WASHINGTON DECISION-MAKERS
FIELD CONFERENCE

The Cost and Practice of Seismic Safety in Washington

Sponsored by
Washington State Department of Natural Resources
Division of Geology and Earth Resources
"Washington State's Geological Survey since 1890"

July 31, 2008
Olympia and Tumwater, Washington

WASHINGTON STATE DEPARTMENT OF
Natural Resources
Doug Sutherland - Commissioner of Public Lands

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WASHINGTON DEPARTMENT OF NATURAL RESOURCES

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Introduction and Overview

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Washington Decision-Makers Field Conference

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Thursday, July 31, 2008

sponsored by the
Washington State Department of Natural Resources
Division of Geology and Earth Resources

Welcome to the 2008 Washington Decision-Makers Field Conference sponsored by the Washington State Department of Natural Resources, Division of Geology and Earth Resources. This year's conference is centered in the Olympia and Tumwater area and takes aim at earthquake hazards in Washington.

A PREVIEW

Our primary objective is to present you with the opportunity to learn first-hand, in an informal outdoor setting, about earthquakes and seismic safety and their impacts on people, economic development, and transportation. We will present knowledge from the latest practical earth-science research by our agency and others. This research is focused on understanding, mitigating, and responding to the impacts of geologic disasters on the citizens and economy of the state.

This conference gives participants a chance to visit sites that are the focus of legislative concerns. We believe that the field-trip format stimulates on-site debate about public policy, strategies for growth, and methods for solving problems.

We will visit:

- the Capitol Campus and Legislative Building, a historic building that has been through three earthquakes and is now retrofitted to modern building codes
- the old Olympia Brewery along the Deschutes River, a 102-year-old brick structure, built on basalt, that has survived three earthquakes with little damage
- Tumwater Historical Park, where a landslide that was caused by the 2001 Nisqually Earthquake is still visible
- the Old Capitol Building (built in 1892) and the downtown area, where we can view earthquake damage and seismic upgrades

THE DECISION-MAKERS FIELD CONFERENCE CONCEPT

Some issues are difficult to understand without seeing their effects for yourself. You will have an opportunity to experience first-hand the issues surrounding earthquake hazards. Participants have been selected to provide a range of legislative, governmental, and private business expertise. Our objective is to let participants see how policy and earth science are connected, and to talk with local, state, and federal governmental officials, activists, and business people about topics that need frank discussion. The result should give participants a broader, more-informed perspective useful in formulating policies. In addition, this field guide provides background on sites and issues, and serves as a handy reference long after the conference is over.

During the conference, participants are expected to be just that—participants. You are encouraged to contribute to the discussion, ask questions, and otherwise join in on deliberations.

We do not seek to set policy or resolve conflicts. Rather, we provide you with opportunities to familiarize yourself with the problems related to earthquake hazards. By bringing together experts who examine the unique technical, geographical, geological, environmental, social, and economic realities of the region, we hope to go beyond merely identifying issues. We want this combination of first-hand experience and interaction among participants to result in a new level of understanding of the state's earthquake hazards and our preparedness for future events.

We have selected a variety of presenters for this conference because we believe it is important for you to hear a variety of viewpoints on issues. However, please note that the views presented during the conference are not necessarily those of the Department of Natural Resources, Division of Geology and Earth Resources.

The Washington Decision-Makers Field Conference is an outreach program of the Department of Natural Resources, Division of Geology and Earth Resources. Its mission is to provide educational opportunities to individuals who make and influence policy on natural resources and related social, economic, and environmental issues in Washington.We appreciate your attendance at this year's conference and your insights for its improvement.

WHO WE ARE

The Department of Natural Resources, Division of Geology and Earth Resources, is Washington's state geological survey. The state geological survey has studied and reported on the state's geology since its creation in 1890. Today, our mission is to study and provide information about the surface and subsurface geology of the state, including aggregate resources, hazards, basic geology, coal, natural gas, and minerals. Our work commonly focuses on the state's most pressing geological issues such as earthquakes, tsunamis, volcanic events, and landslides. We also regulate certain aspects of the mineral and fossil fuel industries, including surface-mine and metal-mine reclamation, oil and gas drilling, gas storage, geothermal drilling, and underground fluids injection.

We are an excellent source of information about the geology and mineral resources of Washington for a wide variety of users, including policy-makers, mineral and oil and gas explorationists, water specialists, other governmental agencies, academics, and the general public. For example, planners use our geological data and interpretations to implement the Growth Management Act, to identify the risks of urban development in Washington’s numerous historical underground coal mining areas, to identify areas susceptible to liquefaction during an earthquake, and to assess slope stability related to timber harvesting practices.

We compile and publish geologic maps, which are basic tools used by geologists, civil engineers, and planners, and produce other publications that provide geologic information on a wide variety of subjects. Currently, the Division has about 300 publications in print; these are for sale at the Washington State Department of Printing or from our office in Olympia. Some publications are available free of charge on our website at http://www.dnr.wa.gov/AboutDNR/Divisions/GER/.

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PROGRAM

STOP 1 **Conference overview and geologic history of Puget Sound**
9:15 *On the Capitol Campus at the sundial*

- **Introduction to the conference and explanation of its format**—Dave Norman, Department of Natural Resources, Division of Geology and Earth Resources
- **Geology and earthquake history of Olympia—**Tim Walsh, Department of Natural Resources, Division of Geology and Earth Resources
- **Demonstration of seismic data gathering techniques—**Trevor Contreras and Ray Cakir, Department of Natural Resources, Division of Geology and Earth Resources
- **Seismic hazards and the Legislative Building —The cost of doing business—**Dwayne Harkness, Architect, Washington State General Administration

STOP 2 **Bedrock geology of the Olympia area**
10:30 *At the Old Olympia Brewery along the Deschutes River*

- **The role of geology in earthquakes**—Tim Walsh, Department of Natural Resources, Division of Geology and Earth Resources
- **Chimney failures during the Nisqually earthquake and the Olympia fault**—Brian Sherrod, U.S. Geological Survey

STOP 3 **Lunch**
12:00 *Tumwater Historical Park*

- **Tumwater Historical District—**Carla Wulfsberg, Director of Henderson House Museum

STOP 4 **Earthquake damage to the Old Capitol and Olympia downtown**
1:00 *Washington's Old Capitol*

- **Earthquake damage in the downtown Olympia area** —Tom Hill, Building Official, City of Olympia

- **Earthquake damage to the Old Capitol Building and what we have done about it**—Tim Walsh, Department of Natural Resources, Division of Geology and Earth Resources
- **Public and private partnerships and what business needs to prepare for earthquakes**—Bob Zimmerman, The Boeing Company
- **Pacific Northwest Seismic Network's role in seismic safety and building instrumentation**—John Vidale, State Seismologist, Pacific Northwest Seismic Network, University of Washington
- **Closing comments**—Doug Sutherland, Commissioner of Public Lands, Department of Natural Resources

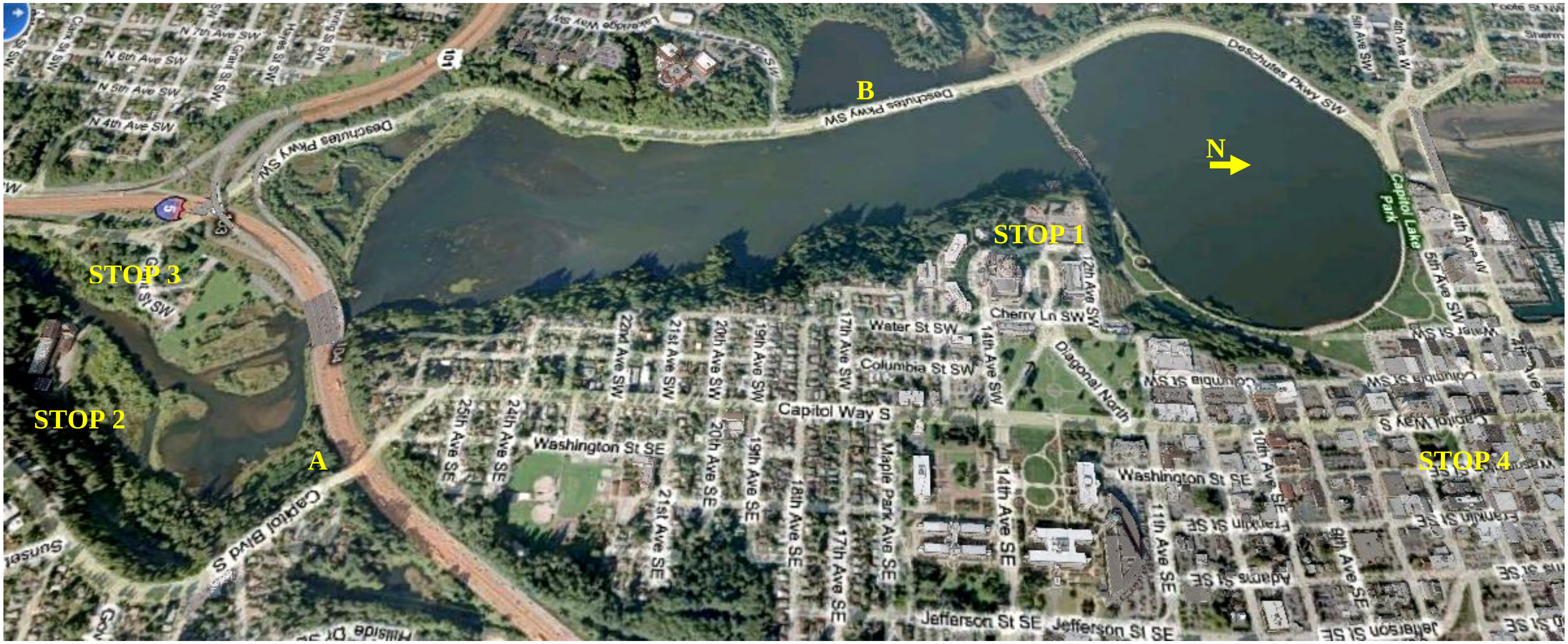

Figure 1. Overview of the trip with stops numbered. Other locations mentioned in this guide are marked with letters and are keyed to photos.

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LIST OF PRESENTERS

Dwayne Harkness was project manager for the national award-winning $120 million rehabilitation of Washington State's Capitol Building completed in 2004. He is a graduate of the University of Oregon School of Architecture and Allied Arts and a licensed architect with 18 years of private practice experience prior to joining the Washington State Department of General Administration in 1994. Mr. Harkness currently manages capital projects for GA and other state agencies. Prior to entering public service, he was responsible for the design and management of numerous public and private projects in the State of Washington.

Tom Hill is the Building Official/Development Engineer and the Permit/Inspections Services Manager for the City of Olympia, Washington. He also serves as a manager for the City of Olympia Emergency Management Emergency Operations Center. Tom has extensive experience in responding to seismic events throughout the entire west coast and has been actively involved in evaluating construction standards for retrofit of existing building stock. He has also directed and participated in a broad range of hazard assessments for land-use and emergency-management planning.

Brian Sherrod is a research geologist with the U.S. Geological Survey. His specialty is paleoseismology of western Washington, especially in the greater Puget Sound region. Current projects include identifying active faulting along the Southern Whidbey Island fault zone, the Seattle fault zone, and the Tacoma fault zone.

John Vidale is Director of the Pacific Northwest Seismic Network, which monitors Washington and Oregon for earthquakes. Until 2006, he was Director of the Institute for Geophysics and Planetary Physics at UCLA, and conducted extensive research on earthquakes and Earth structure. He has been named an American Geophysical Union Fellow, a Gilbert Fellow of the United States Geological Survey, and was awarded the Macelwane Medal of the American Geophysical Union for significant contributions to the geophysical sciences by an outstanding young scientist less than 36 years of age in 1994. His PhD is from Caltech (1987), and his BS in Physics and Geology is from Yale (1981).

Tim Walsh is a licensed engineering geologist and Geologic Hazards Program manager for the Washington Division of Geology and Earth Resources of the Department of Natural Resources. He has practiced geology in Washington for more than 25 years and taught at South Puget Sound Community College for 20 years. Tim has done extensive geologic mapping in all parts of the state and has done tsunami hazard mapping, active fault characterization, and landslide and abandoned coal mine hazard assessments. He has also directed and participated in a broad range of geologic hazard assessments and maps for land-use and emergency-management planning. Tim received bachelor's and master's degrees in geology from UCLA.

Carla Wulfsberg has worked for the City of Tumwater since 1996 developing the historic program at the Henderson House Museum. The program includes interpreting a 1905 house built by a German immigrant who was Brewmaster for the Olympia Brewing Company. Carla also manages the City's artifact and historic photography collections, produces traveling exhibits, public events, a noontime speaker series, a brewery oral history project, two television series, and an annual outdoor harvest festival. An exhibit in progress for 2008 documents the 50th anniversary of the Interstate 5 freeway through Tumwater and Olympia. Carla received a Masters Degree in Public Administration from the Evergreen State College and a Bachelors Degree from UCLA.

Prior to working for the City of Tumwater, Carla developed programs, exhibits, and events for the Seattle Public Library, the Pacific Science Center, and Pacific Lutheran University. In addition, she produced oral history media and film projects, directed an outdoor Scandinavian festival, and for five years hosted a radio show on KRAB-FM.

Bob Zimmerman is the president of Cascadia Region Earthquake Workgroup (CREW) and is a senior manager in Boeing’s Security and Fire Protection organization which administers the company’s emergency management and business continuity activities. Bob is a fire protection engineer by education and has devoted his entire 35-year career to risk reduction and risk management activities.

Stop 1. The Capitol campus is built on loose sand and silt deposited at the end of the last ice age. This material tends to amplify earthquake ground motions. Part of the campus (for instance, a gully under where the greenhouse now stands) also has loose fill placed on it, which further amplifies ground shaking.

Seismic Data Collection Demonstration

Recep Cakir, Ph.D., Geophysicist. *Washington Department of Natural Resources, Division of Geology and Earth Resources*
Trevor Contreras, M.S., Licensed Geologist. *Washington Department of Natural Resources, Division of Geology and Earth Resources*

Geologists from the Division of Geology and Earth Resources conduct seismic surveys to determine the physical properties (seismic velocity and density) of subsurface rock and soil. These surveys provide the data required to develop building codes and make maps of the potential for ground shaking and ground failure. The maps are used by emergency managers, building officials, engineers, insurance providers, facilities managers, land-use planners, and property owners (Fig. 1).

Shallow seismic surveys are quick, inexpensive, non-invasive, and provide key information to determine areas prone to strong ground shaking and failure during earthquakes.

New Equipment and New Techniques

The Division of Geology and Earth Resources upgraded their antiquated seismograph last year with one that uses a standard laptop computer to record the data. Using the new seismograph allows much more data to be recorded (than the previous MS-DOS-based seismograph) and processed quickly.

New seismic techniques termed 'surface-wave techniques' can be used to determine shear-wave velocities in the ground. These surface-wave techniques (active and passive) (Figs. 2a and 2b) have a major advantage over conventional shallow seismic methods because they tolerate and use vibrations from human activity to estimate shear-wave velocities. Since previous seismic surveys couldn't be conducted in noisy environments without large energy sources, these new techniques are well suited for urban areas.

Sensors

A geophone consists of a coil of wire with a magnet suspended inside by springs. When a vibration moves the magnet, an electrical current is produced in the coil. This current is measured by the seismograph and stored on the laptop (Figs. 2a and 2b).

Capitol Campus Surveys

The Division of Geology and Earth Resources conducted two seismic surveys in June 2008 at the Capitol Campus—the first along the path to Capitol Lake and the second east of the Temple of Justice (Fig 3). Results show very low velocity layers under the Capitol Campus. These low velocity layers correspond with soft sediments found in holes drilled in July 2007 for the Executive Office Plaza and Heritage Center and a hole drilled by the Division at Centennial Park. These soft sediments are composed of silt. Silt, when saturated with water, can lose its strength during earthquakes and liquefy.

The silt has a very low shear-wave velocity as seen in Figure 4. The top 30 meters of the soil have an average velocity of 149 meters per second. This average shear-wave velocity (Vs30) is used for seismic soil (site) classification in current building codes. The Division of Geology and Earth Resources collects and uses these values, with probabilistic seismic hazard maps (U.S. Geological Survey), to produce statewide seismic design category maps (Fig. 1). These maps are utilized for building codes in the State of Washington.

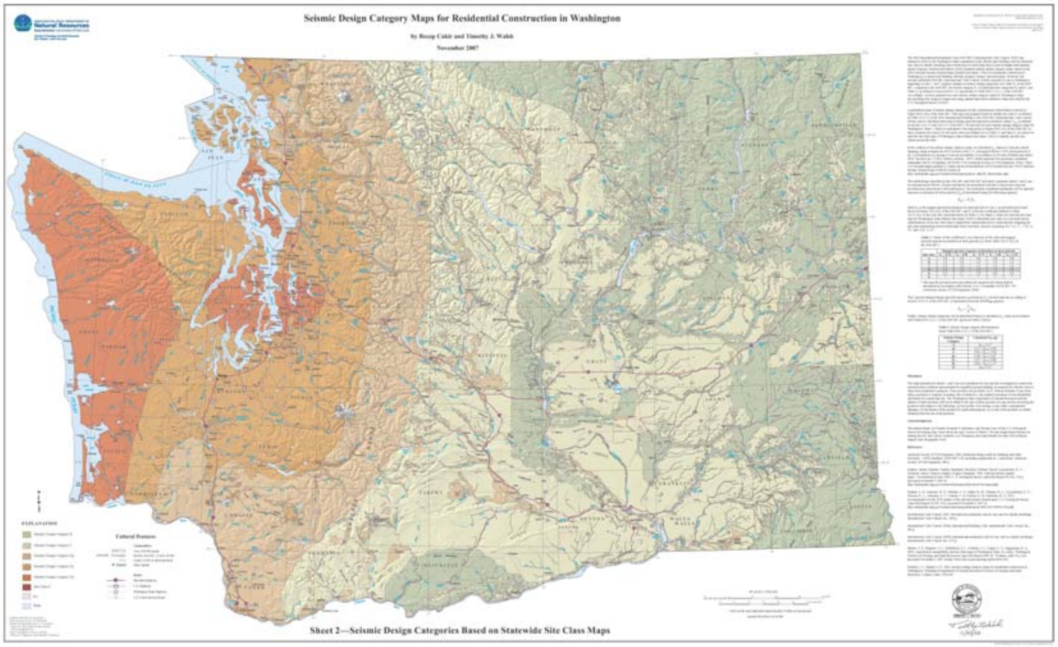


Figure 1. Example of a seismic design category map for residential construction, produced by the Division. Shallow seismic surveys are required to make these maps.

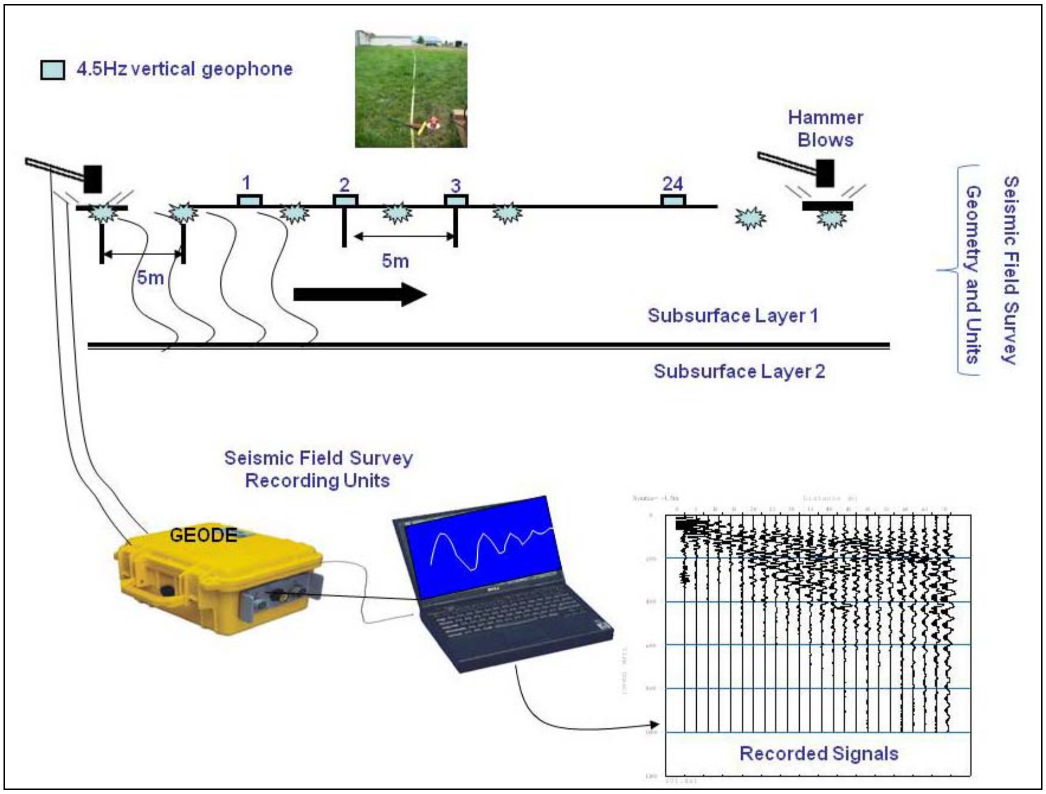


Figure 2a. Schematic view of a typical active surface-wave survey with geophones, a sledgehammer, a seismograph (GEODE), and a laptop.

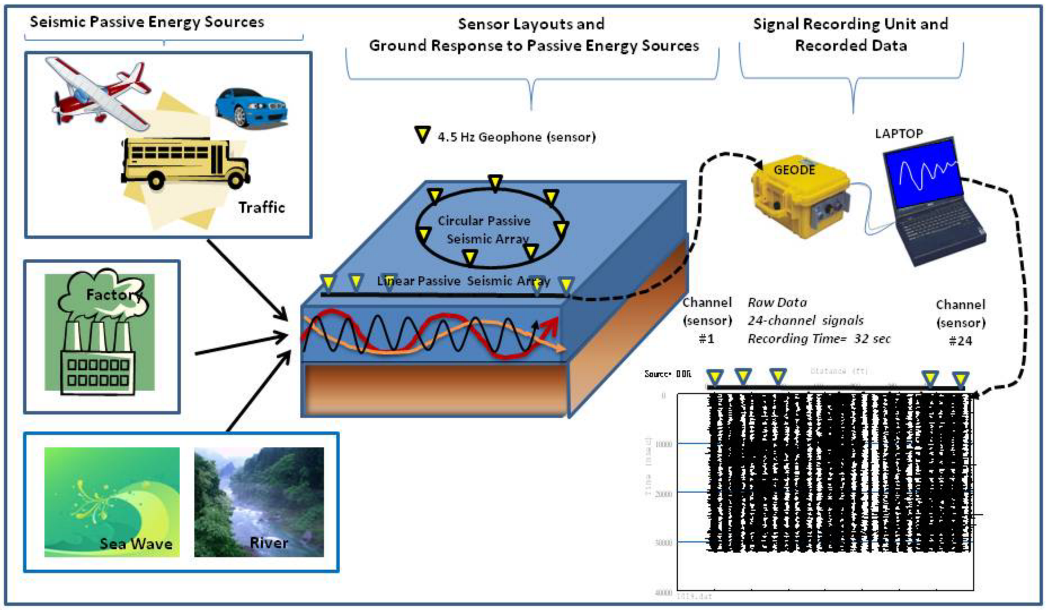


Figure 2b. Schematic view of a passive surface-wave survey. Both cultural and natural sources propagate waves at various frequencies. These waves interact with near-surface geology and are measured by the sensors (as a linear or circular array). The seismograph receives signals from the sensor and the laptop stores the signal. An example of the signals recorded is shown (bottom-right).

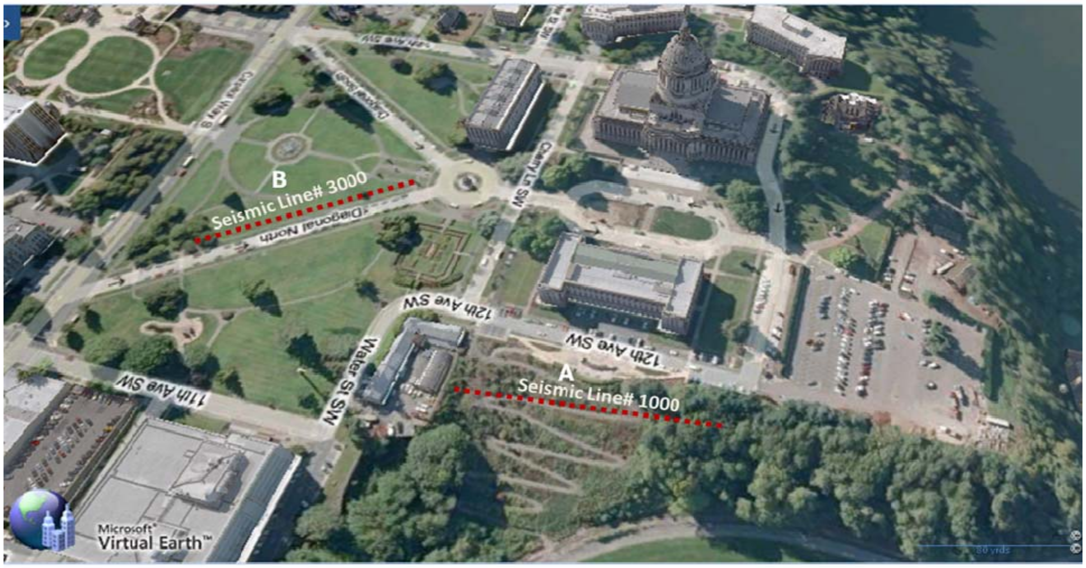


Figure 3. Locations of two seismic lines recorded June 27, 2008, by DNR Division of Geology and Earth Resources. Line A, along path to Capitol Lake and Line B, in grass, east of Winged Victory Monument.

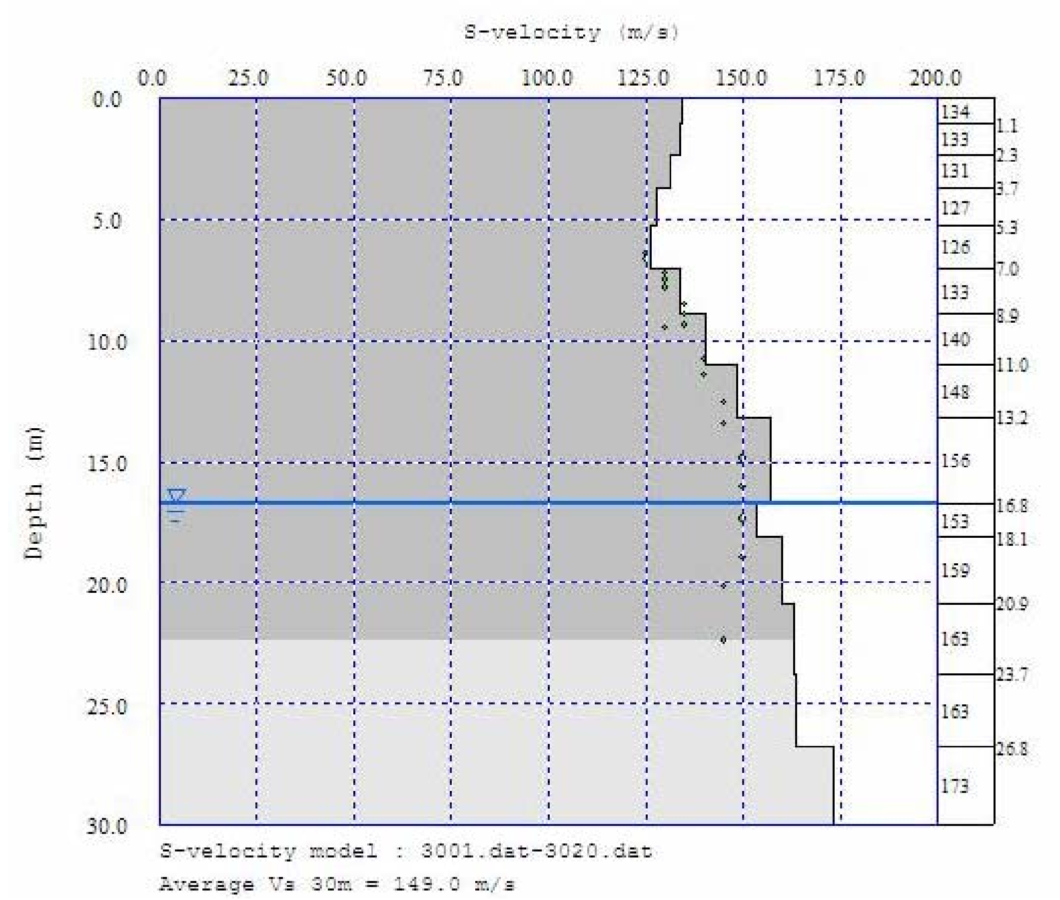
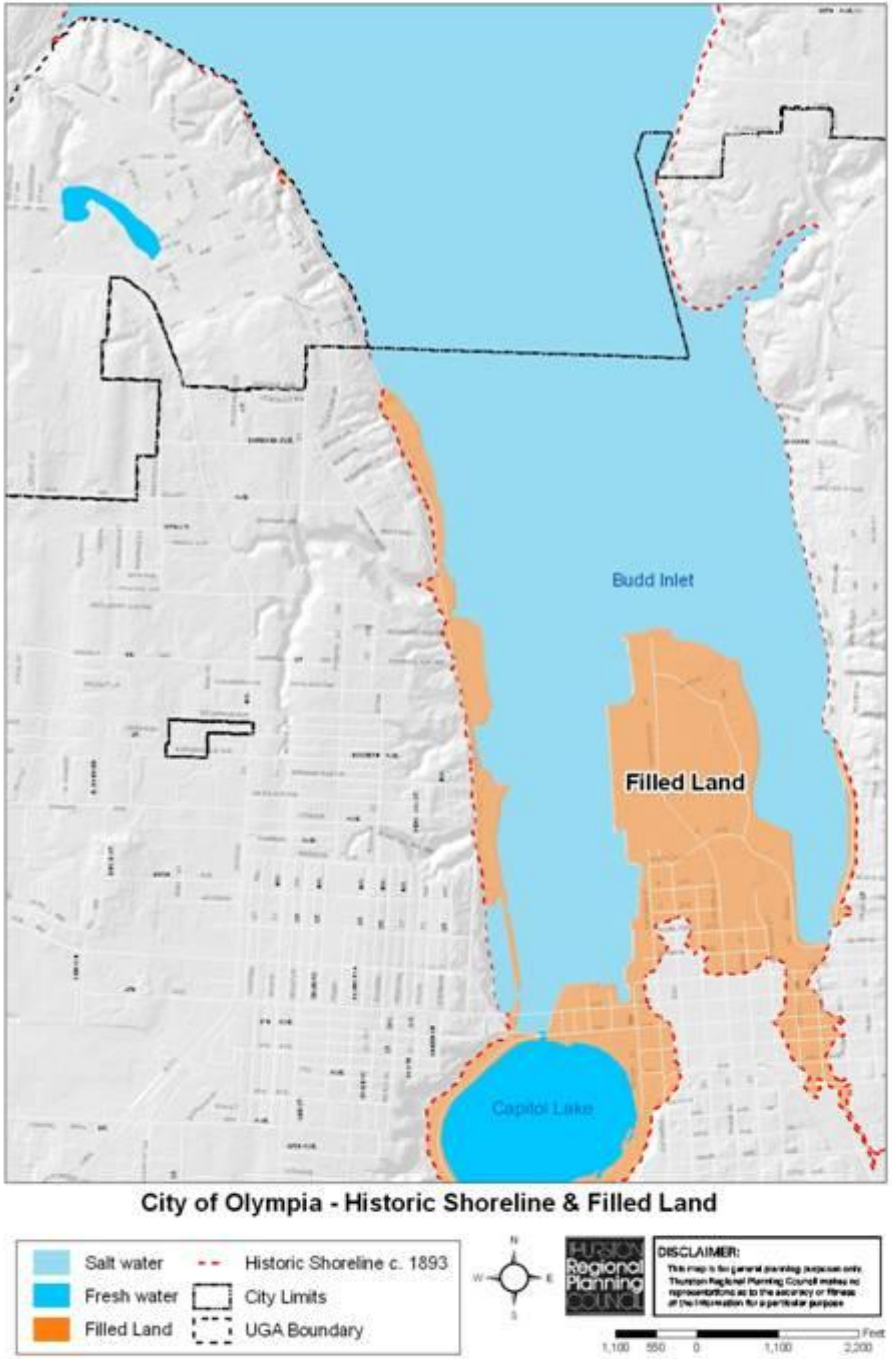


Figure 4. Shear-wave velocity graph from Capitol Campus survey, line B. The graph shows an average velocity of 149 meters per second. This is a very low velocity value, which indicates low strength (seismic site class E). Blue line is the water level measured in wells to north.

Olympia Historical Shoreline

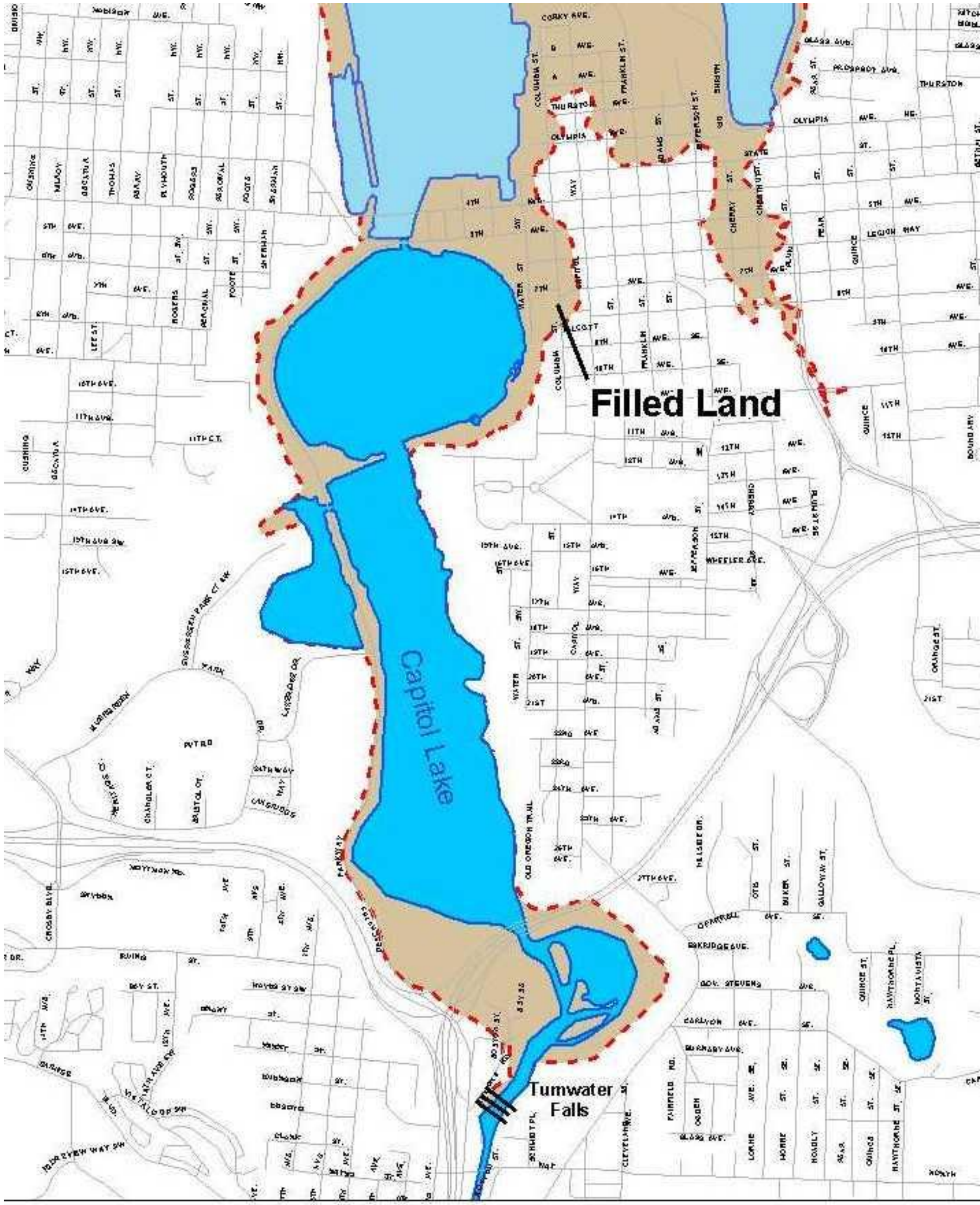
- **434 acres of filled land**
  - Downtown
  - Capitol Lake
- **Added 9,950 ft of new shoreline (1.9 mi)**



City of Olympia - Historic Shoreline & Filled Land

Capitol Lake

- Land fills have reduced the water area by 124 acres.
- <u>Four Basins</u>
  - North
  - Middle
  - Percival Cove &
  - South



Capitol Lake - Historic Shoreline & Filled Land

Stop 2. Old Olympiabrewhouse, built of unreinforced masonry in 1906. Although this building is dilapidated, it was not damaged in the Nisqually earthquake. This building is founded on bedrock, the basalt of the Crescent Formation which make up the Black Hills to the west of here.

Evidence for earthquake-induced subsidence about 1100 yr ago in coastal marshes of southern Puget Sound, Washington

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ABSTRACT

Buried forest and high marsh soils indicate abrupt changes in relative sea level at four coastal localities in southern Puget Sound. At Little Skookum Inlet and Red Salmon Creek, Douglas fir stumps in growth position are buried by salt-marsh peat. At localities along McAllister Creek and the Nisqually River, high marsh soils are buried by tidal-flat mud. Localized liquefaction coincided with submergence of the high marsh soil at McAllister Creek.

Dramatic changes in seed and diatom assemblages across these contacts confirm rapid submergence. At Little Skookum Inlet and Red Salmon Creek, salt-marsh peat immediately above a buried forest soil contains diatoms indicative of low marsh and tidal-flat environments. At McAllister Creek and Nisqually River, low-marsh and tidal-flat diatoms are abundant in laminated mud directly over high marsh peat. Inferences from modern analogs indicate at least 1 m of subsidence at each site and possibly up to 3 m at Skookum Inlet.

Abrupt burial of lowland soils in southern Puget Sound is best explained by coseismic subsidence. Some of the submergence may be the result of coseismic compaction and postearthquake settlement. Widespread buried soils, large amounts of subsidence, coeval submergence across a wide area, and ground shaking at the time of subsidence all point to a large earthquake between 1150 and 1010 cal yr B.P. in southern Puget Sound as the most likely cause of subsidence.

Keywords: diatoms, earthquakes, paleoseismology, Puget Sound, subsidence.

INTRODUCTION

Upper crustal faults represent a poorly understood geologic hazard in the southern Puget Sound region. Authors of past geological and geophysical studies inferred large structures in southern Puget Sound (Gower et al., 1985; Pratt et al., 1997); however, little information exists as to the potential for these structures to cause earthquakes and deformation. In central Puget Sound, movement on the Seattle fault about 1100 yr ago resulted in abrupt uplift of wave-cut platforms to the south of the fault, and subsidence of intertidal marshes to the north (Atwater and Moore, 1992; Bucknam et al., 1992). To the south near Tacoma and Olympia, Washington, aeromagnetic (Blakely et al., 1999) and gravity surveys (Gower et al., 1985) define several large-amplitude geophysical anomalies (Pratt et al., 1997). These anomalies indicate the approximate locations of geologic structures possibly capable of producing large earthquakes (Fig. 1). Because Quaternary glacial deposits bury these geologic structures, assessing the nature and hazard of each structure is difficult. However, given that many of these structures cross the coastline of Puget Sound, stratigraphic studies of coastal marshes are helpful for determining abrupt changes in relative sea level that accompanied prehistoric earthquakes and deformation in southern Puget Sound.

Buried soils below modern tidal marshes indicate episodes of rapid rise in relative sea level and are useful indicators of past earthquakes. Along the Cascadia subduction zone, abrupt contacts between buried soils and overlying intertidal mud resulted from rapid submergence during large subduction-zone earthquakes, including events 300 and 1100 yr ago (e.g., Clague, 1997). Submergence of lowland environments in Chile (1960) and Alaska (1964) changed forests and marshes into barren mudflats (Ovenshine et al., 1976). Similarly, large thrust earthquakes on the Seattle fault ~1100 yr ago caused abrupt subsidence that changed marshes into tidal flats (Atwater and Moore, 1992). In this paper, I document buried soils and abrupt environmental changes, at several coastal sites in southern Puget Sound, that resulted from a large earthquake about 1100 yr ago.

Paleoenvironmental reconstructions based on fossil plants, diatoms, and foraminifers enhance stratigraphic studies of coastal earthquakes. Changes in microfossil assemblages and paleoenvironment across stratigraphic contacts are used to assess the abruptness and magnitude of past submergence events (Hemphill-Haley, 1995; Mathewes and Clague, 1994; Nelson et al., 1996; Shennan et al., 1996). Recent studies concerning the distribution of modern diatoms and plants in intertidal environments make microfossils more useful in paleoseismology because the vertical ranges and salinity tolerances of these organisms are now better known (Hemphill-Haley, 1995; Nelson et al., 1996; Sherrod, 1999).

In this study I adopt an integrated lithostratigraphic and biostratigraphic approach to reconstruct late Holocene relative sea level (RSL) histories at four sites in southern Puget Sound—one locality at Little Skookum Inlet and three in the Nisqually delta (Fig. 1). I use the RSL histories to interpret episodes of rapid submergence of lowland soils, and I consider whether these episodes result from lag and feedback effects associated with slow sea-level rise (Redfield, 1972), or whether they are a product of sudden subsidence associated with large earthquakes.

COASTAL MARSH ENVIRONMENTS AND HOLOCENE SEA-LEVEL RISE

Intertidal marshes form within a narrow elevation range between mean tide level and the

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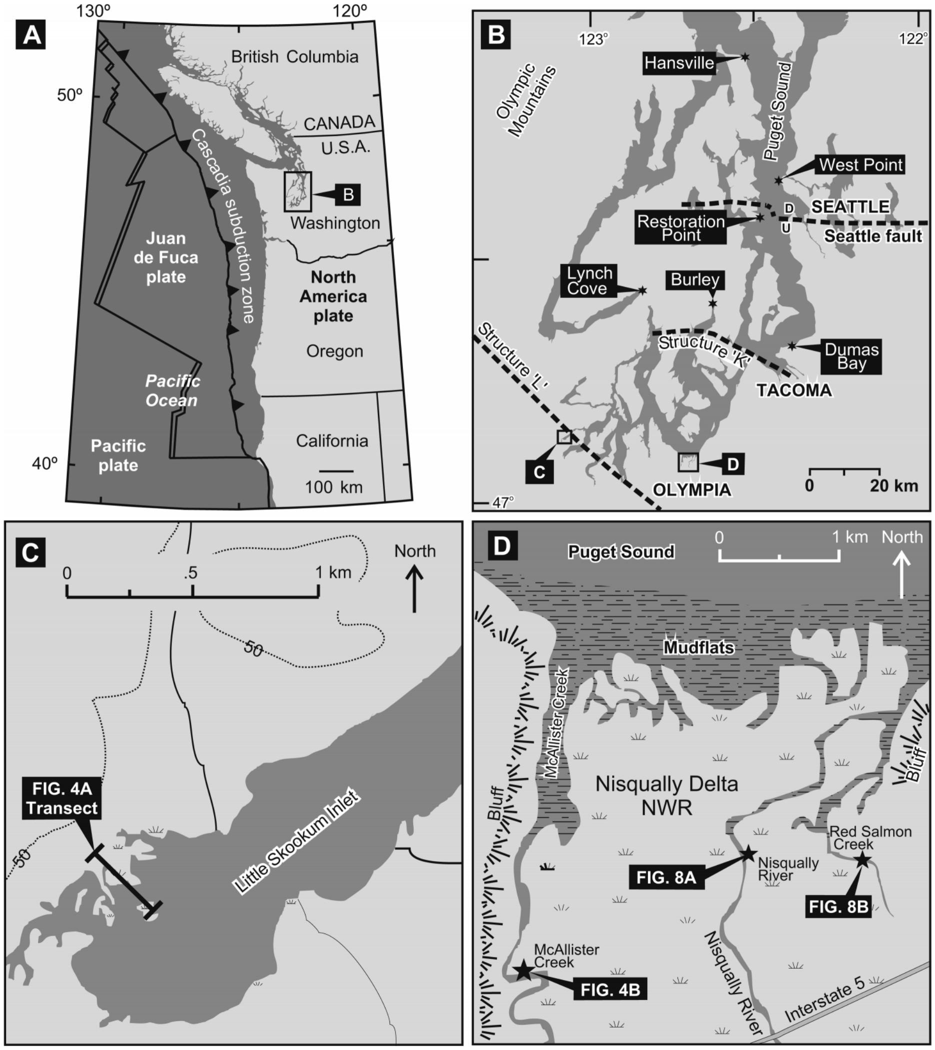

Figure 1. Index maps. (A) Regional setting. (B) Puget Sound and locations of major geologic structures. Fault locations are based on Johnson et al. (1999) and Gower et al. (1985). (C) Location and setting of core transect at Little Skookum Inlet. Dashed contour line = 15 m. (D) Location and setting of surveyed outcrops at Nisqually delta.

upper limits of tides. This characteristic allows geologists to reconstruct RSL changes from age-altitude relationships of fossil marsh deposits. Coastal marsh biota are commonly differentiated into three elevation-salinity zones similar to those established by Macdonald (1977) and Frey and Basan (1985). Fresh-water marshes have surface salinities from 0‰–3‰ and consequently are at or above the extreme high-tide line. Brackish water marshes have salinities from 3‰ to 20‰ and are divided into two subenvironments: low marsh and high marsh. Low marshes lie between mean high water and mean higher high water; high marshes fall between mean high water and extreme high water. Brackish marine environments and tidal flats have the highest salinities, from 20‰ to 35‰, and lie below mean high water.

Deposits of coastal marshes are useful in determining RSL changes following the retreat of the Vashon glacier from the Puget Lowland. Sea level rose rapidly from its glacial minimum of about 120 m below present sea level following deglaciation at about 16 ka (Booth, 1987; Porter and Swanson, 1998). By 5–6 ka, it had risen to within 2–3 m of its present sea level in northern Puget Sound and southern British Columbia (Beale, 1990; Clague et al., 1982). Eronen et al. (1987) found a similar record at northern Hood Canal, where sea level had risen to within about 6 m of its present position by 6 ka. All three studies indicate that relative sea level in the Puget Sound region has risen no more than about 1 m in the past 1000 yr.

STRATIGRAPHY AND PALEOECOLOGY OF COASTAL MARSHES

Field Data Collection

Field teams mapped stratigraphic sections at selected outcrops exposed along tidal channels and along lines of correlated 2.5-cm-long gouge cores, paying particular attention to identify buried soils, plant roots, rhizomes, and liquefaction features. I have supplemented each survey with detailed stratigraphic sections for fossil preparations (Tables 1 and 2). Plant macrofossils, foraminifers, and fossil diatoms identified from the sections from each locality are broadly divided into two biozones (see Fig. 3). I define a biozone as the stratigraphic interval containing a distinctive set of diatoms and plant macrofossils. The boundaries between biozones were visually estimated and coincide with major stratigraphic changes, primarily the burial of lowland soils by intertidal mud or peat that occurred about 1100 yr ago.

Tidal datum levels are useful for reference; I refer mainly to mean lower low water (MLLW) and mean higher high water (MHHW). I determined local mean lower low water (MLLW) on the basis of measurements of the elevation of high tide at each site and the heights of the same tides observed at Seattle by the National Ocean Survey (NOS). I then calculated tidal elevations for the site by assigning to the measured tide level at each site the corresponding level for that same tide at the nearest NOAA tidal benchmark (generally 13 km or less away).

Samples for radiocarbon ages included plant material from outcrops and bark-bearing wood from in situ tree stumps (Fig. 2). I report conventional radiocarbon ages as ^{14}C yr B.P. I used the computer program OxCal (Ramsey, 1995) and the INTCAL98 calibration data of Stuiver et al. (1998) to calibrate the reported ages; the 95% confidence interval of each calibrated age is reported as cal yr B.P. (before A.D. 1950). I also refer to rounded ages for events as occurring years before A.D. 2000; thus, a calibrated age of 900 cal yr B.P. is about 1100 yr ago.

My approach to paleoecological reconstructions relies on combined analyses of plant macrofossils, diatoms, and foraminifers. This approach is powerful because each of the analyses yields distinct paleoenvironmental information that, when combined, leads to a robust

TABLE 1. DESCRIPTION OF STRATIGRAPHIC UNITS AND RADIOCARBON SAMPLES

Unit	Lithologic description	Radiocarbon age		Depth[†]	Lab no.[§]	Material
		(^{14}C yr B.P.)	cal yr*	(m)		
Little Skookum Inlet locality						
LSI-1	Gray mud, massive to laminated, no fossils, occasionally hard, slightly sandy in places.					
LSI-2	Tan gyttja, massive to laminated, no fossils, gradational lower contact.					
LSI-3	Reddish-brown detrital peat, large pieces of wood common, small stems of woody plants abundant, seeds of herbaceous plants observed in field (*Menyanthes* sp., and *Scirpus* sp.).	7030 ± 70	7690–7970 B.C.	0.45	Beta-97230	Peat
		7520 ± 80	8160–8450 B.C.	0.45	Beta-97231	Peat
LSI-4	Gray silty, fine to medium sand, orange mottles, massive					
LSI-5	Gray mud, massive, orange mottles (esp. in upper part of unit), penetrative roots in upper part of unit					
LSI-6	Dark brown woody peat to muddy peat, abundant stems of woody plants, conifer cones, abundant stumps of *Pseudotsuga menziesii* in growth position and occasionally *Alnus rubra.*	1090 ± 60[#]	A.D. 770–1040	0.75	Beta-95912	Wood
		1220 ± 50**	A.D. 860–1150[††]	On tidal flat	Beta-102335	Wood
		1222 ± 15	A.D. 800–970[§§]	On tidal flat	QL-4633	
LSI-7	Brown muddy fibrous peat, rhizomes of *Distichlis spicata* and rarely *Triglochin maritima,* contact with underlying unit sharp (≤1 mm) in most places.	140 ± 60	A.D. 1660–1960	0.67	Beta-117091	Leaf bases
McAllister Creek locality						
MC-1	Brown fibrous peat, muddy, rhizomes of *Distichlis spicata* and *Triglochin maritima.*					
MC-2	Gray mud, massive, no fossils observed.					
MC-3	Brown fibrous peat, slightly muddy, rhizomes of *Scirpus maritimus* and *Juncus* cf. *balticus.*					
MC-4	Gray-brown mud, couplets of laminated silt and clay at base of unit, lamination becoming faint in middle and top of unit, rhizomes of *Triglochin maritima* and *Juncus* cf. *balticus* present at base of unit just above contact with MC-3.	1140 ± 80	A.D. 680–1030	~2.30	Beta-102336	Leaf bases
MC-5	Brown, fine sand, moderately well sorted, distinctive grains of red scoria present throughout.					
MC-6	Orange-brown muddy peat, oxidized in most places.					
Nisqually River locality						
NR-1	Brown fibrous peat, no distinguishable fossils. At or just below river level at low tide, and underlain by gray mud and another fibrous peat (below mud).					
NR-2	Gray-brown mud, couplets of laminated silt and clay at base of units, becoming faint in middle and top of unit.	1030 ± 70	A.D. 870–1190	~3.0	Beta-110150	Leaf bases
NR-3	Brown fine sand, massive, moderately well sorted, unconformity at base with small channel feature.					
NR-4	Gray-brown mud, laminated in places, otherwise massive.					
NR-5	Brown fine sand, massive appearance, moderately well sorted.					
NR-6	Reddish-brown peaty mud, with coarse woody roots (modern) in upper half of unit.					
Red Salmon Creek locality						
RSC-1	Gray fine, micaceous silty sand, massive in appearance. Thin black layer at top (~2 cm thick), mud clasts and stems of woody plants in lower half of unit.	Wiggle match	A.D. 860–940[##]	1.57	See Fig. 2	Wood
		1010 ± 50	A.D. 890–1170		Beta-110746	Wood
		1200 ± 14	A.D. 820–940***		QL-4634	Wood
RSC-2	Brown fibrous peat, *Distichlis spicata* rhizomes and faint lamination in places.					
RSC-3	Brown-gray mud, couplets of laminated silt and clay at base of unit (1–2 cm thick) lamination becoming faint in middle and top of unit, *Triglochin maritima* rhizomes in upper part of unit.	130 ± 60	A.D. 1660–1960	0.80	Beta-109230	Leaf bases
RSC-4	Brown muddy peat, reddish-orange mottles, *Triglochin maritima* and *Distichlis spicata* rhizomes throughout, wood observed above gradational contact at base of unit.					

*2σ, 95% probability.

[†] Depth below modern ground surface.

[§] QL—University of Washington Quaternary Isotope Laboratory; Beta—Beta Analytical, Inc.

[#] Outer 15–25 rings.

**Innermost 16 rings of root slab KW8–5 (age result was assumed on midpoint of sample, or ring 8).

[††] Calibrated age offset by number of tree rings from midpoint of sample to outermost ring (184 tree rings).

[§§] Calibrated age offset by number of tree rings from midpoint of sample to outermost ring (83 tree rings).

[##] Ordered sequence of samples QL-4935 and QL-4937 (see Fig. 2).

***Calibrated age offset by number of tree rings from midpoint of sample to outermost ring (48 tree rings).

TABLE 2. BIOZONES AND PALEOENVIRONMENTAL INTERPRETATIONS

Biozone	Depth (m)*	Dominant fossils	Paleoenvironmental interpretation
Little Skookum Inlet			
BZ2	0.34–0	Macrofossils—*Juncus* sp., *Atriplex patula, Carex lyngbyei,* and *Deschampsia caespitosa.* Needles and buds of *Pseudotsuga menziesii.* Diatoms—*Diploneis interrupta, Nitzschia bilobata, Paralia sulcata, Navicula cincta,* and *Caloneis westii.*	Low to high brackish-water marsh
BZ1	$2.0^{(+)}$–0.34	Macrofossils—*Juncus* sp., *Betula papyifera, Rubus spectabalis, Sambucus racemosa, Carex* cf. *leporina, C.* cf. *aquatilus,* and *Berberis nervosa.* Leaves of *Thuja plicata* and *Taxus brevifolia,* needles of *Picea sitchensis,* and follicles of *Spirea douglasii.* Top of zone marked by forest soil and stumps of *Pseudotsuga menziesii.* Diatoms—*Fragilaria construens, Eunotia pectinalis,* and *Aulacoseira italica.* Diatom preservation in soil horizon was poor.	Fresh-water marsh and Douglas fir forest
McAllister Creek			
BZ2	2.32–0	Macrofossils—*Spergularia canadensis, Carex lyngbyei, Distichlis spicata, Scirpus* cf. *maritimus, Salicornia virginica,* and *Betula papyifera* seeds, and foraminifera. Diatoms—*Melosira nummuloides, Navicula slesvicensis, Mastogloia exigua, Tryblionella debilis, Tabellaria fenestrata,* and *Rhopalodia musculus.*	Brackish-water, low marsh–tidal flat (at base) to high marsh (at top)
BZ1	$2.95^{(+)}$–2.32	Macrofossils—burned conifer needles, *Sambucus racemosa* seeds, scattered foraminifera, and charcoal fragments. Diatoms—*Achnanthes brevipes, Luticola mutica,* and *Navicula cincta,* but most samples poorly preserved.	Brackish-water, high marsh
Nisqually River			
BZ2	3.12–0	Macrofossils—*Salicornia virginica, Triglochin maritima, Spergularia canadensis, Juncus* sp., and *Carex lyngbyei* seeds. Diatoms at base of zone—*Melosira nummuloides, Navicula slesvicensis, Amphora ventricosa, Gyrosigma balticum,* and *Diploneis interrupta.* Diatoms at top of zone—*Aulacoseira italica, Hantzschia amphioxis, Pinnularia borealis,* and *Pinnularia subcapitata.*	Brackish-water, low marsh–tidal flat (at base) to high marsh (at top)
BZ1	$3.4^{(+)}$–3.12	Macrofossils—*Juncus* sp., *Potentilla pacifica,* and *Salicornia virginica* seeds. Diatoms—*Eunotia pectinalis, Pinnularia lagerstedtii, Cosmioneis pusilla, Luticola mutica,* and *Achnanthes brevipes.*	Brackish-water, high marsh
Red Salmon Creek			
BZ2	1.68–0	Macrofossils—foraminifera, *P. menziesii* needles (rare), and seeds of *Atriplex patula, Spergularia canadensis,* and *Triglochin maritima.* Diatoms—*Caloneis westii, Diploneis interrupta, Trachyneis aspera, Mastogloia exigua, Achnanthes brevipes,* and *Melosira nummuloides,* and species of *Navicula* and *Nitzschia* in middle of zone.	Low marsh to tidal flat
BZ1	$2.0^{(+)}$–1.68	Top of zone is marked by thin, charcoal-rich sand layer and in situ stumps of *Pseudotsuga menziesii.* Macrofossils—*P. menziesii* and *Picea sitchensis* needles, and *Sambucus racemosa* seeds. No diatoms were observed.	Douglas fir forest

*Depth below modern ground surface at place where fossil samples were collected.

interpretation. I processed sediment samples for diatoms, plant macrofossils, and foraminifers according to the procedures outlined in Sherrod (1998). Permanent diatom slides were prepared by using evaporation trays to randomly settle the diatoms onto cover slips with Naphrax ($n = 1.7$) as a mounting medium. I counted approximately 400 valves for each sample at magnifications of 787X and 1250X. I used WACALIB (Line and Birks, 1990) to create transfer functions from a weighted averaging technique to infer past changes in elevation and salinity (Sherrod, 1998, 1999).

Little Skookum Inlet Locality

Stratigraphy

The Little Skookum Inlet locality consists of a large tidal marsh and tidal flat bordered by lowland forest northwest of the marsh (Fig. 1). Most deposits beneath the marsh and tidal flat consist of intercalated peat and mud (LSI-1–LSI-6 in Figs. 3 and 4); a lowland soil and fossil Douglas fir stumps are near the top of the sequence. Douglas fir stumps are associated with a buried soil (LSI-6), consisting of a dark brown to black detrital peat with conifer cones, logs, and abundant detrital woody stems. Salt-marsh peat (LSI-7) containing abundant *Distichlis spicata* and rare *Triglochin maritima* rhizomes overlies the buried forest soil (LSI-6). A sharp contact (~1 mm wide) separates the peat from the underlying buried soil.

Radiocarbon ages provide evidence for the timing of submergence and burial of the forest soil at Little Skookum Inlet (Fig. 2). A high-precision radiocarbon measurement on rings 70–95 from a Douglas fir root (counted inward from the outermost ring adjoining bark) yielded an age of 1222 ± 15 ^{14}C yr B.P. (QL-4633, rings 70–95), and calibrates to 1150–980 cal yr B.P. The outermost 15–25 rings of a large Douglas fir root (with attached bark) yielded a conventional radiocarbon age of 1090 ± 60 ^{14}C yr B.P. (Beta–95912). The calibrated age for this sample is 1180–910 cal yr B.P. (Fig. 2). A second sample, from the inner 16 rings of a separate Douglas fir root (with a total of 192 rings), yielded a radiocarbon age of 1220 ± 50 ^{14}C yr B.P. (Beta–102335); the calibrated age for death of this tree is 1090–800 cal yr B.P. (radiocarbon age is offset by 184 yr, the number of tree-ring years from the midpoint of the sample and the outermost ring adjoining bark). The overlap in these two calibrated age ranges implies no statistical difference in the time of tree death. A radiocarbon age on *Triglochin maritima* rhizomes, collected from 65 to 70 cm below the marsh surface (or 45–50 cm above the buried soil) from an outcrop of peat at horizontal coordinate 305 m (Fig. 4), yielded an age of 140 ± 60 ^{14}C yr B.P. (Beta–117091) and a calibrated age of 290–10 cal yr B.P.

Paleoecology

Biozone BZ-1, from the lower part of the stratigraphic sequence, is dominated by macrofossils of lowland forest shrubs and herbs, arboreal taxa, and fresh-water and cosmopolitan diatoms (Fig. 5). Plant macrofossils include follicles of *Spirea douglasii,* seeds of *Betula papyifera, Carex* cf. *leporina, Carex* cf. *aquatilus, Rubus spectabalis, Sambucus racemosa, Juncus* sp., and leaves of *Thuja plicata, Picea sitchensis,* and *Taxus brevifolia.* Dozens of *Pseudotsuga menziesii* (Douglas fir) stumps in growth position crop out at the top of BZ-1. Two samples from just below the top of BZ-1 contained rare foraminifers, possibly infaunal contamination from overlying deposits (one specimen in each of two samples).

Seeds of *Juncus* sp. and salt-marsh plants, including *Atriplex patula, Carex lyngbyei,* and *Deschampsia caespitosa,* dominate the macrofossils of biozone BZ-2. Large numbers of foraminifers are common throughout this zone. The diatoms from BZ-2 are dominated by brackish and marine taxa, including *Diploneis interrupta, Nitzschia bilobata, Melosira nummuloides, Tryblionella debilis, Paralia sulcata,* and *Caloneis westii* (Fig. 5). Smaller quantities of cosmopolitan and fresh-water diatoms are present in this zone.

McAllister Creek Locality

Stratigraphy

The McAllister Creek locality consists of an outcrop ~150 m long of late Holocene sediments exposed in a cutbank of a large tidal creek meander at the Nisqually delta (Figs. 1 and 4). Two beds of fibrous peat (units MC-1 and MC-3) crop out at the base of the section. Each peat contains rhizomes of salt-marsh plants, and the peats are separated by a massive gray mud about 20–25 cm thick (MC-2). A sharp contact (~1 mm) separates the uppermost peat layer (MC-3) from overlying gray-brown, laminated mud (MC-4). A sample of *Triglochin maritima* leaf bases from immediately above the contact yielded a radiocarbon age of 1140 ± 80 ^{14}C yr B.P. (Beta–102336), and a calibrated age of 1270–920 cal yr B.P. (Fig. 2). An oxidized muddy peat (MC-6, modern marsh soil), locally underlain by brown, fine sand (MC-5) caps the outcrop.

A thin sand dike (~2 cm thick at widest point) and sand volcano, consisting of gray fine sand, crops out in the lower part of the outcrop (Fig. 6). During times of exceptionally low water, I observed the dike cutting across MC-1, MC-2, and MC-3. Vented sand, tapering away from the dike, occurs on the upper surface of MC-3; the thickest accumulation of sand (~5 cm) is directly above the dike.

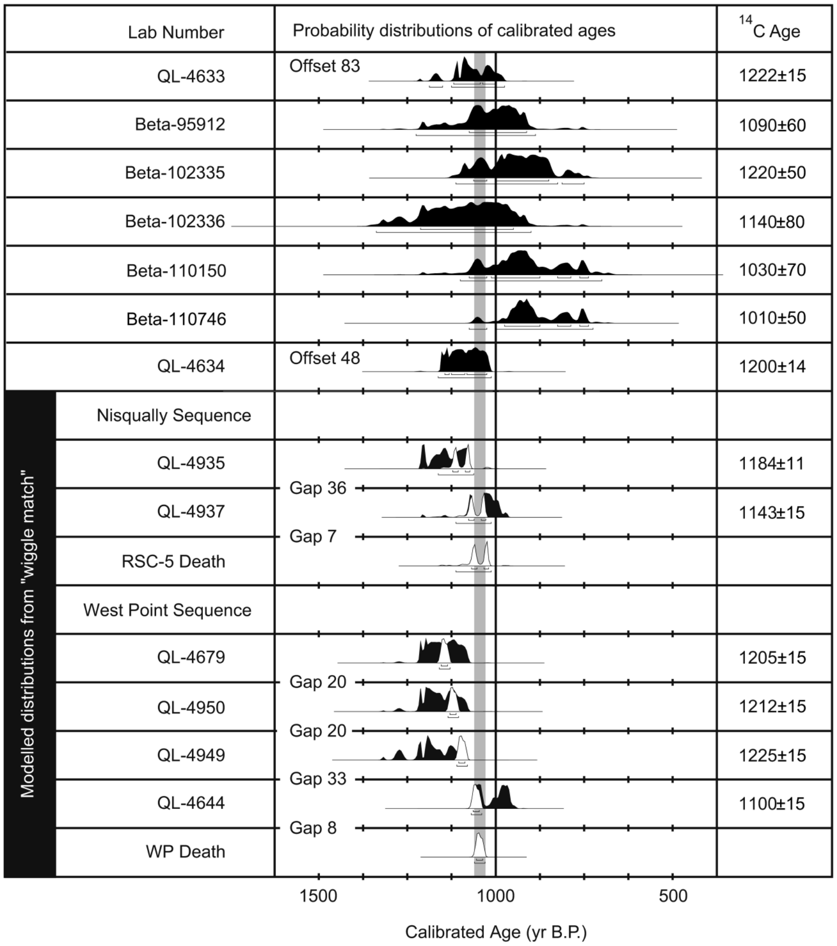

Figure 2. Probability distributions for radiocarbon dates from sites in southern Puget Sound (2σ, 95.4% confidence interval). Black plots are calculated distributions; white plots are modeled distributions from a wiggle-match analysis. The Nisqually and West Point ordered sequences consist of several radiocarbon measurements made on part of a single piece of wood from each site; the gap number indicates the difference in years (tree rings) between each sample. WP Death shows the calibrated age range for the 1050–1020 cal yr B.P. Seattle fault earthquake (Atwater, 1999; data from Brian Atwater, 1998, personal commun.), and RSC-5 Death shows the age range for submergence at Red Salmon Creek. The vertical gray bar corresponds to the 1050–1020 cal yr B.P. age range for the last Seattle fault event. Probability distributions that intersect the gray bar indicate that there is no statistical difference in the dates of the Seattle fault event 1100 yr ago (submergence of West Point; Atwater and Moore, 1992) and submergence in southern Puget Sound. Sample numbers are cross-referenced in the text.

Paleoecology

Charcoal fragments dominate the samples from BZ-1 sieved for macrofossils (Fig. 7). Conifer needles (burned and unidentifiable) and *Sambucus racemosa* seeds are common. Two samples from this zone contain foraminifera. Diatoms from BZ-1 are dominated by taxa common to salt marshes and tidal flats (Fig. 7), including *Achnanthes brevipes, Diploneis interrupta, Luticola mutica, Melosira nummuloides,* and *Navicula cincta. Melosira nummuloides,* a common tidal-flat diatom at the base of the zone, decreases in relative abundance at the top of the zone. *Diploneis interrupta,* a common high or low marsh taxon (Hemphill-Haley, 1995) is subdominant at the base of BZ-1 but becomes more abundant than all other diatoms at the top of the zone.

The base of biozone BZ-2 at McAllister Creek is marked by seeds of *Spergularia canadensis, Scirpus* cf. *maritimus,* and *Distichlis spicata,* and by the disappearance of charcoal fragments (Fig. 7). The change in macrofossils coincides with the sharp contact between the buried marsh soil (MC-3) and the overlying laminated mud (MC-4). Seeds of brackish-and salt-marsh plants, including *Carex lyngbyei, Salicornia virginica,* and *Spergularia canadensis,* dominate the middle and upper parts of BZ-2. Foraminifera show up in several samples, mainly in the middle and upper parts of the zone. Diatoms from BZ-2 consist of assemblages similar to those of BZ-1, but

Locality	Biozone	Lith. Unit	Depth (m)[a]	C^{14} Age[b]	Cal. Age[c]	Environment	Inferred Elevation Shifts	Inferred Salinity Shifts
Red Salmon Creek	BZ-2	RSC-4	2.0 - 1.68			low to high marsh	Little to no change	Little to no change
		RSC-3	1.68 - 1.57	130±60	290 - 10	mudflat/tidal slough		
		RSC-2	1.57 - 0.38			low marsh		
							▶ -1.2 m	+ 26‰
	BZ-1	RSC-1	0.38 - 0		1090 - 1010[d]	Douglas-for forest	Above highest tide	fresh water
				1200±14	1030 - 1010			
				1010±50	1170 - 930			
Nisqually River	BZ-2	NR-6	0.62 - 0			low to high marsh	Little to no change	Little to no change
		NR-5	~1.5 - 0.62			flood sand (?)		
		NR-4	1.80 - ~1.5			mudflat to marsh		
		NR-3	2.24 - 1.80			flood deposit (?)		
		NR-2	3.12 - 2.24	1030±70	1080 - 760	mudflat		
							▶ -0.9 m	+ 15‰
	BZ-1	NR-1	3.18 - 3.12	(upper peat)		high marsh		
			3.23 - 3.18	(mud)		(?)		
							▶ -3.8 m (?)	+ 20‰
			3.43 - 3.23	(lower peat)		high marsh		
McAllister Creek	BZ-2	MC-6	0.35 - 0			low to high marsh	Little to no change	Little to no change
		MC-5	1.30 - 0.35			flood sand (?)		
		MC-4	2.32 - 1.30	1140±80	1270 - 920	mudflat		
							▶ - <0.5 m	No change
	BZ-1	MC-3	2.41 - 2.32			high marsh		
		MC-2	2.53 - 2.41			(?)		
							▶ - 0.6 m	No change
		MC-1	2.92 - 2.53			high marsh		
Little Skookum Inlet	BZ-2	LSI-7	0.34 - 0	140±60	290 - 10	low to high marsh		
							▶ ~1 - 3 m	+ 20‰
	BZ-1	LSI-6	0.50 - 0.34	1222±15[e] 1090±60 1220±50[f]	1150 - 980 1180 - 910 1090 - 800	Douglas-fir forest	Above highest tide	freshwater/forested
		LSI-5	1.06 - 0.50			freshwater lake		
		LSI-4	not present at study core location			stream		
		LSI-3	1.90 -1.06	7030±70 7520±80	7970 - 7690 8450 - 8160	freshwater marsh		
		LSI-2	1.97 - 1.90			freshwater lake		
		LSI-1	2.05 - 1.97			late-glacial (?) lake		

[a] - depth below modern ground surface at location where fossil samples were collected

[b] - radiocarbon age in years B.P.

[c] - calibrated radiocarbon age in cal yr B.P.

[d] - RSC Tree 5 death (Nisqually ordered sequence on Fig. 2)

[e] - offset by 83 years (= # of rings from midpoint ring in sample to outermost ring)

[f] - offset by 184 years (= # of rings from midpoint ring in sample to outermost ring)

Figure 3. Summary of stratigraphy, radiocarbon ages, biozones, and environmental interpretations for each locality. Inferred changes in elevation and salinity are indicated on the right.

there are large changes in the relative percentages of most taxa across the boundary between the two biozones (Fig. 7). The most conspicuous change occurs with *Melosira nummuloides,* which dramatically increases in abundance at the base of BZ-2. *Diploneis interrupta,* a common low to high marsh taxon (Hemphill-Haley, 1995; Sherrod, 1999) decreases in relative abundance across the zonal boundary. The top of BZ-2 is dominated by brackish water marsh and tidal-flat taxa, including *Achnanthes brevipes, Caloneis westii, Gyrosigma eximium, Melosira nummuloides,* and *Mastogloia elliptica.*

Nisqually River Locality

Stratigraphy

The Nisqually River locality consists of a 50-m-long outcrop on the east bank of the Nisqually River, about 1.5 km downstream of Interstate 5 (Figs. 1 and 8). The stratigraphy at this locality resembles the sequence at McAllister Creek. The lower half of the outcrop consists of interbedded peat and mud (NR-1). A sharp (<1 mm wide) contact separates NR-1 from overlying brown-gray, laminated mud (NR-2). *Triglochin maritima rhizomes* 3–5 cm above this contact yielded a radiocarbon age of 1030 ±70 ^{14}C yr B.P. (1080–760 cal yr B.P., Beta–110150) (Fig. 2). The remainder of the section consists of (in ascending order) gray, massive mud (NR-4); massive, fine sand (NR-5); and reddish-brown, sandy mud (NR-6) containing roots and rhizomes of modern salt-marsh plants.

Paleoecology

Seeds of *Juncus* cf. *balticus* and *Potentilla pacifica,* both common high marsh plants, are the dominant macrofossils from biozone BZ-1 at the Nisqually River locality (Fig. 9). *Salicornia virginica* and Graminaeae (*Dactylus* sp.) also appear in this zone but are rare. I did not recover any foraminifera from this zone. Diatoms from BZ-1 are dominated by freshwater and cosmopolitan marsh taxa, including *Eunotia pectinalis, Pinnularia lagerstedtii, Cosmioneis pusilla,* and *Luticola mutica* (Fig. 9). Brackish water species, such as *Diploneis interrupta* and *Achnanthes brevipes,* are also common in BZ-1.

The base of biozone BZ-2 is marked by the disappearance of *Juncus* sp. seeds, and by the presence of *Salicornia virginica, Triglochin maritima,* and *Spergularia canadensis* seeds. This change in the macrofossils occurs at the stratigraphic contact between the buried marsh soil (NR-1, upper peat) and the overlying laminated mud (NR-2). Seeds of salt-marsh plants, including *Juncus* sp. *Atriplex patula, Triglochin maritima, Salicornia virginica,* and *Carex lyngbyei* persist into the middle and upper parts of BZ-2. Samples from the lower half of BZ-2 contained foraminifera.

The diatom flora from BZ-2 contains many brackish water marsh and tidal-flat taxa, particularly in the lower half of the zone. *Melosira nummuloides,* a common tidal-flat diatom, appears for the first time at the base of the zone immediately above the contact between the buried soil and overlying mud (~2 cm, Fig. 9). Other dominant diatoms in the lower half of BZ-2 include *Navicula slesvicensis, Denticula subtilis, Achnanthes delicatula, Trachyneis aspera, Amphora ventricosa,* and other brackish-marine diatom taxa. The upper four samples from BZ-2 contain several valves of fresh-water diatoms, including *Pinnularia borealis, Hantzschia amphioxys, Aulacoseira italica, Cocconeis placentula, Stauroneis anceps,* and *Pinnularia subcapitata.*

Red Salmon Creek Locality

Stratigraphy

The Red Salmon Creek locality comprises a 35-m-long outcrop along a stream bank in the eastern part of the Nisqually delta (Figs. 1

and 8). The lowest unit (RSC-1) is a gray, massive, fine to medium sand, with Douglas fir stumps in growth position at the top. A thin blackened zone in the upper few centimeters of RSC-1 contains charcoal. A sample of wood from the outer rings of a stump rooted in the top of RSC-1 (at horizontal coordinate 4 m) yielded a conventional radiocarbon age of 1010 ±50 ^{14}C yr B.P. (Beta–110746) and a calibrated age range of 1060–780 cal yr B.P. (Fig. 2). High-precision radiocarbon ages from a single root section of another Douglas fir stump yielded ages of 1184 ± 11 ^{14}C yr B.P. (QL-4635, rings 40–45, calibrated to 1170–1050 cal yr B.P., and 1143 ± 15 ^{14}C yr B.P. (QL-4937, rings 3–10, calibrated to 1080–970 cal yr B.P.). A ''wiggle match'' of the ages for QL-4635 and QL-4937 on the calibration curve (Ramsey, 1995) yielded an age of 1090–1010 cal yr B.P. for the death of the tree (Figs. 2 and 3). I obtained a high-precision radiocarbon age of 1200 ± 14 ^{14}C yr B.P. (QL-4934, RSC tree 3 rings 45–50, calibrated to 1180–1060 cal yr B.P.) from another preserved stump at horizontal coordinate 5 m (Fig. 8).

The remainder of the section consists of locally discontinuous, fibrous peat (RSC-2, with rhizomes of *Distichlis spicata*, *Triglochin maritima* leaf bases, and *Juncus* cf. *balticus*), and gray-brown, laminated mud (RSC-3) lying unconformably on RSC-2. A sample of *Triglochin maritima* leaf bases at horizontal coordinate 10 m (80 cm above the contact between RSC-2 and RSC-3) gave an age of 130 ± 60 ^{14}C yr B.P. (Beta–109230) and a calibrated age of 290–10 cal yr B.P. (Fig. 2). A mottled, reddish-brown muddy peat (RSC-4), containing modern roots and rhizomes caps the sequence at Red Salmon Creek.

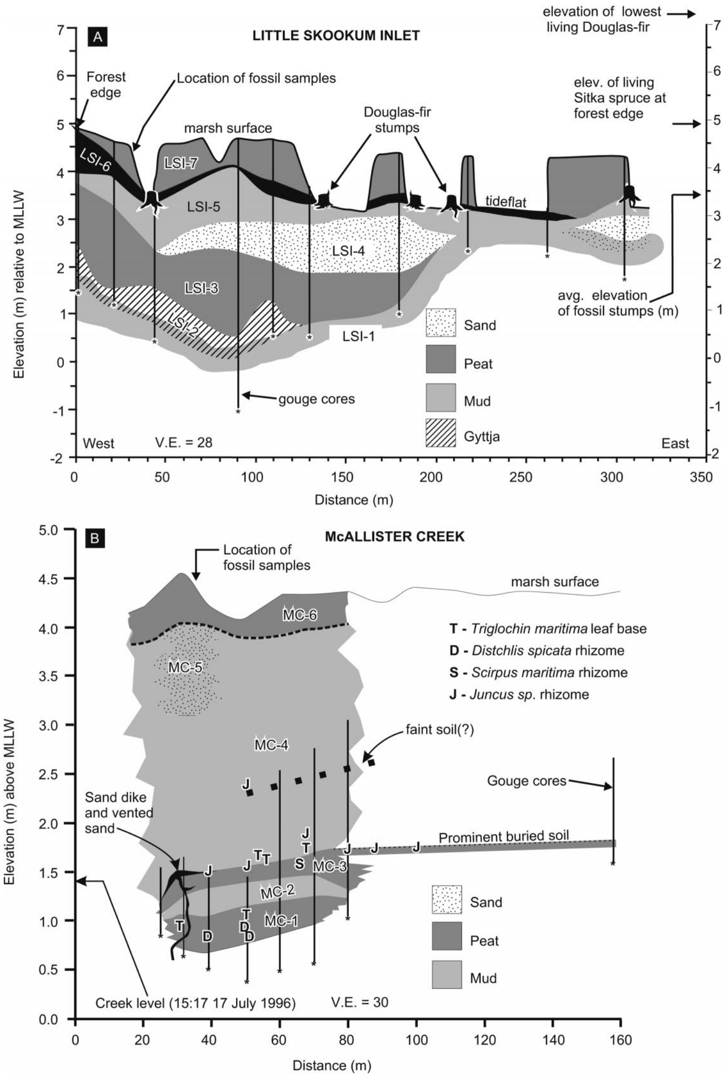

Figure 4. (A) Stratigraphy of the Little Skookum Inlet locality. (B) Stratigraphy of the McAllister Creek locality.

Paleoecology

The macrofossils from BZ-1 at Red Salmon Creek include *Picea sitchensis* and *Pseudotsuga menziesii* needles, and *Sambucus racemosa* seeds (Fig. 10). The top of the zone is marked by abundant charcoal fragments, observed in the field as a blackened zone at the top of RSC-1 (gray sand). Stumps of Douglas fir (*Pseudotsuga menziesii*) in growth position are common at the top of BZ-1, protruding from the top of stratigraphic unit RSC-1. No diatoms were observed in any of the samples processed from BZ-1.

Biozone BZ-2 at Red Salmon Creek contains scarce macrofossils at the base of the zone, but seeds of salt-marsh plants, including *Triglochin maritima*, *Spergularia canadensis*, *Grindelia integrifolia*, *Salicornia virginica*, and *Atriplex patula*, dominate the upper part of BZ-2. Foraminifera are common in every sample from BZ-2. The diatom flora of BZ-2 is dominated by brackish water taxa (Fig. 10). Low marsh and tidal-flat diatoms are at the base of this zone, ~2 cm above the top of RSC-1, including *Caloneis westii*, *Diploneis interrupta*, *Trachyneis aspera*, and *Paralia sulcata.* Species composition gradually changes upward, with *Gyrosigma eximium*, *Achnanthes brevipes*, *Melosira nummuloides*, and *Nitzschia tenuis* dominating the flora in the top half of BZ-2.

PALEOECOLOGICAL INFERENCES OF ELEVATION AND SALINITY CHANGES

I used paleoecological inferences based on forest soils and intertidal deposits to estimate the former elevation of each site through time. For intertidal deposits, I employed a weighted averaging technique to reconstruct past elevation from coastal diatom assemblages. The reconstructions are based on a training set of 39 modern diatom samples, collected from five coastal marshes in Puget Sound, coupled with elevation measurements relative to MLLW (Sherrod, 1998, 1999).[1] Similarity measurements were used to test whether each fossil sample had an appropriate analog in the modern training set (Schweitzer, 1994). All but two fossil samples had good modern analogs (NISQ-15B and MC-04B; see Fig. 11).

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[1] GSA Data Repository item 2001107, diatom data from Puget Sound, is available on the Web at http://www.geosociety.org/pubs/ft2001.htm. Requests may also be sent to editing@geosociety.org.

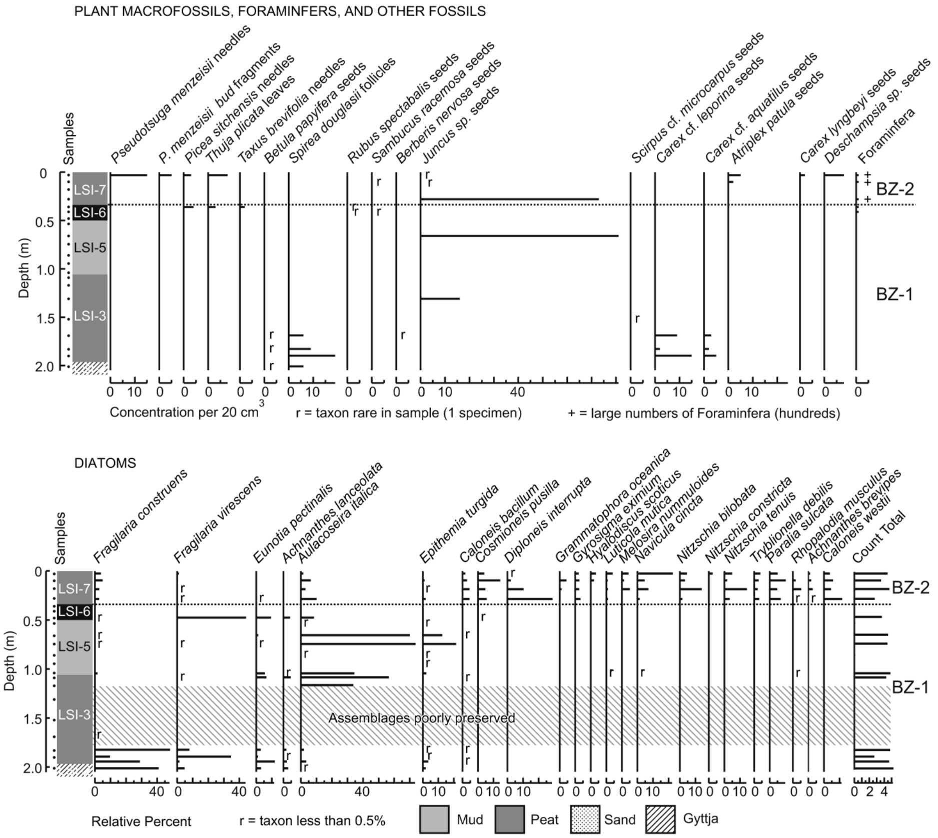

Figure 5. Fossils recovered from the Little Skookum Inlet locality. Biozones are labeled on the right. Lithologic patterns are the same as those shown in Figure 4. (Top) Plant macrofossils and foraminifera, expressed as number of fossils per 20 cc (cc = cm³) of sediment. (Bottom) Relative abundance of fossil diatoms grouped according to stratigraphic succession.

These samples differ from the modern samples because one or two diatom taxa that are not well represented in the modern samples dominate the fossil assemblage (*Diploneis ovalis* and *Tabellaria fenestrata*). I used elevations of modern forest analogs to estimate paleoelevations of soil horizons lacking well-preserved diatom assemblages.

At Little Skookum Inlet and Red Salmon Creek, I used the lowest elevations of living conifers near each site to infer paleoelevations of stump-bearing forest soil horizons (LSI-6 and RSC-1). The lowest modern conifers near the Little Skookum Inlet locality (Fig. 1) were Sitka spruce (*Picea sitchensis*) trees living at the forest-marsh edge at an elevation of 4.8 m above MLLW (Fig. 4). At Red Salmon Creek, the nearest living conifer is a Douglas fir (*Pseudotsuga menzeisii*) at 4.7 m above MLLW. Therefore, I assigned a minimum paleoelevation of 4.8 m and 4.7 m above MLLW for the stump-bearing horizons at the Little Skookum Inlet and Red Salmon Creek localities, respectively. These elevations are limiting minima because the fossil trees may have lived at higher elevations. Paleoelevation estimates are also subject to modification due to local site characteristics. For instance, at Little Skookum Inlet, drainage of the forest area adjacent to the

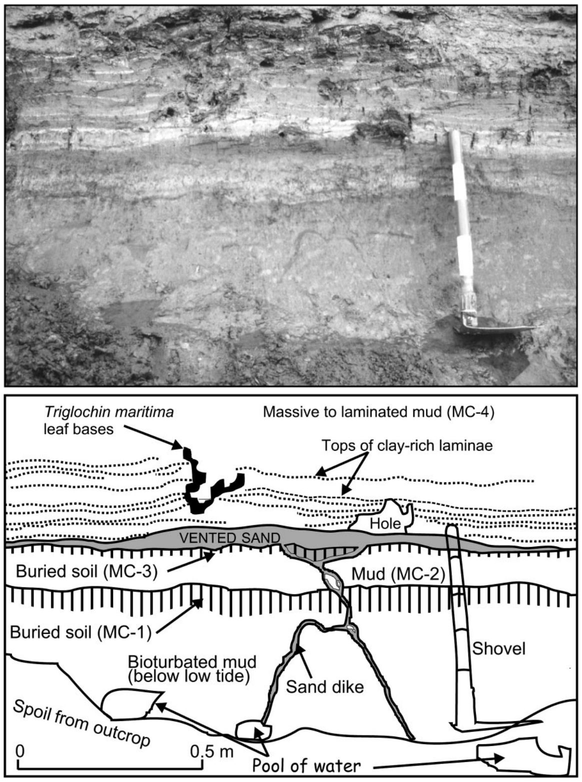

Figure 6. Photograph and tracing of sand dike and volcano observed at McAllister Creek. Bars on shovel handle are 10 cm long.

marsh is impeded, and consequently, Douglas fir is restricted to drier sites at higher elevations (≥7m above MLLW). If hydrologic conditions 1100 yr ago at Little Skookum Inlet were similar to those at the site today, then it is likely that the fossil Douglas fir trees also lived at higher elevations (Fig. 4). At Red Salmon Creek, the local topography at the forest edge is more abrupt, forest soils are better drained, and Douglas fir grows down to the salt-marsh–forest ecotone (Fig. 8).

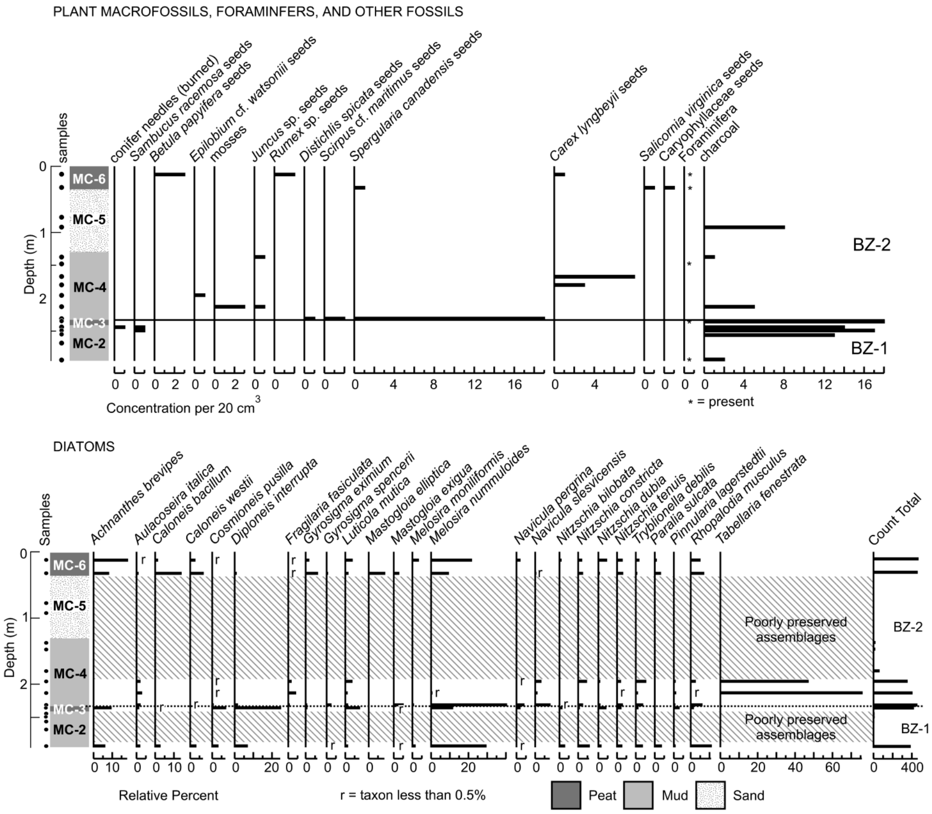

Figure 7. Fossils recovered from the McAllister Creek locality. Biozones are labeled on the right. Lithologic patterns are the same as those shown in Figure 4. (Top) Plant macrofossils and foraminifera, expressed as number of fossils per 20 cc (cc = cm³) of sediment. (Bottom) Relative abundance of fossil diatoms grouped according to stratigraphic succession.

Elevation Reconstructions

Reconstructed elevations (relative to MLLW) for fossil diatom samples show one major elevation change at each site in the past ~1100 yr (Fig. 11). A large decrease in inferred elevation at Little Skookum Inlet, Nisqually River, and Red Salmon Creek occurred between BZ-1 and BZ-2, coinciding with the burial of a lowland soil by intertidal peat or mud at each site about 1100 yr ago. Inferred elevations are highest for the buried soil at each locality; elevations ranged from ~4.8 m (lowest Sitka spruce) to 7.2 m (lowest Douglas fir) at Little Skookum Inlet, ~4.8 m at Red Salmon Creek, and 3.7 m to 4.3 m for the buried high marsh soils at the McAllister Creek and Nisqually River sites.

I infer lower elevations for the estuarine mud or peat that overlies the buried soil at each locality (Fig. 11). The change in elevation is marked by the boundary between BZ-1 and BZ-2. At Little Skookum Inlet, the lowest sample in the salt-marsh peat (LSI-7) above the buried soil (LSI-6) has an inferred elevation of 3.8 m relative to MLLW, or at least ~1–3 m below the pre–1100-yr-old forest floor. In contrast, laminated mud above buried high marsh soils at the McAllister Creek and Nisqually River localities has an inferred elevation of 3.4 m, indicating about 1 m of submergence at each site 1100 yr ago. Inferred elevation for fibrous peat above the buried forest horizon at the Red Salmon Creek locality was 3.5 m, suggesting at least 1 m of submergence at that site.

There are small differences in inferred elevation changes between the sites at Nisqually delta. Diatom assemblages from McAllister Creek indicate about 0.5 m of elevation change, yet lithologic changes and *Triglochin* leaf bases in growth position suggest that submergence could have been as much as 1 m. Submergence at this site failed to kill *Triglochin maritima* and *Juncus balticus*, as seen by growth of *Triglochin* leaf bases and *Juncus* rhizomes in the laminated mud immediately above the buried soil. At Nisqually River, diatom assemblages indicate about 1 m of elevation change, consistent with lithologic changes and *Triglochin* leaf bases in growth position in the mud overlying the buried high marsh soil. At Red Salmon Creek, salt-marsh peat overlying a Douglas fir forest floor suggests at least 1 m of submergence. The differences in inferred elevation change about 1100 yr ago between sites at Nisqually delta are small and could result from several factors. These factors include error in estimating former elevations of intertidal environments, error associated with inferring the elevation of the fossil Douglas fir trees, and possible variable amounts of compaction-induced subsidence following an earthquake. Following abrupt submergence about 1100 yr ago, inferred elevations remained essentially uniform at each site (Fig. 11), suggesting that sedimentation and marsh accretion kept pace with rising sea level.

POSSIBLE CAUSES OF ABRUPT SUBMERGENCE

Coseismic subsidence of the land best explains submergence of lowland soils in southern Puget Sound 1100 yr ago. The submergence happened fast enough to produce sharp (≤1 mm) contacts between the buried lowland soils and overlying estuarine deposits. A sand dike cuts across the high marsh soil at McAllister Creek (MC-3) and vented sand lies on the former soil surface, indicating that submergence of the high marsh soil was accompanied by ground shaking severe enough to cause liquefaction. High-precision radiocarbon ages of submergence-killed trees indicate that submergence of ~1 m occurred between 1150 and 1010 cal yr B.P. Alternative explanations for submergence include settling and compaction, submergence without land subsidence, or breaching of a sandy, bay-mouth bar. However, the lithostratigraphic and biostratigraphic changes observed in southern Puget Sound are not easily explained by these alternatives.

PREHISTORIC EARTHQUAKES IN SOUTHERN PUGET SOUND

This study documents tectonic deformation in southern Puget Sound, an area of no known