a wedge thrust, with the northern, leading edge being a fault-bend wedge-thrust fold.

There also is substantial evidence that earthquakes on the Seattle fault have generated tsunamis. Atwater and Moore (1992) showed that tsunamis inundated part of Whidbey Island and West Point about 1000 years ago (Figure 5). Jacoby and others (1992) further showed that a tree in the tsunami deposit at West Point died the same season of the same year as a drowned forest carried into Lake Washington by a huge landslide from Mercer Island, strongly implicating the AD 900 to 930 seismic event on the Seattle fault. A discontinuous sand layer along Snohomish delta distributaries—Ebey Slough, Steamboat Slough, Union Slough, and the Snohomish River—was probably also deposited by the tsunami from the AD 900 to 930 earthquake (Bourgeois and Johnson, 2001). The locations of these deposits are shown in Figures 1 and 3.

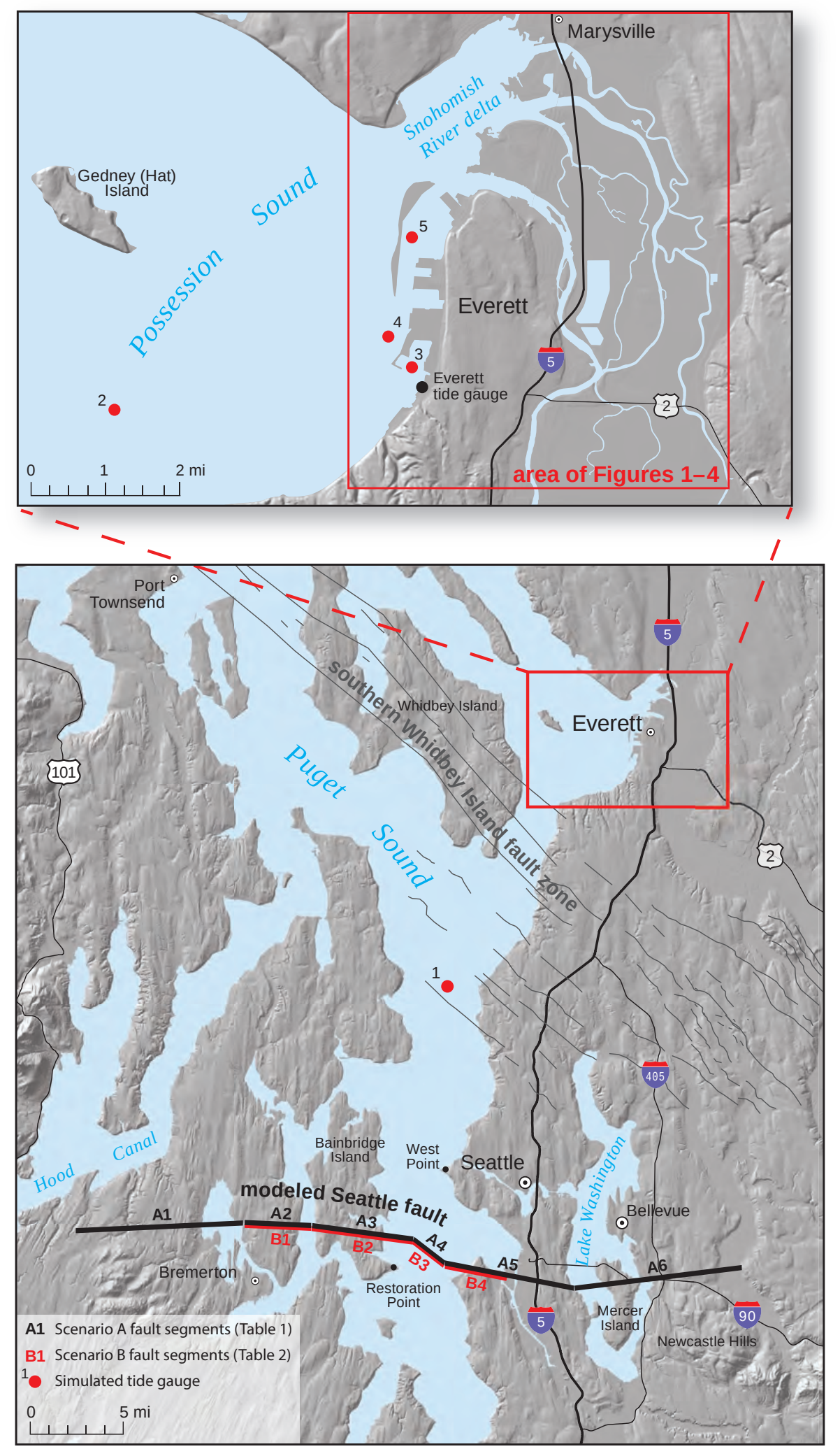

Figure 5. Location of study area, modeled segments of the Seattle fault, and simulated tide gauge stations used to model tsunami time-amplitude histories.

MODELING

The model of Titov and Synolakis (1998), also known as the Method of Splitting Tsunami (MOST) model (Titov and González, 1997), was used by NCTR modelers. It uses a grid of topographic and bathymetric elevations and calculates a wave elevation and depth-averaged velocity at each grid point at specified time intervals to simulate the generation, propagation, and inundation of tsunamis.

In this MOST model study, two deformation models for the Seattle fault were used: Scenario A simulates the AD 900 to 930 event as a credible worst-case scenario of magnitude M_W 7.3. Scenario B simulates a less severe, but more likely M_W 6.7 event. Details of the Seattle fault scenarios are given in Titov and others (2003) and Walsh and others (2003c). The fault parameters (Tables 1 and 2) were derived in a workshop convened by Walsh and attended by T. M. Brocher, T. L. Pratt, B. L. Sherrod, and C. S. Weaver, all from the USGS, and Diego Arcas, F. I. González, H. O. Mofjeld, V. V. Titov, and A. J. Venturato, all from NOAA. The seismic parameters from this workshop were simplified from the rupture models discussed above but are broadly in agreement. Time-amplitude histories for scenario tsunamis were generated for five simulated tide gauges and are shown on Figures 5 and 6.

Scenario A. Seattle Fault M_W 7.3 Event

This scenario is identical to the Seattle fault scenario defined by Titov and others (2003) and was also previously used for modeling inundation in Tacoma (Venturato and others, 2007). This scenario was designed to be a maximum credible event and uses the vertical deformation constraints from the AD 900 to 930 earthquake along the Seattle fault (Bucknam and others, 1992). It is described by six fault segments of varying length and strike, with slip ranging from 1 to 12 m (Table 1).

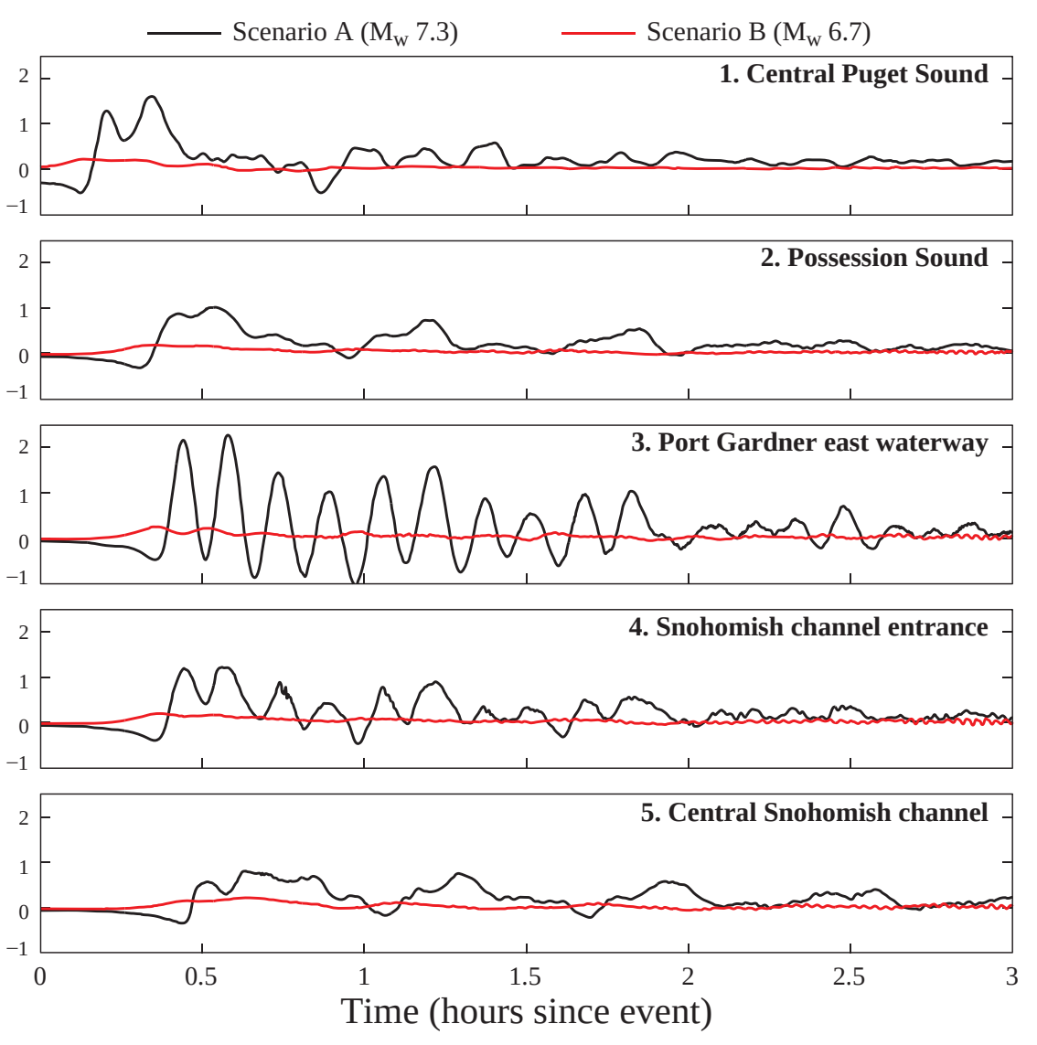

Figure 6. Modeled tsunami amplitudes at the simulated tide gauges shown in Figure 5, arranged by proximity to the Seattle fault.

Table 1. Scenario A seismic fault parameters for a Seattle fault M_W 7.3 earthquake, after Titov and others (2003). Strike is measured from north and dip direction is 90º clockwise from the strike azimuth.

Fault segment	Width (km)	Length (km)	Strike (deg)	Dip (deg)	Slip (m)
A1	35.0	15.2	87.9	60.0	1.0
A2	35.0	6.3	86.6	60.0	1.0
A3	35.0	8.9	96.0	60.0	12.0
A4	35.0	3.2	128.8	60.0	11.0
A5	35.0	11.5	99.3	60.0	4.0
A6	35.0	14.9	81.0	60.0	1.0

Scenario B. Seattle Fault M_W 6.7 Event

This scenario along the Seattle fault is a modified version of the earthquake scenario used by the Earthquake Engineering Research Institute (EERI) and WAEMD for recent seismic hazard assessment studies (Stewart, 2005). This scenario represents a less severe, but more likely event than Scenario A. A Seattle fault earthquake M_W 6.5 or greater is forecast to have a 5 percent chance of occurrence over a 50-year period (Stewart, 2005).

The scenario earthquake used in the EERI studies used a 24-km-long fault centered beneath the cities of Seattle and Bellevue; this resulted in little vertical deformation under the water of Puget Sound and minimized the effect of a potential tsunami. For the present study, the scenario was modified by shifting the event westward along the Seattle fault such that the fault begins at the western end of the original EERI fault and continues west under the central Puget Sound for 24 km (Fig. 5). This scenario uses a simplified fault model with a constant depth and dip angle and uniform 2.8 m vertical uplift derived by scaling down Scenario A to account for the overall smaller magnitude (Table 2).

Table 2. Scenario B seismic fault parameters for a Seattle fault M_W 6.7 earthquake, modified from the scenario earthquake used by EERI (Stewart, 2005). Strike is measured from north and dip direction is 90º clockwise from the strike azimuth.

Fault segment	Width (km)	Length (km)	Strike (deg)	Dip (deg)	Slip (m)
B1	35.0	6.3	86.6	45.0	2.8
B2	35.0	8.9	96.0	45.0	2.8
B3	35.0	3.2	128.8	45.0	2.8
B4	35.0	5.8	99.3	45.0	2.8

RESULTS

Maximum inundation depth and current velocity are model outputs and are displayed on Figures 1 through 4. The depth intervals chosen for Figure 1 (0–2 ft, 2–6 ft, and 6–8 ft) broadly represent hazard to people—inundation up to an adult's knees, from the knees to the head, and over the head. The modeling for Scenario B yielded a maximum inundation depth of 3 ft. Note that tide flats are shown in the aerial photo base maps—but are assumed to be underwater in the model—because the initial model conditions assume that the tide stage is at mean high water. Current velocities are given in knots following Lynett and others' (2014, p. 2049–2050) proposed damage thresholds. They state:

> "although damage in harbors might vary based on the age and location of docks and boats, some generalities about the relationship between tsunami currents and damage can be determined....there is a noticeable threshold for damage initiation at ~3 knots (1.5 m/s). When 3 knots is exceeded, the predicted damage state switches from no damage to minor to moderate damage. Thus, in the simulated data, 3 knots represents the first important current velocity threshold. We then argue that the second threshold is at 6 knots (3 m/s), where damage transitions from moderate to major. A third current speed threshold is less clear, but is logically around 9 knots (4.5 m/s)."

These thresholds were developed almost entirely from observations in ports and harbors and apply to newer harbor facilities. Older (40–50 year-old) or run-down facilities may have slightly lower thresholds (Rick Wilson, California Geological Survey, written commun., 2014). Figures 1–4 show depth of inundation and current velocity for the two scenarios.

DISCUSSION

One investigation has identified paleotsunami deposits in the Everett area. Bourgeois and Johnson (2001) identified numerous locations along sloughs of the Snohomish River delta that showed evidence of abrupt subsidence and an apparently continuous sheet of sand that overlies a soil dated to about AD 800–980 (Figs. 1 and 3), a range that completely contains the inferred age of the last Seattle fault earthquake (AD 900 to 930). These workers also found evidence for an older tsunami deposit (not shown on the figures) whose age is not well constrained. The tsunami model for Scenario A correlates well with all of the AD 900 to 930 tsunami deposit locations—the upstream extent of the model is approximately coincident with the most upstream tsunami deposits. However, because the sloughs are now protected by levees, the tsunami modeled here will behave differently from the AD 900 to 930 event even if the model perfectly matched the dynamics of that earthquake.

Other potential tsunami sources for this area are not well enough understood to be included in this assessment. The southern Whidbey Island fault zone crosses Puget Sound a short distance south of Everett (Dragovich and others, 2002) but is not understood well enough to build a credible seismic scenario model. Tsunamis can also be caused by landslides, both subaqueous and subaerial. Historic landslide-induced tsunamis occurred multiple times in Lake Roosevelt, the impoundment behind Grand Coulee Dam (Lander and others, 1993), in the Tacoma tidal flats in 1894 (Kimball, 1897), the Tacoma Narrows in 1949 (González, 2003), and in the lower Columbia River in 1965 (*Aberdeen Daily World*, February 1, 1965). Shipman (2001) reported a landslide-induced tsunami generated from Camano Island that inundated a Native American village on Gedney (Hat) Island, probably early in the 19th century, as reconstructed from Native American oral history. Figure 7 shows the presumed landslide scar and the clearly vulnerable Gedney Island immediately to the south. While landslide sources clearly present at least a localized tsunami threat, modeling those tsunamis is beyond the scope of this effort.

Limitations of the Maps

The largest source of uncertainty in these model results is the input earthquake event because the nature of the tsunami depends on the initial deformation. The earthquake scenarios used in this modeling were selected to honor the paleoseismic constraints, but the next Seattle fault earthquake may be substantially different from those that have been characterized. Sherrod and others (2000) show that a prior uplift event at Restoration Point (predating the AD 900 to 930 event) was smaller. Paleoseismic trenching of structures subsidiary to the Seattle fault—thought to be coseismic with the main fault trace (Nelson and others, 2002)—indicates that there were at least two earthquakes in the 1500 years before the AD 900 to 930 event. These earthquakes, however, did not uplift prominent wavecut platforms similar to the one made by the AD 900 to 930 event, which suggests that not all earthquakes along the Seattle fault have the same amount of vertical or horizontal displacement. Kelsey and others (2008) suggested that at least some of the previous earthquakes may have been produced by bedding-plane slip on a fault-bend fold and were not located on the main Seattle fault at all. Another significant limitation is that the resolution of the modeling is no greater nor more accurate than the bathymetric and topographic data used—data cells are locally up to 50 m on a side.

The models do not include the influences of changes in tides and are referenced to mean high water. The tide stage and tidal currents can amplify or reduce the impact of a tsunami on a specific community. At the Everett tide gage, the diurnal range (the difference in height between mean higher high water and mean lower low water) is about 11 ft (3.4 m) (accessed on August 8, 2014, at http://www.tidesandcurrents.noaa.gov). 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.

Figure 7. Historic landslide on Camano Head (inset, annotated) may have caused a tsunami at nearby Gedney (Hat) Island and inundated a Native American village.

ACKNOWLEDGMENTS

This project was supported by NTHMP in cooperation with WAEMD. Information about NTHMP is available at http://nthmp.tsunami.gov/. During the study, NCTR maintained close communication with WAEMD and WADGER and, upon completion of the study, a suite of model-derived mapping products were delivered to both agencies in the form of electronic files and, where appropriate, hard copy representations. Reviews by Stephen Slaughter (WADGER) and John Schelling (WAEMD) were helpful.

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11-17-14

Suggested citation: 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 earthquake tsunamis: Washington Division of Geology and Earth Resources Open File Report 2014-03, 1 sheet, scale 1:32,000.

Base map from 2011 Snohomish County NAIP color 3-foot-resolution aerial photos
HARN State Plane coordinate system, Washington South FIPS 4602
North American Datum of 1983
Shaded relief generated from U.S. Geological Survery 10-meter digital elevation model
Digital cartography by Anne C. Olson
Editing and production by Alexander N. Steely and Jaretta M. Roloff