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Mapping Southern Puget Sound Delta Fronts after 2001 Earthquake

A moment magnitude 6.8 earthquake struck southern Puget Sound (Figure 1) on February 28, 2001, causing an estimated $0.7–$1.4 billion in damages to buildings and roadways in the region [*Williams et al.*, 2001]. The earthquake source was 52 km deep, and the epicenter was located close to the Nisqually River delta in the same location as the epicenter of the magnitude 7.1 earthquake of 1949 (http://www.geophys.washington.edu/seis/pnsn/info_general/). These deep earthquakes occurred in the eastward-dipping subducting slab of the Juan de Fuca plate and typically caused less damage than shallower, crustal events of the same magnitude. Details of the seismology and effects of the earthquake can be found at http://earthquake.usgs.gov/activity/latest/eq_01_02_28.html.

Geologists inspected the region immediately after the earthquake and reported numerous ground failures, including landslides along coastal bluffs, lateral spreads, and liquefaction of alluvial sediment in low-lying valleys (see EERI Preliminary Reconnaissance Report at http://maximus.ce.washington.edu/%7Enisqually/). Silt-laden water, or "mud plumes," were also observed near major river deltas in southern and central Puget Sound (Brian Sherrod, personal communication, 2001), suggesting that submarine landslides may have occurred on the seaward-sloping delta fronts. If submarine failures or even weakening of the delta fronts were generated by this earthquake, they could pose a hazard to the ports of Seattle and Tacoma, which have been constructed on artificially filled, intertidal areas at the seaward margin of the deltas. Failures could also threaten the integrity of hazardous waste sites, including several on the U.S. EPA's Superfund list that are located in or near the port facilities.

A joint National Oceanic and Atmospheric Agency (NOAA)-U.S. Geological Survey (USGS) cruise was quickly organized to examine the submerged parts of the Duwamish River delta in Seattle, the Puyallup River delta in Tacoma, and the Nisqually River delta, a wildlife refuge east of Olympia. From March 19 to 30, 2001, the NOAA ship *Rainier* used high-resolution multibeam systems to map the bathymetry of these areas. Although no submarine failures were found on the Nisqually River delta, a variety of failures were observed on the Puyallup and Duwamish River deltas that may be related to the earthquake. Several known landslides, such as the 1894 landslide on the

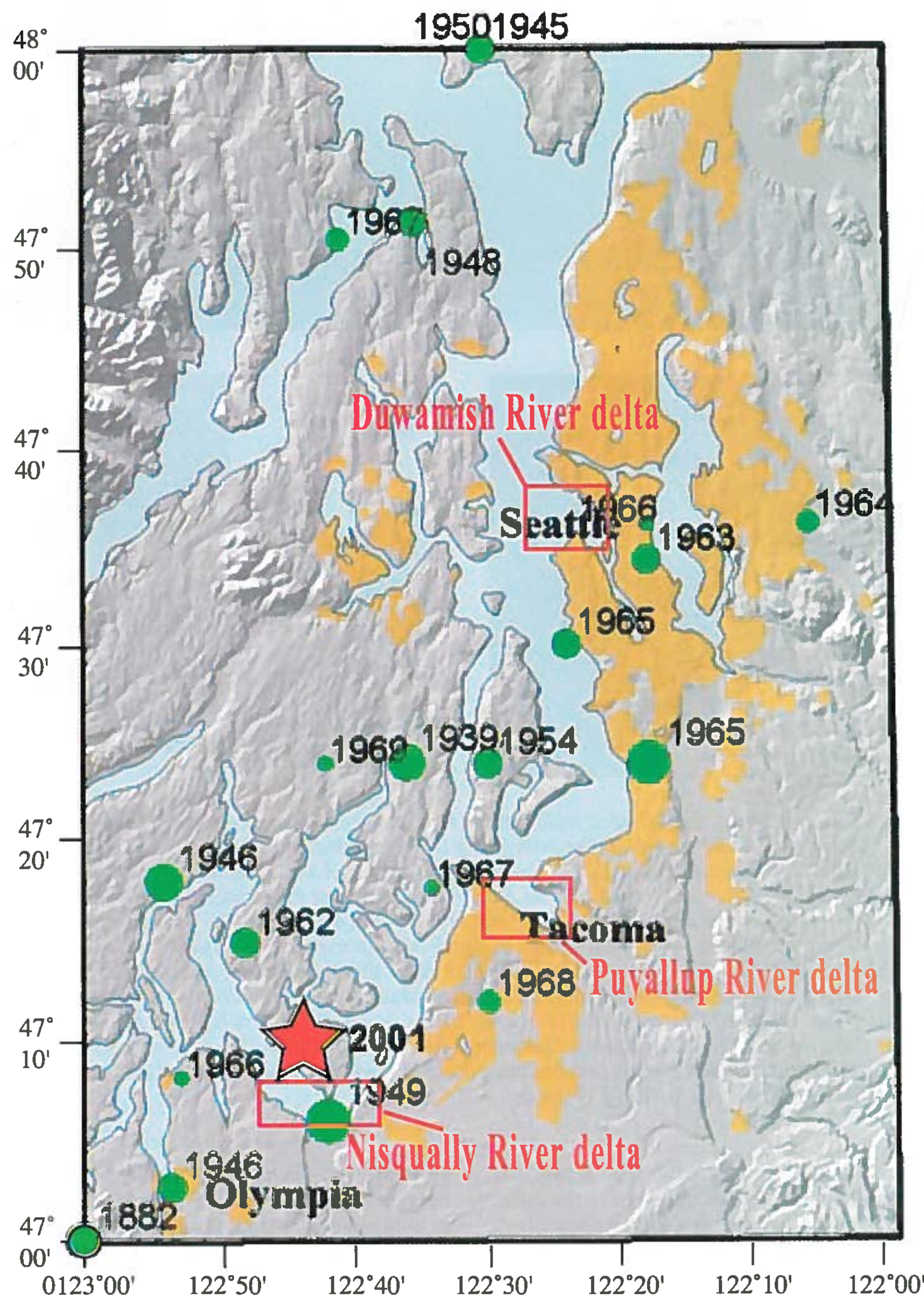

Fig. 1. This view of southern Puget Sound shows the location of the epicenter of the 2001 Nisqually earthquake (red star), distribution and year of historical earthquakes (green circles), populated areas (orange areas), and the three delta fronts (red boxes). Figure modified from http://earthquake.usgs.gov/activity/latest/eq_01_02_28.html.

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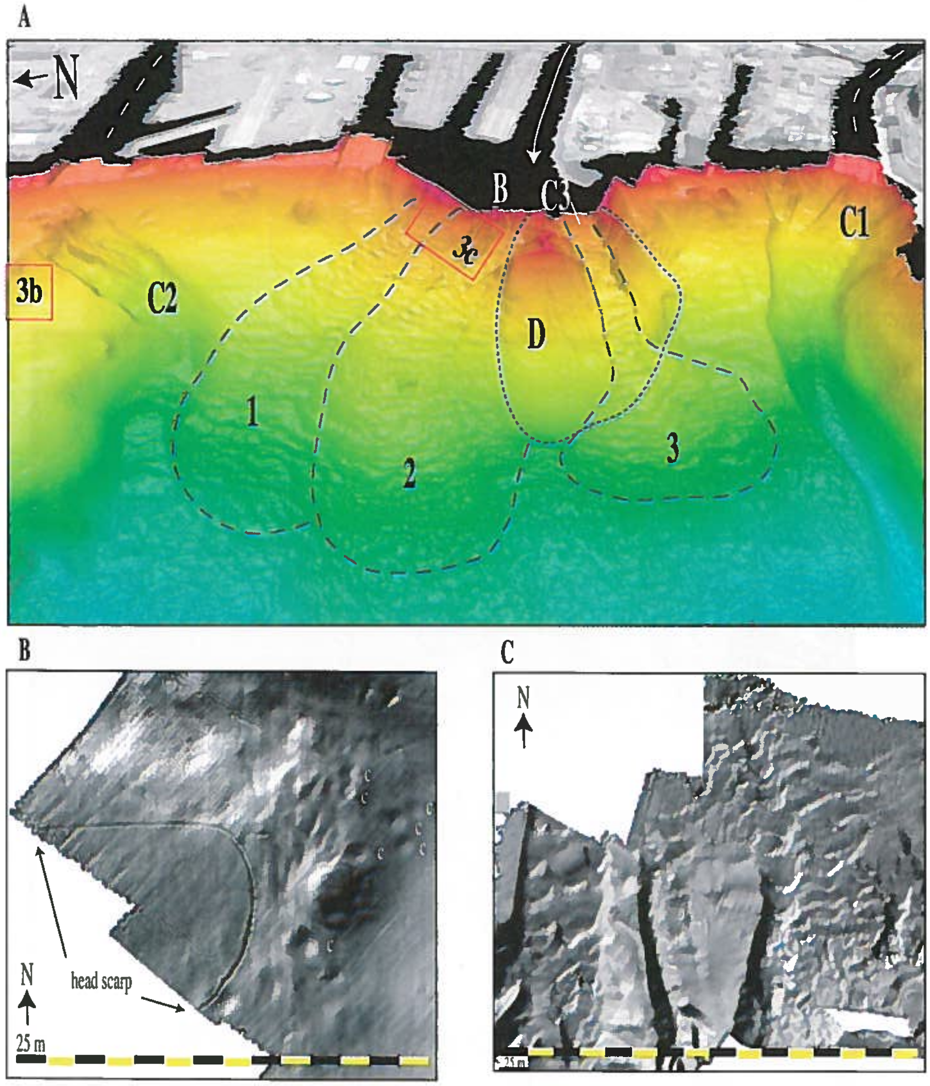

Fig. 2. (a) This oblique color-shaded relief view of Puyallup River delta looks east-southeast. Illumination from 315°, 20° elevation. The bathymetry is 4-m gridded data. The gray-scale land area is 1-m digital orthophotograph draped over a 10-m U.S. Geological Survey digital elevation model. Overlapping delta-front sediment lobes are numbered from oldest to youngest (1 through 3). "C1" is a landslide scar from 1894, "B" is the zone of a 1992 landslide, and "D" is a disposal site. The red box labeled "3b" is the area shown in Figure 3B, and the red box labeled "3c" is the area shown in Figure 3C. "C3" is an erosional channel cut through disposal material. The solid white arrow is the presently active channel, and dashed white lines are former channels of the Puyallup River. (b) This map view (1-m grid) shows an area of craters (circular feature to immediate left of "c") and head scarp. Illumination from 315°, elevation 45°. (c) This map view (1-m grid) shows landslide scars and sediment flows immediately downstream of the active river mouth. Illumination from 315°, elevation 45°.

Puyallup River delta and the 1986 Duwamish Head failure, were also observed in the data, as well as numerous, previously undescribed failures. However, we cannot unequivocally determine whether the failures mapped in March 2001 were caused by the Nisqually earthquake, although the craters, head scarp, and several of the landslides described below are very sharp and well defined, rather than subdued, in appearance, suggesting recent formation. The abundance of landslides, both known and newly revealed by our survey, indicates that the sediment deposits of the delta fronts and adjacent slopes in southern Puget Sound have a high potential for failure.

Certainly, with the new high-quality bathymetric data in hand, we are much better poised to both assess potential failure sites and document any future failures in these three delta fronts triggered by the next major earthquake to strike this region.

Systems

The *Rainier* carries four 10-m multibeam-echosounder (MBES)-equipped survey launches, as well as two launches equipped with single-beam echo sounders. In addition, the *Rainier* has a hull-mounted MBES system. Interested readers are directed to Hughes Clarke et al. [1996] for a description of the MBES technology. One MBES uses a 240-kHz transducer array that generates 101 1.5°-wide receive apertures that cover a nominal 150° maximum swath. Two of the MBESs generate up to 126 1.2°-wide receive apertures that cover maximum swaths of 150°. One of these operates at 180 kHz and the other operates at 50 or 180 kHz. This survey only used the 180-kHz option because of the shallow water depths. The ship and the MBES launches have four-axis motion sensors that detect pitch, roll, yaw, and heave, and were navigated with differential GPS-aided inertial navigation. All data were processed aboard the *Rainier* in near-real time.

Legacy Data

The best available pre-earthquake bathymetry for all three deltas comes from a NOAA compilation of hydrographic-quality, single-beam, echo-sounder data (http://sposerver.nos.noaa.gov/bathy/). These data have a spatial resolution of 1 arc sec (about 30 m) and were collected from 1994 to 1999 in the Nisqually River delta, from 1972 to 1982 in the Puyallup River delta, and from 1978 to 1992 in the Duwamish River delta. All data are spatially referenced to the WGS84 ellipsoid and vertically referenced to mean lower low water. A 30-m digital terrain model (DTM) for each of the three deltas and adjacent basins was generated from these data for comparison with the new data. These DTMs can be viewed at http://walrus.wr.usgs.gov/pacmaps/ps-index.html.

New Data

The four MBES launches mapped about 12 km^2/day and together required only about 14 hr to map each of the deltas. During the evenings aboard the *Rainier*, the multibeam data from each launch were edited for spurious soundings and tide corrected to mean lower low water. To create DTMs, the data from each launch were combined and gridded at 1-m spatial resolution for water depths of 1–50 m, 2-m resolution for depths of 50–100 m, and 4-m resolution at water depths greater than 100 m. The land area is represented by USGS 1-m-resolution digital orthophotos draped over USGS 10-m DEMs. The legacy DTMs and the corresponding new DTMs were compared for changes and the new data were inspected for features that might be related to earthquake-induced failures.

Nisqually River Delta

Although the Nisqually River delta is within a few kilometers of the earthquake epicenter, no failures are found in images at 1-m spatial resolution along the delta front. A color-shaded relief map and several perspective views of the data can be viewed at http://walrus.wr.usgs.gov/pacmaps/ps-index.html. The delta front is relatively steep (12°), narrow (100 m wide), and nearly featureless. A zone of landslides with subdued, rather than sharp, bathymetric definition occurs on the northeastern inner margin of the channel, but the subdued appearance suggests these may be older failures unrelated to the 2001 earthquake.

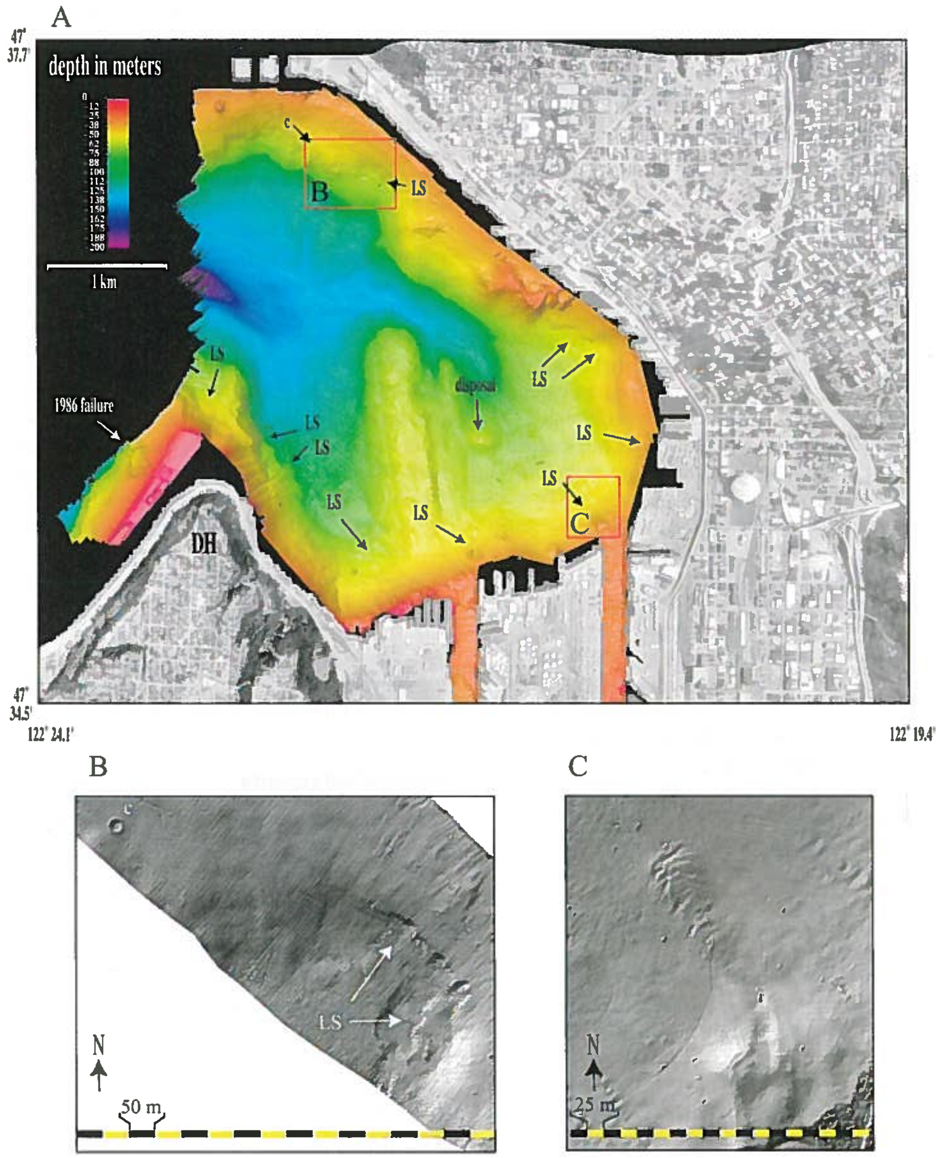

Fig. 3. (a) This color-shaded relief map of the Duwamish River delta is illuminated from 315°, 45° elevation. The bathymetry is 4-m gridded data, and the gray-scale land area is 1-m digital orthophotograph draped over a 10-m U.S. Geological Survey digital elevation model. Arrows indicate areas of landslides (LS) and craters (c), and the 1986 failure is indicated by a white arrow. "DH" is Duwamish Head. Red boxes show locations of Figures 3B and 3C. (b) This map view of a 1-m grid of the area shows a large crater and the zone of landslides. Illumination from 315°, 45° elevation. (c) This map view of a 1-m grid of the area shows one of the landslides immediately adjacent to the Port of Seattle. Illumination is from 315°, 45° elevation.

Puyallup River Delta

The Puyallup River delta is about 20 km northeast of the epicenter of the Nisqually earthquake. The delta forms the gently sloping (3.5°) southeast border of Commencement Bay whereas the northeast and southwest borders are steep-sided walls of a Pleistocene glacial valley [*Booth*, 1978] and the northwest side is open to the main channel of Puget Sound. The length of the Puyallup River is unobstructed from its source on Mt. Rainier to the delta, and the delta front has advanced at an average rate of 2.5 km/k.y. for the past several thousand years [*Dragovich et al.*, 1994]. Several relatively large historic landslides have modified the delta front. A sudden failure of the southwestern corner of the delta front in 1894 (labeled "C1" on Figure 2a) carried away a railroad track and roadway and resulted in two deaths. The present failure scar represents a volume of 2.615 km^3 of material. Another sudden failure occurred in 1992 midway along the delta front (labeled "B" on Figure 2a), although neither this or the 1894 events are correlated to an earthquake. Both failures are located at the mouths of river channels and the three largest submarine channels on the delta front also occur immediately downstream of river mouths. This relationship suggests that sediment loading may have initiated the historic failures as well as the formation, and possibly continued modification, of the submarine channels.

Numerous small slumps and failures are found in the new bathymetric data along the shallow edge of the delta front, especially in the southern half. A linear string of craters as much as 25 m in diameter and 0.5 m deep (labeled "c" in Figure 2b), as well as a head scarp of a large incipient failure (Figure 2b), are found in the northern portion of the delta front (area labeled "3b" in Figure 2). The craters resemble expulsion features and are similar in appearance to large pockmarks [*Hovland and Judd*, 1988; *Kelley et al.*, 1994]. Whether the craters and head scarp were caused by the Nisqually earthquake is problematic because the resolution of the legacy data is too low to resolve such small features for comparison. However, these are precisely the type of features that are expected to be generated by severe ground shaking [*Field et al.*, 1982].

A marine disposal mound (labeled "D" in Figure 2a) is located on the delta front where dumping continued until the mid-1980s. The 1972 to 1982 bathymetric data for the Puyallup River delta clearly show the disposal site as an intact mound that rises about 18 m above the delta-front sediments. The new data show that sometime after 1982 a major breach of the disposal material occurred and now a 100-m-wide, 15-m-deep channel (labeled "C3" in Figure 2a) dissects directly downslope through the disposal material. The erosional channel is directly downstream of the mouth of the active Puyallup River channel. In addition, several relatively large channels as much as 2 m deep, 20 m wide, and 350 m long and landslides on the lower west and upper east sides have eroded into the disposal material.

The surface of the delta front, including the floor of the eroded channel in the disposal site, is mantled with bedforms (Figure 2). The bedforms, with wavelengths of 20–40 m and wave heights of 1.5–2.0 m, would be called large subaqueous dunes using the classification of Ashley [1990]; that is, they formed by a process presumably driven by hyperpycnal flows out of the Puyallup River. However, the bedforms could also be interpreted as creep folds, a slow but persistent gravity-induced downslope transport of sediment. Regardless of the process operating, the new bathymetric data suggest that the middle third of the delta front is prograding northwestward. The bathymetric data suggest that three overlapping lobes of sediment occur on the delta front (labeled 1, 2, and 3 in Figure 2a). Lobe 1, the oldest, is overlapped by lobe 2, which is overlain by the disposal material. Lobe 3, the youngest, was formed in part by channel erosion through the disposal material.

Duwamish River Delta

The Duwamish River delta is about 40 km northeast of the Nisqually earthquake epicenter. The delta front forms the sloping (6° to 10°) southeastern border of Elliott Bay. The southwestern and northeastern sides of the bay are relatively steep (10° to 18°). Although in the past the Duwamish River delta has prograded at rates as fast as 9 km/k.y. [*Dragovich et al.*, 1994], the river has been dammed for the past century so that the delta is now relatively sediment-starved. Numerous sediment slides and craters were found on the Duwamish River delta front (Figure 3), but whether they were caused by the Nisqually earthquake is again equivocal because of the poor resolution and the age of the legacy data. Landslides occur at several places along the delta front and along the sides of Elliott Bay. The landslides vary in size and all appear to have originated close to the break in slope that typically occurs between the 5-m and 10-m isobath. A single large crater on the northeastern side of the bay is located 650 m to the west-northwest of the head of an older landslide scar (Figure 3b). The crater has a 6-m-wide flat floor, is 27 m in diameter at the top, and is 1.6 m deep. Both the crater and the head of the landslide scar occur at a depth of 52 m, suggesting a possible relationship of the features with some unrecognized, buried, possibly weak, geological strata that may be close to the surface at the 52-m isobath.

A series of relatively large landslides occur on the Duwamish River delta front (see Figure 3c for example). The landslides range in width from less than 40 m to more than 300 m and from less than 100 m to more than 500 m long. The heads of all of these landslides are in less than 15 m of water, within a few tens of meters from the Port of Seattle facilities. All of these landslides have a clearly defined head scar, a channel, and a depositional lobe at their terminus.

A series of five channels incises the slope from north to south on the eastern tip flank of Duwamish Head. The southernmost two channels of this group appear to have been formed by landslides with coalesced debris aprons at the base of the slope. Other landslides with a wide range of sizes are also found along the northeastern flank of Elliott Bay in a range of water depths. A landslide scar occurs about 7 km offshore immediately north of Duwamish Head. This is the largest landslide in Elliott Bay, with dimensions of 600+ m long, 350 m wide, and this event removed a 5–10-m-thick section of the slope from the 20-m isobath to beyond the 85-m isobath. Another major sediment failure is located on the western flank of Duwamish Head, in water 15–70 m deep. The failure occurred in 1986 during construction of a sewage outfall system and was thought to involve about 400,000 m^3 of material [*Kraft et al.*, 1992]. Volume calculations using the new data indicate that 349,600 m^3 of material was removed from the slope, which suggests that little or no failure has occurred since the initial event.

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