Puget Sound Tsunami Sources

2002 Workshop Report

A Joint Special Report

National Oceanic and Atmospheric Administration
United States Geological Survey
Washington State Department of Natural Resources
Washington State Military Department Emergency Management Division

On the cover: Puget Sound has a history of tsunamis that includes water waves generated by this landslide at the Tacoma Narrows. The slide occurred three days after the magnitude-7.1 Olympia earthquake of April 13, 1949. It generated a tsunami that reflected off the opposite shore and propagated back to the coast on which the landslide occurred.

NOAA OAR Special Report

Puget Sound Tsunami Sources—2002 Workshop Report

A contribution to the Inundation Mapping Project of the
U.S. National Tsunami Hazard Mitigation Program

Workshop Report Committee:

Frank I. González, compiler, with contributions from Brian L. Sherrod, Brian F. Atwater, Arthur P. Frankel, Stephen P. Palmer, Mark L. Holmes, Robert E. Karlin, Bruce E. Jaffe, Vasily V. Titov, Harold O. Mofjeld, and Angie J. Venturato

Sponsored by:

National Oceanic and Atmospheric Administration
U.S. Geological Survey
Washington State Department of Natural Resources
Washington State Military Department Emergency Management Division

Workshop Organizing Committee:

G. Crawford, F. González (Chair), M. Holmes, H. Mofjeld, B. Sherrod, V. Titov,
A. Venturato, T. Walsh, C. Weaver

June 2003

Contribution 2526 from NOAA/Pacific Marine Environmental Laboratory

NOTICE

Contribution No. 2526 from NOAA/Pacific Marine Environmental Laboratory

For sale by the National Technical Information Service, 5285 Port Royal Road
Springfield, VA 22161

Contents

List of Figures

List of Tables

Puget Sound Tsunami Sources Workshop History

This workshop was jointly sponsored by NOAA's Center for Tsunami Inundation Mapping Efforts (TIME), the U.S. Geological Survey, the Washington State Military Department Emergency Management Division (WAEMD), and the Washington State Department of Natural Resources (WADNR). The Workshop Organizing Committee consisted of:

George Crawford	WA State Emergency Management Division
Frank González (Chair)	NOAA TIME Center
Mark Holmes	U. Washington
Hal Mofjeld	NOAA TIME Center
Brian Sherrod	U.S. Geological Survey
Vasily Titov	NOAA TIME Center
Angie Venturato	NOAA TIME Center
Tim Walsh	WA State Dept. Natural Resources
Craig Weaver	U.S. Geological Survey

This committee held a planning meeting on 24 April 2002. On 9 May, an informational e-mail was distributed to 35 individuals, inviting their participation and soliciting pre-workshop scientific contributions for the workshop web site. The web site served to stimulate and facilitate pre-workshop e-mail discussion and to provide resource material for the subsequent workshop activities. Twenty-three attendees participated in the workshop, held on 10 June 2002 at NOAA's Pacific Marine Environmental Laboratory in Seattle, Washington. The full list of invitees and the pre-workshop contributions are posted on the workshop web site at *http://www.pmel.noaa.gov/tsunami/time/PS_source_wkshp/*. The full list of workshop participants is provided in Appendix A.

At the workshop, the following sub-groups were formed to concentrate on specific source issues:

Earthquake Sources: A. Frankel, C. Garrison-Laney, T. Jovanelly, B. Sherrod, C. Weaver, J. Whisler

Delta Failure and Landslide Sources: J. Gardener, M. Holmes, R. Karlin, R. Kayen, S. Palmer, H. Shipman, T. Walsh, H. Yeh

Paleotsunami Field Evidence: B. Atwater, B. Jaffe, H. Mofjeld, V. Titov

The remaining participants were specialists in tsunami modeling and emergency management, and they participated in each sub-group as needed.

Subsequently, the following individuals served as lead contributors to individual sections of the report: González (Sections 0 and 1), Sherrod, Atwater, and Frankel (Section 2), Palmer, Holmes, and Karlin (Section 3), Jaffe and Atwater (Section 4), Titov, Mofjeld, González, and Venturato (Section 5). In June 2002, a first rough draft was distributed via e-mail list *PugetSources@pmel.noaa.gov* to all workshop invitees and participants for their review. The manuscript went through several rounds of revision and review before completion in June 2003.

Puget Sound Tsunami Sources—2002 Workshop Report

Workshop Report Committee:

Frank I. González, compiler, with contributions from Brian L. Sherrod, Brian F. Atwater, Arthur P. Frankel, Stephen P. Palmer, Mark L. Holmes, Robert E. Karlin, Bruce E. Jaffe, Vasily V. Titov, Harold O. Mofjeld, and Angie J. Venturato

Executive Summary

Potential tsunami sources in Puget Sound were reviewed by a 23-person panel of geoscientists, oceanographers, and emergency managers who participated in a 1-day workshop. Their goal was to lay scientific groundwork for hazard assessment in coastal areas threatened by tsunamis and, in so doing, assist emergency managers that seek to comply with the spirit of the Washington State Growth Management Act, which instructs officials to seek out and consider the "best available science." The panelists recommended that tsunami modelers focus on several kinds of sources, and they also recommended improvements in source identification and modeling.

Tsunami Modeling Recommendations

- *Earthquakes* on the Seattle fault zone, the Tacoma and South Whidbey Island faults, and other structures that generate tsunamis by tectonically raising or lowering the floor of Puget Sound, consistent with best estimates that may include fault parameters used in the USGS National Seismic Hazard Map (Table 2.1 or updates) and paleoseismic estimates of land-level change.

- *Delta slope failures* of the Puyallup, Duwamish, and Snohomish River deltas, with parameters based on the 1894 Commencement Bay event (Table 3.1) and a scaled-down 1964 Valdez event (Table 3.3).

- *Submarine landslides* associated with Quaternary faults (not deltas), with parameters based on currently unpublished seismic profiling data and maps (Table 3.4).

- *Subaerial landslides*, with parameters based on the 1949 Tacoma Narrows landslide (Table 3.2).

- Tsunami modelers should develop these source scenarios in close collaboration with geoscience experts on earthquakes, slope stability, and paleotsunami evidence in Puget Sound.

Science Improvement Recommendations

- Use LIDAR data to update deformation estimates for A.D. 900 Seattle Fault earthquake and for other fault ruptures.

- Do additional fieldwork to document coastal deformation and constrain the eastern end of the Tacoma Fault.
- Expand the existing program of slope instability mapping to increase the geographical coverage and improve the quality of submarine and subaerial landslide assessments, including the acquisition of multibeam bathymetry and sediment cores.
- Improve estimates of wave height and water velocity of prehistoric and recent tsunamis through combined use of sedimentology and inundation modeling.
- Do additional fieldwork to check for tsunami deposits at Lynch Cove, Lake Washington, Lake Sammamish, and other Puget Sound area sites.
- Make and update summary maps that incorporate all available field evidence for tsunami deposits, coseismic deformation, and submarine and subaerial landslides.
- Develop methods to assess the sensitivity of coastal areas to tsunami inundation, based on multiple simulations that reflect the possible range of variations in the source parameters.
- Hold yearly workshops to review the best available scientific information and develop updated recommendations for tsunami inundation mapping in Washington State.

1. Introduction

Future Puget Sound tsunamis are guaranteed by a combination of setting and history. The inland waters and lakes of the Puget Sound lowland cross active faults and contain records of earthquakes and landslides. From geologic and historical evidence, it is known that some of these events have generated tsunamis. A workshop on 23 January 2001 concluded that "Tsunamis and landslides in the greater Puget Sound region pose significant hazards that must be included in local and regional emergency response and development plans" (Crawford *et al.*, 2001). That workshop was organized by the Washington State Military Department Emergency Management Division (WAEMD), the National Oceanic and Atmospheric Administration (NOAA), and the U.S. Geological Survey (USGS), all partners of the U.S. National Tsunami Hazard Mitigation Program (Bernard, 2001).

A major goal of the national tsunami program is to develop tsunami inundation maps for all U.S. coastal communities at risk (González *et al.*, 2001). In 2002, NOAA's Center for Tsunami Inundation Mapping Efforts (TIME) made initial simulations of Seattle-Duwamish waterfront inundation by a tsunami generated by an M 7.3 Seattle Fault earthquake scenario. In 2003, the TIME Center plans to begin numerical simulations and mapping of tsunami inundation in the Puget Sound lowland. Such simulations are intended to help state, county, and municipal officials develop emergency management tools, including evacuation maps, response plans, educational material, and outreach and mitigation programs. The inundation maps are expected to evolve as emergency managers apply them and as researchers revise their scientific basis.

In Washington, this effort provides the basis for community development of a mitigation plan that is in compliance with the Washington State Growth Management Act, under which coastal areas threatened by tsunamis are designated as critical areas (Washington State Office of Community Development, 2002). In 1995, a section was added to the Growth Management Act that requires counties and cities to include the "...best available science when developing policies and development regulations to protect the functions and values of critical areas..." and encourages state officials to "...consult with a qualified scientific expert or team of qualified scientific experts to identify scientific information, determine the best available science, and assess its applicability to the relevant critical areas" (Washington State Legislature, 1995).

In the spirit of complying with these requirements, a Puget Sound Tsunami Sources Workshop was organized by NOAA's TIME Center, the USGS, WAEMD, and Washington Department of Natural Resources (WADNR). This workshop had two specific objectives:

1. Develop quantitative descriptions of potential sources for inundation modeling to assess Puget Sound tsunami hazards.

2. Develop recommendations for improving the scientific basis for source specification and tsunami source modeling.

The 1-day workshop was held on 10 June 2002 at NOAA's Pacific Marine Environmental Laboratory in Seattle, Washington. The 23 participants included scientists with specialties in earthquakes, landslides, delta failures, paleotsunami field evidence, tsunami modeling, and emergency management (Appendix A). Strawman source scenarios, reports, and other relevant reference materials were contributed by invitees prior to the workshop. These were made available on the workshop web site, at *http://www.pmel.noaa.gov/tsunami/time/PS_source_wkshp/* .

The workshop consisted of whole-group discussions and sub-group sessions. First, an open discussion of earthquake, delta failure, and landslide scenarios was held; participants then divided into three sub-groups. Two sub-groups concentrated on developing quantitative descriptions of potential tsunami sources—the first dealt with earthquake uplift and subsidence, the second with slope failures. The third sub-group dealt with geologic records of past tsunamis and their triggers. Finally, an example was presented of a recent tsunami inundation modeling study for the Seattle-Duwamish waterfront area.

2. Earthquake Sources

2.1 Background

Earthquakes at Puget Sound occur along faults in three tectonic settings: within the subducted oceanic plate (Juan de Fuca plate) at depth beneath Puget Sound, within the overriding continental plate (North America plate), and at the boundary fault between those plates.

For each of these sources, the largest earthquakes recur at poorly known, probably irregular, intervals. On average, the intervals are on the order of decades for the Juan de Fuca plate, millennia for the best-known of the upper-plate faults (the Seattle Fault), and centuries for the plate boundary (*http://www.ess.washington.edu/SEIS/PNSN/INFO_GENERAL/eqhazards.html*).

Although few earthquakes result in tsunamis at Puget Sound, each of the three earthquake sources has demonstrated its capability of generating such waves. A landslide that set off a tsunami in Tacoma Narrows occurred a few days after the 1949 earthquake in the Juan de Fuca plate (Noson *et al.*, 1988). The earthquake of ca. A.D. 900 on the Seattle fault caused uplift that triggered a tsunami in central Puget Sound and also caused landslide-generated waves in Lake Washington (Atwater and Moore, 1992). Tsunamis from plate-boundary earthquakes probably account for several sand sheets on northwestern Whidbey Island (Williams and Hutchinson, 2000) and at Discovery Bay (Williams *et al.*, 2002).

2.2 Priority Areas

The workshop focused on coseismic uplift and subsidence along three fault zones as sources for tsunamis in the Puget Sound region—the Seattle Fault, Tacoma Fault, and South Whidbey Island Fault. Also discussed was coseismic subsidence 1100 years ago near Olympia (Sherrod, 2001), and the Cascadia Subduction Zone (CSZ) as a likely source for tsunamis at northwestern Whidbey Island (Williams and Hutchinson, 2000) and Discovery Bay (Williams *et al.*, 2002). Puget Sound probably has additional tectonic sources of tsunamis, particularly vertical displacement along faults beneath the Sound near the latitude of the Strait of Juan de Fuca (Johnson, 2001). These structures, along with rapidly changing views of the Seattle and Tacoma faults, will need reassessment in future workshops.

Maps in Fig. 1 summarize several aspects of the region's earthquake hazards. Figure 1a schematically summarizes the general location of some known fault zones at Puget Sound. This map includes deformation contours for a worst-case event—the modeled crustal deformation pattern for an M 7.3 Seattle Fault earthquake discussed in section 5.0, below. Figure 1b presents the modeled deformation pattern for an M 9.1 earthquake on the CSZ. Figure 1c provides estimates of peak ground acceleration that might be experienced in the Puget Lowlands area with a 2% probability of exceedance in 50 years (Frankel *et al.*, 1996).

Seattle Fault

Tsunami generation models for the Seattle Fault Zone depend on a complicated geometry that was being reassessed as this report was written and revised. This reassessment may produce large changes in fault parameter estimates, in which case the tsunami source models presented in Table 5.1 may require modification.

Previously, the Seattle Fault Zone was inferred to have roots in a widespread, nearly horizontal detachment fault tens of kilometers beneath much of Puget Sound (Pratt *et al.*, 1997). It was also mapped as containing multiple near-surface strands that are rooted in a master reverse fault (Johnson *et al.*, 1999; Blakely *et al.*, 2002). More recently, this master fault has been considered largely disconnected from near-surface strands. Instead, much like a well-studied reverse fault in Japan (Ishiyama *et al.*, 2002), the master fault may terminate kilometers below the surface, and the master fault may deform rocks above it much like the blade of a snowplow. These various interpretations provide many ways of suddenly raising or lowering the floor of Puget Sound—the deformation that would generate a tsunami.

The main mapped strands of the Seattle Fault Zone, from north to south, have been called the Frontal fault, the Blakely Harbor fault, and the Orchard Point fault (Johnson *et al.*, 1999; Blakely *et al.*, 2002). The Frontal fault projects to the surface about 3.5 km north of Restoration Point and may dip steeply to the south (Brocher *et al.*, 2001; Calvert and Fisher, 2001; ten Brink *et al.*, 2002).

A late Holocene earthquake, with a magnitude (M) of 7 or more occurred on the Seattle Fault Zone about 1100 years ago (Bucknam *et al.*, 1992). This earthquake, probably between A.D. 900 and 930 (Atwater, 1999), generated a tsunami known from deposits at West Point (in Seattle), Cultus Bay (at the south end of Whidbey Island), and the Snohomish River delta near

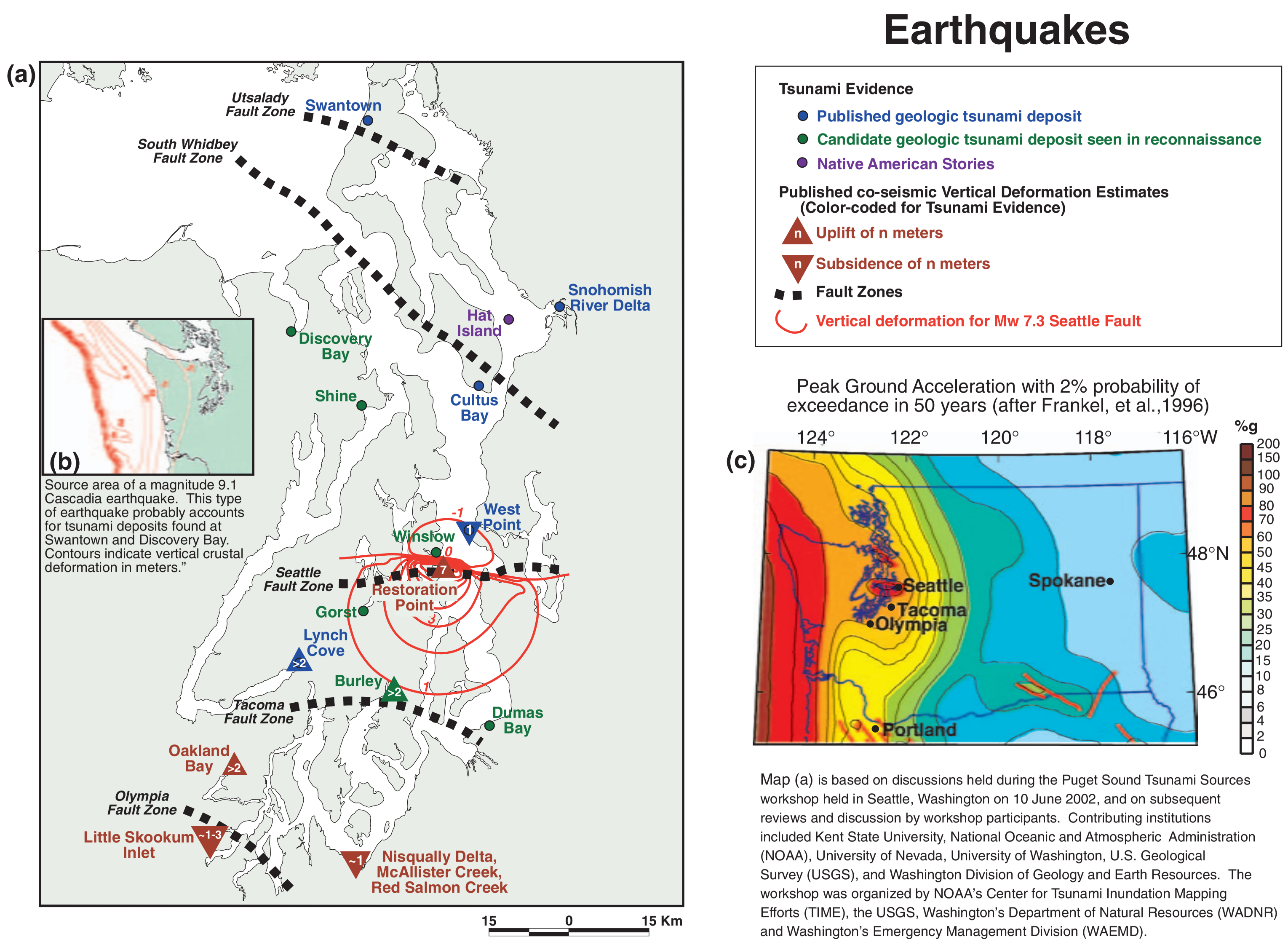


Figure 1: (a) Schematic of fault zone locations in the Puget Sound region, with vertical deformation contours for an Mw 7.3 Seattle Fault. Inset (b) Vertical deformation for an M 9.1 Cascadia earthquake. (c) Pacific Northwest peak ground acceleration with 2% probability of exceedance in 50 years (from Frankel *et al.*, 1996).

Everett (Atwater and Moore, 1992; Bourgeois and Johnson, 2001). The tsunami probably resulted from 5–7 m of uplift in a band 6 km wide south of the fault, and secondarily from as much as 1 m of subsidence to the north. This uplift and subsidence displaced large volumes of water in Puget Sound, whether or not fault rupture extended upward to the floor of the sound.

A south-facing scarp within the Seattle Fault Zone, identified by airborne laser mapping, crosses Bainbridge Island about 2 km north-northwest of Restoration Point (Bucknam *et al.*, 1999). Stratigraphy and structure exposed in trenches excavated across the scarp show a postglacial history of folding and faulting from multiple earthquakes, with the most recent event occurring about 1100 years ago (Nelson *et al.*, 1999; 2002). A full-length report on the trench results was nearing completion as this workshop report was being written.

A north-facing scarp within the Seattle Fault Zone, near the west shore of Lake Sammamish, was recently trenched by Sherrod (2002). He found evidence for one postglacial surface rupture and dated it to the past 13,000 calendar years.

Tacoma Fault

Like the Seattle Fault Zone, the Tacoma Fault separates an area of coseismic uplift from an area of coseismic subsidence (Brocher *et al.*, 2001). The documented examples of these land-level changes date to about 1100 years ago (Bucknam *et al.*, 1992). Though much remains to be learned about its extent and shape, the Tacoma Fault is evident from gravity and aeromagnetic anomalies, seismic tomography, and seismic-reflection lines. The fault likely runs westward and northwestward from Tacoma across much of the Puget Lowland (Fig. 1a). Seismic tomography implies at least 6 km of post-Eocene uplift to the north relative to basinal sedimentary rocks to the south.

Uplift to the north of the fault and subsidence to the south occurred most recently in A.D. 800–1200, not necessarily in a single year (Sherrod *et al.*, 2002). To the northwest at Lynch Cove, tide flats rose as much as 3 m between A.D. 870–990. Uplift 16 km to the east at Burley, accompanied there by liquefaction and a tsunami, allowed woody shrubs to invade former tideflats in A.D. 770–1000. Shells in tideflat mud at North Bay record uplift loosely dated to the past 3000 years. Fossil foraminifera from Dumas Bay limit the eastward extent of uplift north of the fault, for they show that a brackish marsh remained in the intertidal zone throughout the last 2000 years. However, trees at Wollochet Bay, on the south side of the fault, subsided into the intertidal zone. A single radiocarbon age implies that this subsidence occurred A.D. 980–1190, in which case the subsidence postdates uplift at Lynch Cove and Burley by 30–270 years.

The age range of this uplift on the north side of the Tacoma Fault includes times of coseismic uplift and subsidence at many sites around Puget Sound. As noted above, an earthquake raised shorelines along the Seattle Fault Zone in A.D. 900–930; moreover, several shores of southern Puget Sound subsided A.D. 860–940. Therefore, the uplift north of the Tacoma Fault either coincided with a single large event in A.D. 900–930, or it represents a separate earthquake of about that age. However, the subsidence at Wollochet Bay implies either coseismic or aseismic deformation after A.D. 900–930.

South Whidbey Island Fault

The South Whidbey Island Fault is one of several that splay eastward from the Strait of Juan de Fuca and appear to displace postglacial deposits (Wagner and Tomson, 1987). It has been mapped as a transpressional deformation zone that crosses Admiralty Inlet and southern Whidbey Island (Johnson, 1996; 2001). This zone separates pre-Tertiary rocks to the northeast from Eocene volcanic and sedimentary rocks to the southwest. The highest Tertiary rocks have as much as 420 m of relief across the fault, either from vertical tectonic movement (Johnson, 1996) or from subglacial erosion. An earthquake on the South Whidbey Island Fault might produce both vertical and horizontal displacement of the floor of Puget Sound.

Compared with the Seattle and Tacoma structures, the South Whidbey Island Fault may have produced little vertical displacement in the Holocene. The evidence reported thus far comes from northern Whidbey Island, where two sites (Crockett and Hancock Lakes) appear to differ by about 2 m in relative sea-level change about 3000 years ago. The inferred difference is tentative because it has been reported only in abstract and because it has been inferred from differences in the radiocarbon age of intertidal deposits at similar elevation (Kelsey and Sherrod, 2001).

2.3 Event Descriptions

Table 2.1 provides fault parameter estimates for the Seattle and South Whidbey Island Fault Zones as used by the USGS National Seismic Hazard Mapping Project (Frankel *et al.*, 2002). Because of lively research and debate about the structure and Holocene history of these faults, the tabulated parameters represent a recent consensus that is already out of date. The lack of estimates for the Tacoma Fault reflects an early stage of research into the Holocene history of this structure.

2.4 Recommendations

Tsunami Source Modeling

- Seattle Fault: Incorporate the most current fault and earthquake parameters provided by active researchers and the USGS National Seismic Hazard Mapping Project.

- South Whidbey Island Fault: Incorporate the most current fault and earthquake parameters provided by active researchers and the USGS National Seismic Hazard Mapping Project.

Table 2.1: Fault parameters used in making the 2002 version of the USGS National Seismic Hazard Map (Frankel *et al.*, 2002, *http://geohazards.cr.usgs.gov/eq/faults/fsrpage21.html#washington*). End points listed in the table should not be interpreted as a straight line fault trace; they correspond to the two ends of a more complex fault trace that is not detailed here (Art Frankel, personal communication). T, the recurrence time for earthquakes of magnitude M, is especially uncertain. In the characteristic earthquake model, a fault produces earthquakes of one size only (of M 7 in the case of the Seattle and south Whidbey Island faults) at the indicated recurrence interval. In the truncated Gutenberg-Richter model, the fault produces earthquakes in a certain size range (greater than M 6.5, in this case) at the indicated recurrence interval. The 2002 hazard map gives the two models equal weight (Frankel *et al.*, 2002, p. 11).

						Characteristic-earthquake model		Truncated Gutenberg-Richter model	
Fault Zone	**Slip Rate (m/1000 yr)**	**End Points (deg., lat., long.)**	**Length (km)**	**Width (km)**	**Dip (deg)**	**T (yr)**	**M**	**T (yr)**	**M**
Seattle	0.5	47.6, −121.9 47.6, −122.9	71	21	45	5000	7	1000	≥6.5
Tacoma	TBD	TBD	50	TBD	TBD	TBD	TBD	TBD	TBD
S. Whidbey Island	0.6	47.9, −122.3 48.2, −123.0	63	17	60	3000	7	1000	≥6.5

Science Improvement

- Seattle Fault: Use high-resolution topography from LIDAR, verified by field work, to update estimates of crustal deformation for A.D. 900 event.
- Tacoma Fault: Study surface ruptures and shoreline changes that can be associated with the fault.

3. Delta Failure and Landslide Sources

3.1 Background

The working group identified three distinct landslide situations that could result in a significant tsunami affecting local communities bordering Puget Sound: submarine landslides on delta fronts, submarine slides elsewhere in the Sound, and slides from adjacent uplands.

Submarine landslides can originate on the delta slopes of major rivers flowing into the Sound, in particular the Nisqually, Puyallup, Duwamish, and Snohomish rivers. In 1894 a large submarine landslide occurred on the Puyallup River delta in Commencement Bay, resulting in two deaths and the destruction of the Northern Pacific freight docks and other port facilities (Stephen Palmer, unpublished data; Gardner *et al.*, 2001). A smaller submarine landslide in 1943 destroyed jetties along the mouth of the Puyallup River (University of Washington, Department of Oceanography, 1953). In addition to these Puget Sound examples, larger submarine landslides have occurred on river deltas in British Columbia and Alaska. Some of these slides were triggered by large earthquakes, and others resulted simply from river delta evolution, including oversteepening of the delta front. The submarine landslides resulting from the 1964 Alaska earthquake resulted in more than 50 deaths and the near-total destruction of three port communities: Valdez, Seward, and Whittier (Wilson and Torum, 1972; Spaeth and Berkman, 1972; Lander, 1988). At Valdez, large tsunamis were generated by a number of submarine slides, including a massive slide off the Lowe River delta that included the Valdez waterfront and the shore north of town; docks, canneries, the boat harbor, and many boats were totally destroyed, oil tanks were set on fire, and 31 died. At Seward, the earthquake triggered slides on the Resurrection River fan delta, causing a large stretch of waterfront to slide into Resurrection Bay; the slide and the resultant tsunami destroyed almost the entire economic foundation of the community and caused 11 deaths. Whittier suffered 13 fatalities, destruction of docks, oil tank farms, and railroad facilities, due to the earthquake and tsunami waves evidently generated by delta failures. Known historical Puget Sound delta failures, all far smaller than these Alaskan examples, are shown in Fig. 2, as are the locations of major river deltas.

Additional landslides originate on steep submarine slopes that are not part of a delta. Unpublished seismic profiling data and mapping presented by members of the working group (Robert Karlin and Mark Holmes) indicate that large submarine landslides have occurred on submarine slopes in Puget Sound, Lake Washington, and Lake Sammamish that are not associated with large river deltas, but that appear proximal to a number of Quaternary faults that cross the Sound (Karlin *et al.*, 2002). Large prehistoric landslides have been identified on continental shelves and slopes off Europe, Africa, and North and South America (Moore, 1978). Most have been identified through seismic profiling and sediment coring on the continental margins. In addition, some submarine slope failures, such as the Grand Banks landslide of 1929, have occurred during historical times. This landslide caused a tsunami that resulted in the loss of 27 lives in southern Newfoundland (Heezen and Ewing, 1952; Heezen and Drake, 1964; Hasagawa and Kanamori, 1987). The 1929 slide apparently consisted of multiple slumps of many sizes (Piper *et al.*, 1999). In 1998, a large submarine landslide is suspected of contributing to a Papua New Guinea tsunami that caused more than 2200 fatalities (Titov and González, 2001).

Subaerial landslides that fall into Puget Sound with sufficient volume and velocity, and at the appropriate tidal conditions, can generate large water waves. Such a tsunami was generated by a landslide at the Tacoma Narrows that occurred three days after the 1949 Ms 7.1 Olympia earthquake. The landslide occurred on the steep bluff bordering The Narrows, and the fall of the slide debris into the water caused the tsunami (Chleborad, 1994). Native American oral tradition suggests that a large subaerial landslide at Camano Head created a water wave that drowned many people on Hat (Gedney) Island (Shipman, 2001). Because the story does not include ground shaking, this landslide was not necessarily associated with an earthquake. Figures 3

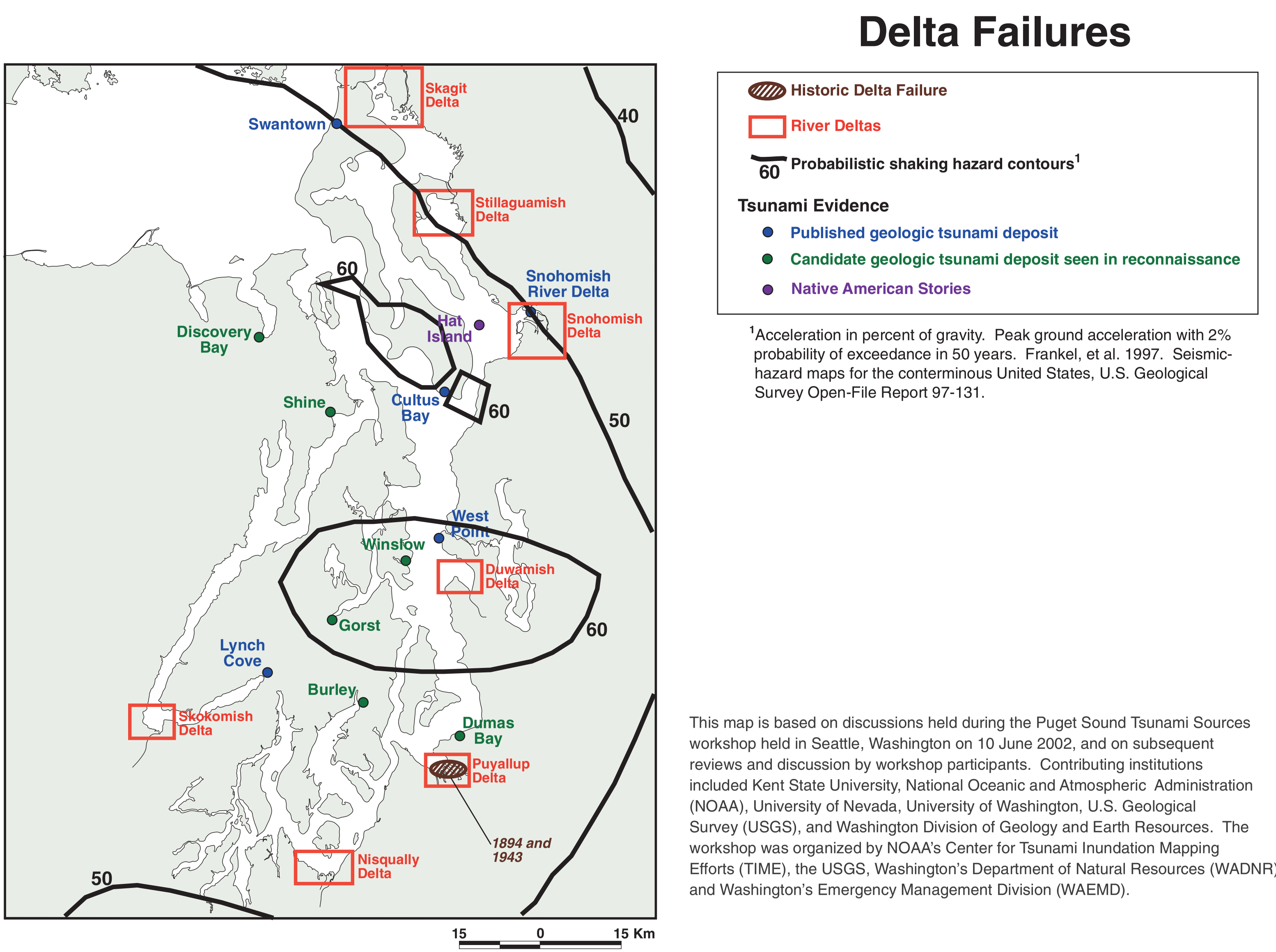


Figure 2: Locations of major river deltas in Puget Sound, including two historic failures of the Puyallup River delta that occurred in 1894 and 1943, and locations for which evidence of past tsunamis exists. Also presented are contours of peak ground acceleration with 2% probability of exceedance in 50 years (Frankel *et al.*, 1997).

and 4 summarize information on both submarine and subaerial landslides discussed at the workshop.

3.2 Priority Areas

Several hypotheses may aid in setting priorities for modeling tsunamis from landslide sources.

River delta failures

Deltas of the Puyallup, Duwamish, and Snohomish Rivers probably pose more of a landslide hazard than do other Puget Sound deltas, as shown by historical submarine landslides on the Puyallup River delta, the proximity of these three deltas to major port facilities, and stability analysis of the Duwamish River delta slope (Kayen *et al.*, 1999).

Non-deltaic submarine landslides

Away from deltas, submarine areas most susceptible to landsliding may be in the vicinity of faults having Quaternary displacement. This inference is based on preliminary mapping of Puget Sound (Fig. 3), Lake Washington, and Lake Sammamish submarine landslides (Fig. 4) by Karlin and Holmes.

Subaerial landslides

Landslides as large as the 1949 Tacoma Narrows failure are the subaerial slides most likely to cause tsunamis in Puget Sound. The two major geological parameters that control the generation of a water wave from subaerial landslides are the volume of the slide mass, and the motion of the mass as it reaches the water body. Some very large prehistoric landslides have been mapped along Puget Sound bluffs; when reactivated, these deep-seated landslides tend to be very slow moving (inches per day), and would not appear to be capable of generating a tsunami.

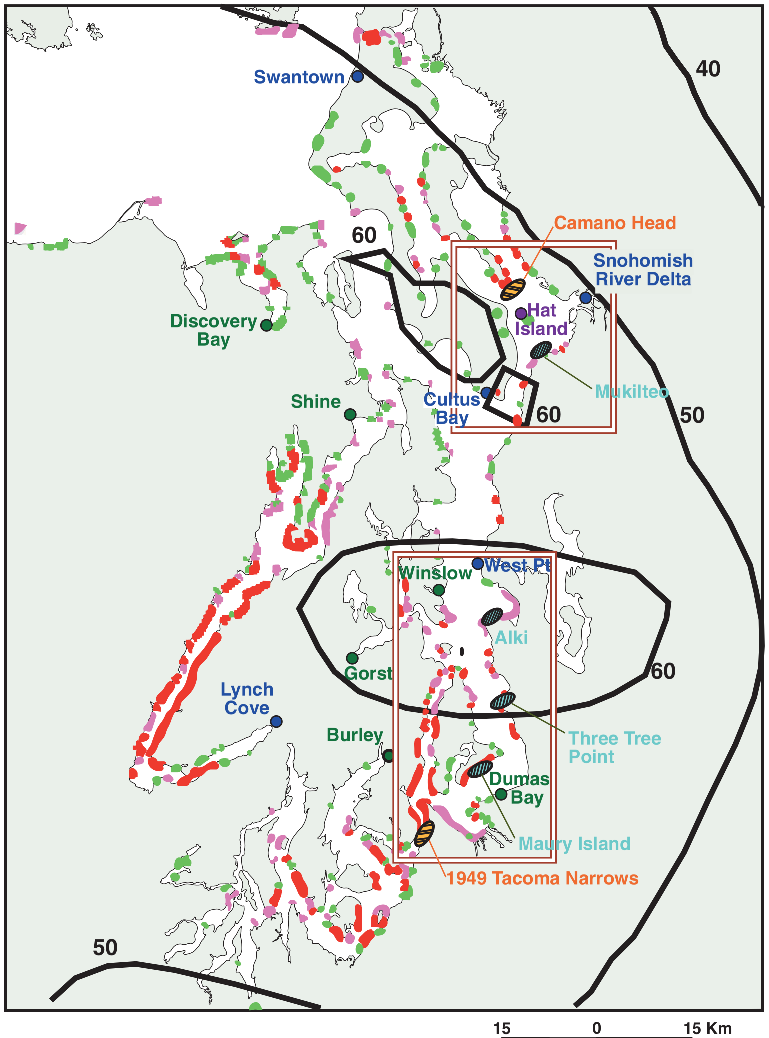
3.3 Scenarios

As further guidance for tsunami modeling, landslides at Puget Sound can be envisioned in several scenarios: landslides with historical precedent in Puget Sound, credible "worst case" landslides based on analogies with other places, and submarine slides not associated with river deltas.

Historical precedent scenarios

The first kind of scenario is based on tsunamigenic Puget Sound landslides such as the 1894 Commencement Bay delta failure and the 1949 Tacoma Narrows subaerial landslide. The geometry of each is well defined from field observations, and summaries of the estimated parameters are provided in Tables 3.1 and 3.2.

Scenario landslides based on local historical precedent offer the great advantage of having dimensions and effects like those known to have occurred



Landslides

Potential landslide zones of concern identified at workshop

Large submarine landslides[1]

Subaerial landslides

Probabilistic shaking hazard contours[1] 60

Steep coastal topography

Deep coastal water

Steep topography near deep water

Tsunami Evidence

Published geologic tsunami deposit

Candidate geologic tsunami deposit seen in reconnaissance

Native American Stories

[1] Unpublished data. See text.

[1] Acceleration in percent of gravity. Peak ground acceleration with 2% probability of exceedance in 50 years. Frankel, et al. 1997. Seismic-hazard maps for the conterminous United States, U.S. Geological Survey Open-File Report 97-131.

This map is based on discussions held during the Puget Sound Tsunami Sources workshop held in Seattle, Washington on 10 June 2002, and on subsequent reviews and discussion by workshop participants. Contributing institutions included Kent State University, National Oceanic and Atmospheric Administration (NOAA), University of Nevada, University of Washington, U.S. Geological Survey (USGS), and Washington Division of Geology and Earth Resources. The workshop was organized by NOAA's Center for Tsunami Inundation Mapping Efforts (TIME), the USGS, Washington's Department of Natural Resources (WADNR) and Washington's Emergency Management Division (WAEMD).

Figure 3: Potential landslide zones, including the location of the 1949 Tacoma Narrows slide and unpublished field data (Karlin and Holmes) for large submarine slides. Also presented are contours of peak ground acceleration with 2% probability of exceedance in 50 years (Frankel *et al.*, 1997), locations for which evidence of past tsunamis exists, and a TIME Center analysis of gridded bathymetric and topographic data to identify sites with steep coastal topography adjacent to deep coastal water.

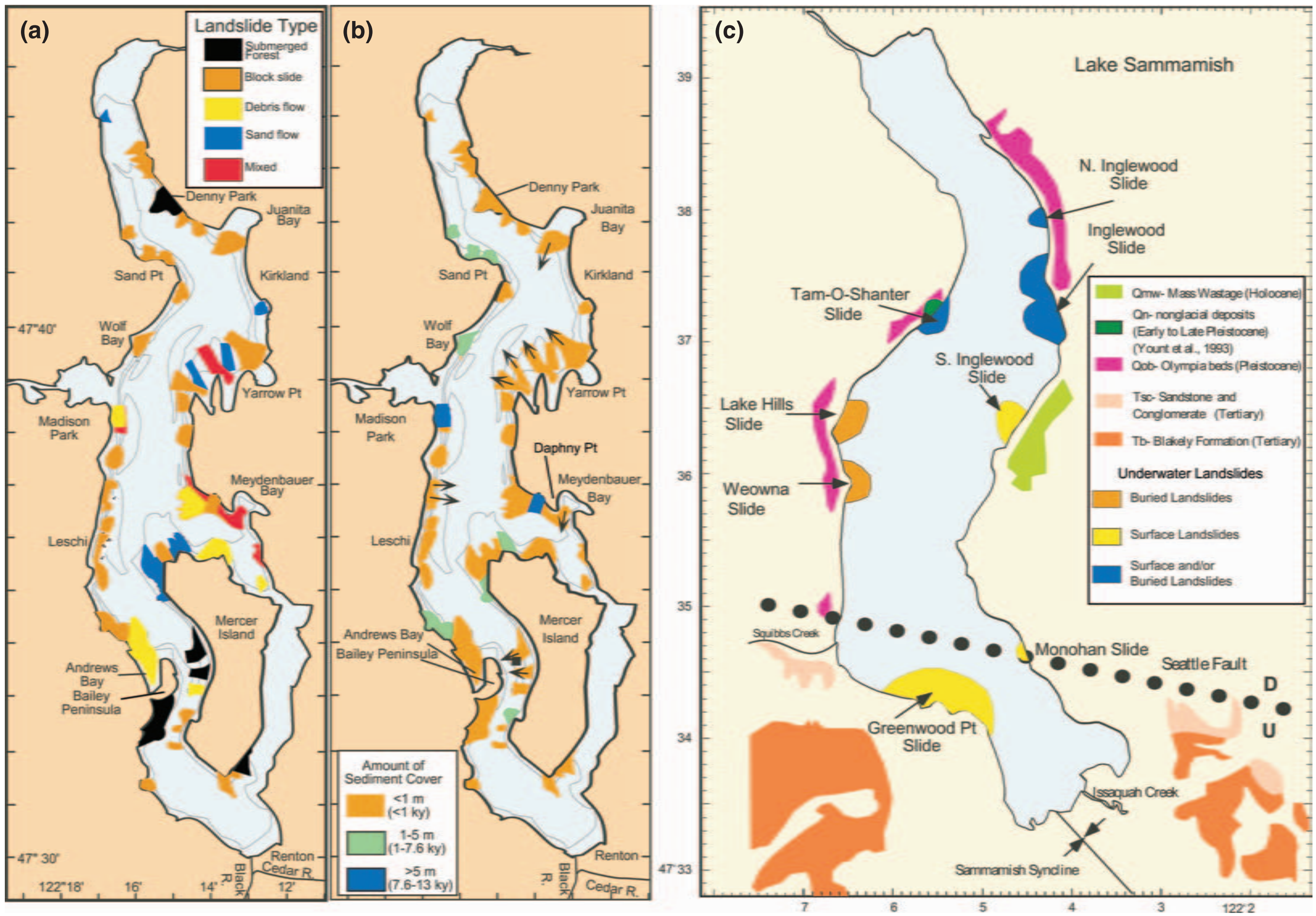


Figure 4: (a) Lake Washington subaqueous landslides mapped from high-resolution single channel seismic reflection profiles and swath sidescan imagery, and classified into submerged forests, coherent block slides, debris flows, sand flows, and mixed slumps. (b) Lake Washington subaqueous landslides classified by age. (c) Lake Sammamish geologic map, showing underwater landslides, onland exposures of pre-Frasier geology, and Holocene mass wasting.

at Puget Sound. Well-defined historic landslides that produced observed water waves provide a means for evaluating tsunami models and for estimating such factors as the velocity of the landslide mass.

Worst-case scenarios

"Worst-case" scenarios for landslides at Puget Sound can be explored by means of analogy with landslides in similar settings elsewhere. For example, as a starting hypothesis, tsunami modelers could assume a landslide about one-third the volume of the 1964 Valdez slide—a giant delta-front failure triggered by the 1964 Alaska earthquake. This particular worst case could be modeled as a delta slope, submarine, or subaerial occurrence. In all cases, however, it probably needs a large earthquake as a trigger. And because the recurrence of large shallow earthquakes on faults at Puget Sound is poorly known at best, defining the likelihood for outsize failures will ultimately depend on better definition of prehistoric earthquake recurrence.

Coulter and Migliaccio (1966) provide the best documentation of the 1964 Valdez submarine landslide. Their Figure 2 shows that Valdez Arm is a long east-west oriented fjord that terminates at the (former) town of Valdez, where it is approximately 3 miles (5 km) in width. A large delta formed by the Lowe and Robe rivers and a large stream flowing from the Valdez Glacier occupies the east end of the fjord, which was the former site of the town of Valdez. They report a total landslide volume estimated at 96 million cubic yards (74 million cubic meters). The delta slopes to a depth of 600 ft at the bottom of the fjord approximately 2 miles west of the tide flat. Based on their Plate 2, the total perimeter of the landslide is approximately 2500 m, and the top to toe distance is about 1200 m; these dimensions require an average thickness of about 25 m. Consequently, one possible geometry of a landslide that is only one third the volume of the Valdez failure would have a width of 1700 m, a thickness of 20 m, and a top to toe length of 800 m.

Could such a landslide fit into the Puyallup or Duwamish River deltas? Both Elliott and Commencement Bays are at the head of fjords that have been significantly filled with sediment during the mid to late Holocene (Dragovich *et al.*, 1994). Large deltas deposited by the Puyallup and Duwamish rivers occupy the head of these flooded fjords, similar in setting to the delta at the head of Valdez Arm. The floor of the fjords in Elliott and Commencement bays are at a depth of approximately 450 ft, somewhat shallower than at Valdez.

Because of the shallower depth of the floors of Elliott and Commencement bays, the top to toe distance of the proposed "worst-case" submarine landslide scenario must be decreased to a distance of 500 m. To accommodate this decrease, the perimeter and thickness of the scenario landslide can be set to 2000 m and 25 m, respectively. These small changes yield a landslide volume of 25 million cubic meters, roughly one third of the volume of the 1964 Valdez failure (Table 3.3).

Commencement Bay is approximately 2.5 miles wide, and similar in width to Valdez Arm. This is more than sufficiently wide to accommodate the "worst-case" delta failure scenario. The Puyallup River is largely free flowing with its water and sediment source originating from Mt. Rainier glaciers. Because of anthropogenic changes to the White/Stuck River channels, sediment supply to the Puyallup delta has significantly increased in the last 100 years. The history of delta landslides (1894 and 1943) clearly indicate the potential instability of this location.

Elliott Bay is just a little over 2 km in width, and the "worst-case" scenario delta failure would just fit within the embayment. Because of anthropogenic changes to the White/Stuck River channels and dams on the Green River, sediment supply to the Duwamish delta has significantly decreased in the last 100 years. However, the Duwamish delta is situated directly above the Seattle Fault, and the predicted ground motions from a major earthquake on this fault could easily exceed the ground motion that caused the 1964 delta failure in Valdez. Because of this factor, failure of the entirety of the Duwamish delta front does not seem far-fetched.

The Snohomish delta appears similar to the Puyallup in width, bathymetric configuration, and sediment supply. From that perspective, it would easily accommodate the "worst-case" scenario.

What is the likelihood of occurrence of this worst-case scenario? Because the most likely trigger for the "worst-case" failure of the Duwamish delta is an M 7 earthquake directly beneath it, on the Seattle Fault, this Duwamish scenario is subject to large uncertainties in estimating the recurrence intervals for such earthquakes (Section 2.2). In the event of a large earthquake on the Seattle Fault, the tsunami from tectonic displacement of the floor of the sound may further destabilize the Duwamish delta when troughs in the tsunami reduce the water load on the delta front.

The Puyallup delta has a rich history of small and moderate-sized failures, and this represents only a 110-year historic record. If delta failures behave like other natural phenomena (e.g., floods or earthquakes), then this short history suggests that the recurrence of an 1894 failure on this delta is relatively frequent on a geologic timescale. Prediction of the recurrence of this failure using statistical methods would no doubt yield a recurrence in the hundreds or few thousands of years, with large uncertainty. This situation is similar to attempts to assign a recurrence to the Seattle Fault. Although the historic Puyallup delta failures were non-seismogenic, the "worst-case" event on the Puyallup delta would likely have a seismic trigger; in this case, the appropriate question would be: "What is the recurrence of major earthquakes on nearby fault structures, especially the Tacoma Fault?"

The Nisqually delta has a significantly shallower slope, is inherently more stable than either the Puyallup, Duwamish, or Snohomish deltas, and was not considered a likely candidate for the modeling study without a more detailed evaluation. The M 6.8 Nisqually earthquake on 28 February 2001 did not trigger a Nisqually delta failure. It is not surprising that this slope remained stable in this earthquake as it did in the somewhat larger 1949 Olympia earthquake. Ground shaking in the port area of Tacoma during the Nisqually earthquake was less than 0.1 g peak ground acceleration and of short duration; this seismic loading was at or below the threshold necessary to generate liquefaction in the worst soil conditions. One hallmark of this earthquake was the paucity of subaerial landslides, likely the result of the severe drought conditions that preceded the event. However, the slopes adjacent to the Salmon Beach landslide triggered by the 1949 Olympia event did fail. If soil moisture conditions were nearer normal, this landslide might have been large enough to reach the Sound and generate a splash wave as was generated in 1949.

The Duwamish delta was shaken more strongly than the Puyallup delta during the Nisqually earthquake, and comparison of pre- and post-earthquake surveying indicated movement of Harbor Island by a number of inches. Whether this was the initiation of a delta failure that might have accelerated if the shaking was significantly stronger and/or longer is speculative. The Snohomish delta was too far distant from the Nisqually earthquake epicenter to experience even moderate shaking.

Non-deltaic submarine slide scenarios

Tables 3.4 and 3.5 provide estimates of the dimensions of selected large landslides in Puget Sound, compiled by Robert Karlin, Mark Holmes, and Shane Smith from high-resolution seismic reflection profiles, sidescan imagery, and bathymetric data. They tend to be located near Quarternary faults that cross Puget Sound, Lake Washington, and Lake Sammamish (Figs. 3 and 4). There are no historical records of these slides, and it is unknown whether they generated tsunamis.

Lake Washington subaqueous slides are presented in Fig. 4a, classified into submerged forests, coherent block slides, debris flows, sand flows, and mixed slumps. Coherent block slides are recognizable in sidescan imagery as displaced blocks with widths more than about 20 m. Block slides show coherent, but often deformed bedding in seismic reflection profiles. Submerged forests are large block slides that have upright or fallen trees on them, with the trees visible on sidescan sonar images. Debris flows show a strong reflective contrast with normal lake sediment, and may contain small boulders interspersed with incoherent sediment flows. Such flows are often found at the toe of block slides, but can occur separately. Sand flows have a bright signature on sidescan records compared with normal sediment. They show little structure, except occasional sand waves. Mixed flows are undifferentiated areas with both debris and incoherent sediment flows. Fig. 4b classifies these slides by age. The seismic reflection profiles show a distinctive sequence of reflectors within the Holocene lake sediments that can be correlated with stratigraphy known from piston coring (Karlin and Abella, 1992; 1996). The Holocene section consists of ∼1 m of transparent soft sediments over a clayey silty seismite deposited throughout the lake about 1100 years ago. The 5–15 cm thick Mazama ash deposited ∼7600 years ago forms a prominent reflector at 3–5 m sub-bottom depth. A strong acoustic contrast of the Holocene lake sediments with a hard blue-gray glacial clay at 7–20 m sub-bottom depths gives a strong, recognizable glacial/ interglacial reflector. Given the sedimentation rates in the lake and the subbottom depths of the 1100-year silt layer at 1 3 m and the 7600-year Mazama ash at 3–5 m, landslides with sediment cover of 1–3 m probably are from 1100 to 7600 years old. Landslides with >5 m sediment covers probably are of early Holocene age.

Lake Sammamish geology, underwater landslides, onland exposures of pre-Frasier geology, and Holocene mass wasting are presented in Fig. 4b. The underwater landslide distribution was determined from high-resolution seismic reflection profiling and sidescan swath mapping by R. Karlin, M. Holmes, and T. Pratt. The geology is modified from Minard and Booth (1988), Booth and Minard (1992) and Yount *et al.* (1993). Also see Prunier (1998).

3.4 Recommendations

Tsunami modelers should work closely with geoscientists who have past experience evaluating slope stability in the Puget Sound region, because it is particularly important for the credibility of the modeling that the source parameters and location of the tsunamigenic landslide are defensible. Two of the slide parameters listed in Tables 3.1 to 3.4—duration and acceleration—are essential to the modeling, but values will be difficult or impossible to obtain through field observations. Landslide source locations are not spatially random, but rather depend on factors that typically make slopes unstable (steepness of slope, geologic conditions, etc.).

Tsunami source modeling

- Tsunami scenarios should include:
  - Delta slope failures of the Puyallup, Duwamish, and Snohomish Rivers, using scenarios similar to the historical 1894 Commencement Bay event summarized in Table 3.1 and a worst-case scenario of unsure but likely very rare occurrence, based on a scaled-down version of the 1964 Valdez submarine landslide as in Table 3.3.
  - Submarine landslides due to non-delta slope failures proximal to known Quaternary faults, including those identified at Alki Point and Maury Island, using scenarios similar to that summarized in Table 3.4.
  - Subaerial landslides of the size and magnitude of the 1949 Tacoma Narrows event, summarized in Table 3.2.

Science improvement

- Expand the existing program of slope instability mapping to increase the geographical coverage and improve the quality of assessments:
  - Acquire multi-beam bathymetric data and denser high-resolution seismic reflection data, first in the areas of potential concern as shown in Fig. 3, and then for the rest of Puget Sound.
  - Collect bottom sediment cores for geological and geotechnical characterization directed toward submarine slope stability assessment.

- Characterize the geometry, nature, and timing of major submarine and subaerial landslides to determine their frequency of occurrence, method(s) of failure, and tsunami generating potential.

Table 3.1: Historic delta landslide.

Justification: Historic precedent based on the 1894 Commencement Bay landslide
Probability of occurrence: Less than 50% in 50 years (recurrence interval of at least 100 years)
Locations: Puyallup, Duwamish, and Snohomish River deltas

Parameter	Probable Range of Values (MKS Units)	Comments
Geometry	Length: 400 m Width: 300 m Thickness: 20 m Volume: 2.4×10^6 m^3 Slope angle: 15 degrees Aspect: Parallel to delta slope fall line	Geometry of this landslide well defined
Time History	Duration: TBD Distance of slide: TBD Initial acceleration: TBD **or** Density: TBD Sediment type: TBD	Parameters can be estimated by back calculation using the 1894 Commencement Bay slide geometry and reported wave height. Volume, slope, density and sediment type can provide a rough estimate of initial acceleration.

Table 3.2: Subaerial landslide.

Justification: Historical precedent based on the 1949 Tacoma Narrows landslide
Probability of occurrence: Recurrence interval of 50 years or more
Locations: Slope north of Tacoma Narrows Bridge—possibly analogous to other steep bluffs along Puget Sound

Parameter	Probable Range of Values (MKS Units)	Comments
Geometry	Length: 150 m Width: 120 m Thickness: 8 m Volume: 1.5×10^5 m^3 Slope angle: 35 degrees Aspect: Parallel to delta slope fall line	Geometry of 1949 landslide well defined
Time History	Duration: 5–10 seconds Distance of slide: 75 m Impact acceleration: TBD **or** Density: TBD Sediment type: TBD	Slope, volume, density, and sediment type can provide a rough estimate of impact acceleration.

Table 3.3: Worst-case delta failure.

Justification: Based on 1964 Valdez submarine landslide volume, scaled by 1/3.
Probability of occurrence: Unknown if this large a landslide can occur at all throughout the study areas. If so, the probability is dependent on that of large earthquakes on nearby faults.
Locations: Major river deltas, especially those of the Puyallup, Duwamish, and Snohomish Rivers.

Parameter	Probable Range of Values (MKS Units)	Comments
Geometry	Length: 500 m Width: 2000 m Thickness: 25 m Volume: 25×10^6 m^3 Slope angle: Site dependent Aspect: Parallel to delta slope fall line?	Geometry of 1964 landslide well defined, but may not be applicable to Puget Sound
Time History	Duration: TBD Distance of slide: TBD Initial acceleration: TBD **or** Density: TBD Sediment type: TBD	Volume, slope, density, and sediment type can provide a rough estimate of initial acceleration.

Table 3.4: Submarine landslide.

Justification: Slides indicated by unpublished seismic profiling data and mapping (R. Karlin, M. Holmes). Tsunami generation potential undetermined. No historic precedent exists.
Probability of occurrence: Unknown
Locations: Proximal to known Quaternary faults that cross Puget Sound, Lake Washington, and Lake Sammamish (see Figs. 3 and 4 for potential landslide zones).

Parameter	Probable Range of Values (MKS Units)	Comments
Geometry	Length: 0.5 to 3 km Width: 0.5 to 5 km Thickness: 50 to 100 m Volume: 2.4×10^6 m^3 (Maximum value that constrains specification of length, width, and thickness) Slope: Variable Aspect: Parallel to slope fall line?	
Time History	Duration: TBD Distance of slide: TBD Initial acceleration: TBD **or** Density: TBD Sediment type: TBD	Estimate parameters by back calculation, using 1894 Commencement Bay slide geometry and reported wave height. Volume, slope, density, and sediment type can provide a rough estimate of initial acceleration.

Table 3.5: Dimensions of selected large landslides in Puget Sound. Table compiled by Robert Karlin and Shane Smith from high-resolution seismic reflection profiles, sidescan imagery, and bathymetric data. Volumes were approximated by a wedge of volume (Width × Length × Thickness)/2.

Name	**Width (m)**	**Length (m)**	**Thickness (m)**	**Volume (10^6 m^3)**	**Type**
Maury Island South	590	1830	60	33	Block slide
Maury Island Mid	300	1330	50	10	Block slide
Maury Island North	1000	2780	50	70	Block slide
Three Tree Point	1750	3390	TBD	TBD	Three complex slides each with multiple events
Restoration Point	1000	1050	TBD	TBD	Block slide, bathymetric expression
Alki Point	1000	2700	5 to 20 for most recent debris flow	7 to 27	Deformation zone covered by debris flow(s), bathymetric expression
Edmonds	1850	2850	120	316	Large block slide, bathymetric expression
Mukilteo	1400	2750	10–15	20 to 29	Sand flow
Edgewater	1280	2940	5 to >40 for most recent slide	10 to >76	Multiple block slides of varying thickness
Possession Point South	630	1250	60 for most recent slide	23	Multiple block slides and events
Possession Point Middle	500	1230	75	23	Two or more block slides and events
Possession Point North	920	1530	75	53	Multiple block slides and events

4. Paleotsunami Field Evidence

4.1 Background

At Puget Sound, tsunami hazards are being identified and quantified by combining geologic field observations with inundation modeling. Although earthquakes, landslides, and delta failures have the potential to generate tsunamis in Puget Sound and nearby lakes, little is known about the frequency and size of tsunamis from these sources. Geologic field evidence useful in tsunami inundation modeling includes: (1) amount and distribution of coseismic uplift and subsidence, (2) size and location of delta failure and landslide scarps and deposits, (3) distribution, grain size, and internal structure of tsunami deposits, (4) microfossils, which are useful in quantifying subsidence and uplift and in identification of tsunami deposits, and (5) dateable material within deposits that help establish tsunami frequency.

Tsunami deposits are especially valuable because they demonstrate that Puget Sound tsunamis have occurred in the past, as illustrated by deposits of the A.D. 900–930 tsunami identified in Seattle, Cultus Bay, and the Snohomish delta (Atwater and Moore, 1992; Bourgeois and Johnson, 2001; Koshimura *et al.*, 2002). Deposits can be used for education of the general public and by emergency managers as solid evidence of a tsunami hazard. For example, locations of identified tsunami deposits appear on a tsunami inundation map for the southwest coast of Washington (Walsh *et al.*, 2000).

4.2 Priority Areas

To identify a tsunami deposit is to identify a tsunami hazard, but tsunami deposits in the Puget Sound area have not been comprehensively identified. Therefore, the entire Puget Sound area is a priority area for tsunami deposit research, except for the very few spots where deposits have already been identified. High potential areas should be explored in a reconnaissance mode, with high priority given to those areas where modeling reasonable source scenarios suggests large tsunamis. This type of collaboration by modelers and field geologists will improve definition of areas with tsunami risk. The area studied should include the shores of Lake Washington because large, potentially tsunamigenic landslides occurred there 1100 years ago, and because currents from a moderate tsunami in Lake Washington could pose a hazard to floating bridges.

4.3 Inferences About Past Tsunamis

What happened at Puget Sound during past tsunamis can be learned, to some extent, from clues in tsunami deposits. Sedimentation models can be used in conjunction with inundation models to interpret tsunami deposits found in the Puget Sound area and help estimate tsunami parameters, including inundation distance, runup height, flow depth, and flow velocity; bottom friction estimates, extremely important in inundation modeling, can also be improved by using velocity estimates from both inundation and tsunami sedimentation models (Titov *et al.*, 2001). If deposits can be dated, then estimates can also be made of tsunami frequency.

4.4 Recommendations

Tsunami source modeling

- Incorporate any available paleotsunami parameter estimates into site-specific tsunami model development, as a test of accuracy and as a possible constraint on model input parameters.

Science improvement

- Map tsunami deposits where present at Puget Sound and Lakes Washington and Sammamish.
- Conduct detailed sedimentology, micropaleontology, and age dating studies at selected tsunami deposit sites.
- Continue the combined use of sedimentation and inundation models to help improve estimates of paleotsunami parameters.
- Compile geologic evidence for coseismic uplift and subsidence, landslides, delta failures, and tsunami deposits and develop maps of this evidence to help constrain and test tsunami models.
- Improve quantification of coseismic uplift and subsidence.

5. Seattle-Duwamish Waterfront Inundation

The NOAA Center for Tsunami Inundation Mapping Efforts (TIME) recently modeled tsunami inundation along the Seattle-Duwamish waterfront (Titov *et al.*, 2003). This modeling provides preliminary estimates of the flooding that might result from a rare event—a large earthquake on the Seattle fault. The computed tsunami results entirely from tectonic uplift and subsidence during the earthquake; not included in the model is delta-front failure, such as discussed in Section 3.

5.1 Background

NOAA's TIME Center has been conducting numerical model simulations of Puget Sound tsunamis for the Washington State Emergency Management Division (WAEMD). The first modeling effort was a relatively coarse-grid simulation covering most of Puget Sound for a tsunamigenic earthquake on the Seattle fault (Koshimura *et al.*, 2002). The results of that simulation were one factor considered by the WAEMD in identifying Puget Sound communities at risk and prioritizing these communities for development of fine-resolution inundation maps.

5.2 Priority Areas

The coarse-grid Puget Sound simulation suggested that, based on the extreme scenario modeled, a significant tsunami could strike the Seattle-Elliott Bay area, which is characterized by high population and critical infrastructure, within a few minutes of an earthquake on the nearby Seattle Fault. Subsequently, the WAEMD funded the NOAA TIME Center to develop inundation map products for the somewhat larger Seattle-Duwamish area.

5.3 Event Description

Source specification

TIME modelers used an M 7.3 earthquake on the Seattle Fault Zone as a nearly worst-case tsunami generating mechanism. Because the recurrence intervals for such an earthquake probably span thousands of years, it is believed that a similar event has a very low probability of occurring in our lifetimes. The justification for modeling this low, but finite, probability event as a credible near-worst-case Puget Sound threat is the significant and growing population and infrastructure that is now at risk.

The model uses assumptions about the dip of the fault plane and the width and length of fault rupture that are within the broad range of possibilities consistent with reports cited in Section 2.2. For instance, the Brocher *et al.* (2001) interpretation suggests dips of ~60° to 80° and fault widths of ~30 km (values not specifically provided in the text, but shown on a figure), while Calvert and Fisher (2001) suggested dip angles of 40° to 80° (60° ± 20°). The slip distribution was constrained, through trial and error, to match available field estimates of vertical displacement at three sites—Alki Point, Restoration Point, and West Point—which presumably occurred as a result of the earthquake in A.D. 900–930. The fault parameters specified for the simulation are provided in Table 5.1. The comparison of computed displacement with field estimates is provided in Table 5.2, and the resulting vertical deformation is illustrated in Fig. 1a, along with the location and values of the vertical deformation field estimates.

It should be noted that different sets of model parameters can produce similar fits to the observations. Thus, each of these two models, though somewhat different, provide a reasonable fit to the observed deformation. In this case, it made little difference in the inundation model results. It is generally true, however, that professional judgment must be applied to assess the geophysical credibility of each model. Because of this, and because the geometry and earthquake history of the Seattle fault remain controversial among Earth scientists, these model parameters need to be reviewed in a separate, formal workshop, in which experts come together to reach a consensus and provide official recommendations. Such a workshop, dedicated to tsunami source specification, is essential to developing site-specific tsunami generation scenarios and the resulting inundation maps. A workshop dedicated to the systematic assessment of current scientific information by a group of experts is a traditional way of establishing the best available science for a particular topic and judging the adequacy of that science to contribute

Table 5.1: Sub-fault parameters for magnitude 7.3 and 7.6 Seattle Fault earthquake models. The M 7.3 vertical deformation pattern is shown in Fig. 1a.

Sub-fault (west to east)	Depth (km)	Length (km)	Width (km)	Strike (deg)	Dip (deg)	M 7.3 Slip (m)	M 7.6 Slip (m)
1	0.5	15.2	20	87.9	60	1	3
2	0.5	6.3	20	86.6	60	1	3
3	0.5	8.9	20	96.0	60	12	14
4	0.5	3.2	20	128.8	60	11	10
5	0.5	11.5	20	99.3	60	4	4
6	0.5	14.9	20	81.0	60	1	3

Table 5.2: Vertical deformation values for field estimates and the M 7.3 and M 7.6 Seattle Fault models. See Fig. 1a for the geographical location of the sites.

Site	Field (m)	M 7.3 Model (m)	M 7.6 Model (m)
Alki Point	4–6.5	3.9	4.0
Restoration Point	7	7.1	7.0
West Point	–1 ± 0.5	−1.2	−1.0

meaningfully to issues of concern—public safety and hazard mitigation, for example.

Accordingly, recommendations below include yearly workshops, because updating tsunami source specification is an important part of developing and improving inundation maps. As an example of source refinement, the Koshimura *et al.* (2002) model is characterized by a magnitude Mw 7.6 with uniform slip of 2.8 m on each of six sub-faults composed of a shallow fault plane dipping 60° situated directly above a deeper fault plane with dip of 25°. A different seismic source model emerges if an earthquake in the range Mw 7.3–7.6 has sources composed of six sub-faults, each with independently assigned slip along a single plane that dips 60° (Table 5.1). The TIME model may need revision as patterns of coseismic vertical deformation become clearer from studies of fault geometry (ten Brink *et al.*, 2002) and high-resolution topographic maps (*http://duff.geology.washington.edu/data/raster/lidar/surfmap/*).

Model results

The model of Titov and Synolakis (1998), also known as the Method of Splitting Tsunami (MOST) model (Titov and González, 1997) was used by TIME modelers to simulate the generation, propagation, and inundation of tsunamis in the Seattle-Duwamish area. Close communication was maintained during the study with WAEMD and the Washington Department of

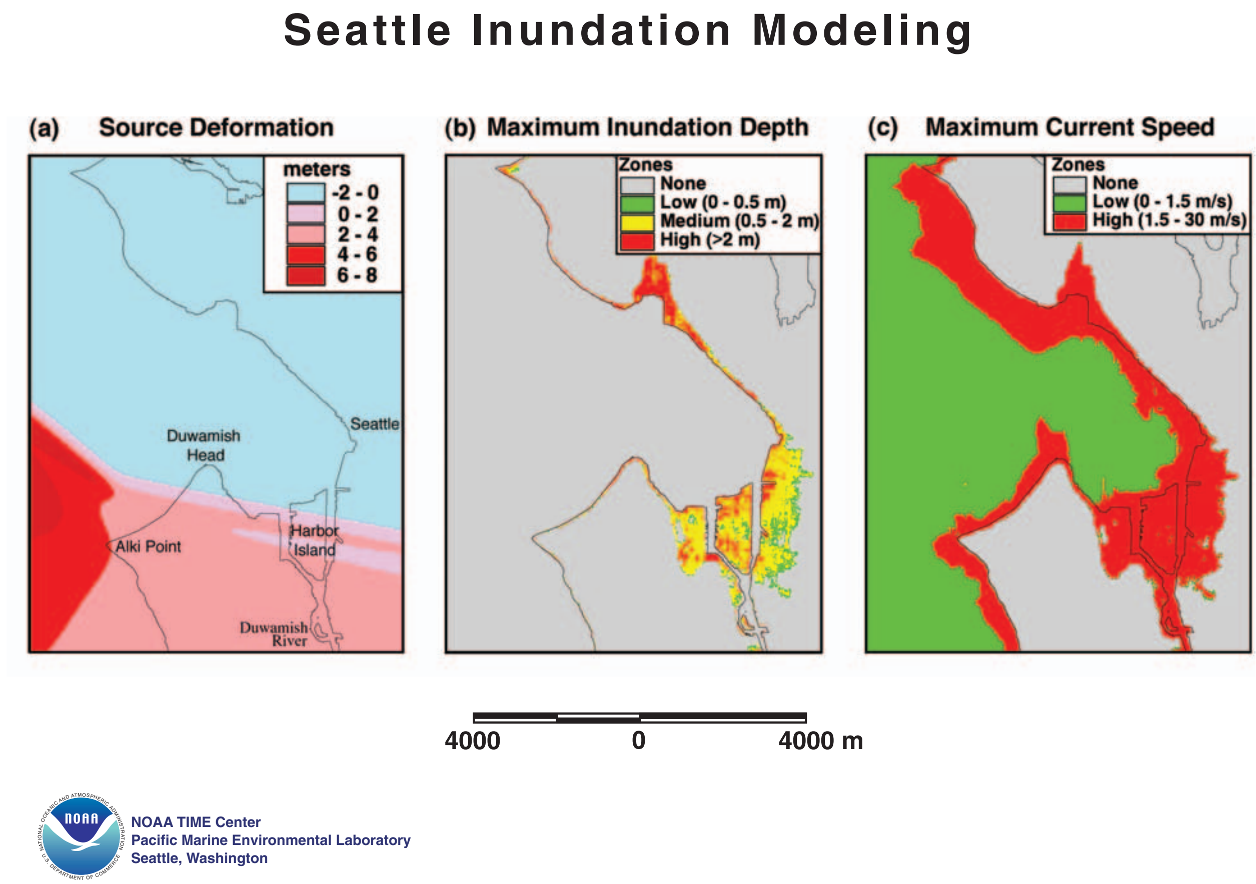


Figure 5: Seattle-Duwamish waterfront inundation modeling products: (a) crustal deformation in the Seattle-Duwamish area; (b) zoned maximum inundation depth; (c) zoned maximum current speed. See text for discussion of selection of ranges for individual zones.

Natural Resources (WADNR) 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. The product suite included an animation of the entire simulation, which is also available for viewing on the Workshop website (*http://www.pmel.noaa.gov/tsunami/time/PS_source_wkshp/*). Three graphical summary products derived from that simulation are presented in Figs. 5a–c.

Figure 5a presents the computed vertical deformation for the Seattle-Duwamish area. The general pattern is one of subsidence as great as 2 m at Duwamish Head, the north end of Harbor Island, and the entire region north of these sites, including the Seattle waterfront, and uplift as great as 4 m south of these sites. The decrease in the modeled uplift eastward from Alki Point may prove inconsistent with uplifted tidal-flat deposits along the Duwamish River (B.F. Atwater, unpublished data).

Figures 5b and 5c present two fundamental modeling products of primary importance to emergency managers—maximum inundation depth (the height of water above land) and maximum current speed, respectively. These products are obtained by monitoring each variable at individual grid points and saving the maximum value attained over the course of the entire simulation. Zonation is then performed to produce the maps shown—i.e., the fine scale details are deliberately suppressed by binning values into zones with ranges that have physical significance to emergency managers. Thus, for an average adult, the depth range zones correspond roughly to "up to knee-high" (Low), "up to head-high" (Medium) and "over the head" (High), and current speed zones are roughly "up to the speed of a brisk walk" (Low) and "faster than a brisk walk" (High). For the Seattle-Duwamish waterfront areas, the computed water depths are greater than 2 m and the current speeds in excess of 2 m/s.

Model limitations

The model has limited ability to simulate tsunami generation and tsunami effects. The model results express few uncertainties about the fault geometry, the spatial distribution of slip, and the amount of surface rupture that generate the tsunami. Although the tectonic deformation illustrated in Fig. 5a is accounted for in the tsunami inundation computations, additional tsunami sources such as delta failure, submarine and subaerial landslides, and liquefaction, were not. Nor does the simulation account for hydrodynamic effects on the tsunami wave and currents of smaller scale features and objects—buildings, automobiles, maritime vessels, large rocks, trees, and the thousands of shipping containers stored on Harbor Island, for example—that would, in some cases, become entrained debris that would act as projectiles. Also ignored are the effects on structures and humans of the tsunami waves and currents, as well as hazards such as the spreading of flammable liquids.

Source uncertainty and sensitivity studies

There is a fundamental difference in the nature of the seismic hazard maps and the inundation map presented here. The seismic hazard maps are developed as a weighted probabilistic distribution of earthquake events. In contrast, the inundation map is deterministic: it is intended to represent a maximum credible event based on an extreme scenario earthquake that occurs rarely.

In a deterministic approach, multiple simulations can be conducted to develop site-specific sensitivity studies. Such studies constrain the possible range of source parameters—e.g., variations in the magnitude, location, dip, slip, etc., of earthquake sources—and then perform tsunami inundation simulations that correspond to the source variations. The result is a mapping of potential source variation into potential tsunami inundation variation that provides additional insight into the vulnerability of a site. This approach is routinely used in many other scientific and engineering disciplines and is frequently referred to as a response study, in which the input to a system is varied systematically and the output is analyzed and interpreted to characterize the system.

As a very simple example of this approach, an M 7.6 Seattle fault event was also modeled, subject to the constraint that the resulting deformation pattern must match the three field observations at least as well as the M 7.3 model. Again, trial and error was used to adjust the fault plane parameters. The M 7.6 slip values and the resulting deformation values at the three field sites are listed in Tables 5.1 and 5.2. The M 7.6 model produced a vertical deformation pattern that was somewhat different, but very similar, to the pattern produced by the M 7.3 model. As a consequence, the M 7.6 model produced tsunami inundation values and patterns that were essentially the same as the M 7.3 event.

5.4 Recommendations

In addition to recommendations in previous sections about tsunami sources, the following may improve tsunami inundation models and mitigation products derived from them.

Science improvement

- Complete Puget Sound LIDAR coastal bathymetric/topographic surveys.
- Complete Puget Sound swath-beam bathymetric surveys.
- Use Puget Sound LIDAR and swath-beam surveys to develop a system of improved bathymetric/topographic computational grids.
- Review and assess existing models for sub-aerial and sub-aqueous slides, and determine the sensitivity of tsunami generation to variations in the model parameters.
- Review and assess existing methodologies for simulating tsunami effects on and interactions with structures and humans.
- Develop hardware and software technologies for fast, efficient multiple simulations.
- Develop methods for site-specific, multiple simulation sensitivity studies.
- Develop improved hazard mitigation products based on site-specific sensitivity studies, in close collaboration with WAEMD and WADNR.
- Conduct yearly workshops to review the best available scientific information and develop recommendations for Washington State inundation mapping.

6. Acknowledgments

Preparation of this report was sponsored by the National Oceanic and Atmospheric Administration, the U.S. Geological Survey, the Washington State Natural Resources Division, and the Washington State Military Department Emergency Management Division. Figures were prepared by Karen Birchfield. The final manuscript was formatted and prepared for publication by Ryan Layne Whitney.

References

Atwater, B.F. (1999): Radiocarbon dating of a Seattle earthquake to A.D. 900–930 [abstract]. *Seismol. Res. Lett.*, *70*, 232.

Atwater, B.F., and A.L. Moore (1992): A tsunami about 1000 years ago in Puget Sound, Washington. *Science*, *258*, 1614–1617.

Bernard, E.N. (2001): The U.S. National Tsunami Hazard Mitigation Program. In *Proceedings of the International Tsunami Symposium 2001 (ITS 2001)* (on CD-ROM), NTHMP Review Session, R-1, Seattle, WA, 7–10 August 2001, 21–27, URL `http://www.pmel.noaa.gov/its2001/`.

Blakely, R.J., R.E. Wells, C.S. Weaver, and S.Y. Johnson (2002): Location, structure, and seismicity of the Seattle fault zone, Washington: Evidence from aeromagnetic anomalies, geologic mapping, and seismic-reflection data. *Geol. Soc. Am. Bull.*, *114*(1), 169–177.

Booth, D.B., and J.P. Minard (1992): Geologic map of the Issaquah quadrangle, King County, Washington. U.S. Geological Survey Miscellaneous Field Studies Map MF-2206, scale 1:24,000.

Bourgeois, J., and S.Y. Johnson (2001): Geologic evidence of earthquakes at the Snohomish delta, Washington, in the past 1200 yr. *Geol. Soc. Am. Bull.*, *113*, 482–494.

Brocher, T.M., T. Parsons, R.J. Blakely, N.I. Christensen, M.A. Fisher, R.E. Wells, and the SHIPS Working Group (2001): Upper crustal structure in the Puget Lowland, Washington: Results from the 1998 Seismic Hazard Investigation in Puget Sound. *J. Geophys. Res.*, *106*(B7), 13,541–13,564.

Bucknam, R.C., E. Hemphill-Haley, and E.B. Leopold (1992): Abrupt uplift within the past 1700 years at southern Puget Sound, Washington. *Science*, *258*, 1611–1614.

Bucknam, R.C., B.L. Sherrod, and G. Elfendahl (1999): A fault scarp of probable Holocene age in the Seattle Fault Zone, Bainbridge Island, Washington. *Seismol. Res. Lett.*, *70*(2), 233.

Calvert, A.J., and M.A. Fisher (2001): Imaging of the Seattle Fault Zone with high resolution seismic tomography. *Geophys. Res. Lett.*, *28*(12), 2337–2340.

Chleborad, A.F. (1994): Modeling and analysis of the 1949 Narrows landslide, Tacoma, Washington. *Bull. Assoc. Eng. Geol.*, *31*, 305–327.

Coulter, H.W., and R.R. Migliaccio (1966): Effects of the earthquake of March 27, 1964 at Valdez, Alaska. U.S. Geological Survey Professional Paper 542-C, 36 pp., 3 plates.

Crawford, G., H. Mofjeld, and C. Weaver (eds.) (2001): Summary of Puget Sound Tsunami/Landslide Workshop, January 23 and 24, 2001. URL `http://www.pmel.noaa.gov/tsunami/Ws20010123/`.

Dragovich, J.D., P.T. Pringle, and T.J. Walsh (1994): Extent and geometry of the mid-Holocene Osceola Mudflow in the Puget Lowland—Implications for Holocene sedimentation and paleogeography. *Wash. Geol.*, *22*(3), 3–26.

Frankel, A., C. Mueller, T. Barnhard, D. Perkins, E.V. Leyendecker, N. Dickman, S. Hanson, and M. Hopper (1996): National Seismic Hazard Maps: Documentation June 1996. U.S. Geological Survey Open-File Report 96-532.

Frankel, A., C. Mueller, T. Barnhard, D. Perkins, E.V. Leyendecker, N. Dickman, S. Hanson, and M. Hopper (1997): Seismic-hazard maps for the conterminous United States. U.S. Geological Survey Open-File Report 97-131.

Frankel, A.D., M.D. Petersen, C.S. Mueller, K.M. Haller, R.L. Wheeler, E.V. Leyendecker, R.L. Wesson, S.C. Harmsen, C.H. Cramer, D.M. Perkins, and K.S. Rukstales (2002): Documentation for the 2002 update of the national seismic hazard maps. U.S. Geological Survey Open-File Report 02-420, 33 pp., URL `http://geohazards.cr.usgs.gov/eq/of02-420/OFR02-420.pdf`.

Gardner, J.V., E.J. van den Ameele, G. Gelfenbaum, W. Barnhardt, H. Lee, and S. Palmer (2001): Mapping southern Puget Sound delta fronts after the 2001 Nisqually earthquake. URL `http://geopubs.wr.usgs.gov/open-file/of01-266/html/article.htm`.

González, F.I., V.V. Titov, H.O. Mofjeld, A.J. Venturato, and J.C. Newman (2001): The NTHMP Inundation Mapping Program. In *Proceedings of the International Tsunami Symposium 2001 (ITS 2001)* (on CD-ROM), NTHMP Review Session, R-2, 29–54, URL `http://www.pmel.noaa.gov/its2001/`.

Hasagawa, H.S., and H. Kanamori (1987): Source mechanism of the magnitude 7.2 Grand Banks earthquake of November 1929: Double couple or submarine landslide. *Bull. Seismol. Soc. Am.*, *77*(6), 1984–2004.

Heezen, B.C., and C.L. Drake (1964): Grand Banks slump. *Bull. Am. Assoc. Petrol. Geol.*, *48*(2), 221–233.

Heezen, B.C., and M. Ewing (1952): Turbidity currents and submarine slumps, and the 1929 Grand Banks earthquake. *Am. J. Sci.*, *250*, 849–873.

Ishiyama, T., K.J. Mueller, M. Togo, K. Takemura, and A. Okada (2002): Geomorphology and kinematics of the Nobi-Ise active fault zone, central Japan: Implications for the kinematic growth of tectonic landforms within an active thrust belt [abstract]. American Geophysical Union 2002 Fall Meeting, abstract S11B-1140, URL `http://www.agu.org/meetings/fm02/waisfm02.html`.

Johnson, S.Y. (1996): The southern Whidbey Island fault: An active structure in the Puget Lowland, Washington. *Geol. Soc. Am. Bull.*, *108*(3), 334–354.

Johnson, S.Y. (2001): Active tectonics of the Devils Mountain fault and related structures, northern Puget Lowland and eastern strait of Juan de Fuca region, Pacific Northwest. U.S. Geological Survey Professional Paper 1643, 45 pp.

Johnson, S.Y., S.V. Dadisman, J.R. Childs, and W.D. Stanley (1999): Active tectonics of the Seattle fault and central Puget Sound, Washington: Implications for earthquake hazards. *Geol. Soc. Am. Bull.*, *111*(7), 1042–1053.

Karlin, R.E., and S.E.B. Abella (1992): Paleoearthquakes in the Puget Sound region recorded in sediments from Lake Washington, U.S.A. *Science*, *258*(5088), 1617–1620.

Karlin, R.E., and S.E.B. Abella (1996): A history of Pacific Northwest earthquakes recorded in Holocene sediments from Lake Washington. *J. Geophys. Res.*, *101*(B3), 6137–6150.

Karlin, R.E., M. Holmes, S.E.B. Abella, and R. Sylwester (2002): Holocene landslides and a 3500 year sediment record of Pacific Northwest earthquakes from Lake Washington, Pacific Northwest. *Geol. Soc. Am. Bull.*, in press.

Kayen, R.L., W.A. Barnhardt, and S.P. Palmer (1999): Geomorphological and geotechnical issues affecting the seismic slope stability of the Duwamish River delta, Port of Seattle, Washington. In *Optimizing Post-Earthquake Lifeline System Reliability, Proceedings of the 5th U.S. Conference on Lifeline Earthquake Engineering*, W.M. Elliott, and P. McDonough (eds.), American Society of Civil Engineers, Technical Council on Lifeline Earthquake Engineering Monograph No. 16, 482–492.

Kelsey, H.M., and B.L. Sherrod (2001): Test for Late Holocene displacement on the Southern Whidbey Island Fault Zone, northern Puget Lowland, Washington. *Seismol. Res. Lett.*, *72*(2), 253.

Koshimura, S., H.O. Mofjeld, F.I. González, and A.L. Moore (2002): Modeling the 1100 bp paleotsunami in Puget Sound, Washington. *Geophys. Res. Lett.*, *29*(20), 1948, doi: 10.1029/2002GL015170.

Lander, J.F. (1988): An analysis of tsunami fatalities in the United States. In *Proceeding of the Natural and Man-Made Hazards in Coastal Areas Conference*, Ensenada, Mexico.

Minard, J.P., and D.B. Booth (1988): Geologic map of the Redmond quadrangle, King and Snohomish Counties, Washington. U.S. Geological Survey Miscellaneous Field Investigations Map MF-2016, scale 1:24,000.

Moore, D.G. (1978): Submarine slides. In *Developments in Geotechnical Engineering,* 14A, Rockslides and Avalanches, 1, B. Voight (ed.), Elsevier Scientific Publishing Company, 564–604.

Nelson, A.R., S.Y. Johnson, R.E. Wells, S.K. Pezzopane, H.M. Kelsey, B.L. Sherrod, L.-A. Bradley, R.D. Koehler, III, R.C. Bucknam, R. Haugerud, and W.T. Laprade (2002): Field and laboratory data from an earthquake history study of the Toe Jam Hill fault, Bainbridge Island, Washington. U.S. Geological Survey Open-File Report 02-0060, URL `http://greenwood.cr.usgs.gov/pub/open-file-reports/ofr-02-0060/`.

Nelson, A.R., S.K. Pezzopane, R.C. Bucknam, R.D. Koehler, C.F. Narwold, H.M. Kelsey, W.T. Laprade, R.E. Wells, and S.Y. Johnson (1999): Holocene surface faulting in the Seattle Fault Zone, Bainbridge Island, Washington [abstract]. *Seismol. Res. Lett.*, *70*(2), 233.

Noson, L.L., A. Qamar, and G.W. Thorsen (1988): Washington State earthquake hazards. Washington Division of Geology and Earth Resources Information Circular 85, 77 pp.

Piper, D.J.W., P. Cochonat, and M.L. Morrison (1999): The sequence of events around the epicentre of the 1929 Grand Banks earthquake: Initiation of debris flows and turbidity current inferred from sidescan sonar. *Sedimentology*, *46*(1), 79–97.

Pratt, T.L., S. Johnson, C. Potter, W. Stephenson, and C. Finn (1997): Seismic reflection images beneath Puget Sound, western Washington State: The Puget lowland thrust sheet hypothesis. *J. Geophys. Res.*, *102*, 27,469–27,489.

Prunier, C.F. (1998): Holocene faulting and landsliding in Lake Sammamish related to the Seattle fault. M.S. thesis, University of Nevada, Reno, NV.

Sherrod, B.L. (2001): Evidence for earthquake-induced subsidence about 1100 yr ago in coastal marshes of southern Puget Sound, Washington. *Geol. Soc. Am. Bull.*, *113*(10), 1299–1311.

Sherrod, B.L. (2002): Late Quaternary surface rupture along the Seattle fault zone near Bellevue, Washington [abstract]. American Geophysical Union 2002 Fall Meeting, abstract S21C-12.

Sherrod, B.L., T. Brocher, and R.C. Bucknam (2002): Asynchronous land-level change along the Tacoma Fault in A.D. 800–1200 [abstract]. *Seismol. Res. Lett.*, *73*(2), 240.

Shipman, H. (2001): The fall of Camano Head: A Snohomish account of a large landslide and tsunami in Possession Sound during the early 1800s. *TsuInfo Alert*, *3*(6), 13–14, URL `http://www.wa.gov/dnr/htdocs/ger/tsuinfo/2001-06.pdf`.

Spaeth, M.G., and S.C. Berkman (1972): The tsunamis as recorded at tide stations and the seismic sea wave warning system. In *The Great Alaska Earthquake of 1964: Oceanography and Coastal Engineering*, Committee on the Alaska Earthquake, National Academy of Sciences, 38–110.

ten Brink, U.S., P.C. Molzer, M.A. Fisher, R.J. Blakely, R.C. Bucknam, T. Parsons, R.S. Crosson, and K.C. Creager (2002): Subsurface geometry and evolution of the Seattle Fault Zone and the Seattle Basin, Washington. *Bull. Seismol. Soc. Am.*, *92*, 1737–1753.

Titov, V.V., and F.I. González (1997): Implementation and testing of the Method of Splitting Tsunami (MOST) model. NOAA Tech. Memo. ERL PMEL-112 (PB98-122773), NOAA, Pacific Marine Environmental Laboratory, 11 pp.

Titov, V.V., and F.I. González (2001): Numerical study of the source of the July 17, 1998 PNG tsunami. In *Tsunami Research at the End of a Critical Decade*, G.T. Hebenstreit (ed.), Kluwer Acad. Pub., Netherlands, 197–207.

Titov, V.V., F.I. González, H.O. Mofjeld, and A.J. Venturato (2003): NOAA TIME Seattle Tsunami Mapping Project: Procedures, data sources, and products. NOAA Tech. Memo. OAR PMEL-124, NOAA, Pacific Marine Environmental Laboratory, 20 pp., in press.

Titov, V.V., B. Jaffe, F.I. González, and G. Gelfenbaum (2001): Re-evaluating source mechanisms for the 1998 Papua New Guinea tsunami using revised slump estimates and sedimentation modeling. In *Proceedings of the International Tsunami Symposium 2001 (ITS 2001)* (on CD-ROM), NOAA/PMEL, Seattle, WA, 7–10 August 2001, 2–5.

Titov, V.V., and C.E. Synolakis (1998): Numerical modeling of tidal wave runup. *J. Waterw. Port Coast. Ocean Eng.*, *124*(4), 157–171.

University of Washington, Department of Oceanography (1953): Puget Sound and Approaches, A Literature Survey. Work performed under Contract No. Nonr-447(00), Task Order 477(06) of the Office of Naval Research, Volume II.

Wagner, H.C., and J.H. Tomson (1987): Offshore geology of the Strait of Juan de Fuca, State of Washington and British Columbia, Canada. Washington Division of Geology and Earth Resources Open File Report 87-1, 16 pp., 7 plates.

Walsh, T.J., C.G. Caruthers, A.C. Heinitz, E.P. Myers, III, A.M. Baptista, G.B. Erdakos, and R.A. Kamphaus (2000): Tsunami hazard map of the southern Washington coast—Modeled tsunami inundation from a Cascadia Subduction Zone earthquake. Washington Division of Geology and Earth Resources Report GM-49, 12 pp., 1 pl. scale 1:100,000.

Washington State Legislature (1995): Growth Management Act—Procedural Criteria for Adopting Comprehensive Plans and Development Regulations. Washington Administrative Code WAC 365-195-900 through 925, URL `http://www.leg.wa.gov/wac/`.

Washington State Office of Community Development (2002): Citations of Recommended Sources of Best Available Science for Designating and Protecting Critical Areas. URL `http://www.ocd.wa.gov/info/lgd/growth/`.

Williams, H., and I. Hutchinson (2000): Stratigraphic and microfossil evidence for late Holocene tsunamis at Swantown Marsh, Whidbey Island, Washington. *Quatern. Res.*, *54*, 218–237.

Williams, H., I. Hutchinson, and A. Nelson (2002): Multiple sources for late Holocene tsunamis at Discovery Bay, Washington State. American Geophysical Union, 2002 fall meeting, abstract S22B-1032.

Wilson, B.W., and A. Torum (1972): Effects of the tsunamis: An engineering study. In *The Great Alaska Earthquake of 1964: Oceanography and Coastal Engineering*, Committee on the Alaska Earthquake, National Academy of Sciences, 361–523.

Yount, J.C., J. Minard, and G. Dembroff (1993): Geologic map of surficial deposits in the Seattle $30' \times 60'$ quadrangle. U.S. Geological Survey Open File Report 93-233, 2 sheets.

Addendum: Seismic Surface Wave Forcing of Water Waves and Seiches (by H. O. Mofjeld)

Well after the workshop, the Mw 7.9 Alaska earthquake on 3 November 2002 generated strong seismic surface waves southward that created damaging water waves in Lake Union (Barberopoulou *et al.*, 2002) and Puget Sound marinas (A. Qamar and W. Steele, private communication). There is also evidence that the Seattle sedimentary basin acted to amplify the seismic surface waves in its vicinity (Barberopoulou *et al.*, 2002). Vertical seismic wave amplitudes as large as 0.3 m were recorded in the Seattle area.

Strong seismic waves will occur in the Puget Sound region as the result of earthquakes on local, Cascadia, and even distant fault zones. Therefore, it is appropriate to include seismic surface waves as potential geophysical sources of dangerous water waves in Puget Sound.

To fully characterize the seismic surface waves as sources, a database is needed that contains the probabilities of their amplitudes, frequencies, and orientations as functions of geographical location. Of particular importance are the horizontal velocities of the ground, since these are the primary mechanism generating the water waves at the shore (Mofjeld, in preparation). These are needed for the fault zones in the Puget Sound region, the Cascadia Subduction Zone, and more distant regions such as Alaska. The orientation is important because the amplitudes of the water waves can be very sensitive to this parameter.

Also needed are observed and synthetic time series of the seismic surface waves to drive water response models. The wave periods of greatest interest are between one to 60 seconds, in terms of generating dangerous waves and seiches within small bodies of water.

The USGS shake map for the Puget Lowland is an essential step forward in developing this database. At present, it provides peak accelerations due primarily to earthquakes on the Seattle Fault, South Whidbey Island Fault, and the Cascadia Subduction Zone. These accelerations need to be integrated in time in order to give peak horizontal velocities. Deep focus earthquakes under the Puget Lowland occur on irregular decadal to multidecadal timescales, as observed in the 20th century. While they are less prone to generate strong seismic surface waves than shallow earthquakes, they cannot be discounted as potential sources.

References

Barberopoulou, A., K. Creager, A. Qamar, G. Thomas, and W. Steele (2002): Local amplification of seismic waves from the Mw 7.9 Alaska earthquake and a damaging seiche in Lake Union, Seattle, Washington. Fall AGU Meeting, Abstracts.

Mofjeld, H.O., F.I. González, V.V. Titov, and J.C. Newman: The generation of seismic seiches and their dependence on seismic wave dispersion and imperfect boundary reflection. In preparation.

Appendix A: Workshop Participants

Brian F. Atwater
Univ. of Washington
Box 351310
Seattle, WA 98195
Phone: 206.553.2927
Fax: 206.553.8350
E-mail: atwater@usgs.gov

Eddie Bernard
NOAA/PMEL
7600 Sand Point Way NE
Seattle, WA 98115
Phone: 206.526.6800
Fax: 206.526.4576
E-mail: eddie.n.bernard@noaa.gov

George Crawford
Washington State Military Dept.
Emergency Management Div.
Camp Murray, WA 98430-5122
Phone: 253.512.7067
Fax: 253.512.7207
E-mail: g.crawford@emd.wa.gov

David Finlayson
School of Oceanography
University of Washington
Seattle, WA 98195
Phone: 206.543.7229
E-mail: dfinlays@u.washington.edu

Arthur D. Frankel
P.O. Box 25046
Lakewood, CO 80225
Phone: 303.273.8556
Fax: 303.273.8600
E-mail: afrankel@usgs.gov

James V. Gardner
Bldg. 15, McKelvey Building
USGS Mailstop 999
Menlo Park, CA 94025
Phone: 650.329.5469
E-mail: jvgardner@usgs.gov

Carolyn Garrison-Laney
Department of Earth and Space Sciences/USGS
63 Johnson Hall, Box 351310
University of Washington
Seattle, WA 98195-1310
Phone: 206.313.7946 cell
E-mail: cegl@u.washington.edu

Frank I. González
NOAA/PMEL
7600 Sand Point Way NE
Seattle, WA 98115
Phone: 206.526.6803
Fax: 206.526.6485
E-mail: frank.i.gonzalez@noaa.gov

Mark L. Holmes
Dept. of Oceanography
Univ. of Washington
Box 357940
Seattle, WA 98195
Phone: 206.543.7313
Fax: 206.543.6073
E-mail: mholmes@u.washington.edu

Bruce E. Jaffe
U.S. Geological Survey Pacific Science Center
University of California
Santa Cruz, CA 95064
Phone: 831.459.2824
Fax: 831.427.4748
E-mail: bjaffe@usgs.gov

Tamie Jovanelly
619 Franklin Ave.
Kent, Oh 44240
(Kent State University)
Phone: 330.678.3962
E-mail: tjovanel@kent.edu

Bob Karlin
University of Nevada, Reno
Dept. of Geological Sciences
M/S 172
Reno, NV 89557-0180
Phone: 775.784.1770
E-mail: karlin@mines.unr.edu

Robert E. Kayen
Bldg. 15, McKelvey Building
USGS Mailstop 999M
345 Middlefield Rd.
Menlo Park, CA 94025
Phone: 650.329.4195
Fax: 650.329.5590
E-mail: rkayen@usgs.gov

Workshop Participants (cont.)

Harold O. Mofjeld
NOAA/PMEL
7600 Sand Point Way NE
Seattle, WA 98115
Phone: 206.526.6819
Fax: 206.526.6485
E-mail: harold.o.mofjeld@noaa.gov

Stephen P. Palmer
Washington State Dept of Natural Resources
Washington Division of Geology and Earth Resources
P.O. Box 47007
Olympia, WA 98504-7007
Phone: 360.902.1437
Fax: 360.902.1785
E-mail: steve.palmer@wadnr.gov

Brian Sherrod
Univ. of Washington
Box 351310
Seattle, WA 98195
Phone: 253.653.8358
206.553.0153 mobil
E-mail: bsherrod@usgs.gov

Hugh M. Shipman
Washington State Dept. of Ecology
3190 – 160th Ave. SE
Bellevue, WA 98008-5452
Phone: 425.649.7095
Fax: 425.649.7098
E-mail: hshi461@ecy.wa.gov

Vasily V. Titov
NOAA/PMEL
7600 Sand Point Way NE
Seattle, WA 98115
Phone: 206.526.5436
Fax: 206.526.6485
E-mail: vasily.titov@noaa.gov

Angie J. Venturato
NOAA/PMEL
7600 Sand Point Way NE
Seattle, WA 98115
Phone: 206.526.6556
Fax: 206.526.6485
E-mail: angie.j.venturato@noaa.gov

Timothy Walsh
Division of Geology & Earth Resources
P.O. Box 47007
Olympia, WA 98504-7007
Phone: 360.902.1432
Fax: 360.902.1785
E-mail: tim.walsh@wadnr.gov

Craig S. Weaver
Univ. of Washington
Dept. of Earth and Space Sciences
Seattle, WA 98195-1310
Phone: 206.553.0627 x
Fax: 206.553.8350
E-mail: craig@geophys.washington.edu
craig@usgs.gov

Jon Whisler
1008 NE 72 St.
Seattle, WA 98115
Phone: 206.336.1639
Fax: 206.524.3543
E-mail: whislerj@u.washington.edu

Harry H. Yeh
Civil and Environmental Engineering
167 Wilcox Hall
Univ. of Washington
Box 352700
Seattle, WA 98195
Phone: 206.685.1024
206.685.8655
Fax: 206.685.3836
E-mail: harryeh@u.washington.edu

U.S. Department of Commerce
National Oceanic and Atmospheric Administration
Pacific Marine Environmental Laboratory
7600 Sand Point Way NE
Seattle, WA 98115