PALEOSEISMICITY AND LANDSLIDING IN THE PUGET SOUND REGION

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Abstract

The goals of this research were to locate and date Holocene submarine landslides in Puget Sound to evaluate the timing and extent to which the area may have been subject to seismic shaking. High-resolution seismic reflection profiles and sidescan swath images were processed to produce digital images of the subsurface structure and the lateral extent of the landslides. Several large submarine slides in Puget Sound have volumes of $> 10^6$ m^3, including slides at Maury Island, Three Tree Point, Alki Point, Skiff Point, Edgewater, Possession, and Mukilteo. A number of landslides coincide with known active crustal faults in the area. Slides at Edgewater, Possession Point, and Mukilteo are associated with the South Whidbey Island fault zone. Slides at Alki Point, Skiff Point, Port Madison, and Port Orchard slides lie on or near the Seattle Fault. In addition, slides near Three Tree Point, Maury Island, and Dash Point may be associated with a previously unrecognized N-S series of faults. Ninety-one sediment cores taken near the toes of the landslides were opened, described, and sampled to obtain radiocarbon ages of turbidites associated with the slides with the intent of determining when the landslides occurred and whether slides in different areas occurred at the same time. In a paper submitted to the Geological Society of America Bulletin, submarine slides Lake Washington were dated at 300, 550, 780, 1000-1100, 1550-1700, 1900-1950, and 2800-3200 years ago. The dates obtained in this project from several locales support these ages as probable earthquake events.

Progress

Raw seismic and sidescan data from four cruises aboard the University of Washington R/V Barnes were downloaded from digital tape (~100 Gb), demultiplexed, and processed to produce raw image files. The numerous image files were in turn decoded and digitally enhanced. Attempts to process the images using standard seismic software to reduce multiples proved very time consuming and not very successful. Consequently efforts along this line were not pursued.

Ninety-one sediment cores up to 5-m in length from near the toes of submarine landslides were opened, curated, described, and sampled for radiocarbon dating where appropriate. Radiocarbon ages on 39 samples from 13 cores were obtained from the University of Arizona ^{14}C laboratory. Rather than dealing with complex carbon reservoir corrections for dating of

distributed organic carbon in the sediments, sampling for age dating was restricted to shells and macrobiota (e.g., twigs, needles, etc.).

In addition, the paleo/rock magnetism of continuous U-channels from four piston cores were measured on a whole core cryogenic magnetometer at Ken Verosub's laboratory at Univ. California, Davis, to see if paleomagnetic dating could be used to refine core chronologies. Possibly because of the high sedimentation rates, this technique was not found to be useful.

Results

Submarine landslide distributions

Large submarine landslides are found throughout Puget Sound. Many of the larger slides are associated with known active faults such as the South Whidbey Island fault and the Seattle fault. However, several slides in the East Passage and in the vicinity of Tacoma fall on linear trends not associated with identified structures. We postulate that these slides may mask buried strike-slip faults which, if true, would break the area into structural domains and change the seismic risk potential of the Seattle-Tacoma-Olympia area.

Landslides associated with the South Whidbey Island fault zone

As shown in Figure 1, numerous large submarine and coastal landslides are found in the vicinity of the South Whidbey Island fault zone (SWIFZ), particularly in Possession Sound and along the coast from Mukilteo to Everett. The frequency of these slides suggests that this structure has been seismically active during the Holocene. For convenience, the slides are grouped by geographic area into 1) Possession Point (west side of Possession Sound), 2) Mukilteo (east side of Possession Sound), and Edgewater (north coast from Mukilteo to Everett).

Figure 1 here.

Possession Point – The western side of Possession Sound has a large number of complex submarine block slides, debris flows, and sand flows which blanket much of the slope. Several strands of the South Whidbey Island fault zone pass through this area and are seen in seismic reflection profiles. Coastal erosion is particularly severe, because weak peaty shales of the Whidbey Formation, which acts as a failure surface, underlie the cliff-forming Double Bluff Formation. At least four discrete submarine slides and debris flows of up to a kilometer in width occur along the submerged southern extension of Possession Point. Because of the active coastal erosion, the large number, and complexity of the slide complexes, it is difficult to attribute specific causes to these features.

Edgewater – Three discrete slide complexes are found on the north-facing coast between the Mukilteo ferry and the city of Everett. The slide nearest Everett appears to be a large sheet flow. The two western complexes consist of a series of individual block slides capped by debris flows. Offshore transects of Shipek grab samples and piston cores reveal that a laterally graded sequence of coarse cobbles and gravel upslope which fines to gravel and sand, sand and mud, then mud downslope. Seismic reflection profiles show that the block

slide deformed and mounded the basin fill beyond the toe of the slide. Because of the high deposition rates in the basin from the Snohomish River, these slides must be relatively recent.

Mukilteo- Located on the mainland south of Mukilteo, this slide is composed of a huge lobate sand sheet that spreads through much of the eastern portion of Possession Sound. The sand sheet severely incised the upper slope and flowed downslope in a large channel before spreading into a lobate sand sheet in the basin. Little hemipelagic sediment covers the slide mass, thus this slide must be fairly recent.

Landslides associated with the Seattle fault

As seen in Figure 2, relatively few submarine landslides are found in the Sound between Edmonds and South Seattle, with the notable exception of a very large submarine block failure off Alki Point. A series of overlapping slides also occurs in Port Madison and appear to be associated with N-S faulting. Our seismic lines which mostly are along the slope, show no evidence of N-S faults offsetting the Seattle fault as proposed by Johnson et al. (Johnson, S. Y., Dadisman, S. V., Childs, J. R., and Stanley, W. D., 1999, Active tectonics of the Seattle Fault and central Puget Sound, Washington; implications for earthquake hazards: Geological Society of America Bulletin, v. 111, no. 7, p. 1042-1053.). Several apparent thrust faults mapped off the western margin of Seattle are found on the slope but have no expression in the basin fill. They offset bedded Pleistocene glacial material and do not appear to be recent. They may be due to gravity sliding of large blocks or perhaps crustal readjustment during isostatic rebound. Only along shore transects are available and it is not possible to assess what appear to be three-dimensional structures.

Figure 2 here

Alki Point – The south-facing coast off West Seattle contains the largest submarine landslide complex in Puget Sound. Strands of the east-west Seattle fault pass onland nearby, but our seismic reflection profiles and those of the USGS (Johnson, et al., 1999) show no clear indication that the fault passes off Alki Point or through Elliot Bay. The large block slides, which are overlain by debris flows, pushed and deformed soft sediment in the basin fill into mounds that are evident in bathymetric charts. This slide was undoubted triggered by the 1000 year old earthquake on the Seattle fault, which caused 3-7 m of uplift at Restoration Point directly across the Sound. It is likely that the landslide would have contributed to a seiche or tsunami, which would have affected the site of the future city of Seattle directly north in Elliot Bay.

Landslides in the East Passage

Unlike the rather quiescent area on the northern footwall of the Seattle fault, numerous large landslides are found on the hanging wall of the fault from Alki Point to Tacoma (Figure 3). Large slide complexes composed of large discrete block slides and debris flows are found off Three Tree Point near Burien and off the southern coast of Maury Island. From the seismic reflection profiles, the slides appear to overlie and in places be cut by faults. It is not possible to determine any sense of fault offset from the profiles. Few landslides are found in Colvos

Passage; however, severe tidal scour with velocities up to 9 knots, may have removed any traces.

Figure 3 here

A number of E-W faults were observed around Vashon Island, Gig Harbor (probably the Tacoma Fault), and in the Tacoma Narrows. Whether these faults continue through Vashon Island and into the East Passage cannot be determined from the available data. The Tacoma fault does not appear to go through Commencement Bay, but may go onshore somewhere between the bay and Point Defiance.

We speculate that a series of north- south strike-slip faults may be present in the East Passage. The faults appear to as linear trends extending from Commencement Bay through Maury Island and into the East Passage. The lines of evidence for this hypothesis are as follows:

1) Landslides lie on linear trends and appear to be associated with faulting.
2) Sediment cores from off Maury Island have large turbidites, suggesting Holocene sliding.
3) V-shaped notches observed in the sediment fill in the East Passage lie on trend with the landslides.
4) The topography on Maury Island has two linear N-S cliffs that lie on trend with the landslides and notches.
5) Numerous historical small earthquakes are located in a cluster on the fault trend.

We note that this hypothesis is inferential. The faults lie in the same direction as the glacial sculpting of the topography, so fault-related morphologies onland might be difficult to identify. On a visit with Sam Johnson (USGS), the PI reviewed USGS deep E-W seismic profiles taken south of Maury Island. The profiles do not appear to show through going faults in the sediment fill. However, the resolution of these lines is more than 10 m, so strike slip faulting with no vertical offset might be difficult to detect. Alternatively the faulting could pre-date the sediment fill. Magnetic anomaly patterns, in data kindly provided by Rick Blakely (USGS), are equivocal as to whether linear trends are present in the East Passage. The presence of these faults is important to assessing seismic hazard, because they may break up the region between the Seattle and Tacoma faults into prisms. This would lessen the length of possible slip and decrease the potential maximum size of an earthquake. However, the available data are not sufficient to resolve this problem. Further high resolution air/water gun profiles are needed.

Landslides in the South Sound

The Tacoma Narrows, the southeastern side of Fox Island, and the eastern side of McNeil Island all contain underwater landslides. These and other coastal areas in the South Sound all have coastal bluffs exposing pre-Fraser age sediments, suggesting that the landslides involve both subareal and submarine material. Coastal erosion of the steep bluffs appears to be fairly severe. Faulting in the Tacoma narrows is very common. however, most faults in Carr Inlet appear to be of Pleistocene age because they are associated with cut and fill glacial deposits.

Figure 4 here

Historical earthquake-induced landslides

The Nisqually delta and Point Defiance slides were caused by the 1949 Olympia earthquake (R. Wallace, USGS, pers. comm.) They show a characteristic retrogressive failure-style morphology where the toe of the delta failed and coherent blocks were back-rotated on a decollement plane. The wavelength of the back-tilted blocks decreases both upslope and laterally (Figure 2). Recent swath bathymetry showed no further failures after the 2000 M7 earthquake.

Radiocarbon dating of landslides

Underwater landslides would be expected to trigger turbidites and sand flows upon deposition. Wood and shell fragments from thirteen cores were dated by AMS 14C to try to establish the ages of the slides. Dating of organic sediment was avoided because of the unresolved problem of determining a carbon reservoir correction for sediments in Puget Sound.

Lake Washington - During this project, a paper entitled "Holocene landslides and a 3500 year sediment record of Pacific Northwest earthquakes in Lake Washington, Pacific Northwest" by R. Karlin, Mark Holmes, S. E. B. Abella, and R. Sylwester was submitted to the Geological Society of America Bulletin. In that paper, seismic reflection profiles and sidescan sonar images were used to map numerous landslides in the lake. Magnetic susceptibility profiles on 36 gravity cores show a characteristic series of magnetic peaks that can be traced throughout the lake. X-radiography and grain size analyses suggest that the magnetic peaks represent anomalous terrigenous layers, which in some cases are turbidites. The areal extent and magnetic signatures of many of the deposits suggest multiple sources, which is consistent with numerous local landslides caused by large earthquakes. Radiocarbon dating and correlation of the downcore magnetic profiles establish a sediment record for the last 3500 years. Large-scale, episodic sedimentary disturbances occurred 300, 550, 780, 1000-1100, 1550-1700, 1900-1950, and 2800-3200 years ago.

Lake Sammamish - A single date from the outer bark of a branch from a drowned upright tree in Lake Sammamish (#42) gave a date of 1092+/- 41 14C years BP. This suggests that the prominent Greenwood landslide failure in Lake Sammamish was caused by the well-documented earthquake on the Seattle fault at 932 AD. Other dates on turbidites from piston cores suggest episodic sedimentary events at 780 years, 1100 years, and ~1700 years, which is in agreement with the ages found in Lake Washington.

In some instances, radiocarbon dating proved less than optimal in trying to construct a chronology. Displaced wood and shell fragments sometimes gave stratigraphically anomalous ages, probably because they were obtained from old reworked sediment layers. For example, ten radiocarbon dates from a core near a slide off Beal's Point showed three age inversions, thereby making interpretation of the chronology difficult. Similarly, near surface dates on two

cores from Possession Sound gave relatively old ages of 2341 +/- 39 14C years and 3370 +/- 46 14C years. Given the high sedimentation rate in that area, these dates do not make sense unless the surficial material had been reworked.

Table 2, shown below, summarizes the 14C dating of anomalous sedimentary intervals of cores taken in the sediment fill near the toes of landslides. Slide locations are given in Figures 1 to 4. For shell dates a carbon reservoir correction of 800 years is used. There are clear indications that the events noted in Lake Washington are confirmed at other sites. This table should be regarded as preliminary, because further dating is needed to verify and refine the core chronologies.

Area	Cruise	Core	14C event age (years)
Three Tree Point	607	33	550
Three Tree Point	607	39	780, 1100
Poverty Bay	607	40	550, 1100
Port Orchard	584	4, 5, 6, 8	550, 780, 1100

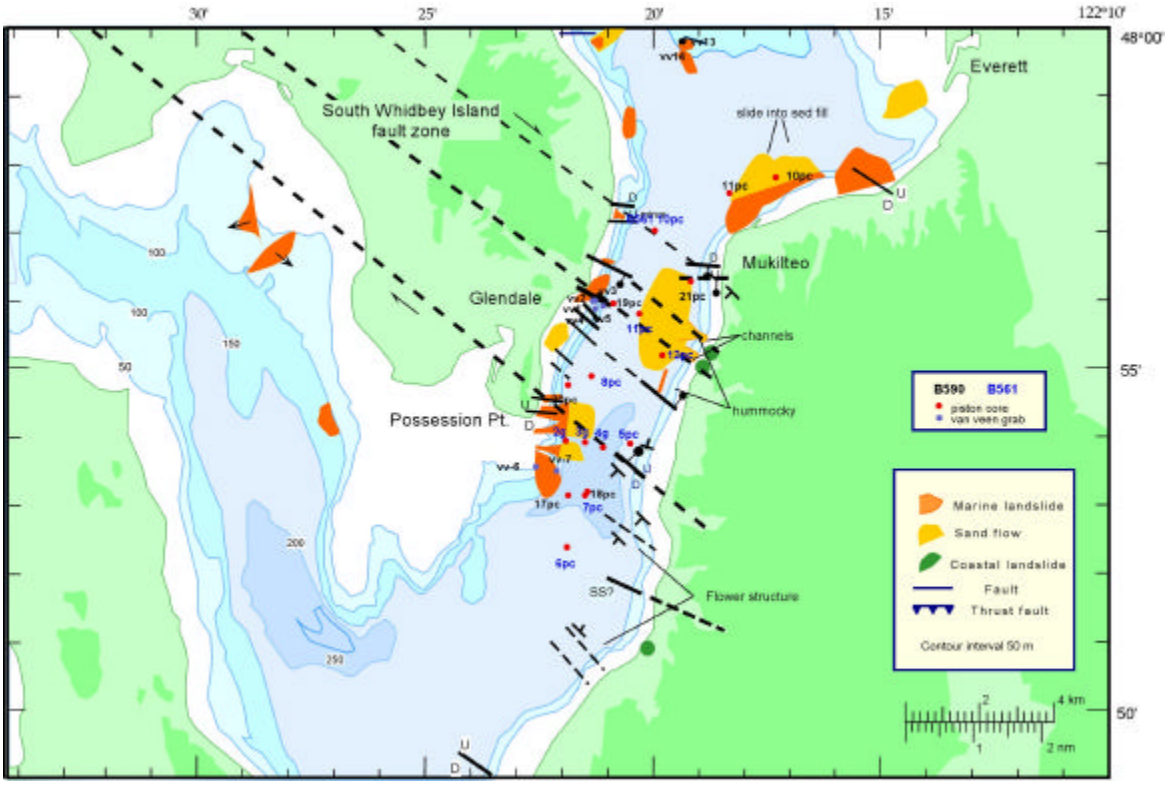
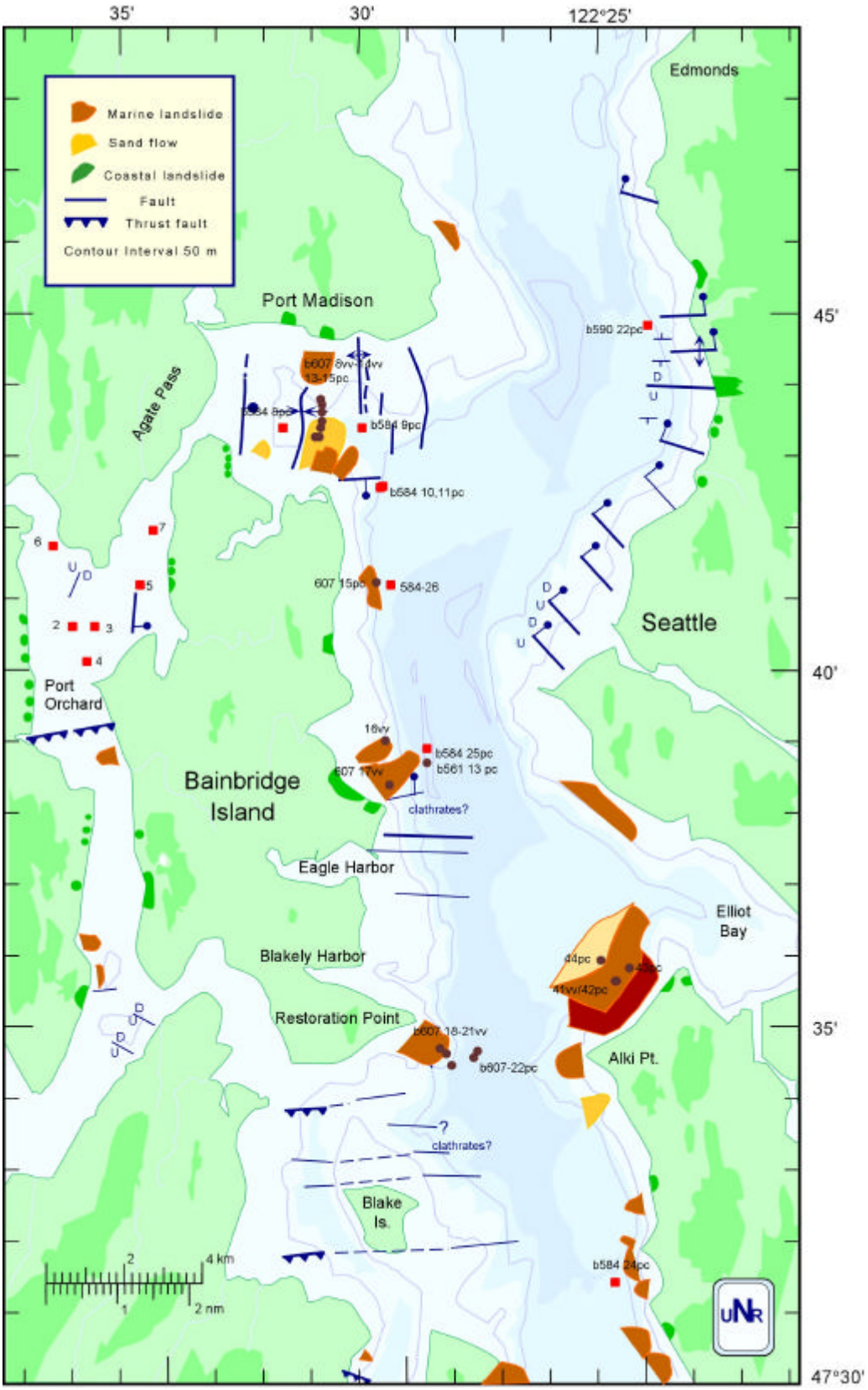
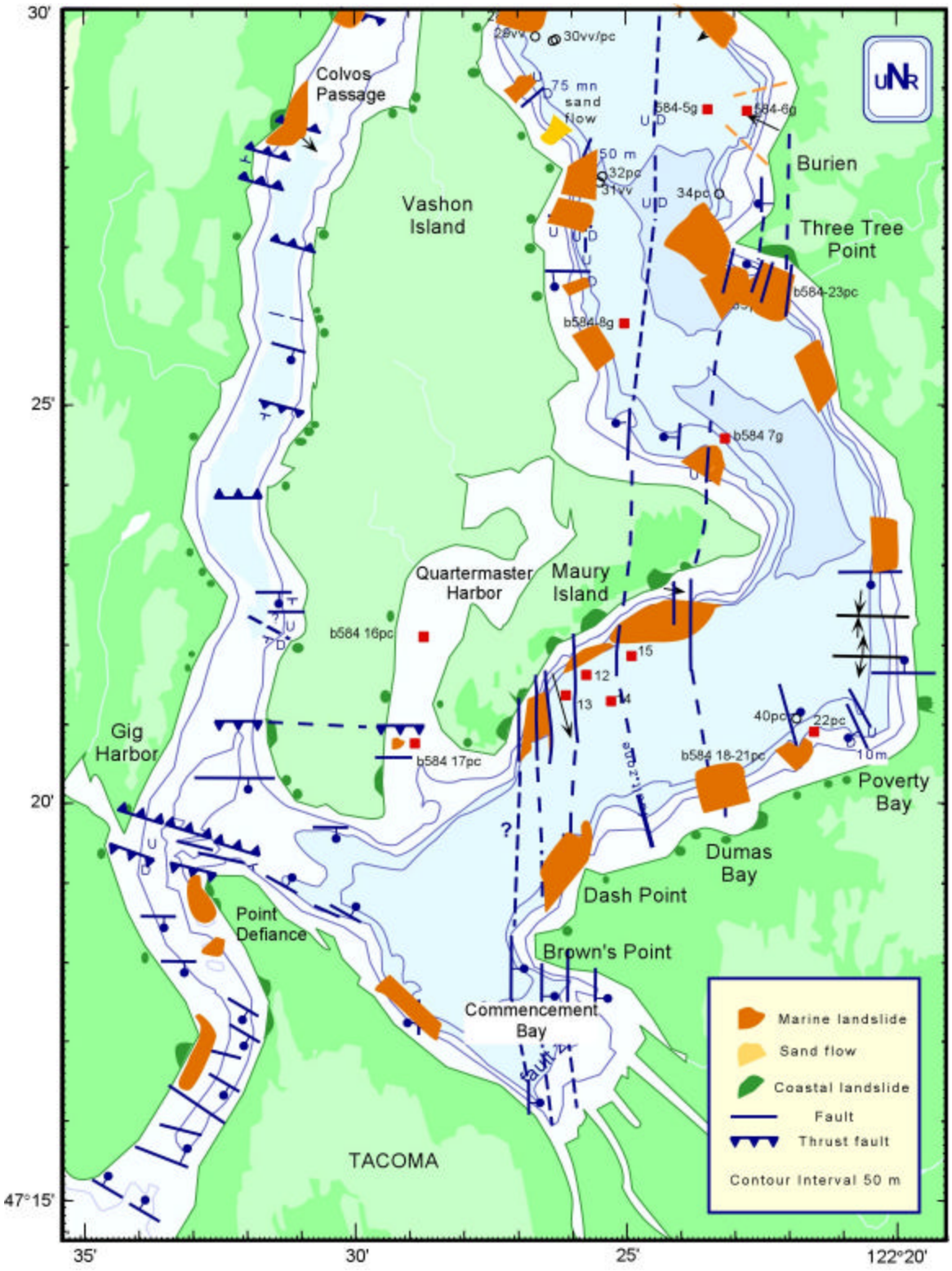

30'
25'
20'
15'
122°10'
48°00'
55'
50'
South Whidbey Island
fault zone
Everett
slide into sed fill
Mukilteo
Glendale
Possession Pt.
channels
hummocky
Flower structure
B590 B561
piston core
van veen grab
Marine landslide
Sand flow
Coastal landslide
Fault
Thrust fault
Contour interval 50 m
4 km
2 nm

Figure 1.


35'
30'
122°25'
45'
40'
35'
47°30'
Marine landslide
Sand flow
Coastal landslide
Fault
Thrust fault
Contour Interval 50 m
Edmonds
Port Madison
Agate Pass
b590 22pc
b607 8vv-14vv
13-15pc
b584 8pc
b584 10,11pc
607 15pc
584-26
Seattle
Port
Orchard
Bainbridge
Island
18vv
b584 25pc
b561 13 pc
607 17vv
clathrates?
Eagle Harbor
Elliot
Bay
Blakely Harbor
44pc
41vv/42pc
Restoration Point
b607 18-21vv
b607-22pc
Alki Pt.
clathrates?
Blake
Is.
b584 24pc
4 km
2 nm
Figure 2.


30'
25'
20'
47°15'
35'
30'
25'
122°20'
Colvos Passage
Vashon Island
Burien
Three Tree Point
Quartermaster Harbor
Maury Island
Gig Harbor
Point Defiance
Dash Point
Dumas Bay
Poverty Bay
Brown's Point
Commencement Bay
TACOMA
75 mn sand flow
50 m
b584 16pc
b584 17pc
b584 18-21pc
b584-5g
b584-6g
b584-23pc
b584 7g
40pc
22pc
10m
Marine landslide
Sand flow
Coastal landslide
Fault
Thrust fault
Contour Interval 50 m
Figure 3.

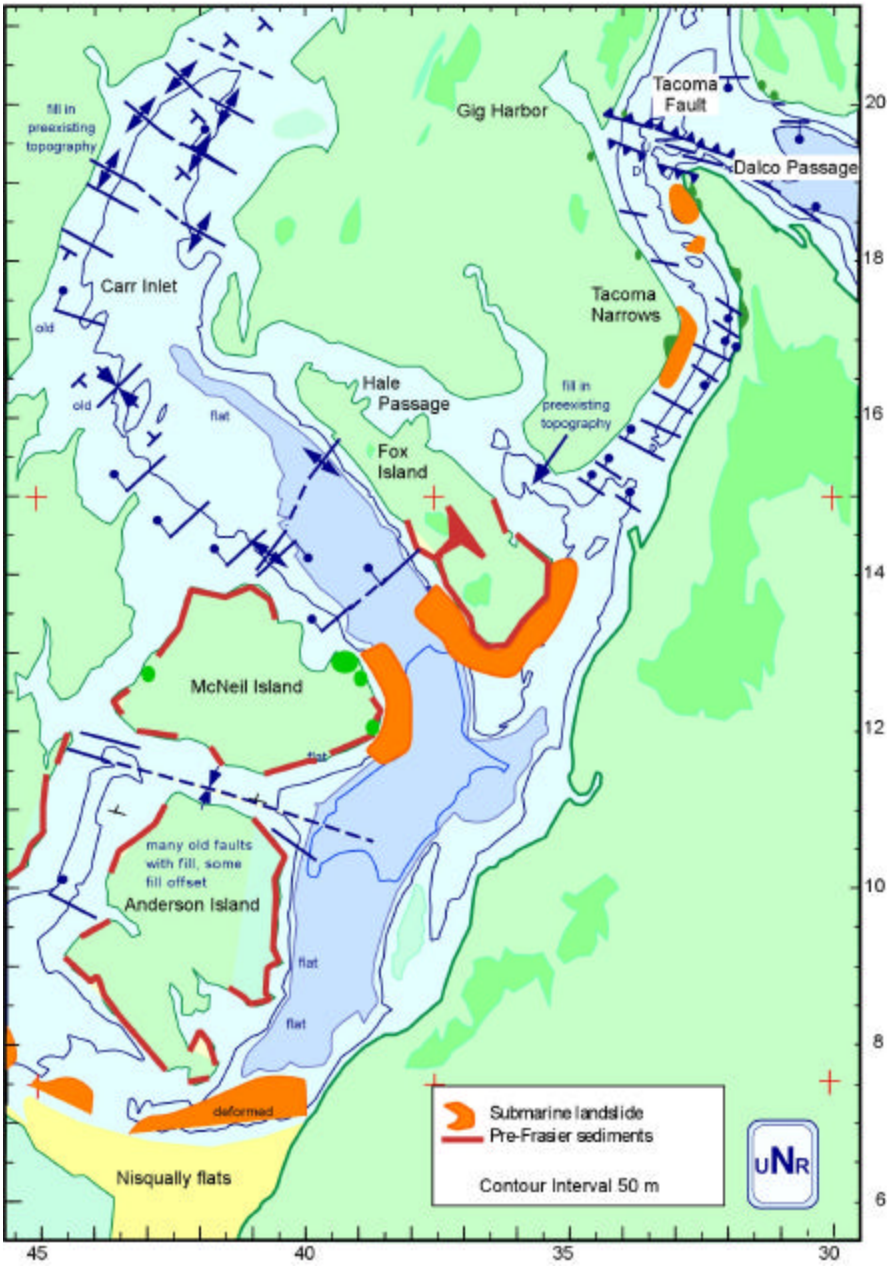

fill in preexisting topography
Gig Harbor
Tacoma Fault
Dalco Passage
Carr Inlet
old
Tacoma Narrows
Hale Passage
fill in preexisting topography
old
flat
Fox Island
McNeil Island
flat
many old faults with fill, some fill offset
Anderson Island
flat
flat
deformed
Nisqually flats
Submarine landslide
Pre-Frasier sediments
Contour Interval 50 m
UNR
20
18
16
14
12
10
8
6
45
40
35
30

Figure 4.