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LATE HOLOCENE ENVIRONMENTS AND EARTHQUAKES IN SOUTHERN PUGET SOUND

by

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A dissertation submitted in partial fulfillment of the
requirements for the degree of

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Abstract

LATE HOLOCENE ENVIRONMENTS AND EARTHQUAKES IN SOUTHERN PUGET SOUND

by Brian L. Sherrod

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Department of Botany

About 1000 years ago, astonishing things happened in the Puget Lowland. Previous work has produced evidence for large, enigmatic vertical displacements, landslides, tsunamis, and huge lahars that flowed from Mt. Rainier. This dissertation presents an equally astonishing finding for the Puget Lowlands: marsh and lowland forest soils subsided into the intertidal zone about 1000 years ago, coincident with a massive earthquake.

Coastal marshes with their diverse biota are an excellent place to study prehistoric earthquakes in Puget Sound. The reason is that plants and animals of the low marsh are different from high marsh biota and can be easily identified by their fossil remains. I present methods for quantitative reconstruction of environmental parameters from salt marsh diatom and seed assemblages that aids greatly in interpreting changes in fossil assemblages from marsh deposits.

A small marsh Bainbridge Island, Washington, contains a 7000-year sedimentary record, allowing me to study the Holocene history of movement on the Seattle fault. Diatom-based transfer functions show that small changes in salinity and elevation of the marsh surface occurred throughout the Holocene, but none of these changes was of the same magnitude as the 1100-year uplift event. A shift from saline to freshwater diatoms occurred between 7700 and 6200 cal yr B.P., and a change from low salinity to high

salinity diatoms occurred about 1700 cal yr. B.P. The earlier changes in salinity (and elevation) are likely related to either storms that breached the gravel beach-berm bordering the marsh to the south, or small-scale uplift events on the order <1 m.

In southern Puget Sound, high marsh soils or lowland forests were abruptly submerged at four widely separated sites. Radiocarbon dates show that the submergence occurred between 1140±80 and 1010±50 ^{14}C yr B.P. (750 - 1260 cal yr B.P.). A combination of stratigraphic evidence and diatom-based transfer functions indicates that the magnitude of submergence was between ~0.5 m and ≥3.4 m, depending on the site. The simplest fault configuration to explain the pattern of shoreline deformation that occurred about 1100 years ago implicates two or more faults, on which large earthquakes occurred at or about the same time.

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CHAPTER 1: INTRODUCTION

Large earthquakes that occur in coastal areas often deform shorelines, uplift intertidal environments, and occasionally cause areas normally not affected by the tides to sink into the intertidal zone. When deformation of a coastal area occurs, it results in rapid environmental changes that leave their mark in the stratigraphic record of coastal marshes. Evidence for past shoreline deformation is used to determine the locations of prehistoric earthquakes, and to define the extent of seismic damage from past earthquakes (Bucknam et al., 1992). Puget Sound is an excellent area to study prehistoric earthquakes and coastal deformation due to the abundance of assessable shoreline and the large number of geologic structures that cut across the coastline.

The marine basins of Puget Sound also have an enigmatic history. While one view looks mainly at the patterns of deglaciation and consequent crustal rebound, other views focus on Holocene sea level rise, and prehistoric movement along the major faults that cut across Puget Sound. The larger picture, which has yet to emerge and would embrace a regional view, is the focus of the present study in southern Puget Sound.

The currently accepted model for the development of the Puget Sound landscape is intrinsically linked to the advance and subsequent retreat of the Vashon stade of the Fraser Glaciation (Booth, 1994). A tacitly accepted interpretation for the formation of Puget Sound is that once isostatic recovery was complete following deglaciation and sea level-rise slowed around 6000 years ago, Puget Sound essentially resembled the present-day estuary. Field mapping for this project in southern Puget Sound suggests that in several aspects, the paleoenvironments of southern Puget Sound were much different than is now generally thought.

North of the Tacoma Narrows and at sites along Hood Canal, many existing salt marshes contain thick sections of salt marsh peat with radiocarbon dates of marine sediments back to the mid-Holocene (Bucknam et al., 1992; Eronen et al., 1987). These sites suggest that coastal wetlands accreted vertically and kept pace with the rising sea level during the middle and late Holocene. South of the Tacoma Narrows, radiocarbon dates at several sites suggest that the oldest marine and brackish water sediments are only about 1000 years old and that these overlie thick freshwater marsh peats and lake sediments. This suggests that tidal waters did not begin to affect most of southern Puget Sound until very late in the Holocene, before which much of the area was occupied by terrestrial environments. Coincident with this striking stratigraphic feature is the presence of widespread high marsh and lowland forest soils with *in-situ* tree trunks buried by the intertidal deposits. Burial of high marsh and lowland forest soils by intertidal deposits suggest widespread paleoenvironmental changes and subsidence in southern Puget Sound, possibly related to prehistoric earthquakes.

These finds raise several important questions. Are the late Holocene environmental changes observed in southern Puget Sound intrinsically linked to the large prehistoric earthquake on the Seattle Fault ca. 1000 years. ago? Is movement on a southern Puget Sound structure responsible for the potential subsidence observed at several sites in southern Puget Sound, or is the subsidence linked to movement on the Seattle fault? Was the southern basin of Puget Sound occupied by a large lake, or series of lakes much like Lake Washington and Lake Sammamish today, until the late Holocene?

PURPOSE AND RATIONALE

The purpose of this study is determine how paleoenvironmental changes in southern Puget Sound relate to prehistoric tectonism and sea level-rise in western Washington. In particular, I emphasize uplift and subsidence patterns recorded in several marshes that parallel major geologic structures located near Olympia and Seattle. The objective is to determine the paleoenvironmental history of southern Puget Sound during the late Holocene and the relationship of past environmental changes to prehistoric earthquakes. My overall research hypothesis states that synchronous environmental changes (e.g., abrupt local regression or transgression) observed in widely-separated coastal marshes relate to past earthquakes.

A direct way to investigate prehistoric earthquakes involves the use of biostratigraphy to infer the amount of uplift or subsidence that accompanied an earthquake. Modern intertidal habitats provide excellent calibration for inferring past environments. This study focuses on postglacial environmental change and seismic events reconstructed from paleoenvironmental signatures left in coastal marsh sediments by diatoms and plant macrofossils.

HYPOTHESES

I propose specific hypotheses in each chapter of this study. These broadly relate to the areas of paleoecology and environmental reconstruction, prehistoric earthquakes, and Holocene paleoenvironments of southern Puget Sound. The following section gives an overview of the general hypotheses for this project.

DIATOM PALEOECOLOGY AND ENVIRONMENTAL RECONSTRUCTIONS

The main idea is that ecological processes control the distribution of sedimentary diatoms and vascular plant seeds across a salt marsh surface, and that resulting species assemblages occur along primary environmental gradients (e.g., salinity and elevation). The opposing view states that the distributions of sedimentary diatoms and vascular plant macrofossils are random and are not controlled by ecological processes. Statistical correlations of observed diatom and seed assemblages in modern sediment samples with measured environmental factors indicate that the distributions of seeds and diatoms are either random or follow predictable pathways.

EARTHQUAKE-FORCED ENVIRONMENTAL CHANGE

Here I assume that burial of forest and high marsh soils, and the onset of salt marsh conditions at several sites in southern Puget Sound relate to sudden subsidence of upland and high marsh environments that accompanied an earthquake approximately 1000 years ago. Recurrent tectonic events are signaled by multiple buried soils. An alternative view states that prehistoric earthquakes did not affect southern Puget Sound; environmental changes inferred from salt marsh stratigraphy are due to non-tectonic causes (e.g., non-tectonic sea level rise and sedimentary processes).

To test these ideas, detailed paleoenvironmental reconstructions determine the direction and magnitude of environmental change associated with the buried soils at each site. Gradual environmental change predicts that sediments deposited in adjacent environments occur on top of one another in a vertical section. Large changes in land level associated with earthquakes may result in stratigraphic sections where sediments deposited in non-adjacent environments (e.g., forest and low marsh) occur one on top of the other. Radiocarbon analyses, and possibly dendrochronologic analyses, provide the required chronologic control for this test.

SOUTHERN PUGET SOUND PALEOENVIRONMENTS

One of the more interesting ideas that has come out of this research states that large areas of southern Puget Sound were formerly occupied by lacustrine and upland marsh environments in the middle and late Holocene. These lakes and wetlands eventually drained or filled with sediment, allowing lowland forests to develop. Later transgression by rising sea level or sudden tectonic subsidence allowed tidal waters to inundate former upland environments. The opposing view states that sea level reached the present position in the late Holocene, followed by a gradual transgression into the lowland, and resulted in deposition and aggradation of intertidal deposits below present day coastal marshes.

To test these ideas, detailed paleoenvironmental reconstructions determine the geologic and botanical development of each study site. The presence of late Holocene lacustrine deposits, freshwater marshes, and buried upland soils in the near surface sediments of southern Puget Sound salt marshes indicate a lack of local marine conditions throughout most of the Holocene. The scale of environmental change in the stratigraphic record is estimated using botanical evidence (modern plant species distributions and diatom-based transfer functions).

LAYOUT OF DISSERTATION

This dissertation is organized into the following chapters:

- Chapter 1. Introduction
- Chapter 2. Using seeds and diatom assemblages from coastal marshes for salinity and elevation reconstructions. This chapter presents the methods and models for quantitative paleoenvironmental reconstructions in coastal marshes of Puget Sound. The statistical methods are focused on diatoms-based reconstructions.
- Chapter 3. Abrupt paleoenvironmental changes triggered by seismogenic uplift in central Puget Sound, Washington, about 1000 years ago. This chapter presents the field and microfossil evidence for uplift in central Puget Sound about 1,000 years ago. The uplift likely resulted from a large earthquake on the Seattle fault system, and possibly from uplift on related geologic structures at or near the same time as the Seattle fault earthquake.
- Chapter 4. Submergence of lowland soils by earthquake-induced subsidence about 1000 years ago at southern Puget Sound, Washington. This chapter presents the field and microfossil evidence for subsidence in southern Puget Sound about 1,000 years ago. Several mechanisms for this subsidence are presented.

- Chapter 5. Late Holocene paleoenvironmental changes and earthquakes in southern Puget Sound, Washington. Here I present a summary of the tectonic and paleoenvironmental changes in central and southern Puget Sound. Tectonic models are offered to explain the local and regional patterns of inferred land deformation that occurred about 1000 years ago.

CHAPTER 2: USING SEEDS AND DIATOM ASSEMBLAGES FROM COASTAL MARSHES FOR SALINITY AND ELEVATION RECONSTRUCTIONS

ABSTRACT

Tides act in predictable ways to distribute living and dead diatoms along gradients of salinity and elevation, and plant seeds in surface soils of salt marshes reflect canopy vegetation. To test these ideas, modern transects were established at several salt marshes in Puget Sound for the purpose of determining modern species/environment gradients and calibrating species assemblages against environmental variables. I use Canonical Correspondence Analysis (CCA) to relate modern diatom assemblages and environmental gradients, and weighted averaging calibration is used to develop transfer functions for inferring missing environmental information. I evaluate seed and plant associations using an association index that reflects the correspondence of seeds from surface soils and canopy vegetation. I use these indices to test whether seeds in surface soils are related to canopy vegetation, and indicate which seeds are useful in describing past plant communities. CCA shows that the effect of salinity and elevation on diatom distributions is significant, indicating that environmental processes control the distribution of diatoms across the salt marsh surface in predictable ways. Salinity is strongly correlated with CCA Axis 1 and elevation with Axis 2. The calibration results indicate that salt marsh diatom assemblages reflect major environmental gradients in Puget Sound salt marshes. Although mixing of allochthonous and autochthonous diatoms does occur, diatom assemblages can be effectively used for quantitative reconstructions of former environmental conditions. Association indices show that seeds of several taxa are useful for inferring past canopy vegetation. These include *Triglochin maritima, Salicornia virginica, Rumex* sp., and *Rosa* sp. Seeds of many common salt marsh plants are over-represented in the seed bank, suggesting that tides and winds distribute seeds widely across the marsh surface.

INTRODUCTION

Relationships between coastal marsh organisms and environmental gradients offer a link to determining past environmental changes in coastal areas. Paleoecologists can begin to understand marsh ecosystems by targeting how species respond to changes in primary environmental factors in salt marshes (Holling, 1992). Diatom and seed assemblages in surface sediments of salt marshes are the product of environmental and taphonomic processes. Environmental processes affect the distributions of diatoms and seeds along gradients such as elevation and salinity. Taphonomy refers to the processes that incorporate microfossils into sedimentary deposits. Taphonomic processes may alter the distributions of previously deposited remains.

This chapter deals primarily with diatom and seed assemblages from surface sediments, both autochthonous and allochthonous. In this chapter I infer taphonomic processes that alter diatom and seed assemblages and I present a method for reconstructing salinity and elevation from sedimentary diatom assemblages. Borrowing techniques from the fossil pollen literature, I also propose methods for assessing the usefulness of individual seed types in paleoecological reconstructions. I focus on diatoms and seeds because paleoenvironmental reconstructions of coastal areas often rely on those types of fossils (Bucknam et al., 1992).

The first method I am proposing relies on the relationship between diatom assemblages and environmental gradients to infer quantitatively environmental information. One approach to quantitative paleoenvironmental reconstruction is to express an environmental variable as a function of community composition data (ter Braak, 1995b). This kind of calibration is more robust for salt marsh reconstructions than reliance on indicator species because it relates the occurrence of diatom assemblages to modern environmental conditions. The resulting transfer functions provide an empirical basis for reconstructing former salt marsh environments. In this chapter I use canonical correspondence analysis (CCA) to explore the relationships between species and environment (ter Braak, 1995a, 1995b), and I use WACALIB (Line and Birks, 1990), an outgrowth of CCA, to obtain transfer functions for predicting past changes in the environment.

A second method relies on the co-occurrence of seeds and plants in coastal marshes. Salt marsh plants tend to occur in zonal communities arranged according to salinity and tolerances to tidal-inundation (Macdonald, 1977; Macdonald and Barbour, 1974). Correspondingly, seeds deposited on the marsh surface should also occur in zonal assemblages, depending on whether taphonomy plays an important role in shaping those assemblages. Depending on local tidal conditions and preservation potential, seeds in surface sediments may be dispersed throughout a marsh or selectively removed after deposition. In this study, I examine vegetation cover and seed relationships in several coastal marshes of Puget Sound. High fidelity environmental reconstructions from coastal marsh stratigraphic sections depend on quantitative comparisons of modern marsh vegetation and seeds for making accurate paleoecological interpretations. Paleoseismic studies are increasingly dependent on accurate environmental reconstructions based partially on fossil seeds (Bucknam et al., 1992). It is important for coastal paleoecologists to understand which seed types and plant remains are truthful indicators of past plant communities and environmental conditions.

Taphonomic processes acting on estuarine microfossils tend to obscure original ecological relationships between the species assemblages and the environment (Denys, 1984, 1994; Sherrod et al., 1989). Species can be selectively removed from an assemblage by breakage or dissolution, or added to an assemblage by tidal current transport. In some cases, taphonomy can so drastically alter the species composition of a seed or diatom assemblage that the original ecological signals reflected by the *in-situ* assemblage are either obscured or obliterated. Without detailed studies on taphonomic and ecological gradients, these factors may be difficult to tell apart. Such studies are needed to show how reliance on the presumed autecology of individual species compares with other processes to yield diatom and seed assemblages of paleoecological value (Denys, 1994).

Some studies of fossil salt marshes require accurate reconstructions of key environmental parameters. Paleoseismic studies in coastal areas, for example, often rely on diatoms to provide assessments of past salinity and elevation changes for inferring histories of earthquake-induced land level changes (Atwater and Hemphill-Haley, 1997; Shennan et al., 1996; Nelson et al., 1996; Hemphill-Haley, 1995). Therefore, determining how sedimentary diatom assemblages are distributed relative to primary environmental gradients in salt marshes is a critical problem for accurate reconstructions. In this paper, I focus on salinity and elevation because these two parameters are most important to coastal paleoecologists. Salinity is often cited as a control on living diatom assemblage (Sullivan, 1982; Amspoker and McIntire, 1978). Elevation within and near the tidal range integrates many environmental factors in salt marshes but primarily is a reflection of tidal inundation (Nelson and Kashima, 1993).

Although little is known about the interaction between salinity and elevation, both factors are important because they ultimately control species composition and paleoecological reconstructions. Which factor is most important ultimately determines the accuracy of paleoecologic reconstructions. Quantitative reconstructions require that: 1) the responses of modern sedimentary diatom assemblages to environmental and taphonomic variables are modeled using a training set of diatom assemblages, and 2) the model results are used to infer missing (or past) environmental variables from samples where direct measurement of environmental variables is not possible (e.g., fossil samples) (Birks et al., 1990, ter Braak, 1995b). In this chapter, I use a set of modern diatom samples to determine how species composition in the surface sediments is related to salinity and elevation.

HYPOTHESES

If elevation and salinity are important in controlling the distribution of plant and microfossil assemblages across a salt marsh surface, then diatom assemblages from surface sediments should be distributed along those gradients. Furthermore, I hypothesize that diatom assemblages occurring in the salt marsh deposits should reflect major environmental gradients and can be used for accurate quantitative reconstructions. Another idea states that plant seeds in surface sediments reflect the original marsh canopy and therefore are useful to infer the composition of the past plant communities in coastal marshes.

HYPOTHESIS TESTING

I statistically correlated diatom assemblages in surficial sediments with measurements of salinity and elevation using CCA. Once robust correlations of species assemblages to environmental factors were established, I obtained transfer functions to infer past environmental conditions. Coefficients of determination (r^2) and residual plots measure the usefulness of the transfer functions.

I determined the relationship between standing vegetation and seeds in surficial sediments using an association index (Delcourt and Pittillo, 1986; Davis, 1984). This index measures the reliability of plant seeds to co-occur with standing vegetation of the same species. Taxa with high index values ($A \geq 0.50$) indicate that the plant and seed tend to co-occur, providing a strong basis for inferring past vegetation communities and environmental conditions.

PREVIOUS RESEARCH

TRANSPORTATION

An important consideration in diatom-based paleoecological studies is determining which diatom frustules were transported from adjacent environments. In some areas, the influx of allochthonous (transported) diatoms far outnumbers the production of autochthonous diatoms (Sherrod et al., 1989; Vos and de Wolf, 1993). Epipsammic diatoms (those that live attached to sand and mud grains) such as *Achnanthes delicatula* and *Opephora parva* are a common autochthonous component in tidal flat assemblages but can be scoured from the substrate by currents and transported in great numbers into tidal channels and onto marsh surfaces (de Jonge, 1985; Vos and de Wolf, 1993).

Some researchers have divided coastal diatoms into broad ecological groups related to specific environments (Vos and de Wolf,1993). While such divisions provide criteria for inferring which diatoms are allochthonous, they do not convey quantitative information about environmental factors that is required for detailed paleoecological reconstruction. Studies of modern coastal diatoms will further our understanding of the factors that control the distribution of diatoms along environmental gradients.

FRAGMENTATION AND DISSOLUTION

Selective removal of diatom taxa from the sedimentary record hinders paleoecological studies. In many cases, delicate taxa are broken during transportation and diagenesis (Nelson and Kashima, 1993) resulting in an impoverished assemblage. Other processes such as chemical leaching, compaction, and sample preparation also lead to fragmentation and dissolution of diatom valves (Vos and de Wolf, 1993).

Fragmentation and dissolution can increase the relative abundance of certain robust types. *Paralia sulcata* is a heavily silicified, chain-forming diatom that is often dominant in coastal deposits (Hemphill-Haley, 1995). The dominance of *P. sulcata* is due in part to a greater resistance to breakage and dissolution (Sherrod et al., 1989, Atwater and Hemphill-Haley, 1997). Samples containing only a few valves of *P. sulcata* should be treated with caution, as these may be the result of reworking or the remnants of an assemblage heavily modified by dissolution (Hemphill-Haley, 1995).

ENVIRONMENTAL GRADIENTS AND DIATOM DISTRIBUTIONS

Studies of living diatoms from coastal environments have shown relationships between species and environmental gradients. A study in the Yaquina Estuary of Oregon found that diatom distributions in the estuary are influenced by salinity, desiccation, and seasonal changes in daylight (McIntire, 1978). McIntire (1978) inferred that species distribution along environmental gradients is a *continuum* rather than a series of discrete, isolated assemblages except in areas where the gradients break down. Sullivan (1982) also found relationships between environmental gradients and species composition, with elevation and vascular plant canopy height as the most important environmental variables. Laird and Edgar (1992) found statistically significant non-uniform diatom distributions in the surface sediments of a New England salt marsh, suggesting that diatoms occur along environmental gradients as a continuum.

While many intertidal diatom taxa are cosmopolitan, they tend to occur in distinct communities in coastal marshes. Nelson and Kashima (1993) documented assemblages specific to tidal flats, low marshes, and high marshes in silty estuaries along the Oregon coast. Hemphill-Haley (1995) also documented distinct assemblages in tidal flats and channel banks, low marshes, and high marshes at Willipa Bay, Washington. Shennan et al. (1996) used Detrended Correspondence Analysis to subdivide diatom assemblages into four categories corresponding to mudflat, transitional low – high marsh, high marsh, and upriver/backswamp environments.

STUDY AREA

Field teams established transects at six intertidal marshes located around Puget Sound, Washington to determine modern species/environment gradients and calibrate species assemblages to environmental variables (Figure 2-1). In most cases, transects extended from the barren mudflat landward to the margin of lowland forests (Figure 2-2). The lagoonal marsh at North Spit along Admirality Inlet is the northern-most locality, while the remaining sites are located at heads of inlets or deltas in central and southern Puget Sound. Data from Winslow marsh was used in the seed analysis (Eckblaw, University of Washington, personal communication, 1994).

Intertidal marshes in Puget Sound form a nearly horizontal surface at about mean higher high water (MHHW) (Figure 2-2). *Distichlis spicata* and *Deschampsia caespitosa* usually characterize this surface, termed the high marsh. At elevations between MHHW and mean high water (MHW), a low marsh forms and is dominated by *Salicornia virginica*, *Triglochin maritima*, and *Jaumea carnosa*. Tidal flats occur between MHW and mean lower low water (MLLW) with occasional colonies of *Triglochin maritima*, *Scirpus maritimus*, and *Carex lyngbyei* occurring along the upper edges of these areas. Average salinity of Puget Sound tidal waters inundating coastal marshes is between 27-30 parts per thousand (ppt, or ‰).

METHODS

FIELD AND LABORATORY METHODS

Field teams employed a 1m^2 quadrat to visually estimate plant species cover. Surface sediment samples and environmental measurements were collected between June and August of 1996 and 1997. Scraping of surface sediments with a steel spoon or spatula ensured collection of only the upper 1 cm or less of sediment (depth measured with a ruler), with the samples placed immediately into a sample bag after collection and sealed. When necessary, I obtained turf samples by cutting a square, 1-cm thick mat from the surface of the turf with a knife and placed the sample directly into a sample bag. I put each diatom sample into formalin within 48 hours of collection. At the time of collection, the surface sediment diatoms samples contained a mixture of both living epipelic diatoms and the remains of diatoms that died at the sampling site or were transported from adjacent environments.

Samples of surface sediment from each station were wrapped in filter paper and squeezed in a syringe to collect interstitial pore water. Pore water salinity measurements used an optical salinity refractometer (accurate to within ±1 ‰), calibrated prior to each measurement with distilled water. Random replicate samples were also analyzed in the field for salinity to test the precision of the measurements (differences within limits of instrument error).

I used a self-compensating level to survey each station relative to the tides by measuring the elevation of either a high or low tide at a local datum. The local tidal level was calculated using the following steps. 1) Determine the height of the observed tide at Seattle, Washington. 2) Set the measured tidal height at the site to the corresponding observed height at Seattle. 3) Offset the measured tidal height by the difference in MHHW between Seattle and MHHW at the nearest NOAA tidal benchmark to the site. The last step assumes that the tidal height at the site is the same as the tidal height of the nearest NOAA Tidal Benchmark (generally <5 km away). The local datum is then assigned an elevation relative to MHHW, from which the elevations of all sampling stations were surveyed.

I prepared diatom samples according to the procedures of Patrick and Reimer (1966). Digestion of organic matter employed 30% hydrogen peroxide, which was followed by several distilled water rinses. Permanent slide preparation used evaporation trays to randomly settle the diatoms onto round cover slips, with Naphrax (refractive index=1.7) employed as a mounting medium. Approximately 400-600 valves for each sample were counted at magnifications of 787x and 1250x, with lower counts for two samples (0 m and 20 m from Lynch Cove, Figure 2-2) that had low diatom densities. Diatom identifications followed published taxonomic monographs. Percentages of each taxon are based on a sum of total diatoms.

To separate plant seeds, I disaggregated 20 cm^3 samples in a dilute Calgon® solution overnight. After wet sieving, seeds and identifiable plant remains were studied under a binocular microscope. All separated plant remains were identified using modern collections housed in the University of Washington, Department of Botany, and published taxonomic monographs (Martin and Barkely, 1961; Berggren, 1981, 1969; Spjut, 1994; Young and Young, 1992).

DIATOM DATA ANALYSIS

My data analysis and results presentation generally follow procedures described by ter Braak (1987-1992), Pan and Stevenson (1996), and Delcourt and Pittillo (1986). I used SPSS version 6.1 (SPSS Incorporated, 1994) for calculations of descriptive statistics of each environmental variable. Shannon values (H'), an index of diversity, were calculated (using natural logarithms) for the samples with PC-ORD (McCune and Mefford, 1995). I used the software package CANOCO version 3.1 to perform CCA (ter Braak, 1987-1992). This technique relates species composition to measured environmental factors. CCA ordinations utilize untransformed environmental variables. Obvious outliers (n=1) were excluded from the analysis.

I used WACALIB ver. 3.1 to calibrate diatom assemblages with salinity and elevation measurements. This technique first calculates the salinity and elevation optimum for each taxon, and then uses those optima to produce transfer functions (Line and Birks, 1990). The transfer functions are used for inferring environmental variables based on the species composition in unknown samples. Coefficients of determination (r^2) between calculated (inferred) environmental variables and observed values of environmental variables allow evaluation of the transfer function's predictive power.

Standard deviations were used to describe variation in inference error around a mean value.

MACROFOSSIL DATA ANALYSIS

I tried to learn whether or not particular seeds or plant remains tend to be found where the plant grew. For this purpose, I used an association index (A) that relates seeds from sediment samples to observed plant cover at each sampling location:

$$A = \frac{B_0}{P_0 + P_1 + B_0}$$

where B_0 is the number of stations at which both the seed and the vegetation of a species were found; P_0 is the number of stations at which the seed is present, but the vegetation is not; and P_1 is the number of stations at which the vegetation is present, but the seeds are not.

The association index ranges from 0 to 1, with an index of 1 indicating that the seed and the vegetation of a species are always found together. An association index of 0 indicates that either the vegetation is found without the seeds (the species is underrepresented in surface soils), or that the seeds were found without the vegetation (the species is over represented in surface soils). I used a value of ≥0.50 to designate high association indices (Davis, 1984; Delcourt and Pittillo, 1986).

RESULTS

Elevation ranged from about 5 m to 2.5 m across all of the study sites, with tideflats having the lowest elevations in general (Figure 2-2, Table 2-1). The highest sampling sites tended to be furthest from the tideflat, except for one site at the Nisqually Delta that showed a slightly higher area adjacent to a tidal channel. The high marshes, dominated by a variety of vascular plants, showed very little relief except at the landward edge, where I distinguished an upper high marsh and a lower high marsh on the basis of a sharp elevational and salinity discontinuity between the two areas. This discontinuity is often marked by the abrupt appearance of salt-intolerant vascular plants on the higher ground (e.g., *Typha latifolia*). Changes in vegetation communities are observed along the transects with increasing elevation and distance from tideflat and tidal channels (Figure 2-3).

Salinity of the interstitial water ranges from a high of 33-28‰ in the mudflats and low marshes, to a low of 0‰ in the alder-willow-cattail swamps bordering several marshes (Figure 2-2, Table 2-1). Vascular plant cover observed along transects corresponded to changes in salinity, with salt-tolerant taxa near the tideflats and salt-intolerant taxa in the higher areas (Figure 2-4). Although salinity declines almost linearly with distance along most transects, it is not linearly related to elevation. A linear regression of salinity (dependant variable) against elevation gave an r^2 of 0.22, indicating a very weak linear relationship between salinity and elevation at the five localities.

At four of the six sites, a sharp break in salinity occurred at the change from the lower high marsh to upper high marsh. Standing water in the upper high marsh areas of several marshes had salinities of 0-1‰. I use the abrupt change in salinity to subdivide the high marsh into two subenvironments; an upper high marsh (with salinity of 0-<5‰) and a lower high marsh (salinity >5‰).

DIATOM ASSEMBLAGES AND GRADIENT ANALYSIS

A total of 234 diatom taxa were identified from 39 surface sediment samples. The assemblages represent both autochthonous and allochthonous diatoms; no attempt was made to separate the two groups. Shannon values (H'), an index of species diversity, range from 3.337 in the lower high marsh to 1.687 in the upper high marsh, with a mean value of 2.611. As shown in Figure 2-5, the lower high marsh samples have larger H' values than upper high marsh samples and tideflat. The number of species (Figure 2-5) is greatest in the lower high marsh samples (S=52) and least in the upper high marsh (S=19).

Diatoms in each sample are well preserved. The presence of members of the genera *Gyrosigma* and *Nitzschia*, suggested minimal mechanical breakage of long, slender taxa. Lightly silicified diatoms (e.g., *Skeletonema costatum*) were also well preserved and showed minimal evidence of breakage or dissolution. Diatoms that produce toxins harmful to humans, primarily members of the genus *Pseudonitzschia*, were also observed.

For the CCA gradient analysis, I used 108 diatom taxa, representing all taxa with relative abundance ~1% in one or more of the 39 samples (Table 2-2). Eigenvalues for the first three ordination axes are $\lambda_1 = 0.509$, $\lambda_2 = 0.251$ and $\lambda_3 = 0.486$; the sum of all canonical eigenvalues is .761. Eigenvalues for CCA Axis 1 and Axis 2 represent 15.5% of the cumulative variance in the species data. Species-environment correlations were high for both axes (Axis 1 = 0.927, Axis 2 = 0.800). Canonical coefficients, t-values, and interset correlations (Table 2-3) represent different statistics for testing the relationship between environmental variables and ordination axes (ter Braak, 1987-1992; Pan and Stevenson, 1996). Canonical coefficients indicate the magnitude of a particular environmental variable's contribution to an ordination axis, with large canonical coefficients (absolute values relative to other coefficient values) being associated with a higher degree of contribution of an environmental variable to a given axis (Pan and Stevenson, 1996). The canonical coefficient of salinity is highest for Axis 1 (-0.80), while the canonical coefficient of elevation is highest for Axis 2 (1.10).

In CCA, computed t-values, interset correlations, and Monte Carlo permutation tests are used to evaluate the relationship between species distributions and environmental variables. Computed t-values are useful for exploratory purposes to determine if a particular environmental variable contributes more to the fit of the species data relative to other environmental variables in the analysis. This is accomplished by comparing the computed t-values from the CCA output to a critical value, which in this case is 2.03. Environmental variables with t-values that exceed the critical t-value are interpreted as having a unique contribution to the fit of the species data (ter Braak, 1987-1992). Interset correlations are the correlation coefficients between the species axes (ordination axes) and the environmental variables (ter Braak, 1987-1992). Based on interset correlations, I infer that the first ordination axis is a salinity gradient (interset correlation = -0.889), while the second axis is an inferred elevation gradient (interset correlation = 0.554). Monte Carlo permutation tests statistically tested whether the diatom species are related to salinity and elevation. The diatom distributions in coastal Puget Sound marshes are significantly related to both salinity and elevation ($P \leq 0.001$, 999 permutations).

The results of the CCA are summarized in two biplots (Figure 2-6) that provide a graphical means for representing how species and sites are related to environmental variables. The length of the arrows for salinity and elevation in Figure 2-6 are proportional to the importance of the environmental variable in the biplot, with the arrows pointing in the direction of increasing values for each environmental variable. The angle between the arrow and an ordination axis shows how well the environmental variable is correlated with an ordination axis (the smaller the angle, the stronger the correlation). A perpendicular line drawn from an arrow through a site or species point shows the relative location of that site (Figure 2-6A) or species (Figure 2-6B) along an environmental gradient (Palmer, 1993).

The biplots indicate that there is a strong relationship between species distributions and the environmental variables. Because salinity is strongly correlated with CCA Axis 1, species that fall on the left side of the diagram are more abundant in areas of higher salinity, while those on the right side occur more frequently in areas of freshwater. Likewise, because elevation is correlated with CCA Axis 2, species that fall in the lower part of the diagram are indicative of lower elevations, while those in the upper part are characteristic of higher elevations. The sites follow a similar distribution pattern in relation to the environmental variables on the diagram.

The ordination separates the sites into three main groups representing the main marsh subenvironments (Figure 2-6). By contrast, species are generally distributed in a continuum along the environmental gradients, with most species occurring in several marsh subenvironments. For the species biplot, certain associations of species were representative of each main marsh subenvironment. Tideflat sites have the highest salinity and lowest elevation and were best distinguished by *Opephora parva, Achnanthes lemmermanii, Achnanthes delicatula* spp. *hauckiana*, and *Paralia sulcata.* The low marsh sites are not distinguishable in their species patterns from tideflat and lower high marsh sites. Lower high marsh sites had the highest diversity (H') and were characterized by species of the genus *Navicula, Denticula subtilis, Luticola mutica*, and others. Upper high marsh sites had the lowest salinity and highest elevation and were characterized by *Pinnularia lagerstedtii, Navicula rhynchocephala, Meridion circulare, Eunotia pectinalis, Synedra rumpens*, and several species of the genus *Gomphonema.* Tideflat taxa were distributed in small amounts throughout most marsh environments, generally decreasing in abundance at higher elevations.

DIATOM CALIBRATION

Bootstrapping analysis allows an error analysis, and this provides a means for evaluating the predictive ability and bias of salinity and elevation transfer functions (Birks et al., 1990). A regression analysis of diatom-inferred salinities against observed values yields an r^2 of 0.82 (Figure 2-7C). Residual salinity is within ±5‰ of the observed values in all but four cases (Figure 2-7D). Five samples fell outside the range of one standard deviation, and three cases fell outside the range of two standard deviations. Slight systematic trends in residual salinity may indicate that the current transfer function does not explain a certain amount of variance (Pan and Stevenson, 1996). A regression analysis of diatom-inferred elevation and observed values (Figure 2-

7A) yields a r^2 of 0.78. Residual elevation is within 30 cm (~ one standard deviation) of the observed value in all but 10 cases, and within 50 cm in all but 3 cases (Figure 2-7B). Only one case fell outside the range of two standard deviations. For both environmental variables, the predictive ability of the transfer function is greater for samples in the middle of the environmental gradients than for samples falling at the extremes of the gradients.

RELATIONSHIP OF VASCULAR PLANT SEEDS TO MARSH ENVIRONMENTS

Seeds were extracted from surface soils to relate seed occurrences to standing vegetation using an association index (Appendix A). The results of the association index calculation show that four taxa (out of 47) are well represented in the seeds recovered from the surface sediments (Table 2-4). These taxa include two common salt marsh species, *Triglochin maritima* and *Salicornia virginica*. Two other species, *Rumex* sp. and *Rosa* sp. are also well represented, though the actual number of observations for these taxa are low.

Over-represented species are those taxa for which seeds were observed in sediment samples collected where the standing vegetation does not occur. Common salt marsh plants in this category include *Deschampsia caespitosa, Potentilla pacifica, Juncus balticus*, and *Atriplex patula* (Table 2-4). Several arboreal and upland taxa also occur in this group, including *Pseudotsuga menzeisii, Thuja plicata, Holodiscus discolor, Alnus rubra, Rubus* sp., and mosses (leaf bracts).

Under-represented taxa are those species that commonly occur in the standing vegetation but are rare in the seeds recovered from surface sediments. These taxa include *Plantago maritima, Scirpus acutus*, and several species of Graminaeae (Table 2-4). In general, the under-represented category is much smaller than the over-represented.

DISCUSSION

The results of the CCA support the hypothesis that environmental processes act in predictable ways to distribute living and dead diatoms along environmental gradients. Monte Carlo permutation tests indicate that salinity and elevation significantly control the distribution of diatom assemblages across the salt marsh surface. The ordination diagram shows that distinct diatom assemblages occur in the upper high marsh subenvironment where abrupt changes in salinity and elevation occur, while diatom assemblages tend to occur as a continuum in other marsh subenvironments. Similarly, at Yaquina Estuary, Oregon, Amspoker and McIntire (1978) observed a sharp discontinuity in the diatom flora where the salinity dropped below 5‰ and attributed the floristic change to differences in osmotic regulation between fresh- and brackish-water diatoms. Snoeijs (1995) observed changes in epiphytic diatom assemblages in the Baltic Sea when salinity dropped to low values. These studies, combined with the present results, suggest that the distribution of diatom assemblages in salt marshes is controlled in a large part by salinity.

The higher diversity in the high marsh samples, relative to upland and tideflat areas, may reflect mixing of autochthonous and allochthonous diatoms in the high marsh. The distribution patterns observed are likely related to two factors; salinity tolerance of individual taxa living in the high marsh and spatial patterns in the distribution of allochthonous diatoms by tidal currents. Laws (1988) observed similar relationships between diatom assemblages in surficial sediments of San Francisco Bay and environmental gradients. Laws (1988) found that mainly salinity and depth controlled diatom distributions. He also cited higher species diversity in areas where mixing of brackish and freshwater diatoms occur. Similar patterns are apparent at marshes in Puget Sound, where offshore taxa are carried into the marsh during high tides and deposited, with the upper limit to the distribution of transported diatoms primarily controlled by the elevation of MHHW.

Epipsammic and tychoplanktonic diatoms dominate the tideflat and lower marsh subenvironments. Occurrences of these diatoms in salt marsh environments suggest that they are transported from adjacent environments and deposited at higher elevations. Earlier work by de Jonge (1985) found that loosely attached diatoms living on mudflats and in channels are scoured off the substratum by tidal currents and transported into adjacent environments. This process of stripping epipsammic diatoms and transporting the frustules into adjacent environments is cited as a principal taphonomic process affecting the composition of salt marsh diatom assemblages (Sherrod et al., 1989; Hemphill-Haley, 1995b). The results of the present study show that while transportation alters diatom assemblages, it does so in predictable ways and results in assemblages that may in some cases reflect environment gradients.

The findings also provide support for the hypothesis that diatom assemblages occurring in salt marsh deposits reflect major ecological processes and can be used for accurate quantitative reconstructions. The results of the calibration indicate that, salt marsh diatom assemblages reflect gradients of salinity and elevation and thus can be effectively used for quantitative reconstructions of former environmental conditions. This suggests that mixing of allochthonous and autochthonous diatoms occurs in a predictable manner along elevation and salinity gradients, possibly as a response to differences in the amount of tidal inundation. The present study indicates that salinity can be predicted within ±5 ‰ and elevation to within ±0.50 m. By broadening this study and adding additional sites, it may be possible to improve on the predictive power of the calibration model and investigate the second hypothesis further. CANOCO allows passive samples (samples added to an existing ordination) in the ordination analysis, so that fossil samples can be directly related to modern training sets (ter Braak, 1995a). Shennan et al. (1996) used similar techniques to estimate the magnitude of submergence (elevation changes) accompanying past earthquakes along the Pacific Northwest coast but did not take into account the role of salinity or other environmental variables. Estimated error in the elevation changes indicated by Shennan et al. (1996) were 0.5 m, consistent with the error of the diatom-based elevation predictions for the present study.

The results of the present study suggest diatoms can be used as the basis for quantitative reconstructions of both salinity and elevation in paleoecological studies. The method presented is equally applicable to studies based on other types of microfossils, especially Foraminifers and vascular plant seeds (Nelson and Kashima, 1993).

PLANT MACROFOSSILS

Seeds from surface sediments included many taxa, although most are either underrepresented or over represented. The well-represented seeds, though small in number, include common salt marsh plants in Puget Sound, *Triglochin maritima* and *Salicornia virginica*. Seeds of these two species in surface sediments therefore implies that these plants lived at the same site. Because these plants most commonly occur in high and low marsh environments, finding these seeds in fossil assemblages provides a proxy for interpreting the position of MHHW in the past.

A large number of taxa are over represented in the seeds collected from surface sediments. Several reasons may explain the large number of over-represented taxa. First, tidal currents may distribute certain taxa over a wide area, causing seeds to float into areas where the plant does not live. Second, windblown seeds, needles, and leaf fragments may fall into brackish water marshes and become incorporated into the sediments. Last, species that grow and flower in early spring and summer may have been missed during the field surveys because they were not actively growing at the time of the surveys. However, this last reason is likely a minor factor because field data was collected from several sites at different times during the growing season.

Tidal currents likely play an important role in determining the distribution of several taxa. At North Spit, Sammy-Saquitne (University of Washington, personal communication, 1996) suggested that the surface distribution of seeds from certain taxa, including *Atriplex patula* and *Salicornia virginica*, were redistributed to higher areas by flood tides. At several sites, *Spergularia canadensis* seeds occur in higher numbers across wide areas where the plant itself is absent or rare. Perhaps *Spergularia canadensis* produces abundant seeds that are easily moved by tidal currents.

Graminaeae are the largest group in the underrepresented category probably because the seeds are small, delicate, and mostly designed for wind transport. Perhaps Graminaeae seeds are blown out of the area, and those seeds that do not fall to the marsh surface are either washed away or do not preserve well in the sediment.

CONCLUSIONS

1. Salinity and elevation are important in determining the distribution of diatom assemblages in surface sediments of coastal Puget Sound marshes.
2. Diatom assemblages are useful for quantitative reconstructions of salinity and elevation in paleoecological studies.
3. Diatom-based transfer functions can predict salinity within 5‰ and elevation within 0.5 m.
4. Macrofossils of two common salt marsh plants, *Triglochin maritima* and *Salicornia virginica*, are well represented in the surface sediments, and thus may serve as reliable indicators of past vegetation.

Table 2-1. Descriptive statistics of salinity measurements from interstitial water of surface (0-1 cm) sediments, and elevation of sampling stations relative to MLLW.

Variable	N	Mean	Std. Dev.	Minimum	Maximum
Salinity (‰)	39	18.1	10.7	0	33
Elevation (m)	39	3.59	.58	2.38	4.63

Table 2-2. List of diatom taxa in the CCA analysis. Included for each taxon is its taxonomic authority, number of sites at which occurred, average abundance in all samples, and marsh subenvironments that each taxon was observed (according to Figure 2-6, UHM = upper high marsh, LHM = lower high marsh, LM = low marsh, and MF = tideflat/mudflat). Codes are shown for certain taxa on Figure 2-6.

Code	Species Name	Sites	Average Abundance	Occurrence in Marsh Subenvironments
ACHAFF	*Achnanthes affinis* Grun.	10	0.7	MF, LHM, UHM
ACHBIV	*A. brevipes* Ag.	26	0.8	MF, LM, LHM, UHM
ACHDEL	*A. delicatula* (Kütz.) Grun. in Cl. & Grun.	14	1.3	MF, LHM, UHM
ACHGEM	*A. grimmei* Krasske	1	0.6	LHM
ACHGRI	*A. sp. 1* (A. cf. grimmei)	4	1.1	LHM
ACHHAU	*A. delicatula spp. hauckiana* Grun.	30	3.9	MF, LM, LHM, UHM
ACHLAN	*A. lanceolata* (Breb.) Kütz.	17	5.3	MF, LHM, UHM
ACHLEM	*A. lemmermannii* Hust.	10	0.2	MF, LM, LHM
ACHMIN	*A. minutissima* Kütz.	12	0.7	MF, LM, LHM
AMPCOF	*Amphora coffeaeformis* A. Meyer	29	0.7	MF, LM, LHM, UHM
AMPDES	*A. decussuta* Grun. in Cleve & Grun.	1	0.0	MF
AMPPED	*A. pediculus* (Kütz.) Grun. in A. Sm.	8	0.1	MF, LHM
AMPRUT	*Berkeleya rutilens* (Trent ex Roth) Grun.	5	0.3	LHM
AMPSTR	*Amphipleura strigosa* Hust.	1	0.1	UHM
AMPVEN	*Amph. ventricosa* Greg.	18	0.8	MF, LM, LHM, UHM
BACPAX	*Bacillaria paxillifer* (O. Muller) Hend.	17	0.2	MF, LM, LHM, UHM
CALBAC	*Caloneis bacillum* (Grun.) Cl .	9	0.4	LM, LHM
COCDIR	*Cocconeis dirupta* Greg.	4	0.2	MF, LM
COCPEL	*C. peltoides* Hust.	15	0.5	MF, LM, LHM
COCPLA	*C. placentula* Ehrenb.	10	0.1	MF, LM, LHM, UHM
COCSCU	*C. scutellum* Ehrenb.	33	1.5	MF, LM, LHM, UHM
COSPUS	*Cosmoneis pusilla* W. Sm.	24	2.1	LM, LHM, UHM
CYMAFF	*Cymbella affinis* Kütz.	3	0.0	LHM
DENSUB	*Denticula subtilis* Grun.	25	1.7	LM, LHM, UHM
DIMMIN	*Dimeregramma minor* (Greg.) Ralfs in Pritch.	21	1.0	MF, LM, LHM, UHM
DIPELL	*Diploneis elliptica* (Kütz.) Cl.	18	0.4	LM, LHM, UHM
DIPINT	*D. interrupta* (Kütz.) Cl.	20	0.4	MF, LM, LHM
DIPOVA	*D. ovalis* (Hilse) Cleve	4	0.1	LM, LHM, UHM
DIPSMI	*D. smithii* (Breb. ex W.Sm.) Cl.	17	0.5	MF, LM, LHM
ENTALA	*Entomoneis alata* (Ehrenb.) Ehrenb.	12	0.2	MF, LM, LHM, UHM
EUNPEC	*Eunotia pectinalis* (O. Mull.) Raben.	7	0.2	MF, , UHM

Table 2-2. Continued

Code	Species Name	Sites	Average Abundance	Occurrence in Marsh Subenvironments
FRACAP	*Fragilaria capucina* Desm.	1	0.0	UHM
FRACON	*Frag. construens* (Ehrenb.) Grun.	9	0.5	LM, LHM, UHM
FRAFAS	*Frag. fasciculata* (Ag.) Lange-Bert.	23	0.6	MF, LM, LHM, UHM
FRASHU	*Frag. shultzii* Brockm.	2	0.1	MF
FRAVIR	*Frag. virescens* Ralfs	19	4.3	LM, LHM, UHM
FRUCRU	*Frustulia creuzburgensis* (Krasske) Hust.	10	0.3	MF, LM, LHM, UHM
FRURHO	*Frus. rhomboides* (Ehrenb.) De Toni	2	0.1	MF, LHM,
FRUVUL	*Frus. vulgaris* (Thwaites) De Toni	8	0.1	MF, LM, LHM,
GOMANG	*Gomphonema angustatum* (Kütz.) Raben.	4	0.1	LM, UHM
GOMCLE	*G. clevei* Fricke in A. Schmidt	1	0.0	UHM
GOMPAR	*G. parvulum* (Kütz.) Kütz.	4	0.2	UHM
GOMSUB	*G. subclavatum* (Grun. in Schn.) Grun. in Van Heurck	1	0.0	UHM
GOMVAL	*G. valentinica* Nickalajev	3	0.4	MF, LM
GYRBAL	*Gyrosigma balticum* (Ehrenb.) Rabenh.	7	0.2	MF, LM, LHM
GYREXI	*G. eximium* (Thwaites) Boyer	18	1.0	LM, LHM,
GYRSPE	*G. spenceri* (W. Sm.) Cl.	6	0.1	MF, LHM
HANAMP	*Hantzschia amphioxys* (Ehrenb.) Grun.	10	0.2	LM, LHM, UHM
HYASCO	*Hyalodiscus scoticus* (Kütz.) Grun.	1	0.1	MF, LM, LHM, UHM
LUTMUT	*Luticola mutica* (Kütz.) Mann	17	0.3	MF, LM, LHM, UHM
MELMON	*Melosira moniliformis* (O. Muller) Ag.	31	3.0	MF, LHM, UHM
MELNUM	*M. nummuloides* Ag.	15	0.6	MF, LM, LHM, UHM
MERCIR	*Meridion circulare* (Grev.) Ag.	23	2.9	LM, UHM
NAVAGN	*Navicula agnita* Hust.	6	0.4	MF, LM, LHM
NAVCIN	*N. cincta* (Ehrenb.) Ralfs in Pritch.	8	0.6	MF, LM, LHM, UHM
NAVCRT	*N. cryptotenella* Lange-Bert.	23	3.4	MF, LM, LHM, UHM
NAVCRY	*N. cryptocephala* Kütz.	24	1.0	MF, LM, LHM, UHM
NAVDIG	*N. digito-radiata* (Greg.) Ralfs in Pritch.	32	1.5	MF, LM, LHM
NAVDIS	*N. distans* (W. Sm.) Ralfs in Pritch.	8	0.1	MF, LM, LHM
NAVGRE	*N. gregaria* Donk.	6	0.1	MF, LM, LHM, UHM
NAVIND	*N. indifferens* Hust.	33	2.7	MF, LHM, UHM
NAVOCC	*N. occuliformis* Hust.	19	0.8	MF, LM, LHM, UHM
NAVPER	*N. peregrina* (Ehrenb.) Kütz.	16	0.3	MF, LM, LHM, UHM
NAVPHY	*N. phyllepta* Kütz.	24	0.5	MF, LM, LHM, UHM
NAVPRM	*N. perminuta* Grun. in Van Heurck	21	0.3	LM, LHM
NAVPSS	*N. pseudosicula* ???	10	0.4	MF

Table 2-2. Continued

Code	Species Name	Sites	Average Abundance	Occurrence in Marsh Subenvironments
NAVRHY	*N. rhynchocephala* Kütz.	1	0.0	MF, LM, LHM, UHM
NAVSLE	*N. slesvicensis* (Grun.) Van Heurck	2	0.1	LM, LHM, UHM
NAVVEN	*N. veneta* Kütz.	14	0.8	LHM
NAVVIR	*N. viridula* (Kütz.) Ehrenb.	7	0.4	UHM
NITANG	*Nitzschia angustatum* Lange-Bertalot	1	0.0	MF, LM, LHM
NITBIL	*Nitz. bilobata* W. Sm.	10	0.1	LM, LHM
NITCON	*Nitz. constricta* (Kütz.) Ralfs in Pritch.	4	0.1	MF, LM, LHM
NITDUB	*Nitz. dubia* W. Sm.	21	0.3	LM, LHM
NITFAS	*Nitz. fasciculata* (Grun.) Grun. in Van Heurck	6	0.1	MF, LM, LHM, UHM
NITFON	*Nitz. fonticola* Grun. in Van Heurck	12	0.5	MF, LM, LHM
NITFRU	*Nitz. frustulum* (Kütz.) Grun. in Cl. & Grun.	11	0.5	MF, LM, LHM, UHM
NITLIM	*Nitz. limnicola* (Ag.) W. Sm.	21	1.6	LM, LHM
NITLIN	*Nitz. linearis* W. Sm.	2	0.1	UHM
NITLIT	*Nitz. littoralis* (Grun.) in Cl. & Grun.	3	0.3	MF, LM, LHM, UHM
NITLON	*N. longa* Grunow	25	0.9	MF, LHM
NITPAL	*Nitz. palea* (Kütz.) W. Sm.	5	0.1	MF, LM, LHM, UHM
NITREC	*Nitz. recta* Hantzsch ex Raben.	39	3.5	MF, LM, LHM, UHM
NITTEN	*Nitz. tenuis* W. Sm.	7	0.4	MF, LM, LHM, UHM
NITTRY	*Tryblionella debilis*	28	0.9	MF, LM, LHM
OPEMAR	*Opephora marina* (Grun.) Petit	8	0.8	MF, LM
OPEPAC	*O. pacifica* (Grun.) Petit	4	0.2	MF, LM, LHM, UHM
OPEPAR	*O. parva* (Van Heurck) Krasske	24	1.8	MF, LM, LHM, UHM
PARSUL	*Paralia sulcata* (Ehren.) Cl. (undiff.)	33	11.8	MF, LM, LHM, UHM
PINAPP	*Pinnularia appendiculata* (Ag.) Cl.	1	0.1	LHM
PINLAG	*P. lagerstedii* (Cl.) A. Cl.-Euler	34	7.5	LM, LHM, UHM
PINMIC	*P. microstauron* (Ehren.) Cl.	3	0.4	UHM
PINSUB	*P. subcapitata* Greg.	10	0.7	UHM
PLASTA	*Plagiogramma staurophorum* (Greg.) Heiberg	1	0.0	MF, LM, LHM
PLATRO	*Plagiotropis vitrea* (W. Sm.) Grun. in Cleve & Grun.	3	0.1	MF, LHM
PLESAL	*Pleurosigma salinarum* (Grun.) Grun. in Cleve & Grun.	10	0.2	MF, LHM
RHOCUR	*Rhoicosphenia curvata* (Kutz.) Grun.	2	0.1	LHM, UHM
RHOMUS	*Rhopalodia musculus* (Kütz.) O. Muller	8	0.1	MF, LM, LHM, UHM
SKECOS	*Skeletonema costatum* (Grev.) Cl.	3	0.1	LM, LHM, UHM
SURBRE	*Surirella brebissonii* Krammer & Lange-Bert.	20	1.4	MF, LM, LHM, UHM
SYNRUM	*Synedra rumpens* Kütz.	10	0.4	LHM, UHM

Table 2-2. Continued

Code	Species Name	Sites	Average Abundance	Occurrence in Marsh Subenvironments
SYNULN	*S. ulna* (Nitzsch) Ehrenb.	18	0.3	MF, LM, LHM, UHM
TABFEN	*Tabellaria fenestrata* (Lyngb.) Kütz.	6	0.9	LHM
TRAASP	*Trachyneis aspera* (Ehrenb.) Cleve	8	0.1	MF, LM

Table 2-3. Canonical coefficients, approximate t-values, and interset correlations of environmental variables.

Variable	Canonical Coefficients		t-values of Canonical Coefficients		Interset Correlations	
	Axis 1	Axis 2	Axis 1	Axis 2	Axis 1	Axis 2
Salinity	-0.80	.83	-10.3	5.8	-0.889	0.229
Elevation	0.33	1.10	4.3	7.7	0.669	0.554

Table 2-4. Association indices for seeds and plant remains from surface sediment samples at five Puget Sound marshes.

	Index variable			
	B	P_0	P_1	A
Well-represented macrofossils				
Triglochin maritima	22	8	5	0.63
Salicornia virginica	17	8	8	0.52
Rumex sp.	1	1	0	0.50
Rosa sp.	1	0	1	0.50
Over-represented macrofossils				
Deschampsia caespitosa	6	4	3	0.46
Potentilla pacifica	11	2	12	0.44
Distichlis spicata	13	2	21	0.36
Juncus balticus	5	8	2	0.33
Atriplex patula	9	17	8	0.26
Carex lyngbyei	5	7	7	0.26
Onenanthe sarmentosa	2	3	3	0.25
Jaumea carnosa	5	3	15	0.22
Agrostis alba	2	8	0	0.20
Grindelia integrifolia	1	6	2	0.11
Alnus rubra	1	10	0	0.09
Typha latifolia	1	10	0	0.09
Spergularia canadensis	0	17	0	0.00
Holodiscus discolor	0	5	0	0.00
Rubus sp.	0	5	0	0.00
Angelica lucida	0	4	0	0.00
Pseudotsuga menzeisii	0	4	0	0.00
Urtica dioica	0	4	0	0.00
Cuscuta salina	0	2	1	0.00
'Aster'	0	2	0	0.00
Ranunculus repens	0	2	0	0.00
Thuja plicata	0	2	0	0.00
Mosses	0	1	1	0.00
Ericaceae	0	1	0	0.00
Gaultheria shalon	0	1	0	0.00
Juncus effusus	0	1	0	0.00
Picea sitchensis	0	1	0	0.00
Plantago spp.	0	1	0	0.00
Prunus sp.	0	1	0	0.00
Trifolium sp.	0	1	0	0.00

Table 2-4. Continued

	Index variable			
	B	P_0	P_1	A
Under-represented macrofossils				
Plantago maritima	3	4	7	0.21
Hordeum sp.	1	0	7	0.13
Glaux sp.	0	0	16	0.00
Festuca rubra	0	0	9	0.00
Scirpus acutus	0	3	4	0.00
Calamagrostis sp.	0	0	4	0.00
Compositae	0	0	4	0.00
Anemone sp.	0	0	2	0.00
Agropyron sp.	0	0	1	0.00
Arbutus menzeisii	0	0	1	0.00
Galium sp.	0	0	1	0.00
Salix sp.	0	0	1	0.00
Taraxeum officinale	0	0	1	0.00

B - number of stations at which both the seed and the vegetation of a species were found

P_0 - number of stations at which the seed is present, but the vegetation is not

P_1 - the number of stations at which the vegetation is present, but the seeds are not

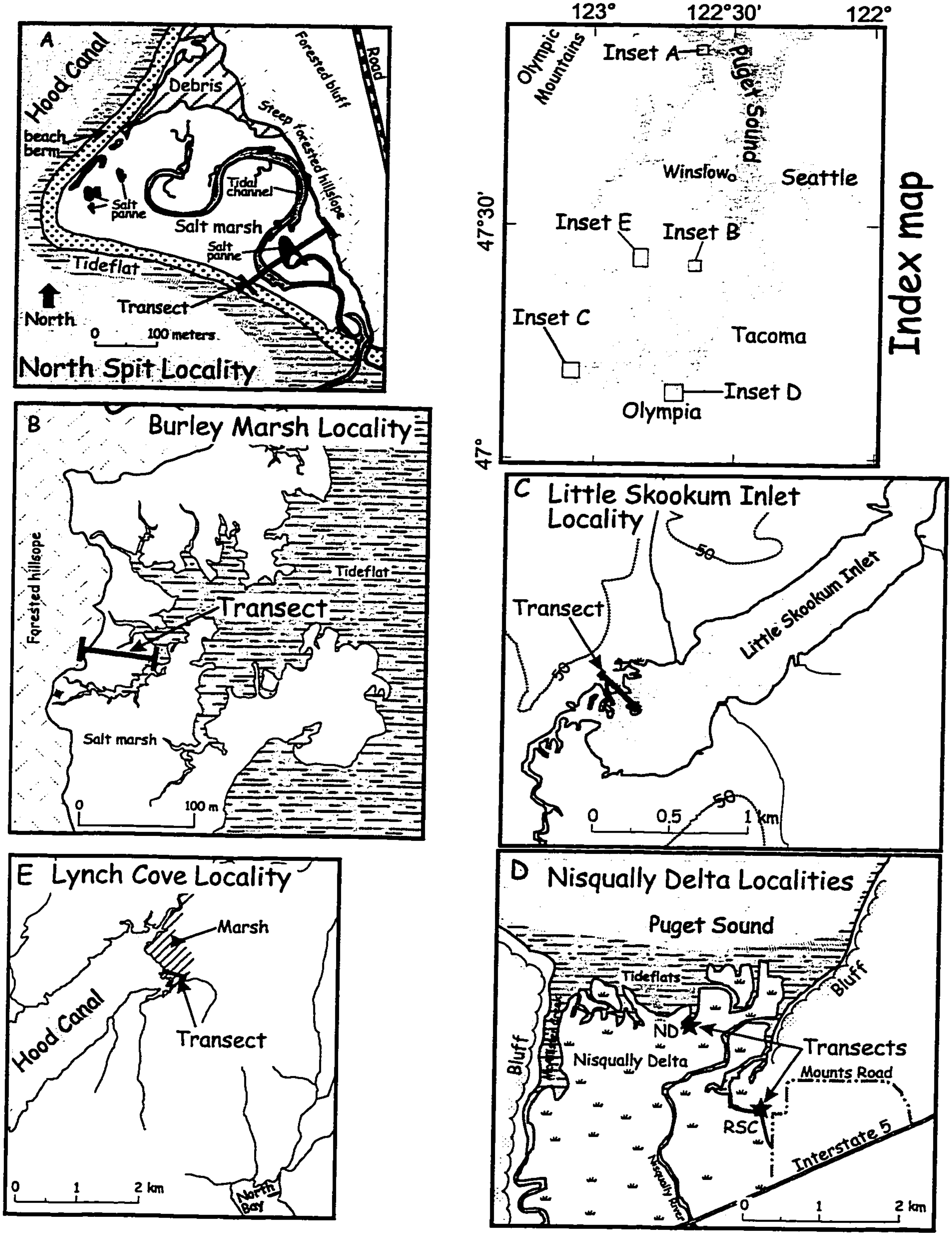


Figure 2-1. Location and setting of modern transects surveyed and sampled in Puget Sound, Washington.

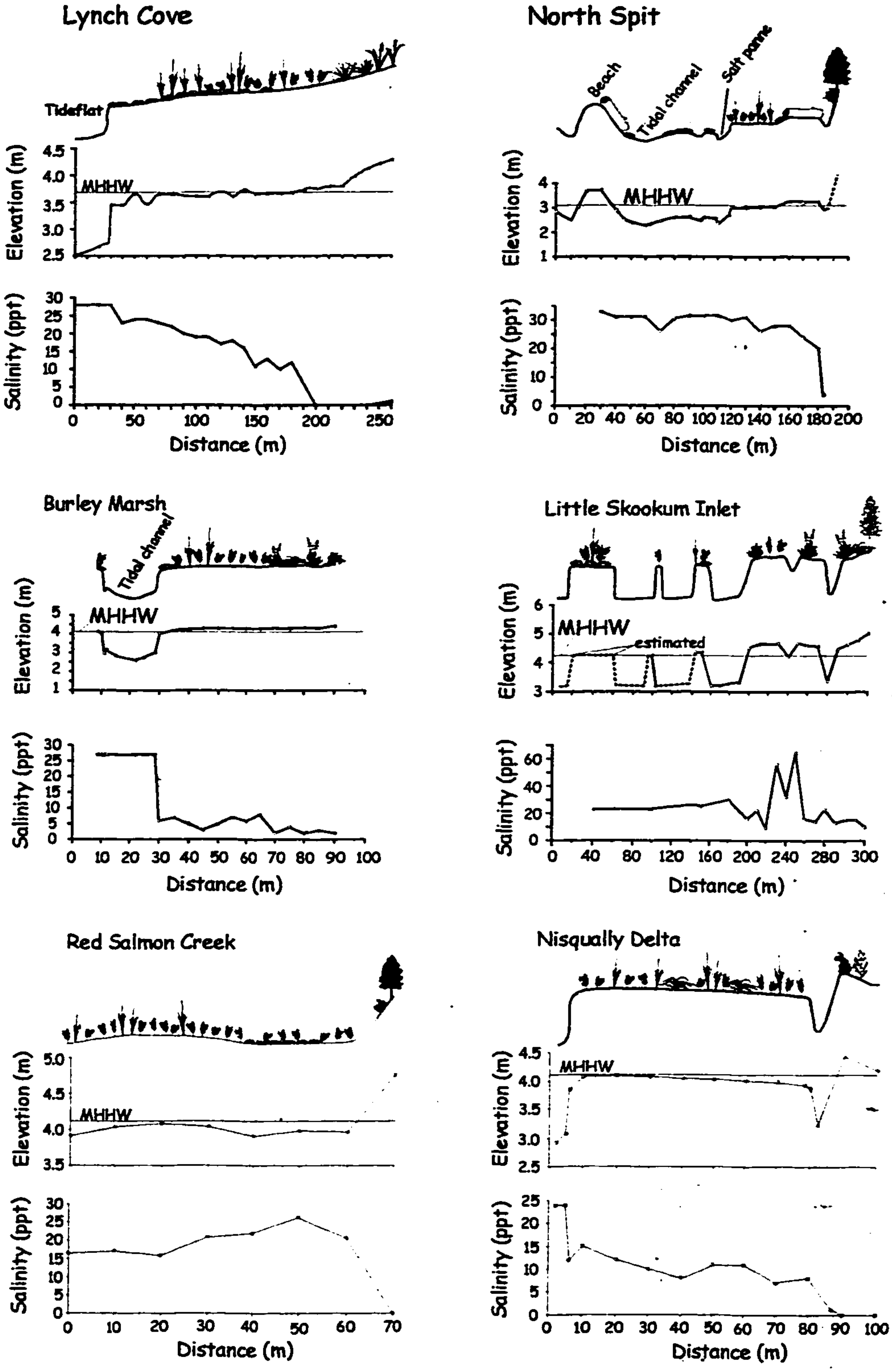
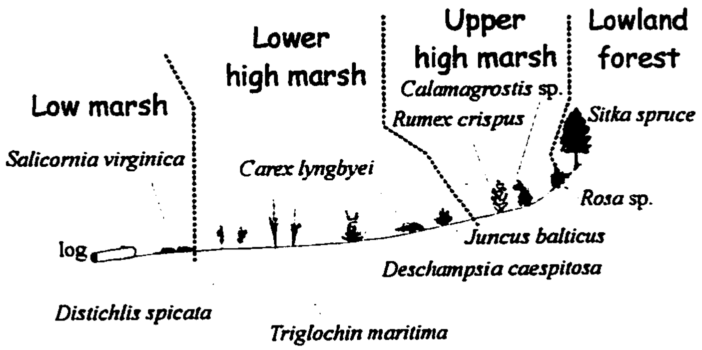


Figure 2-2. Profiles of modern transects at Puget Sound showing vertical plant zonation. Plots of elevation and salinity measurements are shown below each profile. The position of MHHW at each site is shown on the elevation curve.

EXPLANATION



MHHW - Mean Higher High Water (estimated from tidal measurements)
ppt -parts per thousand (‰)

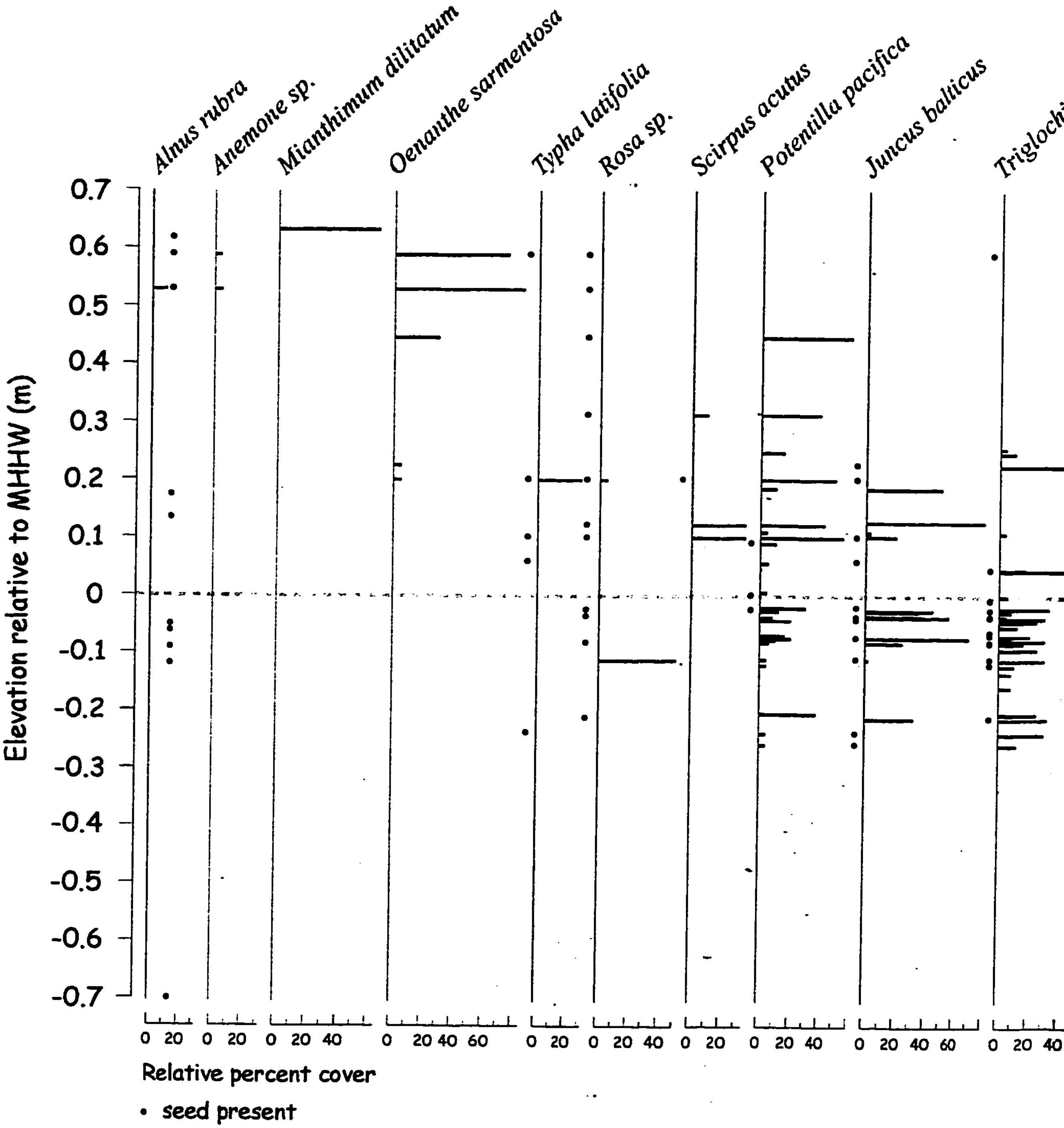
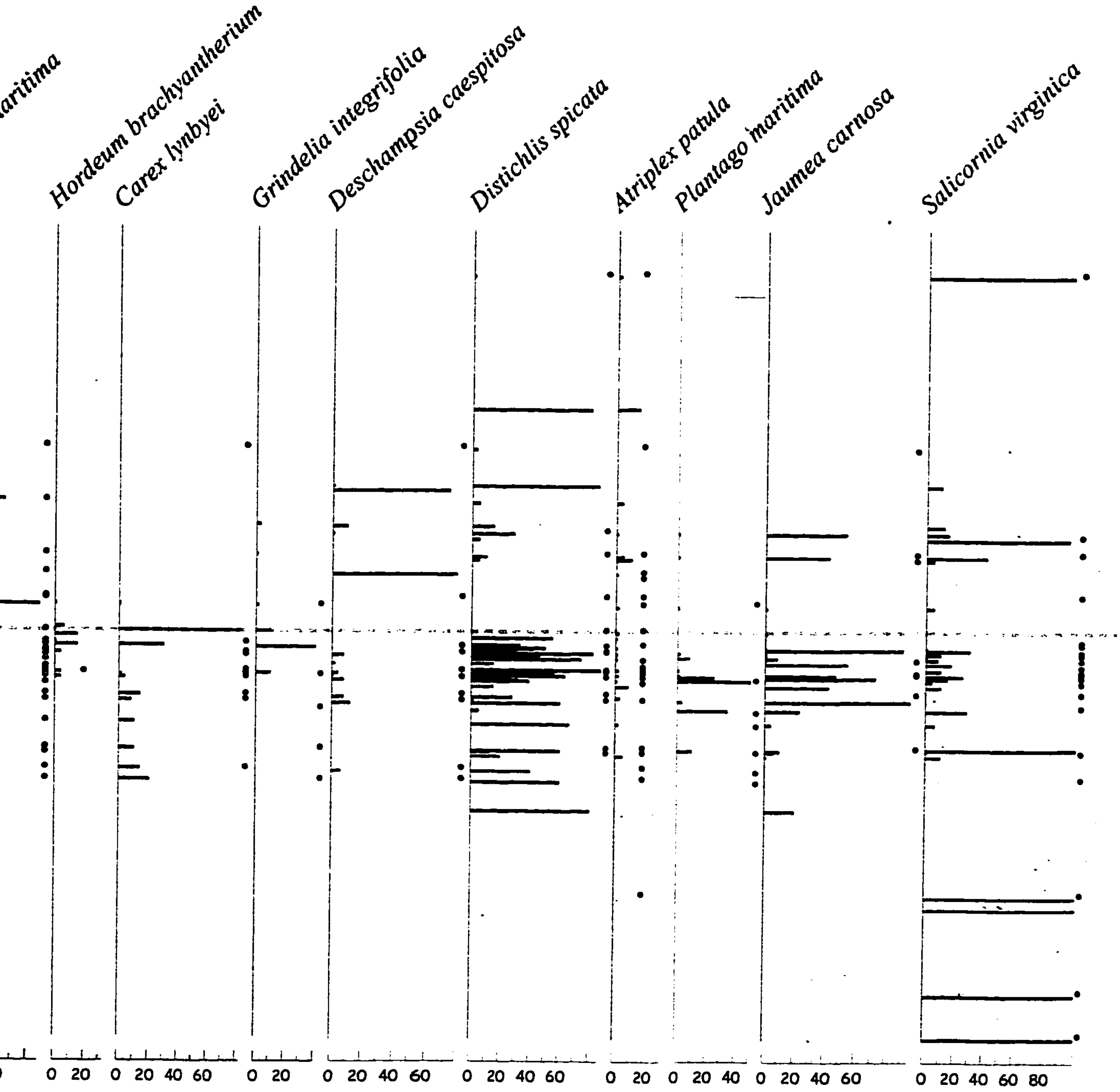


Figure 2-3. Percent cover of important plants found in coastal Puget Sound marshes plotted relative to MHHW. Occurences of seeds are indicated by dots adjacent to plot for each species.


aritima
Hordeum brachyantherium
Carex lynbyei
Grindelia integrifolia
Deschampsia caespitosa
Distichlis spicata
Atriplex patula
Plantago maritima
Jaumea carnosa
Salicornia virginica
0 20
0 20 40 60
0 20
0 20 40 60
0 20 40 60
0 20
0 20 40
0 20 40 60
0 20 40 60 80

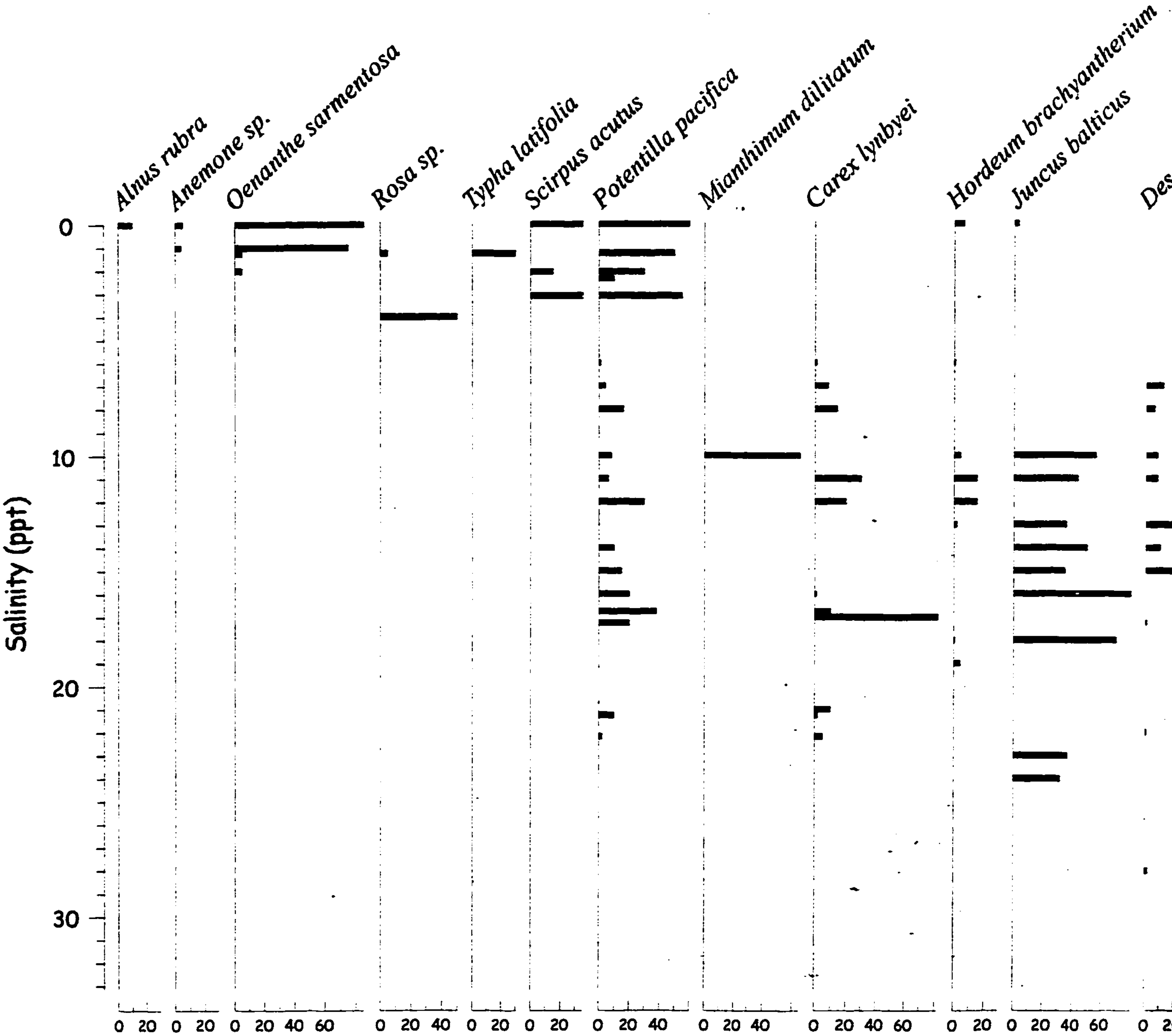
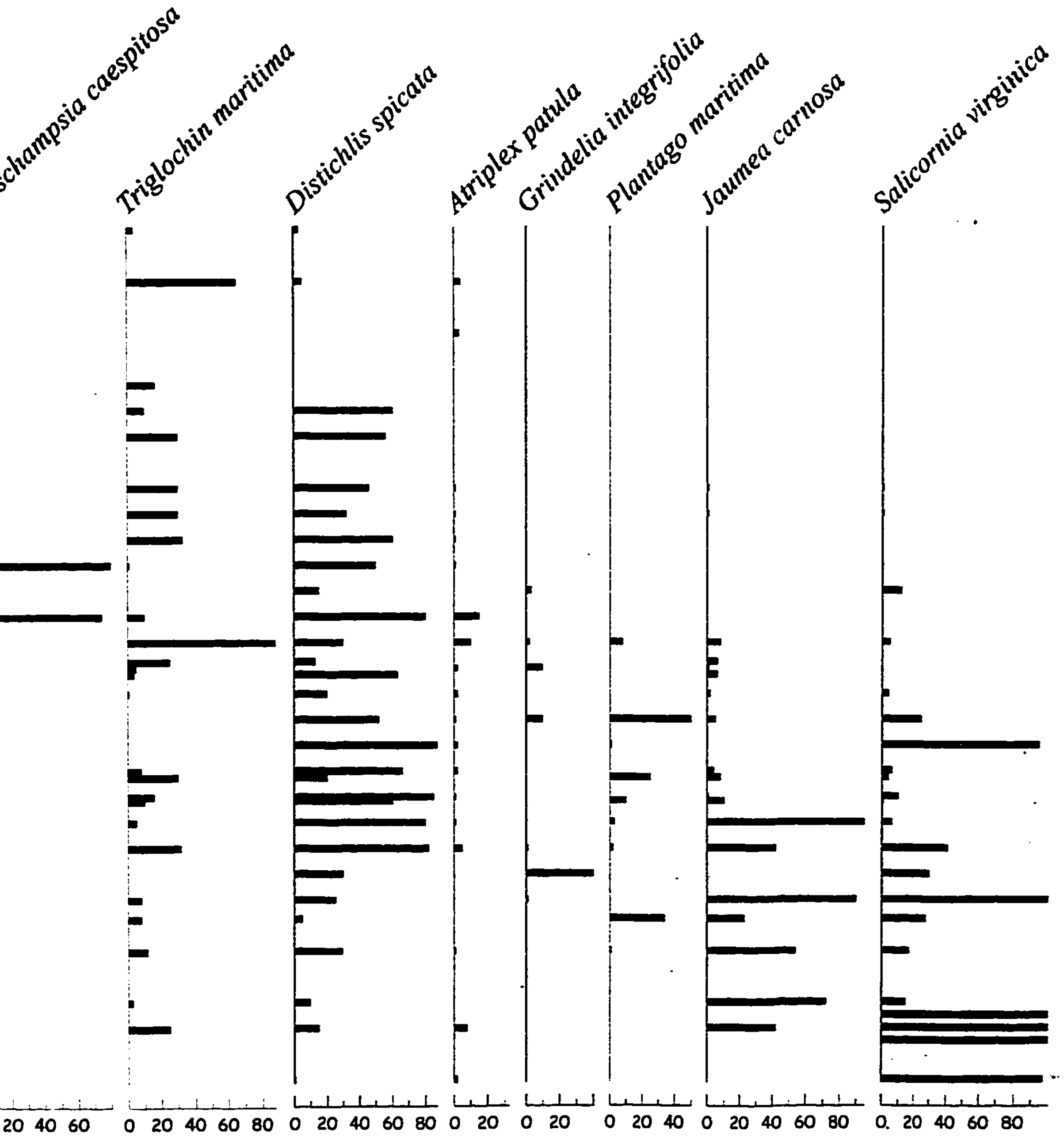


Figure 2-4. Percent cover of important plants found in coastal Puget Sound marshes plotted relative to salinity.



schampsia caespitosa
Triglochin maritima
Distichlis spicata
Atriplex patula
Grindelia integrifolia
Plantago maritima
Jaumea carnosa
Salicornia virginica
20 40 60
0 20 40 60 80
0 20 40 60 80
0 20
0 20
0 20 40
0 20 40 60 80
0 20 40 60 80

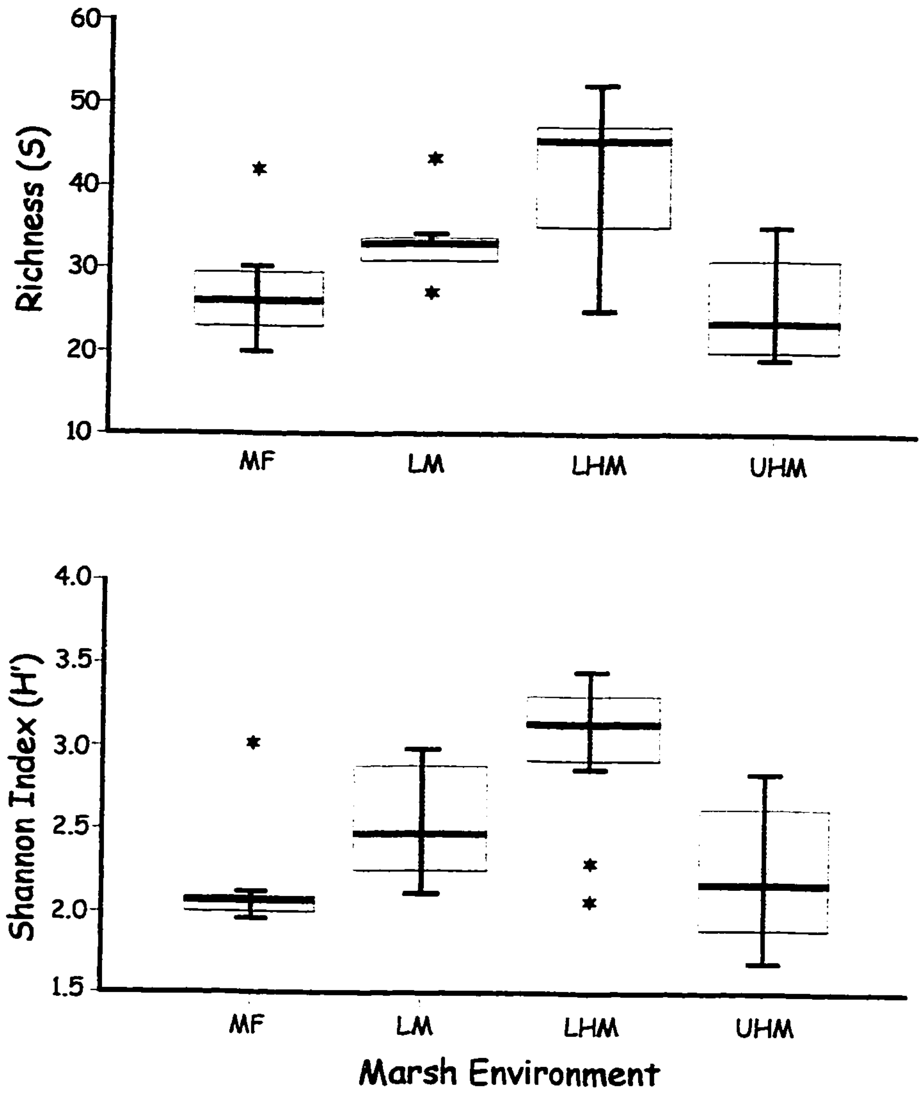


Figure 2-5. Boxplots of Shannon indices (H', calculated using natural logarithm) for diatom assemblages in Lynch Cove surficial sediments. Station numbers correspond to distance on transect. Outliers are shown by an asterisk.

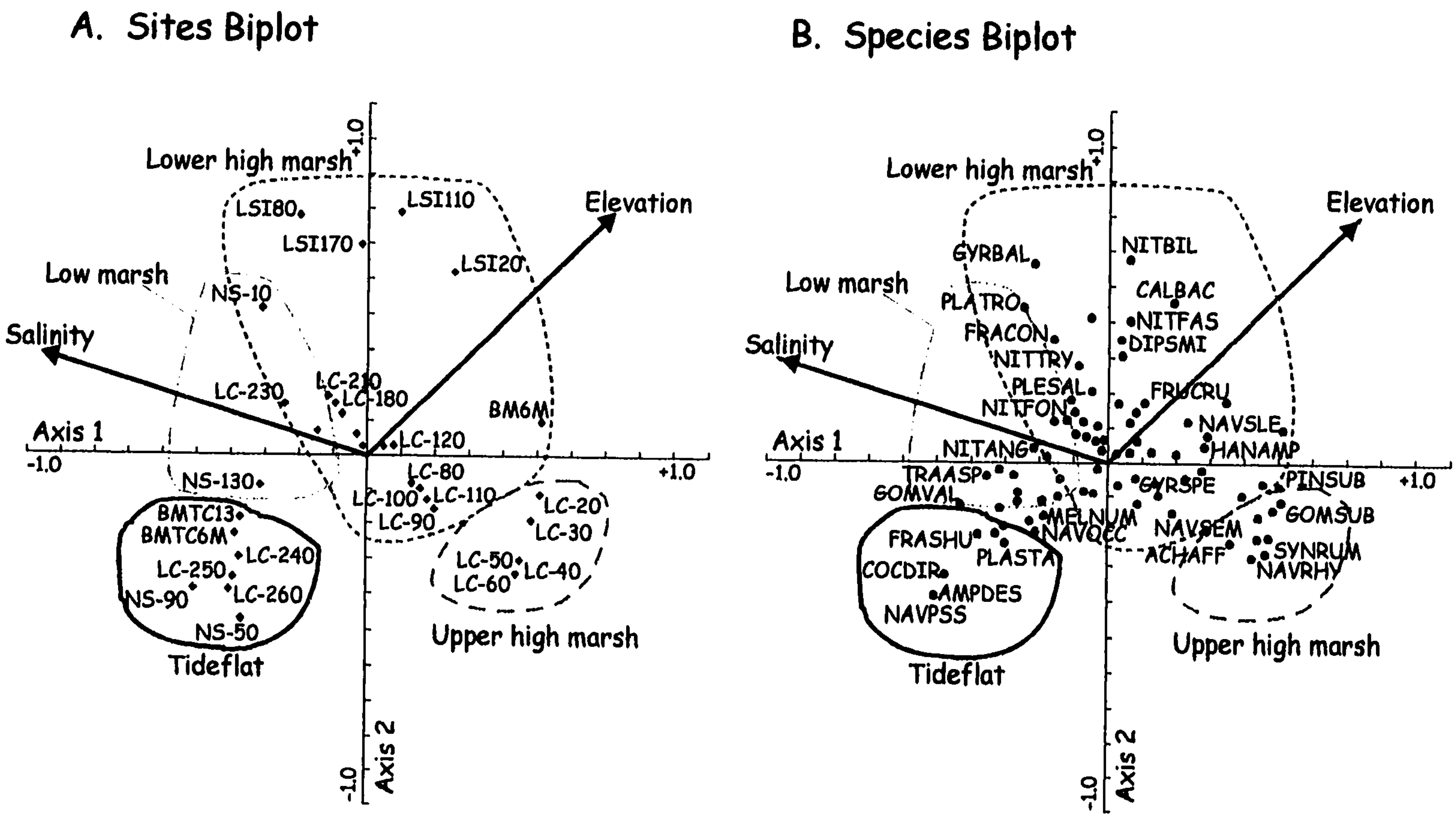


Figure 2-6. Ordination diagrams for sites (A) and species (B) based on canonical correspondence analysis of the Lynch Cove diatom data. Salinity and elevation gradients are indicated by arrows. Species codes are presented in Table 2 and site numbers correspond to a sampling station along a transect. General groupings of sites and species in each marsh subenvironment are indicated. See text for interpretion of ordination diagrams.

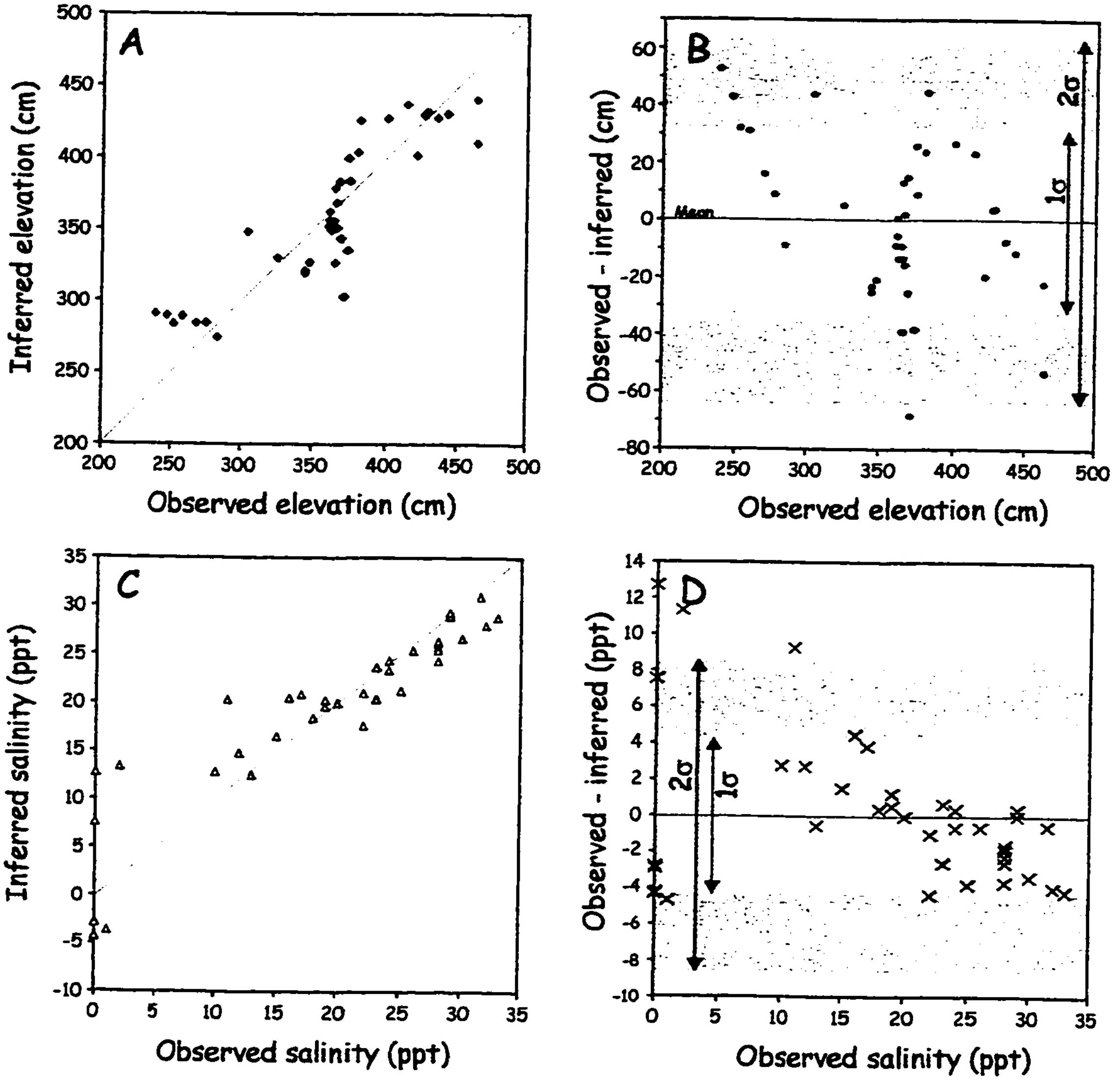


Figure 2-7. Graphs of calibration results. A. Scatter diagram of diatom-inferred salinity and observed salinity with fitted linear regression line. B. Residuals for diatom-inferred salinity from regression analysis. C. Scatter diagram of diatom-inferred elevation and observed elevation with fitted linear regression line. D. Residuals for diatom-inferred elevation from regression analysis.

CHAPTER 3: ABRUPT PALEOENVIRONMENTAL CHANGES TRIGGERED BY SEISMOGENIC LAND LEVEL CHANGES IN CENTRAL PUGET SOUND, WASHINGTON

ABSTRACT

Changes in the inferred elevation and salinity of a marsh at Restoration Point, located in central Puget Sound, Washington, suggest two or three periods of abrupt change in relative sea level. The latest of these raised a marine shoreline ~6-7.5 m during an earthquake 1000 cal yr B.P. This uplift produced an abrupt shift from sediments containing obligate marine diatom taxa to sediments containing freshwater diatoms (e.g. from sediments containing *Paralia sulcata*, *Opephora parva*, *Achnanthes delicatula*, *Trachyneis aspera*, *Cocconeis scutellum*, and *Melosira nummuloides*, to sediments dominated by *Eunotia camelus*, *Eunotia pectinalis*, *Meridion circulare*, *Gomphonema angustatum*, *Gomphonema parvulum*, and *Pinnularia subcapitata*). A similar shift from saline to freshwater diatoms occurred between 7700 and 6200 cal yr B.P.

Paleoecological inferences indicate one, possibly two, episodes of abrupt uplift along the Seattle fault in the past 7700 years. Elevation inferences suggest 6.0-7.5 meters of uplift and a change in salinity from ~28‰ to 0‰ about 1000 cal yr B.P., consistent with previous work at this site. A second possible uplift event of ~1.5 m occurred between 7700 and 6200 cal yr B.P. and may relate to an earlier earthquake on the Seattle fault.

A brackish water marsh became a tideflat at the site about 1700 cal yr B.P. Subsidence at Restoration Point could have resulted from either pre-seismic strain accumulation causing subsidence along the Seattle fault or subsidence during a great subduction zone earthquake. Alternatively, waves breaching the beach berm bordering the site to the south could have allowed tides temporarily to flood the former brackish water marsh behind the beach berm.

INTRODUCTION

The Seattle fault, a blind reverse fault in central Puget Sound, Washington, poses a poorly understood hazard that fault poses to a major metropolitan area. Determining the history of movement on that fault is difficult because the fault does not rupture the ground surface. However, coastal geomorphology and paleoenvironmental analysis of coastal marshes along the fault trace can be used to infer past earthquakes that resulted in land level changes, for a large fold above the fault intersects the coastline of Puget Sound.

Geomorphic and stratigraphic evidence shows that a large earthquake (M~7.5) occurred about 1000 years ago on the Seattle fault (Bucknam et al., 1992; Atwater and Moore, 1992; Jacoby et al., 1992). The earthquake resulted in approximately 7 meters of uplift south of the fault and slight subsidence north of the fault (Figure 3-1). The fault is now recognized as the Seattle fault zone; seismic reflection data indicates a series of four south-dipping faults with evidence for up to 500 m of Quaternary displacement (Johnson et al., 1994). The northernmost strand of the Seattle fault zone probably ruptured about 1000 years ago (Pratt et al., 1997). Given that the Seattle fault has evidence for a large late Holocene earthquake and has a long history of movement (Johnson et al., 1994), then a primary concern for hazard assessment is the recurrence of earthquakes on the Seattle fault capable of producing land level changes. Accordingly, the seismic hazard to the Seattle region is greater if the Seattle Fault shows evidence for repeated large earthquakes during the Holocene.

In this paper, I use changes in a coastal marsh to infer past earthquakes at a site along the Seattle fault. My evidence comes mainly from sediment cores from which I infer sudden changes in relative sea level that might be associated with prehistoric earthquakes on the Seattle fault and changes in the elevation of the marsh surface. The marsh, underlain by a Holocene stratigraphic section spanning the past 7600 years, provides an ideal location for studying the coastal paleoenvironments at Restoration Point.

SETTING

Restoration Point is a small peninsula located at the southeast end of Bainbridge Island, 11 km west of downtown Seattle (Figure 3-1). Being within the Seattle fault zone, the site should be sensitive to land level changes associated with past earthquakes in that fault zone. The studied marsh is situated on the south side of a low-lying wavecut platform that extends eastward into Puget Sound cut on the Blakely Formation, an Oligocene tuffaceous sandstone and mudstone. A raised, gravel beach berm separates the marsh from the bedrock platform to the south.

OBJECTIVE AND HYPOTHESES

Marsh paleoecology provides a powerful tool for reconstructing past coastal and upland environments to investigate relative sea level changes and prehistoric tectonic events (Hemphill-Haley, 1995; Nelson, 1992; Clague et al., 1982). Salt marsh paleoecology was used to infer sudden changes in relative sea level associated with the Seattle fault earthquake 1000 years ago (Bucknam et al, 1992; Atwater and Moore, 1992) but has not been applied to the history of earthquakes along the Seattle fault before 2000 years ago. This limitation leaves several questions about the earthquake history of central Puget Sound: Did large earthquakes similar in magnitude to the event 1000 years ago occur repeatedly in the Holocene? If so, did they result in multiple episodes of land deformation? Do sedimentary records at Restoration Point contain a long history of Holocene relative sea level changes?

In this study, marsh paleoenvironments are reconstructed to detect earthquakes along the Seattle fault over the past 8000 years. Geologic evidence for inferring past uplift events includes raised shoreline features and stratigraphic couplets indicating abrupt lowering of relative sea level (Figure 3-1). Stratigraphic evidence for inferring uplift includes tideflat deposits overlain by upland meadows or freshwater marsh deposits, without intervening brackish water marsh deposits (Bucknam et al., 1992).

Floristic changes inferred through paleobotanical analysis of marsh sediments indicate abrupt uplift, especially where tideflats or low marshes are raised out of the range of tides (Thilenius, 1995). Biostratigraphical analysis of cores from potentially uplifted sites (Figure 3-2) are used to develop environmental histories that are then used to infer abrupt changes in land level.

I focus on two specific hypotheses:

1. paleoenvironmental change at the studied site records gradual sea level rise and vertical accretion of marsh deposits in the middle and late Holocene;
2. recurrent large earthquakes occurred on the Seattle fault during the Holocene that resulted in land level changes; an episode of uplift about 1000 years ago at the site resulted in an abrupt environmental change.

PREVIOUS WORK

LAND-LEVEL CHANGES ALONG THE SEATTLE FAULT

Early explorers to present-day geologists have hypothesized about uplift along the Seattle fault. Restoration Point appeared anomalous to Capt. George Vancouver, who named the peninsula in 1792 (Lamb, 1984). Kimball (1897) recognized that both Restoration Point, and Alki Point located on the east side of Puget Sound near Seattle, were recently uplifted wave-cut platforms. Following on Kimball's work, Yount (1983) suggested that the bedrock platform was the result of Holocene tectonic uplift but could not confirm that termination of the platform feature to the north of Restoration Point was due to tectonics rather than preservation.

Bucknam et al. (1992) and found evidence of sudden uplift and Atwater and Moore (1992) evidence for subsidence, about 1000 years ago at several sites along the Seattle fault. Bucknam et al. (1992) interpreted the upper part of the marsh sequence at Restoration Point as a tidal flat deposit, indicating that the site lay close to sea level prior to 1000 years ago, and was subsequently abruptly uplifted during a single earthquake about 7 meters. Atwater and Moore (1992) found sand sheets mantling two former tidal marshes in central and northern Puget Sound and attributed these deposits to a tsunami that was generated during the uplift event about 1000 years ago. They also found evidence that a site at West Point, just north of downtown Seattle, subsided at least 1 m at about the same time as uplift at Restoration Point.

HOLOCENE RELATIVE SEA LEVEL CHANGE IN PUGET SOUND AND BRITISH COLUMBIA

Rates of relative sea level change in the Puget Sound region were estimated by Clague et al. (1982) and Beale (1990). Clague et al. found that sea level rose to within 2 meters of its present position by 5000 years ago at several sites along the coast of mainland British Columbia (Figure 3-3). They also concluded that sea level has not risen by more than 1 to 2 meters during the last 4500 years based on the continued deposition of terrestrial organics in low-lying Fraser River delta bogs.

In northern Puget Sound, Beale (1990) showed a relative sea level record similar to that of the mainland coast of British Columbia (Figure 3-3). Data from salt marshes in northern Puget Sound show that sea level rose to within 2-3 meters of present sea level between 5000 and 3000 years ago, and only rose 1 meter between 3000 and 1000 years ago. Her data also show that in northern Puget Sound, like British Columbia, sea level has not risen by more than 1 meter in the last 1000 years.

In areas of Puget Sound and coastal British Columbia where no known active faults are located, little relative sea level rise occurred in the last 5000 years (maximum 3 meters, with less than 1 meter in the last 1000 years). These measurements help to constrain any estimate of late Holocene land deformation by placing limits on the expected amounts of relative sea level rise expected at a given site.

METHODS

FIELD AND LABORATORY METHODS

The stratigraphy of the marsh was mapped in the field using gouge corer and trenches excavated with a backhoe. I surveyed field locations using an automatic level. A field crew collected a core from the marsh in 1993 by pounding plastic pipe into the sediment; each section of the core was 2 m long. Approximately 47 cm of compaction occurred in the upper one meter of sediment during the coring, and little compaction occurred in other sections. I obtained additional cores from the same location in 1994 using a Livingstone piston corer and a Russian peat corer to enable more complete and detailed study of the upper 1 meter of sediment. Radiocarbon samples were taken from the large diameter core and from a trench (Bucknam et al., 1992).

Field crews used a self-compensating level to survey the elevation of the marsh surface relative to the tides by measuring the elevation of either a high or low tide at a local datum. The local tidal level was calculated using the following steps. 1) Determine the height of the observed tide at Seattle, Washington. 2) Set the measured tidal height at the site to the corresponding observed height at Seattle. 3) Offset the measured tidal height by the difference in MHHW between Seattle and the nearest NOAA tidal benchmark to the site. The last step assumes that the tidal height at the site is the same as the tidal height of the nearest NOAA Tidal Benchmark (generally <5 km away). The local datum is then assigned an elevation relative to MHHW, from which the elevations of all sampling stations were surveyed.

For laboratory analysis and description, I split each core segment longitudinally and took volumetric samples every 10-cm for diatoms (1 cc) and loss-on-ignition (1 cc) and macrofossils (3 cc). A volcanic ash layer in the lower part of the sequence was examined for the presence of glass shards. Sediments were taken for macrofossil analysis by volumetrically sampling between 3 to 10 cc of sediment, measured by displacement of distilled water in a graduated cylinder. The samples were soaked and desegregated in a

0.5% solution of Calgon for 24-48 hours and wet sieved using 1mm and 0.3 mm sieves. To identify macrofossils, I examined each sieve fraction under a dissecting microscope and picked all identifiable seeds, fruits, leaves, ostracodes, and other macrofossils for later enumeration. I used reference works (Martin and Barkely, 1961; Berggren, 1981, 1969; Spjut, 1994; Young and Young, 1992), a seed collection at the University of Washington, Department of Botany, and plant specimens at the University of Washington Herbarium. After identification, I catalogued and stored all macrofossils in glycerin to prevent desiccation and decomposition. I took additional samples for Foraminfera and ostracode analysis and prepared each according to standard U.S. Geological Survey procedures for calcareous microfossils. The procedures are similar to those used for plant macrofossils except that a buffered Calgon solution is used to prevent decalcification of the ostracode and Foraminifera tests.

Diatom sample preparation followed the procedures of Patrick and Reimer (1966) and Abbott and Ernissee (1983). Organic matter was digested in 30% hydrogen peroxide, followed by several distilled water rinses and controlled centrifugation to remove clay-sized materials. I prepared permanent slides preparation by using evaporation trays to randomly settle the diatoms onto round cover slips (Battarbee, 1973) with Naphrax (n=1.7) as a mounting medium. Approximately 400 valves for each sample were counted at magnifications of 1000 and 1250X. I based my diatom identifications on taxonomic monographs.

NUMERICAL METHODS

I used transfer functions from a weighted averaging technique (with both modern and fossils diatoms) to infer past changes in elevation and salinity (Line and Birks, 1990). Correspondence analysis showed that diatom distributions are primarily controlled by salinity and elevation (Sherrod, in press). This step enables interpretation as to which environmental gradient most greatly affects modern diatom assemblages. Weighted averaging calibration was accomplished using the computer program WACALIB ver 3.1 (Line and Birks, 1990). Diatoms from a set of 40 surface sediment samples collected at several Puget Sound coastal marshes were related to known environmental factors such as salinity and elevation, and transfer functions developed once these relationships were known (for details of analysis and methods, see Chapter 2, and ter Braak, 1995b).

SENSITIVITY OF THE PALEOENVIRONMENTAL RECONSTRUCTIONS

Environmental reconstructions based on correlation of surface sedimentary diatom assemblages with fossil diatom assemblages yield robust results (see Chapter 2; Sherrod, in press; Shennan et al., 1996; Hemphill-Haley, 1995). Bootstrap analyses with modern diatom samples indicate that past elevations can be inferred to within ±0.50 m and salinity within ±5‰ (Sherrod, in press). However, accurate salinity and elevation inferences assume that the modern samples are good analogs for the fossil samples. To test this assumption, I calculated squared-chord distance measures between the modern and fossil samples (Schweitzer, 1994). These calculations suggest that all but 4 stratigraphic samples have a suitable analog in the modern diatom data set from Puget Sound.

A limitation to inferring past salinity and elevation changes at Restoration Point are environmental changes associated with the gravel beach berm that runs along the south side of the site (Bucknam et al., 1992). Prior to uplift 1000 years ago, this berm may have served to protect the site from waves and tides, essentially isolating the back berm marsh from the tides. Sandy bars can be breached during storms, creating stratigraphic changes that mimic an abrupt lowering of the marsh surface during an earthquake (Nelson, 1992). Likewise, during periods of berm accretion, the marsh may be isolated from the tides, creating low salinity conditions behind the berm that may resemble stratigraphically an abrupt raising of the marsh surface during an earthquake. Thus, it is difficult to separate coseismic land level changes from berm breaching or accretion in the stratigraphic record at this site.

RESULTS

STRATIGRAPHY AND CHRONOLOGY

I recognized seven stratigraphic units at the site (Figure 3-4 and Table 3-1). The lower two-thirds of the section consists of organic sediment (mostly fibrous and detrital peat, and organic mud). The upper part of the section consists mainly of inorganic mud, with a dense turf at the top.

The subsurface stratigraphy suggests a small bowl-shaped basin that is deepest near the center and shallows gradually toward the edges. The stratigraphic units appear to thin to the north, towards the back edge of the marsh. A gravel bar borders the marsh to the south, and organic sediments occur below a gravel veneer on the seaward side of the bar. A thin volcanic ash is present in laminated mud (Unit 1) in the deeper portions of the section. This tephra, interpreted as Mazama ash on the basis of mineralogy and glass shard morphology (D. R. Mullineaux, U.S.G.S., personal communication, 1994), accumulated 7500 cal yr B.P. and provides a minimum age for the base of the section (6850±50 ^{14}C yr B.P.; Bacon, 1983).

The most striking stratigraphic change occurs in the upper meter of section (at 87 cm below ground surface), where dark colored peat abruptly changes into a yellowish-orange inorganic mud (Figure 3-4). Rounded charcoal clasts and thin sand layers are present just above the sharp contact between the peat and mud. Clasts of charcoal obtained near the top of the mud (Unit 5) gave an age of 1,560±90 ^{14}C yr B.P.

The study core is a composite of two separate cores (core C and core D) that were collected within 50 cm of each other. The cores were correlated on the basis of the distinctive stratigraphic change from peat (Unit 5) to mud (Unit 6) at 87 cm in depth (Figure 3-5). The upper 30 cm was hand-dug using a shovel, and was correlated to core D using field measurements from the ground surface.

I plotted radiocarbon dates on an age vs. depth plot, and fitted a simple linear regression line to the points (Figure 3-6). The fitted line explains a large amount of variation in the limited data set ($r^2 = 0.989$). The line does not intersect the origin of the plot presumably because the rate of sediment accumulation since uplift was very slow. This is also evident from the dates themselves; a calendrical age of 1290 – 1690 cal yr B.P. (1,560±90 ^{14}C yr B.P.) was obtained on a sample of well-rounded charcoal at a depth of approximately 30 cm. The regression line is used to estimate ages of events and stratigraphic changes observed at the site.

BIOSTRATIGRAPHY

I divided the macrofossil and diatom assemblages into five biozones, labeled BZ1 through BZ5 (Figure 3-7 and 3-8, Table 3-2). The zones broadly coincide with major stratigraphic units but in some cases, the zone boundaries do not fall exactly at the lithostratigraphic contact. Each biozone is briefly describe and interpreted below; for all data descriptions see Appendix 1. All indicated depths are taken from the top of the core (ground surface).

BIOZONE BZ1 (4.04 -3.10 m)

Zone BZ1 occurs wholly within lithostratigraphic Unit 1, at the base of the section. It is dominated by a large amount of *Juncus* cf. *bufonius* seeds (about 1400 seeds in a single 3 cc sample). Smaller amounts of *Scirpus* cf. *maritimus* seeds and *Carex* sp. seeds were also present. *Typha latifolia* seeds are common throughout the zone (at concentrations of about 5-35 seeds per sample). The zone contains abundant *Aulacoseira islandica* (up to 68% of the count tally), common *Stauroneis anceps* and *Navicula radiosa*, and rare (< 5%) *Sellaphora pupula*, *Fragilaria construens*, *Pinnularia viridis*, *Eunotia pectinalis*, and *Nitzschia palea*.

The macrofossils and diatoms found in Zone BZ1 show that a small freshwater to slightly brackish water marsh occupied the site when these sediments were deposited.

The presence of large amounts of *Juncus* cf. *bufonius* seeds suggests that the site experienced freshwater to slightly brackish water. *Scirpus* cf. *maritimus* seeds at the base of this zone suggests that the marsh occasionally experienced somewhat salty conditions, possibly due to salt spray from nearby marine environments. Persistent occurrences of *Typha latifolia* seeds indicate that the salinity of the marsh was not greater than about 2 ppt (Ekblaw, D., University of Washington, personal communication, 1994). The diatoms from zone BZ1 are best described as tolerant of freshwater to very low salinity waters. *Aulacoseira islandica* is characteristic of small freshwater lake and pond environments but can tolerate slightly brackish water (Laws, 1983; Pankow, 1976). The remaining dominant taxa in this zone are considered cosmopolitan marsh taxa and can occur in freshwater to slightly brackish water marshes (Atwater and Hemphill-Haley, 1997; Nelson et al., 1996).

BIOZONE BZ2 (3.10 – 2.20 m)

Zone BZ2 begins in the upper part of Unit 1 and extends upward to the top of Unit 2 (Figures 3-8 and 3-9, and Table 3-2). This zone is characterized by the first appearance of Foraminifera in concentrations ranging from 1 to about 30 tests per three cc of sediment. Seeds of salt marsh plants, including *Atriplex patula*, *Potentilla pacifica*, and *Scirpus* cf. *maritimus* appear first in this zone, at concentrations generally less than 12 seeds/3 cc of sediment. Seeds of freshwater to low salinity taxa also appear in this zone, including *Typha latifolia*, *Carex* sp., and *Scirpus acutus*. Needles of *Pseudotsuga menziesii*, leaves of *Thuja plicata*, Ostracod valves, and *Daphnia* sp. ephippia are present throughout the zone. Diatoms from zone BZ1 are characterized by large amounts of *Fragilaria construens* (up to ~55% of the count tally), *Aulacoseira italica* (up to ~30%) and *Sellaphora pupula* (up to ~ 40%). Noteworthy but less common taxa in this zone include *Pinnularia viridis*, *Stauroneis anceps*, *Rhopalodia musculus*, *Luticola mutica*, *Achnanthes delicatula*, *Melosira nummuloides*, *Grammatophora oceanica*, *Caloneis bacillum*, *Eunotia pectinalis*, and *Gomphonema angustatum* (and others, see Figure 3-8).

The macrofossils in Zone BZ2 show that a salt marsh developed at the site between 7500 years ago and 5600 years ago. The presence of *Atriplex patula, Potentilla pacifica, Scirpus cf. maritimus*, and Foraminifera indicate that a high marsh was developed at the site (Nelson et al., 1996). The co-appearance of freshwater (*Typha latifolia*) and arboreal taxa (*Pseudotsuga menziesii*) with high marsh taxa is consistent with a fringing freshwater marsh and neighboring lowland forest trees immediately adjacent to the salt marsh. Similar conditions exist today at many salt marshes in Puget Sound. The diatom assemblages observed in the zone are indicative of brackish water marsh assemblages in coastal Washington (Hemphill-Haley, 1995; Sherrod, in press). Mixtures of obligate salt-tolerant taxa (e.g., *Melosira nummuloides*) and obligate freshwater taxa (e.g., *Aulacoseira italica*,) suggest that conditions in the marsh spatially varied from highly saline areas in the lower or seaward reaches of the marsh to freshwater conditions in the upper or landward reaches of the marsh.

BIOZONE BZ3 (2.20 – 0.84 m)

Zone BZ3 begins at the base of Unit 3 and extends upward to the top of Unit 4. The base of the zone (at approximately 2.20 m) is marked by an increase in *Fragilaria* cf. *schulzii* and *F. virescens*, and by the presence of *Atriplex patula* seeds. The rest of the zone is characterized by seeds of *Carex* sp., *Triglochin maritima, Atriplex patula, Potentilla pacifica*, and small numbers of Foraminifera (*Trochammina* sp.). Ostracodes and *Daphnia* sp. ephippia occur in large numbers in several samples at the top of this zone.

Large amounts of several *Fragilaria* species characterize zone BZ3. *Fragilaria construens* and *Fragilaria* cf. *schulzii* constitute almost all of the diatoms (up to 95%) in several samples from the lower part of this zone. *Nitzschia frustulum* dominates many of the samples in the upper half of zone BZ3, with relative percentages up to ~ 85%. Subdominant diatoms in this zone include *Sellaphora pupula, Fragilaria virescens, Navicula peregrina, Pinnularia viridis, Stauroneis anceps*, and *Odontella aurita*. Several species occur rarely in the zone, including *Pinnularia, Gomphonema angustatum, Eunotia pectinalis*, and *Aulacoseira italica.*

The sporadic occurrence of *Triglochin maritima* and *Atriplex patula* seeds, and the presence of Foraminifera, together show that a brackish marsh occupied the site from about 3000 years ago (estimated age) to about 1700 years ago. The sharp increase in ostracode valves and *Daphnia* ephippia at the top of the zone suggests that conditions at the site changed abruptly at about 1700 years ago, causing an abrupt rise in the number of *Daphnia* ephippia. The top of zone BZ3 coincides with the sharp contact between lithostratigraphic units 4 and 5. An environmental change associated with the change in sedimentation (from unit 4 to unit 5) at the site probably resulted in conditions not favorable to *Daphnia,* resulting in a large increase of ephippia. *Daphnia* sp. is commonly associated with freshwater lakes and ponds with ephippia occurring when conditions not conducive to reproduction occur (e.g., a change in temperature, water chemistry, or desiccation; Pennak, 1953, p. 357.

Biozone BZ3is interpreted as an intertidal marsh deposit based on the presence of *Navicula peregrina, Odontella aurita,* and large amounts of several *Fragilaria* species that commonly occur in brackish coastal environments. The dominant diatoms (mainly *Fragilaria*) in zone BZ3 are cosmopolitan taxa tolerant of a wide variety of environmental conditions. *Fragilaria* cf. *schulzii,* a marine to brackish water diatom commonly found attached to sand grains, dominates the lower part of this zone (Krammer and Lange-Bertalot, 1991). *Fragilaria construens* (var. *venter*) was observed living in tideflat sediments at False Bay in northern Puget Sound (Tynni, 1986). Many of the remaining taxa observed in the zone are also cosmopolitan and occur in coastal marshes.

BIOZONE BZ4 (0.84 – 0.22 m)

Zone BZ4 comprises the macrofossils and diatoms found in lithostratigraphic Unit 5. The top of the zone was placed at 0.22 m on the basis of the lithostratigraphic contact between units 5 and 6. Cuppressaceae leaves (*Thuja plicata*) are the most common macrofossils in this zone (up to 30 leaves per 3 cc sample). Minor amounts of *Pseudotsuga menziesii* needles and ostracodes also appear in this zone (Figure 3-7).

The diatom assemblages from BZ4 contain several salt-tolerant diatoms in successive samples. The base of the zone, at the contact between lithostratigraphic unit 4 and 5, has large amounts of *Fragilaria virescens* (~65% of the count tally). Several salt tolerant and obligate marine diatoms appear in the middle and upper parts of this zone; most notably, *Achnanthes delicatula, Cocconeis scutellum, Grammatophora oceanica, Fragilaria fasiculata, Melosira nummuloides,* and *Odontella aurita.* Other marine diatoms, including *Paralia sulcata, Opephora parva,* and *Trachyneis aspera,* appear in the zone at low percentages.

Several of the diatoms in this zone are characteristic of tideflat and low marsh environments. Modern tideflat samples from Puget Sound (Sherrod, in press) typically contain ~2% of *Trachyneis aspera,* while marsh samples rarely contain this taxon at all. A sample from the upper part of BZ4 contains 3.5% of *Trachyneis aspera,* and also includes several other diatoms commonly found in tideflat sediments (*Achnanthes delicatula, Cocconeis scutellum,* and *Opephora parva*). I interpret the zone as a tideflat deposit on the basis of a diatom assemblage indicative of lower intertidal environments occurring within mineral sediment.

BIOZONE BZ5 (0.22 – 0 m)

Zone BZ5 consists of dark gray to black muddy peat and turf, largely the roots of plants growing at the site today. *Potentilla pacifica* seeds appear at the base of BZ5, while *Eleocharis palustris* seeds emerge at the top. Minor amounts of *Juncus sp.* seeds and *Typha latifolia* seeds also appear in this zone. Diatom assemblages from this zone are characterized by occurrences of *Eunotia camelus, Eunotia pectinalis, Caloneis bacillum, Fragilaria capucina, Gomphonema angustatum, Gomphonema parvulum, Meridion circulare, Navicula radiosa, Fragilaria virescens,* and *Pinnularia subcapitata.* Salt-tolerant diatoms such as *Rhopalodia musculus, Luticola mutica, Paralia sulcata,* and *Achnanthes delicatula* rarely were observed (<1%) in this zone.

The fossils from this zone suggest that the tideflat environment of BZ4 changed to a freshwater marsh sometime after about 1500 years ago. The presence of *Potentilla pacifica* seeds at the base of the zone suggests that somewhat salt-tolerant plants inhabited the site, presumably immediately after uplift of the site 1000 years ago. At the top of the zone, fossils indicative of the vegetation growing at the site today occur; chiefly *Eleocharis palustris, Typha latifolia*, and *Juncus effusus*. The diatom assemblage in zone BZ5 is characteristic of a small freshwater marsh. *Eunotia camelus* and *Eunotia pectinalis* are common attached diatoms in modern freshwater marshes and bogs (Patrick and Reimer, 1966). Vos and de Wolf (1993) described several members of the genera *Eunotia* and *Gomphonema* as epiphytes and halophobous species. I interpret this zone as a freshwater marsh because freshwater (salt-intolerant) epiphytic diatoms dominate the assemblage. Rare occurrences of *Paralia sulcata*, and other salt-tolerant diatoms, possibly represent windblown diatoms, breaking waves occur at the site today less than 200 meters from the coring site in an upwind direction.

DIATOM-BASED ELEVATION AND SALINITY INFERENCES

Stratigraphic changes in the diatom assemblages suggest that changes in salinity and elevation of the site occurred in the past. I used transfer functions from weighted-averaging calibration of diatom assemblages to determine the magnitude of Holocene salinity and elevation changes. Similarity analyses (not shown) indicate that all but four stratigraphic samples had good modern analogues from the training set.

The uplift at Restoration Point about 1100 years ago raised the site several meters above the tides (Bucknam et al., 1992). For this reason, a surface sample from Restoration Point was included in the modern training set to provide a modern analog for the site following uplift. In the reconstructions, I assigned an elevation of 9.26 m (above Mean Lower Low Water, or MLLW) to samples from unit 6 (BZ5), based on the work of Bucknam et al. (1992).

ELEVATION INFERENCES

The site lay in brackish water intertidal environments for most of the mid-late Holocene based on the results of diatom-based inference of past changes in elevation. Inferred elevations show that the marsh surface lay slightly above Mean Higher High Water (MHHW) for the early part of the record (Figure 3-9, 4.04-3.10 m). An increase in inferred elevation of about 1.5 m was observed between about 7200 cal yr B.P. (estimated ages based on fitted line to calibrated radiocarbon dates). Between about 6400 years ago and 1700 cal yr B.P. (estimated ages), the site lay at about MHHW, with only minor excursions occurring over this time period. The general trend from about 6400 to 1700 cal yr B.P. is for the surface of the site to gradually decrease in elevation.

The largest fall in inferred elevation occurs immediately above the contact between lithostratigraphic Units 4 and 5 (peat to mud; sharp contact). Just above the contact between Units 4 and 5, inferred elevation abruptly decreases somewhere between 1.8 to 3.6 m. Immediately above this excursion, inferred elevation returned to values similar to those that occurred before the excursion (Figure 3-9) and remained at those elevations throughout Unit 6.

Abrupt increases in inferred elevations occur at the top of the section. Between Units 6 and 7, inferred elevation increases about 6.0-7.5 m. The uppermost sample in Unit 5, a tideflat deposit, has an inferred elevation between 2.48 – 4.24 m. Samples from Unit 6, deposited in a post 1100-yr uplift freshwater marsh, are assigned an elevation of 9.26 m (R. C. Bucknam, U.S.G.S., personal communication, 1998). Thus, the inferred elevation changes between Units 5 and 6 are about 6-7 m.

SALINITY INFERENCES

The site was within brackish-water salinity ranges for almost all of the record, with freshwater occurring only in the upper part of the section. However, salinity shows much more variability throughout the Holocene than do inferred elevations (Figure 3-9). Inferred salinity varied between 8-28 parts per thousand (‰) from >7600 years ago to about 1500 years ago. An abrupt decrease in salinity, from ~25‰ to 0‰, occurred across the change from lithostratigraphic Unit 6 to 7 (at the top of the section). This change occurred sometime after about 1500 years ago based on the radiocarbon dates from the site. Despite bioturbation in Unit 7, inferred salinity remained at 0 ‰ throughout this unit.

DISCUSSION: HOLOCENE ENVIRONMENTAL CHANGES AND EARTHQUAKES

Environmental reconstructions at Restoration Point bear on several issues pertaining to the history of the Seattle fault (Figure 3-10). Diatom and macrofossils show that the site changed from a tideflat to a freshwater marsh when the site was uplifted about 1100 years ago between 6-7 m, supporting the conclusions of Bucknam et al. (1992). Environmental changes at the site prior to 1100 years ago point to either earlier uplift and subsidence events, or to events associated with accretion or breaching of the sandy berm bordering the site.

Raised shoreline features at Restoration Point indicate about 6.5-7 meters of uplift about 1100 years ago (Bucknam et al., 1992). This uplift produced the change from BZ4 to BZ5: a tideflat abruptly became a freshwater marsh. The best microfossil evidence for this rapid change in environment about 1000 years ago at Restoration Point is the disappearance of tideflat diatoms common in BZ4 and the appearance of freshwater diatoms and plant seeds (*Eleocharis palustris* and others) in BZ5.

EARLIER EARTHQUAKES ON THE SEATTLE FAULT?

An earthquake prior to the event 1100 years ago on the Seattle fault is suggested by biostratigraphic changes in the top of Unit 1. A change in the macrofossils and diatom flora at 3 m in depth suggests that about 1.5 m of uplift occurred at Restoration Point ~7200 cal yr B.P. Uplift of that magnitude is sufficient to change the ecology of coastal marshes (Thilenius, 1995). Alternatively, changes in sandy berm accretion rates at Restoration Point could also change the marsh ecology, resulting in biostratigraphic changes similar to those produced by uplift. At the present time, neither cause can be ruled out.

If biostratigraphic changes at Restoration Point are the result of tectonic uplift, the Seattle fault has a longer Holocene history than previously thought. Thorson (1996) presented the 'transient stress hypothesis', which states that the Puget lobe of the Cordilleran ice sheet modulated the storage, release, and subsequent recovery of tectonic stresses in the Puget lowland. He suggests that glacial loading of Puget Sound in the late Pleistocene resulted in a >15,000 year hiatus of earthquakes on the Seattle fault. His transient stress model predicts that the late Holocene offset (1100 years ago) is a return to the normal background stress conditions of the Seattle fault. Thorson contends that the recurrence interval for earthquakes on the Seattle fault is much shorter than the 15,000-year hiatus and thus is potentially unknowable at the present time. The results of paleoenvironmental analysis at Restoration Point suggest at least one earlier earthquake on the Seattle fault (about 7200 cal yr B.P.) resulted in small, but measurable land level changes.

Magnetic susceptibility measurements from lake cores also suggest recurrent earthquakes on the Seattle fault. Karlin and Abella (1996) hypothesized that a series of turbidites in Lake Washington possibly represent recurrent earthquakes in the Puget Sound region that triggered slumping of sediments within the lake basin. From magnetic susceptibility profiles of nine piston cores taken from several areas of Lake Washington, they show a large susceptibility peak at about 6000 years, and a smaller but important peak at ~6500 years ago. Three events with apparent ages of 7200, 7400, and 7700 years may be associated with deposition of Mazama ash in the lake basin. The susceptibility peak at 6500 years ago is broadly correlative in time with the earlier uplift event hypothesized from the stratigraphic record at Restoration Point (between 7700 and 6200 years ago). This proposed uplift event was large enough to alter the marsh ecology at Restoration Point, and could conceivably have caused enough ground shaking to generate landslides into Lake Washington.

WAS THE MAJOR UPLIFT 1100 YEARS AGO PRECEDED BY SUBSIDENCE?

A second earlier event in the stratigraphic record at Restoration Point occurred shortly after 1700 years ago (Figure 3-9). The most obvious evidence for this event is the change from detrital peat (unit 4) to mottled mud (unit 5) at 0.84 m in depth. Coincident with this change in sedimentation is an abrupt change from a brackish water marsh flora (zone BZ3) to a tideflat flora (zone BZ4). This change in both sediment type and paleoenvironment at the site suggest that the site subsided slightly into a lower part of the tidal range (between 1.8 to 3.6 m of subsidence). Subsidence at this site could result from a thrust earthquake on a splay of the Seattle fault zone south of Restoration Point, or possibly from a Cascadia subduction zone earthquake. A Cascadia subduction zone earthquake between 1500 - 1700 years ago is suggested by a high marsh soil buried by estuarine muds found throughout Willipa Bay (soil S of Atwater and Hemphill-Haley, 1997), broadly correlative in time with hypothesized subsidence at Restoration Point about 1700 year ago.

An alternative explanation for the environmental change 1700 years ago is that waves breached the beach barrier bordering the site to the south. It is common for large beach berms in Puget Sound to develop low salinity brackish marshes behind the berm, even though the elevation of the marsh surface can sometimes be below the height of ordinary high tides. Beach berms at modern intertidal marshes buffer most of the back-berm marsh from highly saline tidal waters, creating very low salinity conditions immediately behind the berm, as observed in marshes at Dumas Bay, Foulweather Bluff, and Winslow today (Bucknam et al., 1994; B.L. Sherrod, unpublished data). Berms can be breached during severe storms, allowing tidal waters to enter the normally buffered marsh. The berm at Foulweather Bluff marsh in Kitsap County, Washington was breached by a storm in the early 1980's, flooding the marsh with salt water (Kunze, 1984). Within a short period of time, the beach berm built back to pre-storm elevations, insulating the back-barrier marsh from normal tides. Occasionally, breached berms will remain open, with tidal water entering the marsh on every cycle. Roadside signs at Lake Hancock, on Whidbey Island, indicate that the berm protecting a forested wetland from tidal water was breached in the early 1930's during a severe storm, and has remained open to tidal water since. The ecology of the Lake Hancock marsh quickly changed from a lowland forest to high salinity low marsh as a result of this storm. Storm events can produce lasting effects on marsh vegetation, and may produce a stratigraphic signature similar to rapid subsidence. Therefore, at sites with a beach berm like Restoration Point, it is difficult to determine whether an increase in salinity at some time in the past is due to a sudden drop in land level or to a sudden breach in the barrier berm. The stratigraphic signature of an event like that described above mimics a subsidence event.

CONCLUSIONS

1. A large earthquake 1000 years ago uplifted a tideflat out of the intertidal zone, resulting in a freshwater marsh developing on the former tideflat surface. Total uplift was between 6- 7 meters.
2. Shortly after 1700 years ago, the marsh records a sudden increase in salinity and a decrease in elevation which could either result from subsidence or a breach in the barrier berm. Environmental changes associated with this event about 1700 years ago indicate that a brackish intertidal marsh abruptly changed to a tideflat.
3. An earlier uplift event is hypothesized about 7200 cal yr B.P. Uplift for this event is estimated at about 1.6 meters.

Table 3-1 - Generalized description of stratigraphy and chronology.

Unit No.	Field Description	Radiocarbon Chronology			
		Reported Age (14C yr B.P.)	Calibrated Ages cal yr B.P.[1]	Location in Unit	Beta No./Material
6	Black mud with occasional orange mottles, abundant living roots in upper 10 cm.	Modern marsh soil			
5	Yellowish-reddish brown (7.5YR4/4) sandy mud to mud; rounded detrital charcoal; occasional gravel clasts in the lower 10 centimeters; upper part (ca. 30 cm) of this unit becomes black in color; abundant orange mottles in upper part.	1,560±90	1690 – 1290 (1440)	Top	36045/charcoal
4	Reddish-brown (5YR2/3) detrital peat, thickest in the center of the marsh; partially preserved rhizomes of *Scirpus acutus*, abundant blonde roots (segdes?) and sedge leaves.	1,770±70	1840 – 1520 (1650)	Top	29143/peat
3	Olive (10YR2/3) massive mud; gelatinous appearance; abundant conifer needles, woody stems, and small seeds; unit is overlain by a thin layer of moss and appears to be inclined slightly to the north.	No dates			
2	Reddish brown (2.5YR3/4) detrital peat, *Scirpus acutus* rhizomes, woody stems with attached bark, conifer needles, occasional thin layers of brown mud. Similar in appearance to the Middle Peat.	5,630±100	6670 – 6200 (6400)	Bottom	N.A.[3]/peat
1	Greenish gray (2.5Y4/1) mud with light brown laminations that are disrupted or contorted in places; entire unit appears to be at a slight angle from horizontal with respect to the rest of the stratigraphic units; top of Unit 1 varies from approximately 1.5 meters to 3.25 meters below ground surface (BGS); gradational contact with overlying unit. White (N8/0) volcanic ash, approximately 2 cm thick; occurs at 3.4 meters BGS near the raised beach berm and 3.75 meters BGS near the center of the basin; interpreted to be Mazama ash	6,845±50[2]	7720 – 7540 (7600)	Middle	

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[1] age in parentheses corresponds to the age with the highest probability from the calibration curve. Ages calibrated with OxCal ver. 3.0 (Ramsey, 1995) using Gröningen data (CAL10.dta). No error multiplier was applied to the radiocarbon ages.

2 Bacon, 1983

3 see Bucknam et al., 1994

Table 3-2. Biozones and paleoenvironmental interpretations.

Biozone	Depth (m)	Dominant Fossils*	Paleoenvironmental Interpretation
BZ5	0.22 – 0 m	*Eleocharis palustris* (12), *Juncus sp.* (71), and *Potentilla pacifica* seeds. Minor occurrences of *Typha latifolia*. Diatoms include *Eunotia camelus*, *Eunotia pectinalis*, *Caloneis bacillum*, *Fragilaria capucina*, *Gomphonema angustatum*, *Gomphonema parvulum*, *Meridion circulare*, *Navicula radiosa*, *Fragilaria virescens*, and *Pinnularia subcapitata*. Rare diatoms (< 1%) include *Rhopalodia musculus*, *Luticola mutica*, *Paralia sulcata*, and *Achnanthes delicatula*.	Freshwater marsh
BZ4	0.84 – 0.22 m	*Thuja plicata* (up to 32) were the only identifiable plant macrofossil recovered. Dominant diatoms include *Fragilaria virescens* (~65%), *Achnanthes delicatula*, *Cocconeis scutellum*, *Grammatophora oceanica*, *Fragilaria fasiculata*, *Melosira nummuloides*, and *Odontella aurita*. Rare occurrences of *Paralia sulcata*, *Opephora parva*, and *Trachyneis aspera*	tideflat
BZ3	2.20 – 0.84 m	Foraminifera (28), *Typha latifolia* seeds (24), *Scirpus acutus* type seeds (8), *Potentilla pacifica* seeds (<7), and *Carex sp.* seeds (12) dominate the macrofossils of this zone.), Ostracodes (169), *Daphnia sp.* ephippia (46), Minor amounts of ostracodes (<3), Umbelliferae (<4), *Rumex sp.* (1), *Triglochin maritima* seed (1), and Cupressaceae leaves (<5) were observed. Dominant diatoms *Fragilaria construens* and *Fragilaria cf. schultzi* (up to 95%), *Nitzschia frustulum* (up to ~85%). Subdominant and rare diatoms are *Sellaphora pupula*, *Fragilaria virescens*, *Navicula peregrina*, *Pinnularia viridis*, *Stauroneis anceps*, *Odontella aurita*, *Pinnularia, sp.*, *Gomphonema angustatum*, *Eunotia pectinalis*, and *Aulacoseira italica*.	brackish water marsh
BZ2	3.10 – 2.20 m	*Pseudotsuga menzeisii* needles (300), ostracodes (133), *Daphnia sp.* ephippia (<10), *Sphagnum* sporangia/ microphylls (13/48), *Atriplex patula* (13), and *Scirpus cf. maritimus* are the dominant macrofossils. Minor amounts of *Gaultheria shalon* seeds, *Scirpus maritimus* seeds, *Potentilla pacifica* seeds, *Daphnia sp.* ephippia, and Foraminifera (all <10). Dominant diatoms include *Fragilaria construens* (up to ~ 55%), *Aulacoseira italica* (up to ~ 30%) and *Sellaphora pupula* (up to ~ 40%). Rare taxa include *Pinnularia viridis*, *Stauroneis anceps*, *Rhopalodia musculus*, *Luticola mutica*, *Achnanthes delicatula*, *Melosira nummuloides*, *Grammatophora oceanica*, *Caloneis bacillum*, *Eunotia pectinalis*, and *Gomphonema angustatum*.	low salinity brackish to freshwater marsh
BZ1	4.04 -3.10 m	*Juncus cf bufonius*. seeds (1452) and *Typha latifolia* seeds (32), with small amounts of *Carex sp.* (6), *Scirpus cf. maritimus* seeds (8), and *Sphagnum sp.* sporangia (10). Diatoms include *Aulacoseira islandica* (68%), *Stauroneis anceps*, *Navicula radiosa*. Rare occurrences (< 5%) of *Sellaphora pupula*, *Fragilaria construens*, *Pinnularia viridis*, *Eunotia pectinalis*, and *Nitzschia palea*	low salinity brackish marsh-freshwater marsh

*macrofossils = maximum observed amount expressed as number per 3 cc of sediment in parentheses.
diatoms = maximum relative percent in parentheses

Table 3-3. Weighted averaging results for diatom inferred elevation and salinity. Inference error (RMSE) is based on a bootstrap analysis of modern training set.

Depth (meters)	WA Elevation WA	+RMSE[1] Elevation	-RMSE[2] Elevation	WA Salinity[3]	+RMSE[1] Salinity	-RMSE[2] Salinity
0	9.37	10.25	8.48	-4	3	-10
0.05	5.36	6.24	4.47	-3	3	-10
0.10	10.86	11.74	9.97	-4	3	-10
0.15	6.22	7.10	5.33	-3	3	-10
0.20	4.85	5.73	3.96	-3	3	-9
0.45	3.36	4.24	2.47	24	31	18
0.55	3.37	4.25	2.48	27	33	20
0.65	3.45	4.32	2.56	23	29	16
0.75	2.4	1.12	-0.65	24	30	17
0.82	3.87	4.74	2.98	10	17	4
0.85	3.86	4.74	2.97	28	35	22
0.95	3.45	4.33	2.56	21	27	14
1.25	8.37	9.25	7.48	-4	3	-10
1.55	3.52	4.40	2.63	20	26	13
1.65	3.67	4.55	2.78	16	23	10
1.92	3.93	4.81	3.04	28	34	21
1.95	3.87	4.75	2.99	28	35	22
2.02	3.48	4.36	2.59	24	30	18
2.10	3.98	4.86	3.10	16	23	10
2.19	4.00	4.88	3.11	21	28	15
2.22	4.51	5.39	3.62	11	18	5
2.44	4.02	4.89	3.13	20	26	14
2.73	3.93	4.80	3.04	26	32	20
2.84	4.45	5.33	3.56	19	25	13
3.00	5.47	6.34	4.58	9	15	2
3.09	3.85	4.73	2.96	25	32	19
3.39	4.00	4.88	3.11	11	17	5
4.00	4.13	5.00	3.24	18	24	11

[1] - upper error value - root mean square error of inference from bootstrap analysis of modern training set added to WA value.

[2] - lower error value - root mean square error of inference from bootstrap analysis of modern training set subtracted from WA value.

[3] – inferred salinity values less than 0 are possible in the weighted averaging technique due to inherent error. For graphical purposes in Figure 3-9, inferred salinity results less than 0 are *a priori* set to 0.

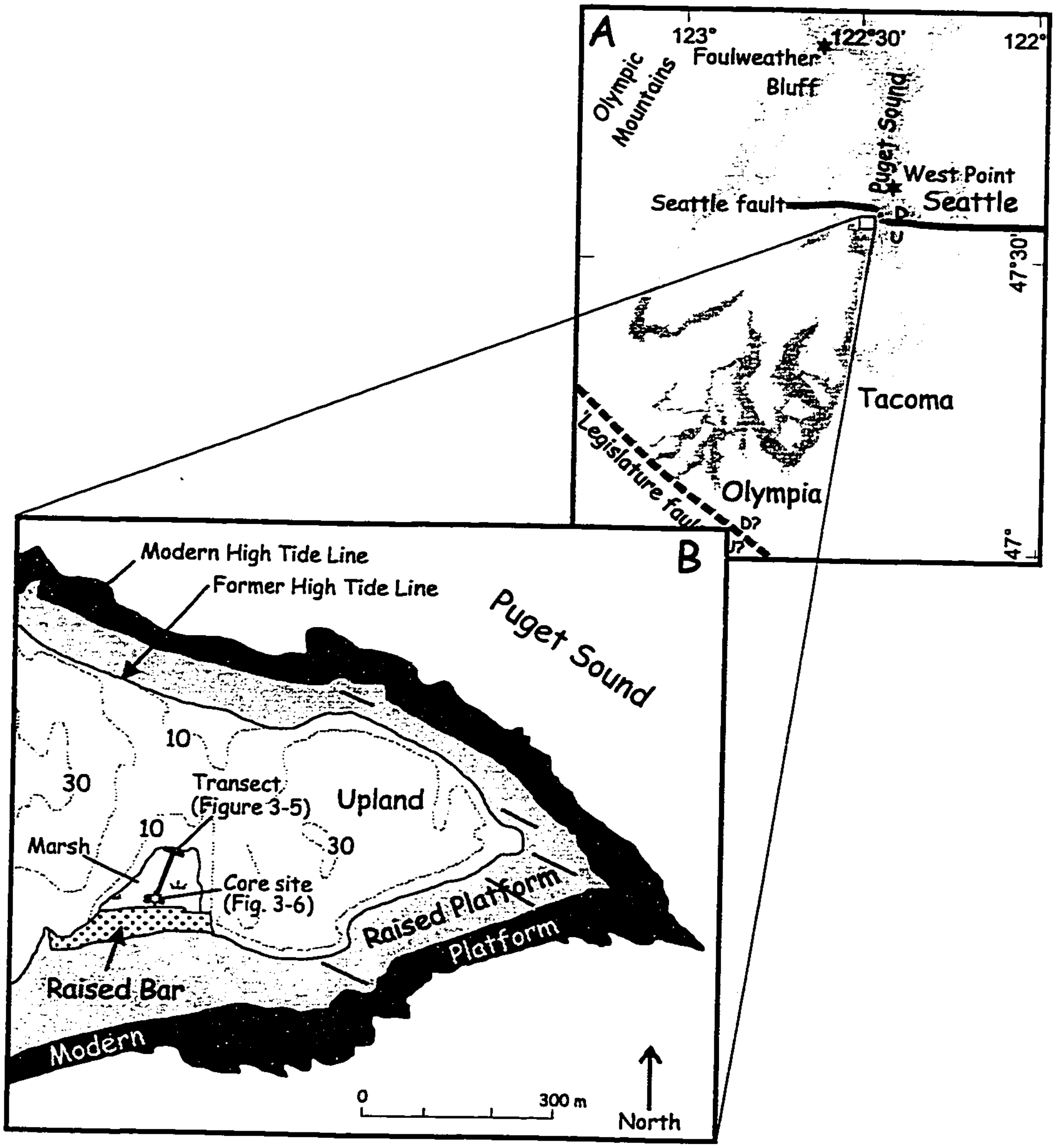


Figure 3-1. A. Location map of Puget Sound, Washington. B. Site map of Restoration Point showing uplifted platform, modern platform, uplifted gravel bar (beach berm), and modern freshwater marsh from which the study cores were collected. Uplift at this site 1100 years ago was about 7 meters, as measured by the difference in the elevations of the former shoreline angle and the present shoreline angle (Bucknam et al., 1992).

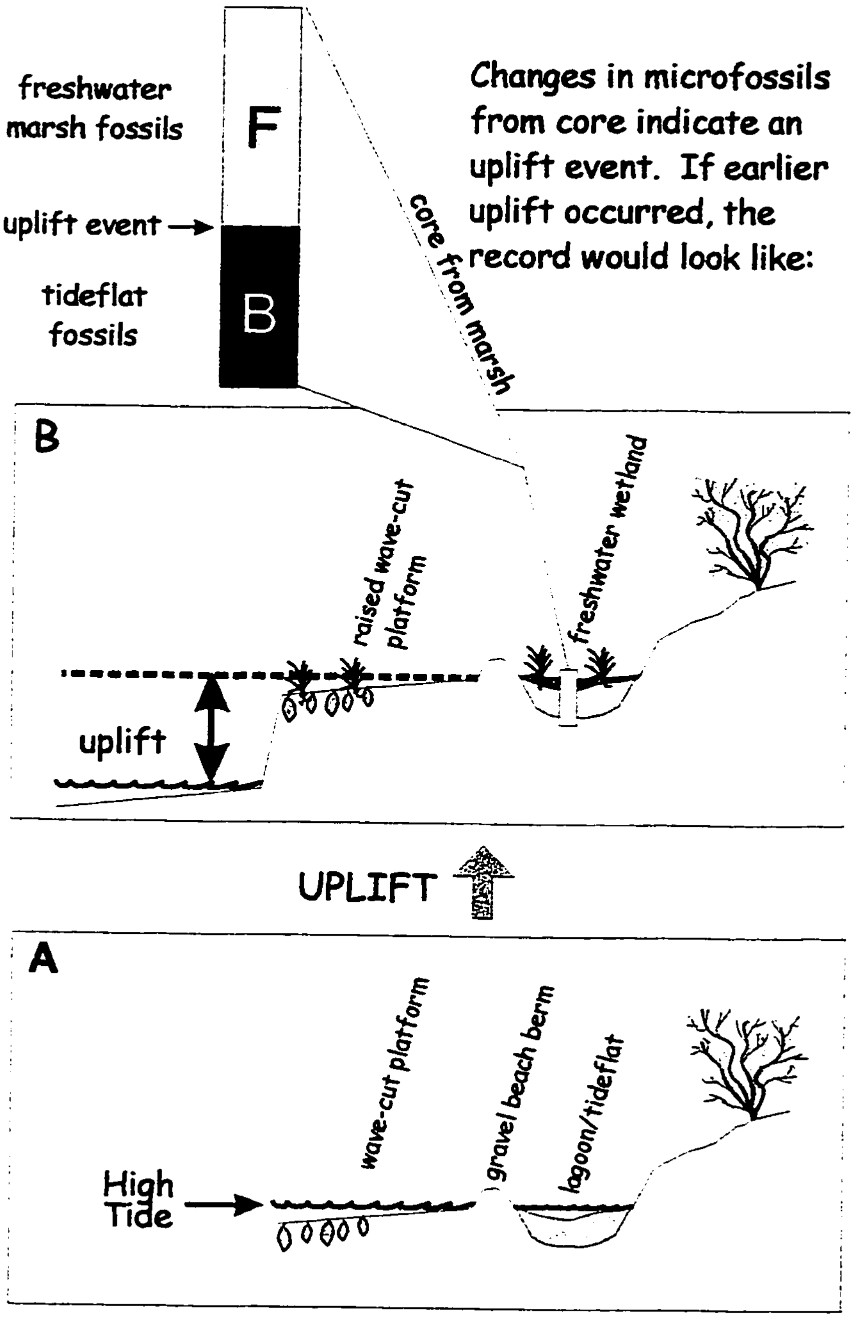


Figure 3-2. Geologic evidence used to infer uplift at a coastal site. *A*. Pre-uplift conditions at site, with wave-cut platform and molluscan infauna in intertidal zone. A small intertidal lagoon/mudflat exists behind gravel beach berm. B. Post-uplift site conditions, showing raised wave-cut platform, raised gravel beach berm, and small freshwater wetland occupying area of former lagoon. Core sediments from the wetland contain fossils indicative of a brackish water tideflats overlain by a freshwater wetland. Repitition of the brackish-freshwater couplet in earlier parts of the core suggests earlier episodes of uplift. Dates from core sediments help constrain timing of uplift events.

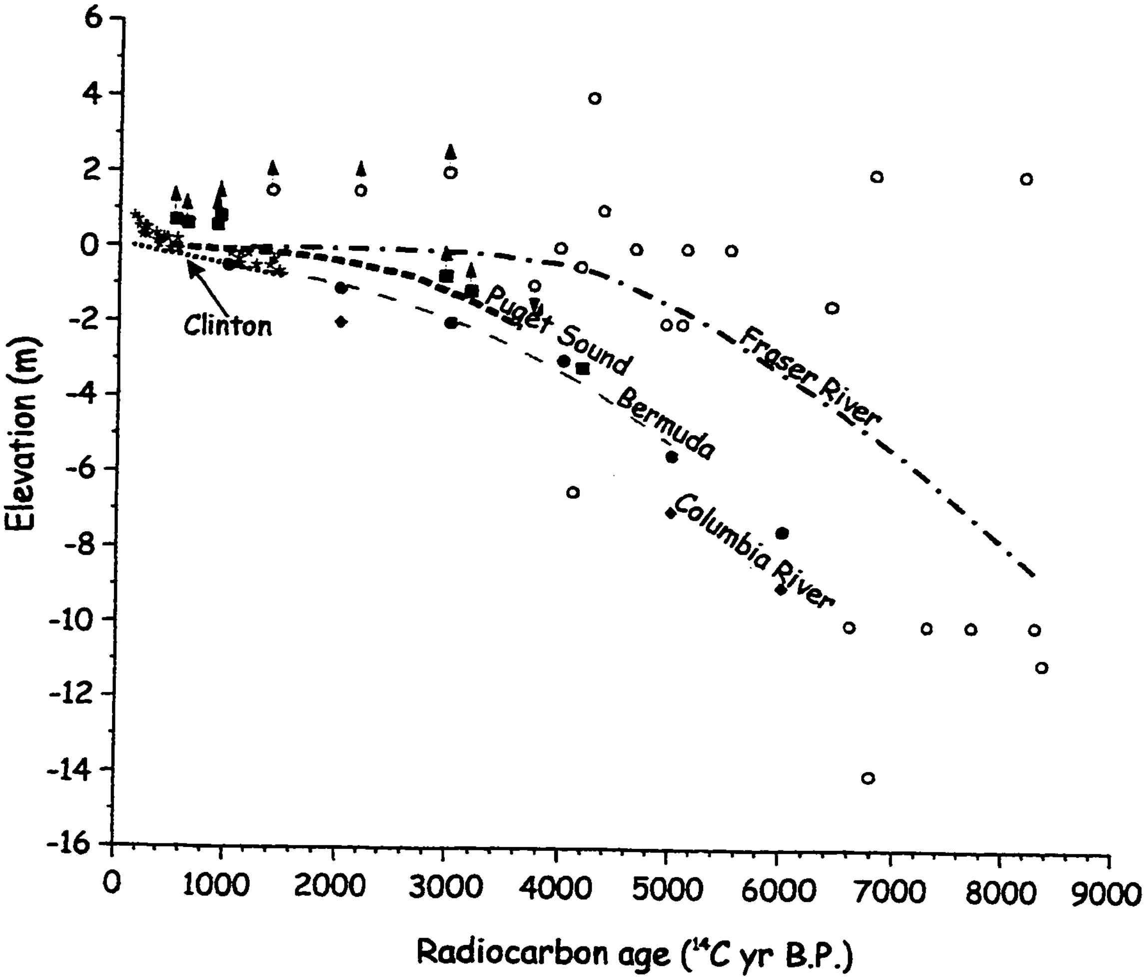


Figure 3-3. Plot of late Holocene relative sea level rise from Bermuda, Columbia River (Tushingham, A.M. and Peltier, W.R., 1992, 1993), British Columbia (Clague et al, 1982), and northern Puget Sound (Beale, 1990), and Clinton, Connecticut (van de Plassche et al., 1998). Sea level curves for each area are shown by the heavy lines, and indicate a relative sea level rise of 2.5 - 4 meters between 5000 and 3000 years and less than 1 meter in the past 1000 years.

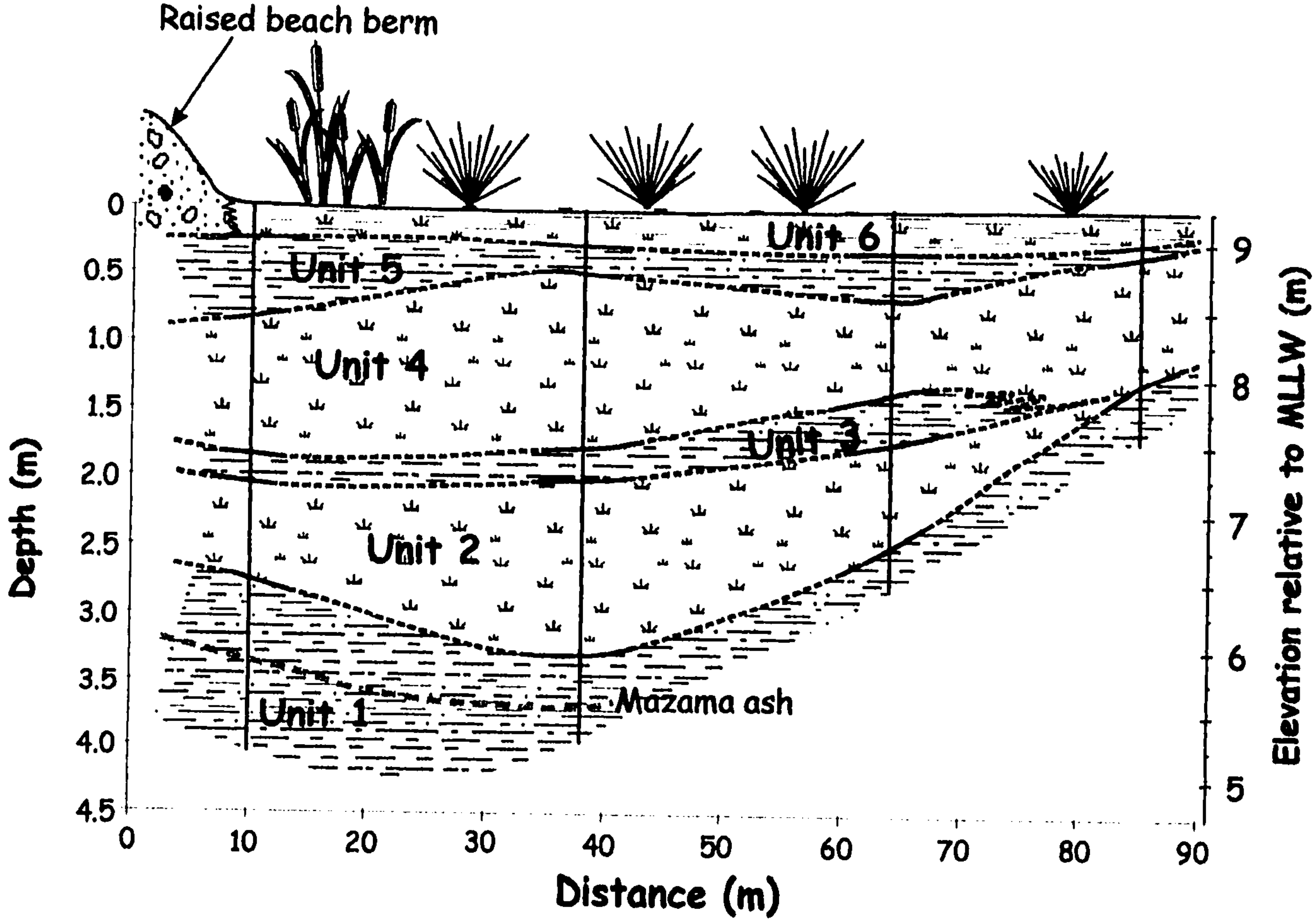


Figure 3-4. Cross-section of subsurface sediments in north-south transect through marsh. The stratigraphic units are: Unit 1 - greenish-gray, laminated mud containing a thin volcanic ash; Unit 2 - reddish-brown, detrital peat with *Scirpus acutus* rhizomes and conifer needles; Unit 3 - olive-colored, massive mud containing conifer needles, stems, and small seeds; Unit 4 - reddish-brown, detrital peat with *Scirpus acutus* rhizomes; Unit 5 - yellowish-brown, sandy mud to mud with rounded detrital charcoal fragments; Unit 6 - black mud with turf at top (roots of living plants). Additional stratigraphic data from Bucknam and others, 1994)

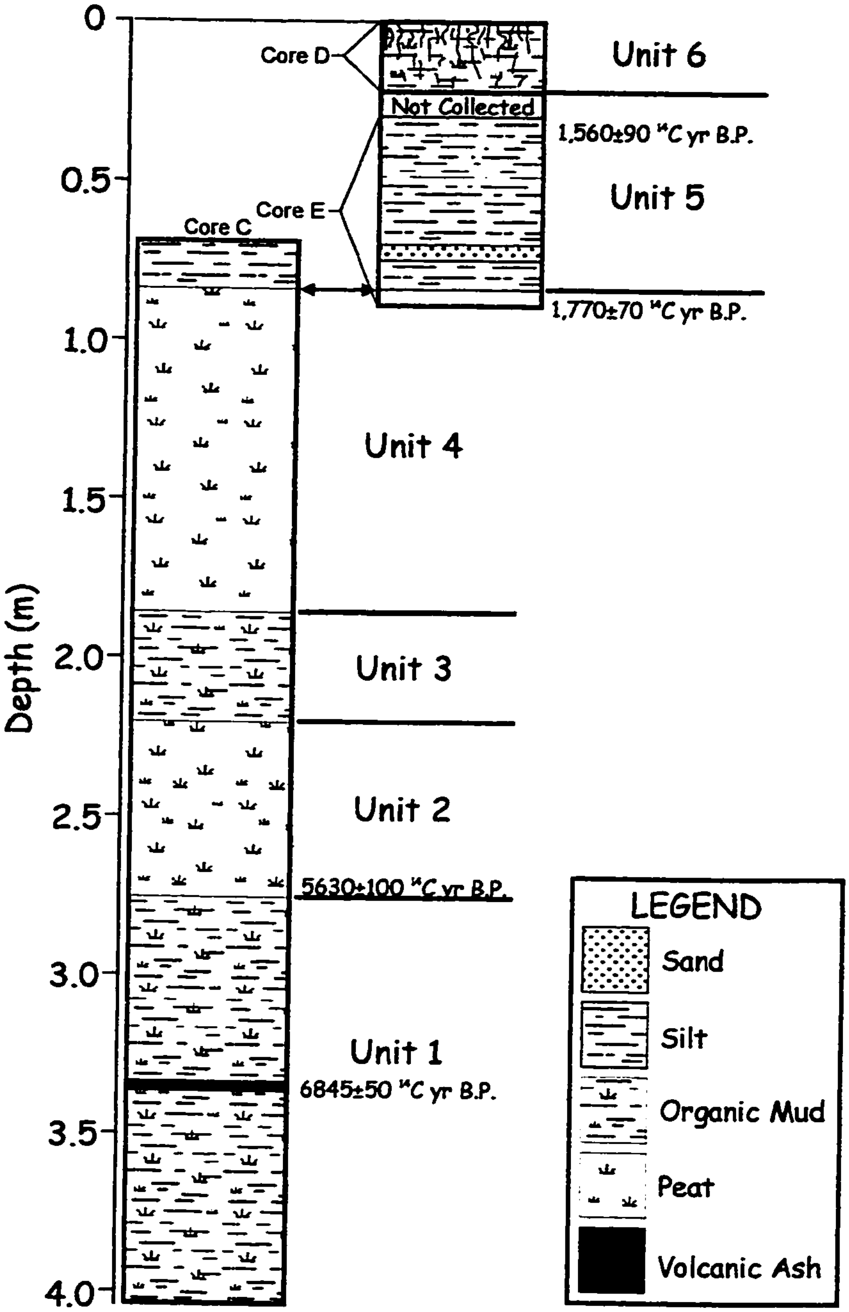


Figure 3-5. Lithology and radiocarbon ages of the study cores. Correlation of three cores is based on common stratigraphic contacts and direct measurements from the ground surface. See Table 1 for additional lithologic descriptions and information on radiocarbon analyses.

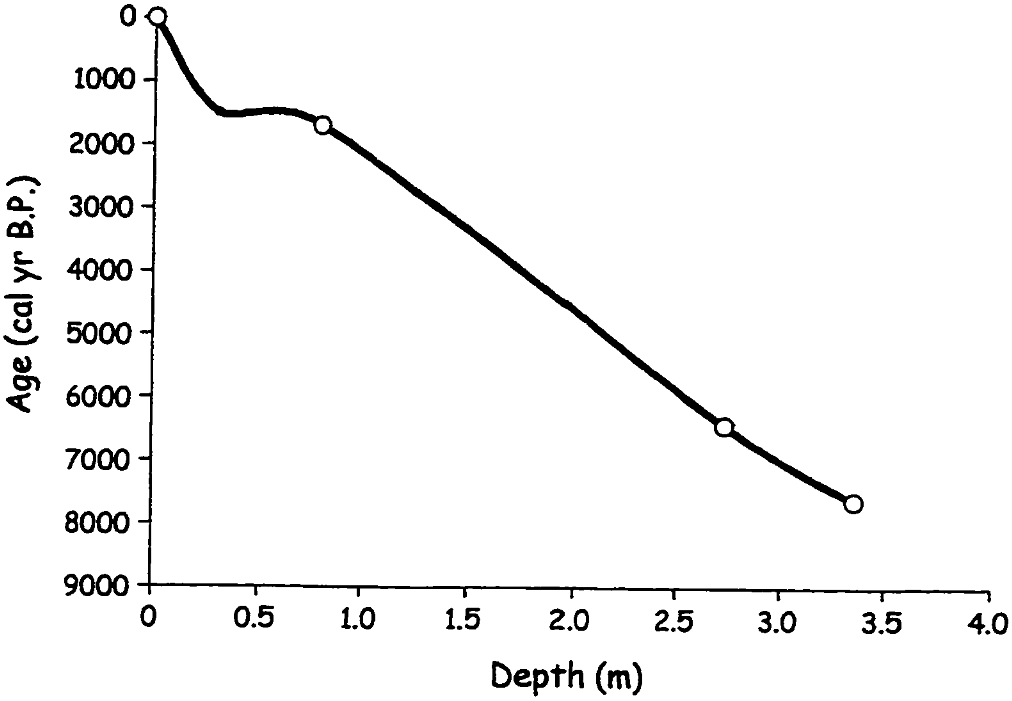


Figure 3-6. Radiocarbon age vs. depth of radiocarbon and tephra samples from Restoration Point cores.

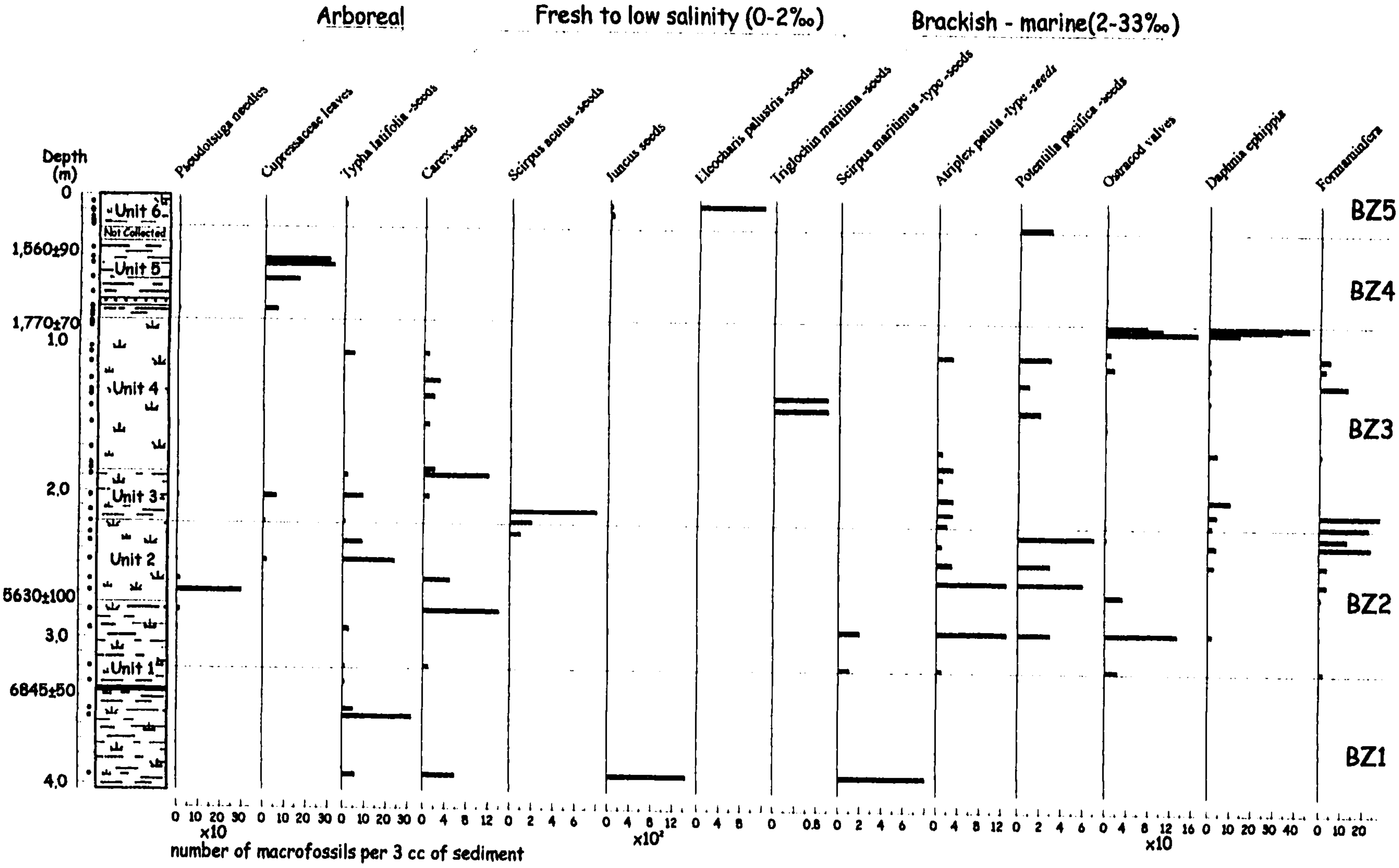


Figure 3-7. Macrofossil diagram from Restoration Point core. Macrofossil concentrations are expressed as number per 3 cubic centimeters of wet sediment. Biozones are indicated on the right side of figure. Core lithology and radiocarbon dates are shown on the left. Small dots beside depth scale indicate depths of macrofossil samples.

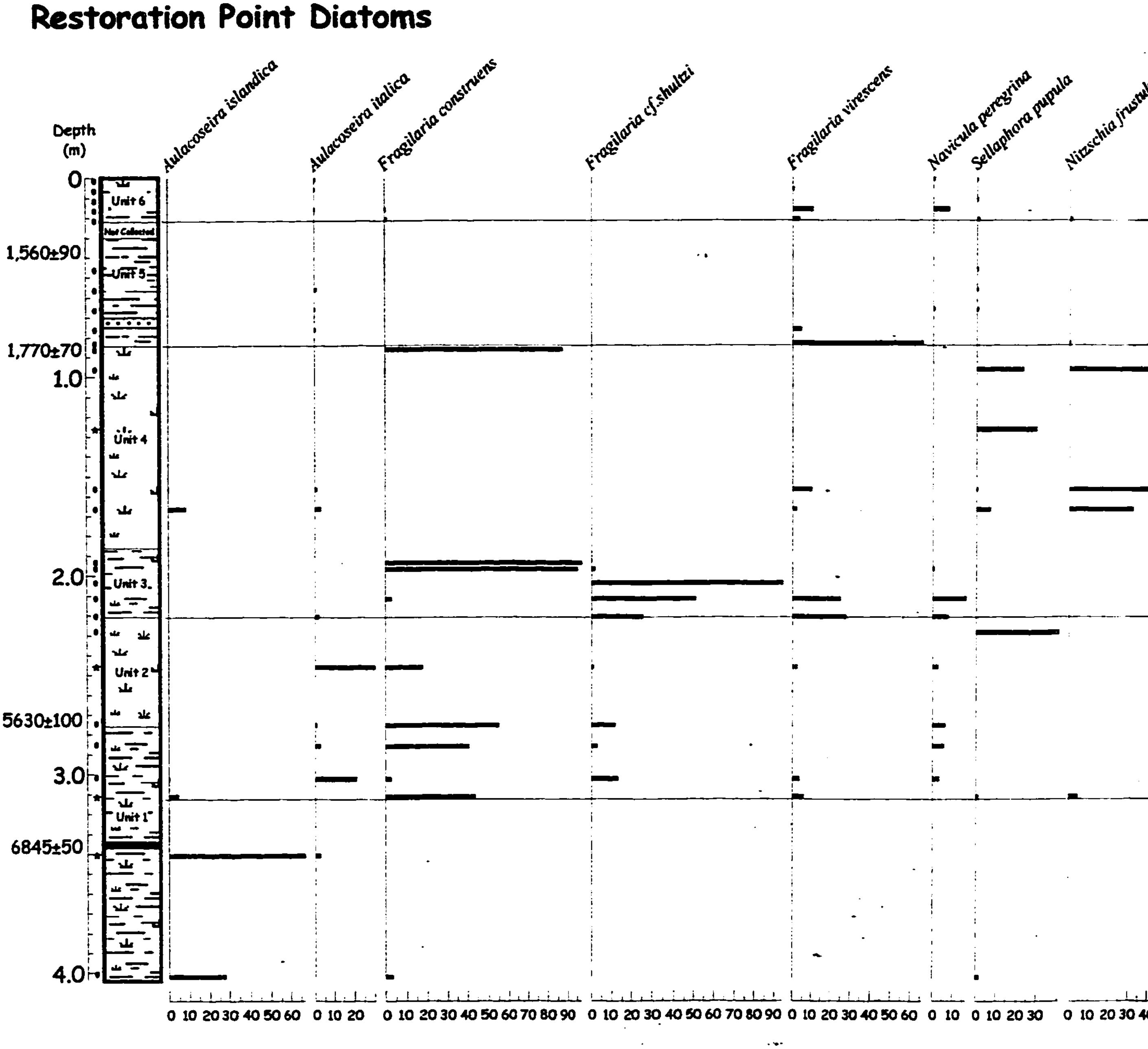
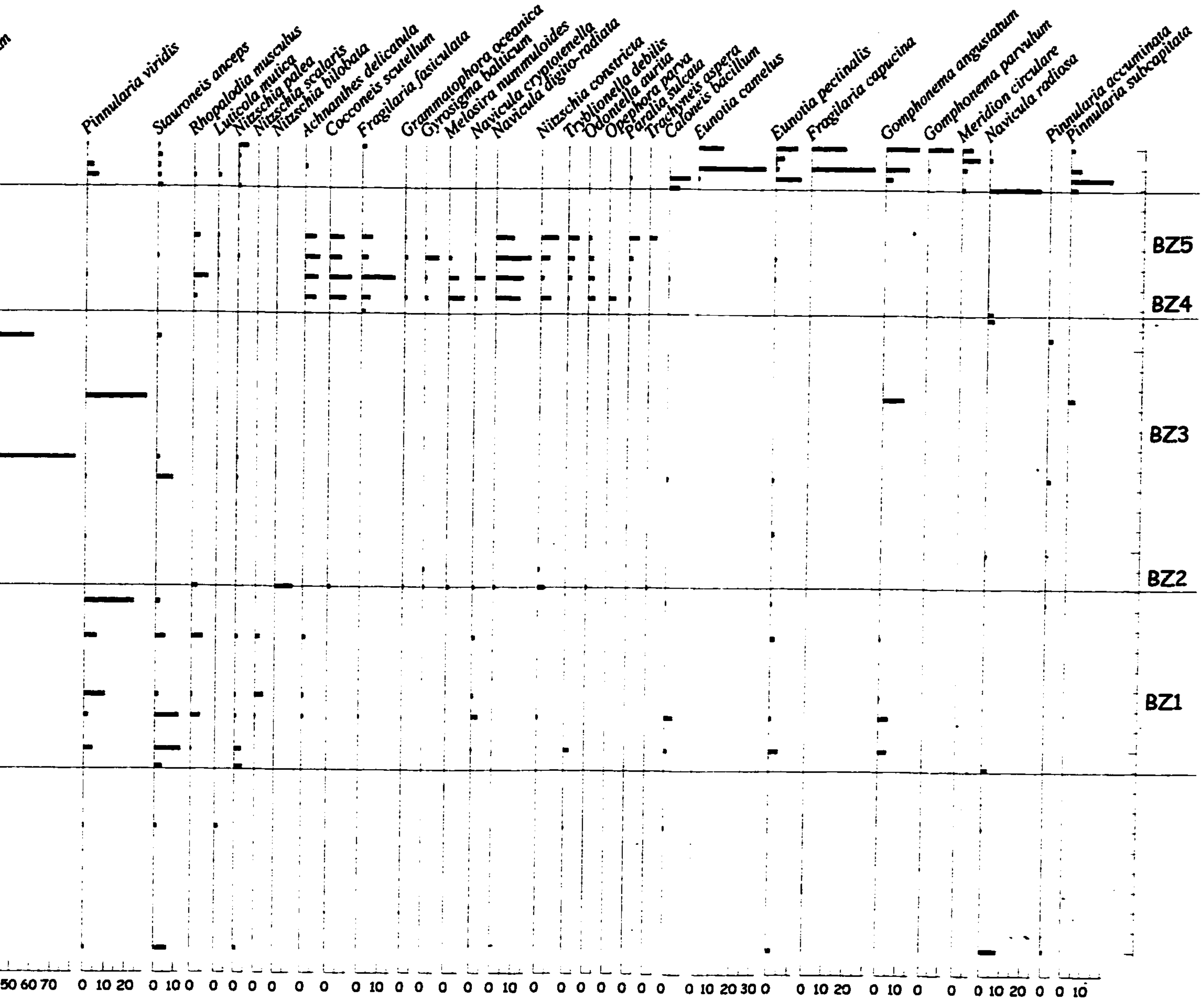


Figure 3-8. Diatom diagram of selected taxa from Restoration Point. Diatom abundances are expressed in terms of relative percent. Biozones are indicated on the right side of figure. Core lithology and radiocarbon dates are shown on the left. Small dots beside depth scale indicate depths of diatom samples and stars indicate samples with no close modern analog.


Pinnularia viridis
Stauroneis anceps
Rhopalodia musculus
Luticola mutica
Nitzschia palea
Nitzschia scalaris
Nitzschia bilobata
Achnanthes delicatula
Cocconeis scutellum
Fragilaria fasiculata
Grammatophora oceanica
Gyrosigma balticum
Melosira nummuloides
Navicula cryptotenella
Navicula digito-radiata
Nitzschia constricta
Tryblionella debilis
Odontella aurita
Opephora parva
Paralia sulcata
Trachyneis aspera
Caloneis bacillum
Eunotia camelus
Eunotia pectinalis
Fragilaria capucina
Gomphonema angustatum
Gomphonema parvulum
Meridion circulare
Navicula radiosa
Pinnularia accuminata
Pinnularia subcapitata
BZ5
BZ4
BZ3
BZ2
BZ1
50 60 70
0 10 20
0 10
0
0
0
0
0
0
0
0 10
0
0
0
0
0 10
0
0
0
0
0
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0
0 10 20 30
0
0 10 20
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0
0 10 20
0
0 10

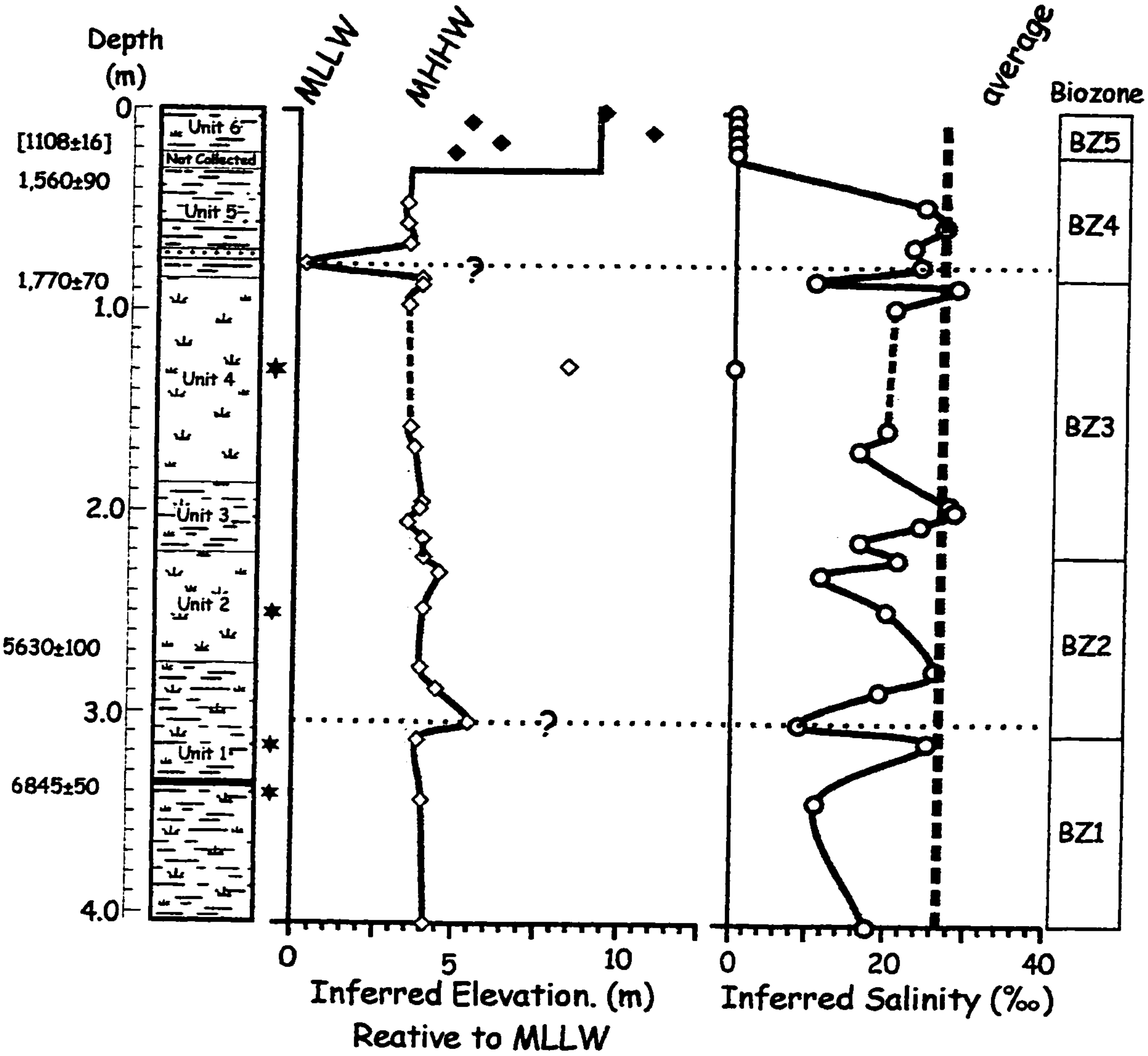
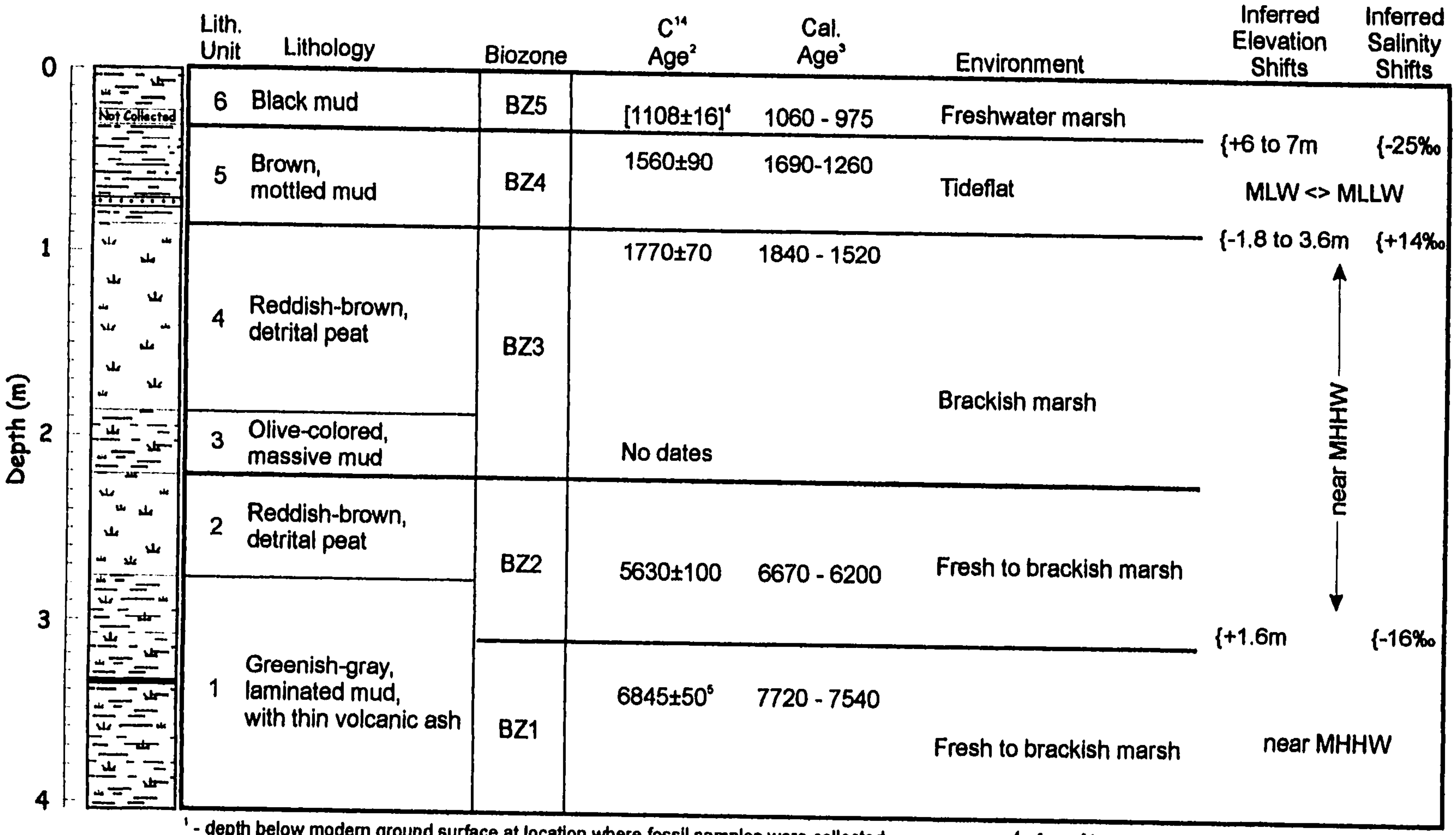


Figure 3-9. Weighted averaging calibration of stratigraphic samples from Restoration Point. The uplift about 1000 years ago at the site is shown by the abrupt increase in inferred elevation at the top of the core. A possible uplift event of about 1.6 meters occurred at about 3.0 meters in depth. The thick line connects the WA results for both elevation and salinity, and the gray bands around the connecting lines equal the error (RMSE) associated with the analysis. Black stars to the right to the core diagram indicate depths of samples with no close modern analog. Small dots beside depth scale indicate depths of diatom samples. Samples from Unit 6 (at the top of the sequence) were assigned an elevation of 9.26 m, assuming that Unit 6 was deposited in a freshwater marsh following uplift 1100 years ago at about the same elevation as the modern marsh as Restoration Point.



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

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

[3] - calibrated radiocarbon age in calendar years AD/BC.

[4] - from Atwater and Moore, 1992.

[5] - from Bacon, 1983.

Figure 3-10. Summary of stratigraphic changes and environmental reconstructions at Restoration Point.

CHAPTER 4: SUBMERGENCE OF LOWLAND SOILS BY EARTHQUAKE-INDUCED SUBSIDENCE ABOUT 1000 YEARS AGO IN SOUTHERN PUGET SOUND, WASHINGTON

ABSTRACT

Submerged forest and high marsh soils indicate abrupt environmental changes at four localities in southern Puget Sound. At Little Skookum Inlet and Red Salmon Creek, *in-situ* Douglas-fir stumps are buried by salt marsh peat. The stumps are surrounded by a peaty forest soil at Little Skookum Inlet. At localities along McAllister Creek and Nisqually River, high marsh soils are overlain by laminated tideflat mud. Samples of wood and *Triglochin maritima* rhizomes indicate that submergence occurred between 1140±80 and 1010±50 ^{14}C yr B.P. (750 – 1260 cal yr B.P.).

Liquefaction coincided with submergence of the high marsh soil at McAllister Creek. An upward-directed sand dike was injected through subsurface deposits and breached the former marsh surface. A small volcano formed by vented sand directly above where the sand dike broke the soil surface.

Fossil seeds and diatoms indicate abrupt environmental changes at the time of submergence. At Little Skookum Inlet and Red Salmon Creek, salt marsh peat a few centimeters above a buried forest horizon contain diatoms indicative of low marsh and tideflat environments (e.g., *Trachyneis aspera, Caloneis westii*, and *Melosira nummuloides*). At McAllister Creek and Nisqually River, laminated muds directly over high marsh peat were dominated by low marsh and tideflat diatoms (e.g., *Melosira nummuloides*).

Estimates of submergence were based on weighted-averaging of fossil diatom assemblages and paleoecological inferences. The largest amount of submergence was at Little Skookum Inlet and Red Salmon Creek (≥3.4 m and ≥1.2 m, respectively). Submergence was less at McAllister Creek (~0.5 m) and Nisqually River (~1 m).

Submergence of lowland soils in southern Puget Sound is best explained by coseismic subsidence of the land. Alternative explanations include submergence without tectonic subsidence, submergence without land subsidence, and breaching of a sandy, bay-mouth bar. It is likely that some, but not all, of the submergence is the result of ground shaking and post-earthquake settlement. It is difficult to explain the observed submergence solely by rising sea level when other studies have shown that only minor fluctuations of sea level on the order of 10-30 cm occurred in the last 1400 years. Intertidal marsh deposits at Nisqually Delta predate submergence in southern Puget Sound and required an open connection for tidal waters, negating the presence of a bay-mouth barrier. 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 about 1000 years ago in southern Puget Sound as the most likely cause of subsidence.

INTRODUCTION

Buried soils below modern tidal marshes indicate episodes of rapid relative sea level rise. Along the Cascadia subduction zone, contacts between buried soils and overlying intertidal mud resulted from rapid submergence during large subduction zone earthquakes (Clague, 1997). Submergence of lowland environments in Chile (1960) and Alaska (1964) changed forests and marshes into barren mudflats (Ovenshine et al., 1976; Atwater, 1996). Similarly, large thrust earthquakes on the Seattle fault ~1100 years ago caused abrupt subsidence that changed marshes into barren tideflats (Atwater and Moore, 1992).

Although the late Holocene in Puget Sound, Washington is marked by uplift and subsidence of tidelands, by landslides, and by large surface displacements along faults, yet little is known about the geologic structures responsible for these events (Gower et al., 1985; Bucknam et al., 1992; Walsh et al., 1997). The Seattle fault, originally defined on the basis of a large gravity and magnetic anomaly, is now recognized as a blind thrust fault beneath central Puget Sound (Johnson et al., 1994). Movement on the Seattle fault about 1100 years ago resulted in abrupt uplift of wave-cut platforms to the south of the fault, and subsidence of intertidal marshes to the north (Bucknam et al., 1992; Atwater and Moore, 1992). To the south near Olympia, Washington, aeromagnetic surveys define a linear structure about 80 km long (Figure 4-1) that trends northwest-southeast (Gower et al., 1985; R. Blakely, U.S.G.S., personal communication, 1998). This geophysical lineament, herein called the Legislature fault, may be an additional source of Holocene earthquakes and associated land deformation.

Paleoenvironmental reconstructions based on fossil plants, diatoms, and Foraminifera 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 (Mathewes and Clague, 1994; Shennan et al, 1996; Nelson et al, 1996; Hemphill-Haley, 1995). Recently, 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 becoming known (Hemphill-Haley, 1995; Nelson et al., 1996; Bucknam et al., 1997; Sherrod, in press).

In this paper, I use microfossils to reconstruct the relative sea level (RSL) history and submergence of soils at four sites in southern Puget Sound - one locality at Little Skookum Inlet and three at Nisqually delta (Figure 4-1). I ask whether Holocene submergence at Puget Sound resulted in deposition and gradual accretion of tidal-marsh deposits (Mudge, 1862; Redfield, 1972), and whether sudden tectonic subsidence resulted in abrupt tidal inundation of former forests and marshes.(Figure 4-2).

SETTING

Subparallel arms of southern Puget Sound occupy troughs eroded by subglacial streams (Booth, 1994). One of these arms, Little Skookum Inlet, has a salt marsh at its southwest end (Figure 4-1). Over 6 m of organic and inorganic sediments lies below the modern salt marsh. Dotting the modern tideflat surface are barnacle encrusted remains of Douglas-fir stumps in growth position. These stumps suggest a relative sea level rise of late Holocene age.

The Nisqually delta is one of the most pristine deltas in Puget Sound, despite conversion of much of its tidal marshes into pasture (Downing, 1983). Much of the delta is covered by brackish intertidal marsh vegetation, except for areas behind an earthen dike at the Nisqually National Wildlife Refuge, where freshwater shrubs and herbs dominate. McAllister Creek, Red Salmon Creek, and the Nisqually River itself dissect the delta and expose Holocene sediments in the channel banks. These exposures, dominated by laminated estuarine mud and massive sand, provide my basis for reconstructing past RSL changes.

METHODS

FIELD AND LABORATORY METHODS

The stratigraphy of each locality was mapped at selected outcrops exposed along tidal channels, and along lines of correlated gouge cores 2.5-cm in diameter. Field locations were surveyed using an automatic level and related to tidal heights. Field crews used a self-compensating level to survey the elevation of each sampling station relative to the tides by measuring the elevation of either a high or low tide at a local datum. The local tidal level was calculated using the following steps. 1) Determine the height of the observed tide at Seattle, Washington. 2) Set the measured tidal height at the site to the corresponding observed height at Seattle. 3) Offset the measured tidal height by the difference in MHHW between Seattle and MHHW at the nearest NOAA tidal benchmark to the site. The last step assumes that the tidal height at the site is the same as the tidal height of the nearest NOAA Tidal Benchmark (generally <5 km away). The local datum is then assigned an elevation relative to MHHW, from which the elevations of all sampling stations were surveyed.

Radiocarbon samples included plant material from outcrops and wood from *in-situ* tree stumps (Figure 4-3). I selected wood samples from roots with adhering bark. *Triglochin maritima* leaf bases and rhizomes from outcrops were also selected for dating. Conventional ages were calibrated with OxCal ver 3.0 (Ramsey, 1995) using Gröningen data (CAL10.dta). No error multiplier (k) was applied to the radiocarbon ages. Calendrical ages are reported as cal yr B.P., with "B.P." denoting "before A.D. 1950" (Stuiver and Pearson, 1986). Calibrated ages are quoted using error ranges of two standard deviations (95.4% confidence intervals).

For paleoenvironmental analyses, I removed box cores in 1-m long segments from outcrops (modified plastic downspout). After collection, I wrapped each box core segment in aluminum foil for storage in a cold room. Sediments for macrofossil analysis were taken by volumetrically sampling 20 cc of sediment, measured by displacement of distilled water in a graduated cylinder (Eckblaw, D., University of Washington, personal communication, 1994). After sampling, I soaked and disaggregated each sample in a buffered 0.5% solution of Calgon for 24-48 hours (U.S. Geological Survey calcareous microfossil procedure), followed by wet sieving with 1mm and 0.3 mm sieves. The resulting coarse and fine sieve fractions were examined under dissecting microscopes and all identifiable seeds, fruits, leaves, ostracodes, and other macrofossils were picked and enumerated. Reference works (Martin and Barkely, 1961; Berggren, 1981, 1969; Spjut, 1994; Young and Young, 1992), a seed collection housed in the Department of Botany at the University of Washington, , and plant specimens at the University of Washington Herbarium were used to identify macrofossils. After identification, I catalogued and stored all macrofossils in a dilute alcohol/glycerol solution to prevent desiccation and decomposition.

Diatom sample preparation followed the procedures of Patrick and Reimer (1966). Digestion of organic matter employed 30% hydrogen peroxide, which was followed by several distilled water rinses. I used evaporation trays to randomly settle the diatoms onto cover slips (Laws, 1983; Battarbee, 1973) with Naphrax (n=1.7) employed as a mounting medium. Approximately 400 valves for each sample were counted at magnifications of 787X and 1250X. Diatom identifications were based on taxonomic monographs.

NUMERICAL METHODS

I used a set of transfer functions to calibrate modern diatom assemblages with salinity and elevation measurements. Diatoms from a set of 40 surface sediment samples collected at several Puget Sound coastal marshes were related to salinity and elevation (for details of analysis and methods, see Sherrod, in press, and ter Braak, 1995b). I used CANOCO ver 3.1 for correspondence analysis (ter Braak, 1987-1992), which shows that salinity and elevation primarily control diatom distributions in intertidal environments (Sherrod, in press). This step enables interpretation as to which environmental gradient most greatly affects modern diatom assemblages. I used the computer program

WACALIB ver. 3.0 (Line and Birks, 1990) to determine transfer functions. This technique first calculates the salinity and elevation optimum for each taxon, and then uses those optima to produce transfer functions (Line and Birks, 1990). The transfer functions are used for inferring environmental variables based on the species composition in fossil samples. Coefficients of determination (r^2) between calculated (inferred) environmental variables and observed values of environmental variables allow evaluation of the transfer function's predictive power.

SENSITIVITY OF THE PALEOENVIRONMENTAL RECONSTRUCTIONS

Bootstrapping analysis allows an analysis of error associated with the calibration procedure, and provides a means for evaluating how well the salinity and elevation transfer functions perform (Birks et al., 1990). A regression analysis of diatom-inferred salinity against observed values yields a r^2 of 0.82. Residual salinity is within ±5‰ of the observed values in all but four cases. Slight systematic trends in residual salinity may indicate that the current transfer function does not explain a certain amount of variance. A regression analysis of diatom-inferred elevation and observed values yields a r^2 of 0.78. Residual elevation is within 30 cm of the observed value in all but 10 cases, and within 50 cm in all but 3 cases. For both environmental variables, the predictive ability of the transfer function is greater for samples in the middle of the environmental gradients than for samples falling at the extremes of the gradients.

Accurate reconstruction of salinity and elevation assumes that the modern diatom samples are good analogs for the fossil samples. To test this assumption, I calculated squared-chord distance measures between the modern and fossil samples (Schweitzer, 1994). Analog comparisons are first made using modern samples with known environmental measurements to determine the cut-off point for close modern analogs. All fossil samples with a squared chord distance measure greater than this value (0.72 for proportional data) do not have a close modern analog in the training set (labeled with a '+' on Figs. 4-16 and 4-17. These calculations indicate that all but two stratigraphic samples have a suitable analog in the modern diatom data set from Puget Sound.

RESULTS

STRATIGRAPHY AND CHRONOLOGY

Field teams surveyed stratigraphy at each of four localities (Figures 4-4, 4-5, 4-6, and 4-7, Table 4-1). I supplemented each survey with detailed stratigraphic sections for fossil preparations. At each locality, particular attention was paid to identify buried soils, plant roots and rhizomes, and liquefaction features.

Summary of stratigraphy and chronology

Stratigraphic features at each suggest sudden subsidence during an earthquake. Intertidal outcrops of each locality contain buried lowland soils having sharp contacts with overlying estuarine deposits, and two localities have tree stumps in growth position immediately below intertidal deposits. A sand dike connected to vented sand on the surface of a buried marsh soil at McAllister Creek indicate ground shaking at the time of submergence.

Stratigraphic changes at each site indicate abrupt late Holocene environmental changes that occurred in southern Puget Sound. At the Little Skookum Inlet and Red Salmon Creek localities, Douglas-fir forests sank into the intertidal zone such that salt marsh peat began to accumulate over the former forest horizons. At McAllister Creek and Nisqually River, peat indicative of high marsh environments (with rhizomes of *Distichlis spicata* and *Juncus* cf. *balticus*) sank to lower elevations so that laminated mud indicative lower intertidal environments begin to accumulate over the marsh peat.

Radiocarbon dates suggest that the buried soils at each site are correlative in time. Samples of tree stumps and marsh plants yielded ages for submergence of lowland soils and southern Puget Sound ranging from 1010±50 to 1140±80 ^{14}C years B.P. (Table 4-1 and Figure 4-3). Combining probability distributions during calibration of radiocarbon ages gave an age range for submergence of 920-1060 cal years A.D. (2 sigma, 95. 4% confidence interval, k=1).

Little Skookum Inlet Locality

The Little Skookum Inlet locality consists of a large tidal marsh and tideflat, bordered by lowland forest west of the marsh (Figure 4-1). Stratigraphic data from Little Skookum Inlet consists of gouge core descriptions and mapping of outcrops along a 305-m long transect across salt marsh and tideflat (Figure 4-1). The non-vegetated tideflat surface is at an elevation of ~3.1 m above Mean Lower Low Water (MLLW), well above the height of most low tides. Marsh vegetation is dominated by *Distichlis spicata* and *Salicornia virginica* in low marsh areas, and *Deschampsia caespitosa* in high marsh areas. *Picea sitcheneis* (Sitka spruce) grows at the edge of the forest bordering the marsh. *Tsuga heterophylla* (western hemlock) and Thuja plicata (western redcedar) grow at elevations about 0.5 to 1 m higher than Sitka spruce. The lowest modern *Pseudotsuga menzeisii* (Douglas-fir) was found at an elevation of 7.2 m above MLLW, slightly over 2 m above the lowest living Sitka spruce..

Most deposits beneath the marsh and tideflat consist of peat or mud (Figure 4-4). The lowest deposit in the sequence is bluish-gray mud (LSI-1), massive to laminated in places, and barren of visible fossils in the field. The top of this unit has about 3 meters of relief over a distance of 150 meters, mainly from a 2-3 m deep depression in the western half of the transect (Figure 4-4).

A tan gyttja, (LSI-2), laminated in places, overlies the gray mud within the depression in unit LSI-1 (Figure 4-4). A 2-3 cm gradational contact separates the gyttja from the underlying gray mud. The gyttja disappears in the eastern half of the transect where the underlying LSI-1 is highest.

A reddish-brown detrital peat (LSI-3) overlies above the tan gyttja (LSI-2), and appears to cap the fill of the small depression in the gray mud (LSI-1). A gradational contact 1-2 cm wide occurs between LSI-3 and the underlying tan gyttja. Wood and plant seeds are abundant in places within LSI-3. Two bulk peat samples from the upper 1 cm of LSI-3 provide radiocarbon ages of 7030±70 ^{14}C years B.P. (Beta-97230) and

7520±80 ^{14}C years B.P. (Beta-97231). Calibrated ages for these dates are 7660-7930 cal years B.P. and 8130-8420 cal years B.P. respectively (Table 4-1, Figure 4-3).

A gray, fine to medium sand (LSI-4) with a gravelly base overlies the detrital peat (LSI-3) in most places. This sand is absent in the marsh subsurface beside the forest adjacent to the marsh and again disappears over the small rise in LSI-1 between 200 and 275 m on the transect (Figure 4-4). In places, fining-upward sand layers are interbedded with layers of greenish-gray mud.

A massive, gray mud with orange mottles (LSI-5)is currently being exhumed on the modern tideflat, exposing dozens of sub-fossil Douglas-fir stumps rooted in the top of unit LSI-5. The contact between LSI-4 and LSI-5 is gradational over about 1 cm. The mud (LSI-5) is silty in places and is very stiff, making it hard to penetrate with a gouge corer. The 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. In several places, roots of alder and willow in growth position can be seen protruding from the surface of LSI-5.

Two samples of tree rings (from roots of separate Douglas-fir stumps) gave radiocarbon ages for burial of the forest soil at Little Skookum Inlet. The outermost 15-25 rings of a large Douglas-fir root (with attached bark), and yielded a radiocarbon age of 1090±60 ^{14}C years B.P. (Beta-95912). The calibrated age for this sample is 910-1170 cal years B.P. (Figure 4-3). A second sample, from the inner 16 rings of a Douglas-fir root (with a total of 192 rings), yielded a radiocarbon age of 1220±50 ^{14}C years B.P. (Beta-102335); the calibrated age for death of this tree is 990-1220 cal years B.P. (offset by184 years, the number of tree-ring years from the midpoint of sample and bark). The overlap in these two calibrated age ranges implies no statistical difference in the time of tree death.

Salt marsh peat (LSI-7) overlies the buried forest soil (LSI-6). A sharp contact (~1 mm wide) separates the peat from the underlying soil. The peat is slightly muddy in most places, and contains abundant *Distichlis spicata* rhizomes. *Triglochin maritima* rhizomes and leaf bases are rare in this unit. A radiocarbon age on *Triglochin maritima* rhizomes collected from 65 to 70 cm below the marsh surface (or 45-50 cm above the top of LSI-6) from an outcrop of peat at horizontal coordinate 305 m, yielded an age of 140±60 ^{14}C years B.P. (Beta-117091), and a calibrated age of 290-0 cal years B.P. (Figure 4-3).

McAllister Creek Locality

The McAllister Creek locality consists of a ~150 meter long outcrop of late Holocene sediments exposed in a cut-bank of a large tidal creek meander at the Nisqually delta (Figure 4-1 and 4-5). The upper part of the outcrop is exposed at most low tides; the adjacent bed of McAllister Creek is deeply scoured, keeping the lowest strata in the section constantly under water. I identified six lithostratigraphic units from a combination of outcrop mapping and gouge core descriptions.

Most of the outcrop displays basal peat overlain by rhythmically laminated silt and clay. Two beds of fibrous peat (units MC-1 and MC-3), separated by a massive gray mud about 20-25 cm thick (MC-2), outcrop at the base of the section (Figure 4-5). The lower peat bed (MC-1) contains rhizomes of *Distichlis spicata* and *Triglochin maritima*, while the upper peat (MC-3) contains tubers of *Scirpus maritimus* and rhizomes of *Juncus* cf. *balticus*.

Gray-brown mud (MC-4) above the uppermost peat bed (MC-3) consists of rhythmically deposited couplets of laminated silt and clay. The lamination and rhythmic bedding diminish upward. A possible marsh soil, only a few centimeters thick and faint in color, occurs in the middle of this unit (Figure 4-5), and contains *Juncus* cf. *balticus* rhizomes. Vigorous growth of *Triglochin maritima* is evident from well preserved leaf bases just above the sharp contact (~1 mm) between the uppermost peat bed and the overlying gray mud. Rare Juncus rhizomes were observed in the lower part of MC-4. A sample of Triglochin leaf bases from immediately above the contact yielded a radiocarbon age of 1140±80 ^{14}C years B.P. (Beta-102336), and a calibrated each of 920-1260 cal years B.P. (Figure 4-3).

The remainder of the exposed section consists of an oxidized muddy peat (MC-6), locally underlain by brown, fine sand (MC-5) (Figure 4-5). The peat is orange-brown and contains the rhizomes of modern salt marsh plants. The sand is brown, massive, and well sorted. Distinctive grains of reddish scoria are present throughout MC-5. Neither unit displays obvious sedimentary structures.

A thin sand dike and sand volcano, consisting of gray fine sand, crops out in the lower part of the outcrop. During exceptionally low water, the dike cuts across the upper part of MC-1, and all of units MC-2 and MC-3. Vented sand occurs on the upper surface of MC-3, with the thickest accumulation of sand directly above the dike. The vented sand tapers away from the dike, disappearing about 5 meters away.

Nisqually River Locality

The Nisqually River locality consists of a 50-meter long outcrop (Figure 4-6) on the east bank of the Nisqually River, about 1.5 km downstream of Interstate 5 (Figure 4-1). Low-flow river level is at about 0.85 meters above MLLW at low tide. Erosion of the meander bank at this site exposes about 3 meters of deposits above the low-tide river level.

The lower half of the outcrop consists of interbedded peat and mud. The lowest unit (NR-1) contains intercalated brown fibrous peat and gray mud. The peat beds (designated upper peat bed and lower peat bed) lack roots or rhizomes identifiable to species. Brown-gray mud (NR-2) that overlies upper peat in NR-1 consists of laminated silt and clay deposited rhythmically in couplets. A sharp (<1 mm wide) contact) separates NR-1 from NR-2. *Triglochin maritima* rhizomes from 3-5 cm above this contact yielded a radiocarbon age of 1030±70 ^{14}C years B.P. (Beta-110150). The calibrated age range for this sample is 750-1070 cal years B.P. No additional materials considered reliable for radiocarbon dating were observed.

The top of NR-2 is marked by an unconformity. A channel about 10 meters wide was eroded into the underlying mud (Figure 4-6). Massive, brown, fine sand (NR-3) overlies the unconformity and fills the former channel.

The remainder of the section consists of three units, comprising the upper half of the sequence. Gray mud (NR-4), similar to NR-2 but massive, overlies the fine sand (NR-3). A second massive, fine sand (NR-5) overlies NR-4 but lacks clear channel-cut features. Reddish-brown, sandy mud caps the stratigraphic sequence, and contains roots and rhizomes of modern salt marsh plants.

Red Salmon Creek Locality

The Red Salmon Creek locality comprises a 35 m outcrop along a stream bank in the eastern part of the Nisqually delta (Figure 4-1 and 4-7). The floor of the tidal creek is ~1.5 m above MLLW, with about 0.5 m of flowing water in the channel at low tide. The outcrop is capped by a salt marsh dominated by *Distichlis spicata, Jaumea carnosa*, and *Salicornia virginica*. A small tidal channel enters Red Salmon Creek at the western end of the outcrop. Douglas-fir stumps in growth position protrude from this and other nearby outcrops along Red Salmon Creek.

The lowest unit (RSC-1) is a gray, massive, fine to medium sand. An interbed of gray silt was observed at several places in the upper 0.5 m of RSC-1. *In-situ* Douglas-fir stumps protrude from the top of RSC-1, with roots penetrating downward into the sand (Figure 4-7). A sample of wood from the outer rings of a stump at horizontal coordinate 4 m (Figure 4-7) yielded a radiocarbon age of 1010±50 ^{14}C years B.P. (Beta-110746) and a calibrated age range of 780-1060 cal years B.P. A thin blackened zone containing charcoal occurs in the upper few centimeters of RSC-1.

Brown fibrous peat (RSC-2), containing rhizomes of *Distichlis spicata* and *Juncus* cf. *balticus* directly overlies RSC-1. Decomposed rhizomes of *Triglochin maritima* were observed in several places. The peat is locally discontinuous, disappearing altogether at a nearby outcrop.

Gray-brown mud (RSC-3) unconformably overlies RSC-2 (Figure 4-7). Couplets of laminated silt and clay, conspicuous at the base of RSC-3, persist upwards to about 60 cm below modern ground surface in most places. *Triglochin maritima* leaf bases are common in the upper part of RSC-3. A sample of Triglochin leaf bases at horizontal coordinate 10 m (80 cm above the contact between RSC-2 and are RSC-3) gave an age of 130±60 ^{14}C years B.P. (Beta-109230) and a calibrated age of 280-0 cal years B.P.

A reddish-brown muddy peat (RSC-4) caps the sequence at Red Salmon Creek, with orange mottles throughout. (Figure 4-7). The contact between RSC-3 and RSC-4 is gradational, usually about 3-5 cm wide. Modern roots and rhizomes of *Distichlis spicata* and *Triglochin maritima* occur all through RSC-4.

MACROFOSSIL AND DIATOM BIOZONES

Plant macrofossils, Foraminifera, and fossil diatoms are broadly divided into two biozones at each locality (BZ-1 and BZ-2). The boundaries between fossil zones coincide with major stratigraphic changes, primarily the burial of lowland soils by intertidal mud or peat that occurred about 1000 years ago. Summary descriptions and interpretations of each zone by site are presented in Table 4-2.

Little Skookum Inlet Locality

BZ-1 (2.0-0.34 m). Follicles of *Spirea douglasii*, a freshwater wetland shrub species, and an arboreal taxon, *Betula papyifera* (Figure 4-8), dominate macrofossils recovered from the lower part of BZ-1. The lower half of this zone contains seeds of *Carex* cf. *leporina* and *Carex* cf. *aquatilus*.. Seeds of *Juncus* sp. are abundant in the middle and upper half of BZ-1. Arboreal and lowland-forest shrub taxa, namely *Thuja plicata, Picea sitchensis, Taxus brevifolia, Rubus spectabalis*, and *Sambucus racemosa*, dominate the macrofossils found in the buried forest soil (LSI-6). Stumps of *Pseudotsuga menziesii* (Douglas-fir) in growth position are common and *Alnus rubra* (Red alder) stumps are rare at the top of this unit. A peaty soil (LSI-6) surrounds many of the stumps exposed in outcrop. Scattered Foraminifera were found in two samples just below the top of the zone.

Diatom samples from BZ-1 are dominated by several cosmopolitan and freshwater taxa. These include *Fragilaria construens*, *F. virescens*, *F. brevistriata*, *Eunotia pectinalis*, *Aulacoseira italica*, *A. islandica*, *Epithemia turgida*, and *Gomphonema angustatum* var. *sarcophagus* (Figure 4-9). Diatom assemblages are too poorly preserved for study (only small fragments observed) between 1.82 a.m. and 1.18 m below modern ground surface, and within the upper two thirds of the buried soil (LSI-6) between 0.45 and 0.34 m.

BZ-2 (0.34-0 m). Seeds of *Juncus* sp. and salt marsh plants, including *Atriplex patula*, *Carex lyngbyei*, and *Deschampsia caespitosa*, dominate the macrofossils of BZ-2 (Figure 4-8). Needles and leaves of several arboreal taxa appear at the top of this zone. Large numbers of Foraminfera are common throughout this zone.

The diatoms from BZ-2 are dominated by brackish water taxa, including *Diploneis interrupta*, *Nitzschia bilobata*, *Melosira nummuloides*, *Tryblionella debilis*, *Paralia sulcata*, and *Caloneis westii* (Figure 4-9). Cosmopolitan taxa are common, including *Cosmioneis pusilla* and *Fragilaria construens*. Freshwater taxa also appear in small numbers, the most common being *Aulacoseira italica* (Figure 4-9).

McAllister Creek Locality

BZ-1 (2.95-2.32 m). Charcoal fragments dominate the samples from BZ-1 sieved for macrofossils (Figure 4-10). 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 brackish water taxa common to salt marshes and tideflats (Figure 4-11). The diatom assemblages are dominated *by Achnanthes brevipes*, *Diploneis interrupta*, *Luticola mutica*, *Melosira nummuloides*, and *Navicula cincta*. *Melosira nummuloides*, a common diatom at the base of the zone, drops in relative abundance at the top of the zone. *Diploneis interrupta*, subdominant at the base of BZ-1, becomes more abundant than other diatoms at the top of the zone.

BZ-2 (2.32-0 m). The base of BZ-2 is marked by seeds of *Spergularia canadensis*, *Scirpus cf. maritimus*, and *Distichlis spicata*, and by the disappearance of charcoal fragments (Figure 4-10). The change in macrofossils coincides with the sharp contact between the buried marsh soil (MC-3) and the overlying laminated mud (MC-4). The middle and upper portions of BZ-2 are dominated by seeds of common salt marsh plants, including *Carex lyngbyei, Salicornia virginica*, and *Spergularia canadensis* (Figure 4-10). *Epilobium* sp. seeds, moss bracts, and *Betula papyifera* seeds are rare in 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 there are large changes in the relative percentages of most taxa across the boundary between the two biozones (Figure 4-11). 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 (Atwater and Hemphill-Haley, 1997; Sherrod, in press) decreases in relative abundance across the zonal boundary. *Tabellaria fenestrata*, a common benthic freshwater taxon, dominates the assemblages from samples taken higher in BZ-2. The top of BZ-2 is also dominated by brackish water marsh and tideflat taxa, including *Achnanthes brevipes, Caloneis westii, Gyrosigma eximium, Melosira nummuloides*, and *Mastogloia elliptica* (Figure 4-11).

Nisqually River Locality

BZ-1 (3.4-3.12 m). Macrofossils from this zone are dominated by seeds of *Juncus* cf. *balticus* and *Potentilla pacifica* (Figure 4-12). *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. These include *Eunotia pectinalis, Pinnularia lagerstedtii, Cosmioneis pusilla*, and *Luticola mutica* (Figure 4-13). Brackish water species, including *Diploneis interrupta* and *Achnanthes brevipes*, are also common in BZ-1.

BZ-2 (3.12 - 0 m). The base of BZ-2 is marked by the absence 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. Foraminifera tests were observed in samples from the lower half of BZ-2.

The diatom flora from BZ-2 contains many brackish water marsh and tideflat taxa, particularly in the lower half of the zone. *Melosira nummuloides* appears for the first time at the base of the zone, immediately above the contact between buried soil and overlying estuarine mud (~2 cm; Figure 4-13). Other dominant diatoms in the lower half of BZ-2 include *Navicula slesvicensis, Deticula subtilis, Achnanthes delicatula, Trachyneis aspera, Amphora ventricosa*, and other brackish to marine diatom taxa (Figure 4-13). Samples from between ~1.65 to ~0.45 m contain diatom assemblages too poorly preserved for study (mainly small fragments) or do not contain any diatom remains. However, the upper four samples from BZ-2 contain several valves of freshwater diatoms, including *Pinnularia borealis, Hantzschia amphioxis, Aulacoseira italica, Cocconeis placentula, Stauroneis anceps*, and *Pinnularia subcapitata* (Figure 4-13).

Red Salmon Creek Locality

BZ-1 (2.0-1.68 m). The macrofossils from BZ-1 at Red Salmon Creek include *Picea sitchensis* and *Pseudotsuga menziesii* needles, and *Sambucus racemosa* seeds. 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.

BZ-2 (1.680 m-0 m). Macrofossils are scarce low in BZ-2 and become more common in the upper half of the zone. Seeds of *Atriplex patula* and *Scirpus acutus*, and *Pseudotsuga menziesii* needles are rare in the lower part of BZ-1 (Figure 4-14). The upper part of BZ-2 is dominated by seeds of salt marsh plants, *including Triglochin maritima, Spergularia canadensis, Grindelia integrifolia, Salicornia virginica,* and *Atriplex patula.* Charcoal fragments are scattered throughout BZ-2 but never abound in any sample. Foraminifera are common in every sample from BZ-2.

The diatom flora of BZ-2 is dominated by brackish water taxa. Low marsh and tideflat diatoms occur at the base of this zone, about ~2 cm above the top of RSC-1 (Figure 4-15). The dominant diatoms *include Caloneis westii, Diploneis interrupta, Trachyneis aspera, and Paralia sulcata* (Figure 4-15). 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.

SUMMARY OF PALEOECOLOGICAL INTERPRETATIONS

The change from BZ-1 to BZ-2 occurred when soils formed in either lowland forests or upper intertidal marshes abruptly sank into the lower intertidal zone about 1000 years ago (Table 2). I interpret the submergence as abrupt because lower intertidal organisms (e.g., *Melosira nummuloides* and *Trachyneis aspera*) appear directly over either forest soils or upper high marsh soils. The change in fossils across the top of the forest or high marsh soils indicate ~0.5 to >2 meters of submergence. I did not observe evidence for positive sea level tendencies prior to submergence (e.g., appearance of more saline organisms a few centimeters below the contact between the two zones; Shennan et al., 1996). At Little Skookum Inlet, scattered Forminifera just below the contact of BZ-1 and BZ-2 are likely an infauna that penetrated into the upper few centimeters of buried soil after submergence. Live benthic Foraminfera commonly occur up to 20 cm below intertidal marsh surfaces in British Columbia (Ozarko et al., 1997).

The macrofossils and diatoms show that lowland forests and freshwater marshes existed at Little Skookum Inlet and Red Salmon Creek up until the time of abrupt submergence. Deposits from freshwater marshes and forests make up the lower $^2/_3$ of the section at Little Skookum Inlet, and no evidence for brackish water environments appears until BZ-2. Because *Aulacoseira italica*, a freshwater planktonic taxon, dominates LSI-5 (gray mud), an open pond or a lake existed at Little Skookum Inlet prior to development of Douglas-fir forests (LSI-6). At Red Salmon Creek, a Douglas-fir forest developed on sands possibly deposited by lahars from Mount Rainier. The National lahar deposited sand and mud throughout the Nisqually River drainage between 800 and 1000 years ago (Hoblitt et al., 1995).

DIATOM-BASED ELEVATION AND SALINITY INFERENCES

I used a weighted averaging technique to reconstruct past elevation and salinity from coastal diatom assemblages (see Chapter 2 for details). The reconstructions are based on a training set of 39 modern diatom samples, collected from 5 coastal marshes in Puget Sound, coupled with measurements of salinity and elevation above MLLW. Elevation and salinity reconstructions are shown in Figure 4-16 and 4-17, and are summarized in Figure 4-18.

Similarity measurements were used to test whether each fossil sample had an appropriate analog in the modern training set. Based on the similarity measures, all but two fossil samples had close modern analogues (NISQ-15B and MC-04B, denoted by '+' on Figures 4-16 and 4-17). These samples differ from the modern samples because they are dominated by one or two diatom taxa that are not well represented in the modern samples (*Diploneis ovalis* and *Tabellaria fenestrata*).

At Little Skookum Inlet and Red Salmon Creek, for elevations of stump-bearing forest soil horizons (LSI-6 and RSC-1) were estimated using the lowest elevations of modern Douglas-fir near each site. The lowest modern Douglas-fir near the Little Skookum Inlet locality (Figure 4-1) was the trunk of a large Douglas-fir logged in this century. This stump is at 7.2 m above MLLW (Figure 4-4). At Red Salmon Creek, the nearest living Douglas-fir is 4.7 m above MLLW. Therefore I assigned an elevation of 7.2 m and 4.7 m for the stump-bearing horizons at the Little Skookum Inlet and Red Salmon Creek localities, respectively. The differences in elevation of the lowest modern Douglas-fir at each site is due to local topography and forest type. At Little Skookum Inlet, the forest floor adjacent to the marsh is very flat. Trees that live closer to the marsh (*Picea sitchensis* and *Thuja plicata*) can tolerate the relatively wet conditions at the marsh edge. As elevation increases further from the marsh edge, the forest floor becomes drier and Douglas-fir dominates. At Red Salmon Creek, the local topography is more abrupt. Unlike the Little Skookum Inlet locality, there are no standing freshwater areas between the salt marsh and forest, so *Picea sitchensis* and *Thuja plicata* are absent. As elevation increases at the edge of the marsh above the influence of the tides, lowland forest trees and shrubs dominate. These elevations indicated are limiting minima for paleoelevation inferences because the fossil trees could have lived at higher elevations. For salinity inferences, buried forest horizons were assigned a salinity of 0 parts per thousand (‰).

Elevation Reconstructions

Reconstructed elevations (relative to MLLW) for fossil diatom samples show one major elevation change at each site in the last ~1000 years (Figure 4-16). A large decrease in inferred elevation at the Little Skookum Inlet, Nisqually River, and Red Salmon Creek localities occurred between BZ-1 and BZ-2, coinciding with the burial of a lowland soil by intertidal peat or mud at each site about 1000 years ago. Inferred elevations are highest for the buried soil at each locality; elevations ranged from 7.2 m to 4.7 m for the buried forest soils (LSI-6 and RSC-1, respectively), and 3.7 m to 4.3 m for the buried high marsh soils (MC-3 and NR-1 (upper peat), respectively).

I infer lower elevations for the estuarine mud or peat that overlies the buried soil at each locality (Figure 4-16 and 4-18). The lowering 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 ~3.4 m below the pre-existing forest floor. By contrast, laminated mud above buried high marsh soils at the McAllister Creek and Nisqually River localities has an inferred elevation of 3.4 m (Figure 4-16), only about 0.5 to 1 m (McAllister Creek) and 0.9 m (Nisqually River) below the high marsh level. Inferred elevation for fibrous peat above the buried forest horizon at the Red Salmon Creek locality was 3.5 m, suggesting at least 1.2 m of submergence at that site.

There are small differences in inferred elevation changes between the sites at Nisqually delta. At McAllister Creek, I infer an elevation change of ≤1 m. Submergence at this site failed to kill *Triglochin maritima* and *Juncus balticus*, as seen by the vigorous growth of *Triglochin* leaf bases and high-angle *Juncus* rhizomes in the laminated mud immediately above the buried soil. The presence of the leaf bases and rhizomes shows that those plants were growing in a rapidly aggrading muddy environment, possible at the edge of a tideflat. 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. 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 forest floor suggests at least 1.2 m of submergence. The differences in inferred elevation change about 1000 years ago at Nisqually delta are small and could result from several factors. These factors include error in estimating former elevations of intertidal environments, and error associated with inferring the elevation of the fossil Douglas-fir.

Following abrupt submergence at each locality about 1000 years ago, inferred elevations were remarkably uniform across the study area (Figure 4-16). Reconstructed elevations for samples from BZ-2 at each locality all fall within the intertidal zone, suggesting that sedimentation and marsh accretion kept pace with rising relative sea level (gradual change). A minor elevation change occurs within BZ-2 at McAllister Creek and Nisqually River, but does not have a distinct stratigraphic change associated with it (Figure 4-16 and 4-18).

Salinity Reconstructions

The buried soils at three localities gave the lowest inferred salinities. At Little Skookum Inlet and Red Salmon Creek, the buried Douglas-fir forest horizons (LSI-6 and RSC-1, both ~1000 years old) are assigned a salinity of 0‰, because Douglas-fir grows well above even the highest tides today in Puget Sound (Franklin and Dyrness, 1988). At McAllister Creek, the buried marsh soil (MC-3) gives an inferred salinity of ~20‰, while at the Nisqually River locality the buried soil (NR-1) had a salinity value of ~6‰ (Figure 4-17).

Inferred salinity increased with the abrupt submergence that is marked by the top of the buried soil and the change from BZ-1 to BZ-2 at three of the sites (Figure 4-17 and 4-18). At Little Skookum Inlet, salinity increased to ~20‰ in the muddy peat (LSI-7) five cm above the top of the buried forest soil. Salinity abruptly rose from 0‰ in the buried forest horizon at Red Salmon Creek (RSC-1) to ~25‰ in the peat (RSC-2) 2-4 cm above the sharp contact between the two stratigraphic units (Figure 4-17). No change in inferred salinity occurred in the laminated mud (MC-4) above the buried soil at McAllister Creek. At Nisqually River, the laminated mud (NR-2) above the buried soil has an inferred salinity of ~20‰ (Figure 4-17).

Salinity values for samples taken from BZ-2 at each site are remarkably uniform (Figure 4-17). Inferred salinity shows little variation in BZ-2 except for small excursions at Nisqually River (~7‰ change at a sample elevation of 1.65 m; Figure 4-17) and Red Salmon Creek (~5‰ change at a sample elevation of 2.2 m; Figure 4-17) . The stability of salinity in BZ-2 contrasts with the abrupt changes in salinity that occurred about 1000 years ago, coincident with the burial of lowland soil at each site.

DISCUSSION

ABRUPT VS. GRADUAL SUBMERGENCE

Submergence of lowland soils in southern Puget Sound is best explained by coseismic, subsidence of the land. 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. Radiocarbon dates of submergence-killed trees and *Triglochin maritima* rhizomes from estuarine deposits immediately overlying marsh soils indicate that submergence of less than 0.5 m to 3.4 m occurred between 690-1200 cal years A.D. The submergence is not readily explained by compaction alone, by submergence without land subsidence, or by breaching of a sandy, bay-mouth bar.

Submergence without tectonic subsidence. Some of the subsidence observed at Nisqually delta possibly resulted from shaking-induced compaction and settlement. Much of the delta is underlain by glacial and deltaic sediments (unpublished report, Department of Geological Sciences, University of Washington) that could compact and settle when shaken during an earthquake. Settlement like this occurred during the 1964 Alaska earthquake (Plafker and Kachadoorian, 1966). However, the buried soil at Little Skookum Inlet, where the most inferred subsidence occurred, is underlain by stiff Pleistocene mud that is not likely to compact more than a few tens of centimeters.

Submergence without land subsidence. Although rapid rise in water level of the sea can result in submergence of lowland soils, it is difficult to explain the observed submergence by just rising sea level. A record of late Holocene sea level fluctuations from Clinton, Connecticut shows that minor fluctuations on the order of 10-30 cm occurred in the last 1400 years , possibly related to thermal expansion of sea water (van de Plassche et al., 1998). These fluctuations are not large enough to account for the submergence ~1000 years ago in southern Puget Sound. Abrupt changes in macrofossils and diatoms at each locality also indicate rapid submergence. The abrupt change in fossil assemblages cannot have resulted from gradual sea level rise unless assemblages showing gradual transitions have been selectively removed from the stratigraphic record at each locality by erosion. It is unlikely that the submergence of soils from different coastal environments (upper high marsh and forests) in widely separated inlets of Puget Sound could happen at the same time due to non-tectonic mechanisms, such as erosion or breaching of a bay-mouth bar. More likely, deformation above a crustal structure resulted in widespread subsidence of coastal environments at about the same time

Breaching of sandy bay-mouth barriers. If barrier bars blocked entrance of Little Skookum Inlet and Nisqually delta, then simultaneous breaching of these bars would allow the tides to rise in areas behind the bars and produce buried soils similar to those produced by subsidence during an earthquake. Previous research documents the presence of widespread brackish environments in southern Puget Sound for at least the last few thousand years (Bucknam et al., 1992). Deposits beneath intertidal marshes and tideflats at North Bay (Bucknam, R., U.S.G.S., personal communication, 1998), Burley marsh, and Nisqually Delta show that tidal waters reached the heads of most tidal embayments and inlets more than 1000 years ago. Development of intertidal marshes ~1000 years old at Nisqually Delta (McAllister Creek and Nisqually River localities) required an open connection for tidal waters, negating the presence of a bay-mouth barrier at those sites (Atwater, 1992). Narrow, deep channels likely prevented development of bay-mouth barriers in Little Skookum Inlet capable of completely sealing off the inlet from Puget Sound.

EARLIER EVENTS

An earlier submergence event is suggested from the stratigraphy and paleoecology of the Nisqually River locality (Figure 4-18). The lower part of NR-1 contains abundant freshwater diatoms (eg., *Eunotia pectinalis*) and is overlain by a muddy interval containing low marsh and tideflat diatoms (e.g., *Diploneis interrupta and*

Opephora parva) (Atwater and Hemphill-Haley, 1997). The observed changes in the diatom flora suggest submergence of a freshwater to low salinity, brackish water marsh into the lower intertidal zone, possibly up to 3.8 meters of submergence (Figure 4-18). This event is speculative at this time because it is based on a sparse amount of evidence.

SOURCE OF SEISMICITY ABOUT 1000 YEARS AGO

I speculate that the Legislature fault (structure 'L' of Gower et al., 1985) is the source of deformation in southern Puget Sound. This geophysical lineament is only structure large enough to produce the effects I see in southern Puget Sound (Figure 4-19). This structure was originally defined using aeromagnetic surveys and gravity mapping and interpreted as a fold in Eocene basalt underlying most of southern Puget Sound (Gower et al., 1985; Pratt et al., 1997). The structure is very linear and about 80 km long; if it is a fault, it could produce earthquakes up to M~7.5 (? ref). Alternative sources for earthquakes include numerous smaller faults (e.g., north of Nisqually delta; Gower et al., 1985) but would likely require coupled earthquakes to produce the extent of submergence inferred for southern Puget Sound.

RELATIONSHIP TO OTHER PAST EARTHQUAKES

Up to 6-7 m of land deformation occurred in central Puget Sound about 1100 years ago (Figure 4-19) from a large earthquake on the Seattle fault (Bucknam et al., 1992). Submergence in southern Puget Sound along the Legislature fault and uplift along the Seattle fault (Bucknam et al., 1992) occurred about the same time between 1100 to 1000 years ago (Figure 4-3). This approximate coincidence is open to many interpretations, none of which can be ruled out at this point: (1) uplift in central Puget Sound coincided with subsidence in southern Puget Sound (Figure 4-19).. In this case, rupture on the Seattle fault and one or more faults in southern Puget Sound within several decades could produce the inferred deformation patterns. Alternatively, rupture on a deep reverse fault could produce uplift in central Puget Sound and subsidence in southern Puget Sound. At the present time, the geometry and locations of faults in the Puget

Sound region is so poorly known that neither case can be ruled out. (2) Slip on the Seattle fault about 1100 years ago predated, by as much as 100 years, slip on a fault in southern Puget Sound, which caused the subsidence at Little Skookum Inlet and Nisqually delta. At the present time, this hiatus is not strongly supported by radiocarbon ages.

Uplift also occurred 1100 years ago at Lynch Cove and Burley (Figure 4-19), about 20 km north of Nisqually delta and Little Skookum Inlet (Bucknam et al., 1992). This uplift occurred at about the same time as the Seattle fault event but lacks a clearly defined fault source. The distance separating the area of uplift and subsidence suggests that more than one structure or splays of a large structure is responsible for the pattern of late Holocene land deformation.

Submergence in southern Puget Sound may correlate with submergence of coastal wetlands along the Pacific coast about 100 km to the west (Atwater and Hemphill-Haley, 1997) and with unusual eruption of liquefied sand in that area (Atwater, 1992). Soil W of Atwater and Hemphill-Haley (1997) possibly corresponds to submergence along the Washington coast between 900 and 1300 years ago (Atwater, 1992). Subsidence of up to 2 m occurred several hundred kilometers inland during the 1964 Alaska subduction zone earthquake (Plafker, 1969). It is possible that some of the submergence in southern Puget Sound resulted from inland subsidence during a great subduction zone earthquake about 1000 years ago. However, evidence against submergence ~1000 years ago has been found in marshes at Dumas Bay and Hansville (Figure 4-1 and 4-19),, suggesting a more localized mechanism for the subsidence.

SIGNIFICANCE AND CONCLUSIONS

1. A buried soil records abrupt submergence between 910 and 1270 cal years B.P. at Little Skookum Inlet and at three localities at Nisqually delta. High precision radiocarbon ages place the time of submergence between 985 and 1115 cal yr B.P.

The most likely cause of submergence is subsidence during an earthquake on one or more faults in the Puget Sound region..

2. The coseismic subsidence ranged from at least3.4 m at Little Skookum Inlet to as little as ~0.5 m on parts of the Nisqually delta.
3. Salinity increased because of the subsidence by as much as 25 parts per thousand.
4. A sand dike connected to vented sand at the Nisqually delta indicates ground shaking at the time of subsidence.

Table 4-1. Generalized description of stratigraphic units.

Unit	Description	Radiocarbon Age				
		(^{14}C yr B.P.)	cal yr B.P.[1]	Depth (m)[2]	Lab No.[3]	Material
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 7520±80	7660 - 7930 8130 - 8420	0.45 0.45	Beta-97230 Beta-97231	peat 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[4] (1220±50)[5]	910 - 1170 990 - 1270[6]	0.75 on tideflat	Beta-95912 Beta-102335	wood wood
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	290 - 0	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 with 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	920 - 1260	~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. Occurs at or just below river level at low tide, and is underlain by a 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	750 - 1070	~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.					

Table 4-1. Continued

Unit	Description	Radiocarbon Age				
		(^{14}C yr B.P.)	cal yr B.P.[1]	Depth (m)[2]	Lab No.[3]	Material
Red Salmon Creek locality						
RSC-1	Gray fine, micaceous sand, silty, massive in appearance. Thin black layer at top (~2 cm thick), mud clasts and stems of woody plants observed in lower half of unit.	1010±50	780 - 1060	1.57	Beta-110746	wood
RSC-2	Brown fibrous peat, *Distichlis spicata* rhizomes and faint lamination observed in places.					
RSC-3	Brown-gray mud, couplets of laminated silt and clay at base of unit (1-2 cm thick) with lamination becoming faint in middle and top of unit, *Triglochin maritima* rhizomes in upper part of unit.	130±60	280 - 0	0.80	Beta-109230	leaf bases
RSC-4	Brown muddy peat, reddish-orange mottles, Triglochin maritima and Distichlis spicata rhizomes throughout, wood observed in places above gradational contact at base of unit.					

[1] 2 sigma, 95% probability, k=1

[2] depth below modern ground surface

[3] Beta – Beta Analytical, Inc

[4] app. outer 15-25 rings

[5] innermost 16 rings of root slab KW8-5 (age result was assumed on midpoint of sample, or ring 8)

[6] calibrated age offset by number of tree rings from midpoint of sample to outermost ring (184 tree rings)

Table 4-2. Biozones and paleoenvironmental interpretations.

Biozone	Depth (m)[1]	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*.	Freshwater marsh and Douglas-fir forest
BZ1	$2.0^{(+)}$ - 0.34	Macrofossils - *Juncus sp.*, *Betula papyifera*, *Rubus spectabalis*, *Sambucus racemosa*, *Carex* cf. *leporina*, *Carex* cf. *aquatilus*, and *Berberis nervosa*. Leaves of *Thuja plicata* and *Taxus brevifolia*, needles of *Picea sitchensis*, and *Spirea douglasii* follicles. Top of zone marked by forest soil and stumps of *Pseudotsuga menziesii*. Diatoms - *Fragilaria construens*, *Eunotia pectinalis*, and *Aulacoseira italica*. Diatom preservation in the soil horizon was poor.	low to high, brackish water marsh
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 (at base) to high marsh (at top)
BZ1	$2.95^{(+)}$ – 2.32	Macrofossils - burned conifer needles, *Sambucus racemosa* seeds, scattered Foraminifera, and charcoal fragments. Diatom - *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 the top of the zone - *Aulacoseira italica*, *Hantzschia amphioxis*, *Pinnularia borealis*, and *Pinnularia subcapitata*.	brackish water, low marsh (at base) to high marsh (at top)
BZ-1	$3.4^{(+)}$ – 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			
BZ-2	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 the middle of the zone.	Low marsh to tideflat
BZ-1	$2.0^{(+)}$ – 1.68	The top of this 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 in this zone.	Douglas-for forest

[1] – depth below modern ground surface at place where fossil samples collected

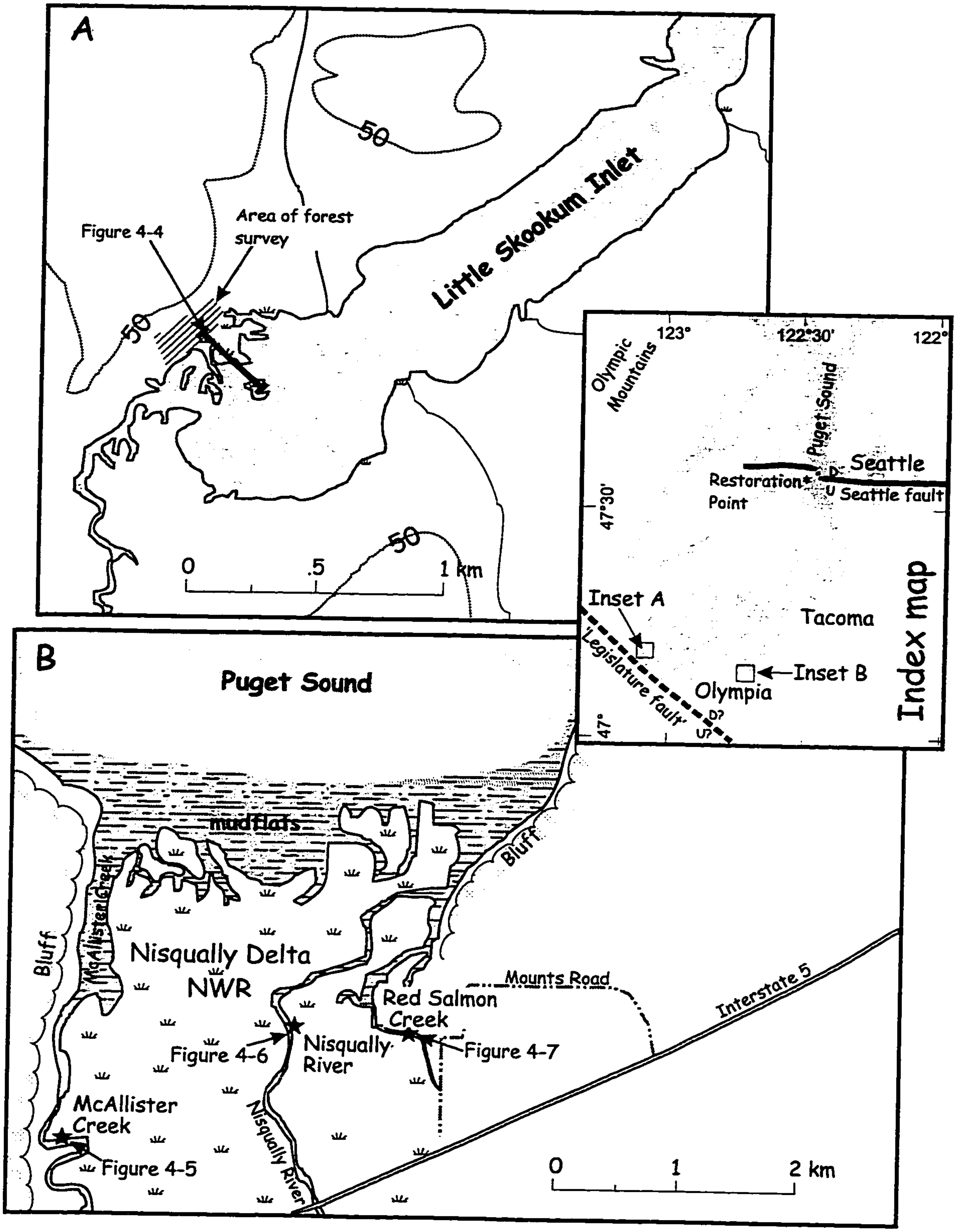


Figure 4-1. Index map of Puget Sound, showing location of major faults. A. Location and setting of transect surveyed at Little Skookum Inlet. Dashed contour line = 15 m. B. Location and Setting of surveyed outcrops at Nisqually delta.

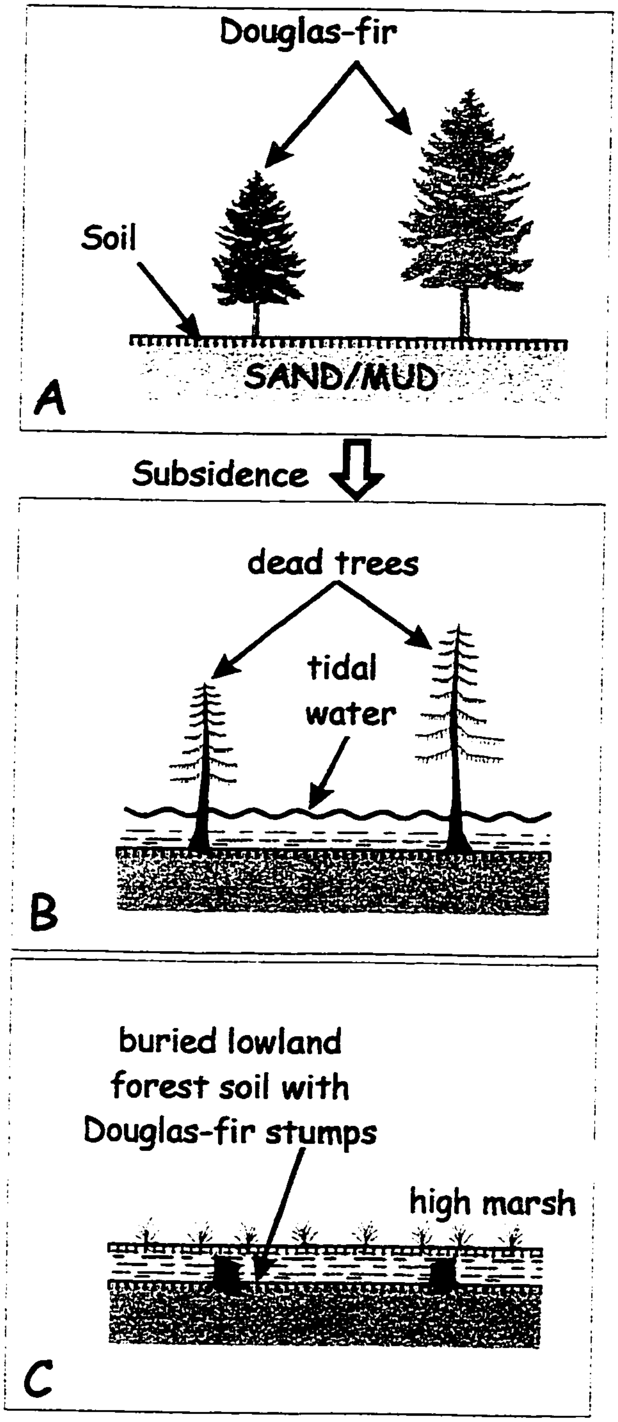


Figure 4-2. Conceptual model of buried forest soil beneath modern salt marshes in southern Puget Sound. A.. Forest soil with living Douglas-fir. B. Forest soil buried by intertidal deposits after subsidence during an earthquake. Trees were killed by submergence in salt water. C. High marsh soil develops over buried forest soil. Tree stumps rot of at level of sediment accumulation shortly after burial and are buried by accretion of salt marsh peat.

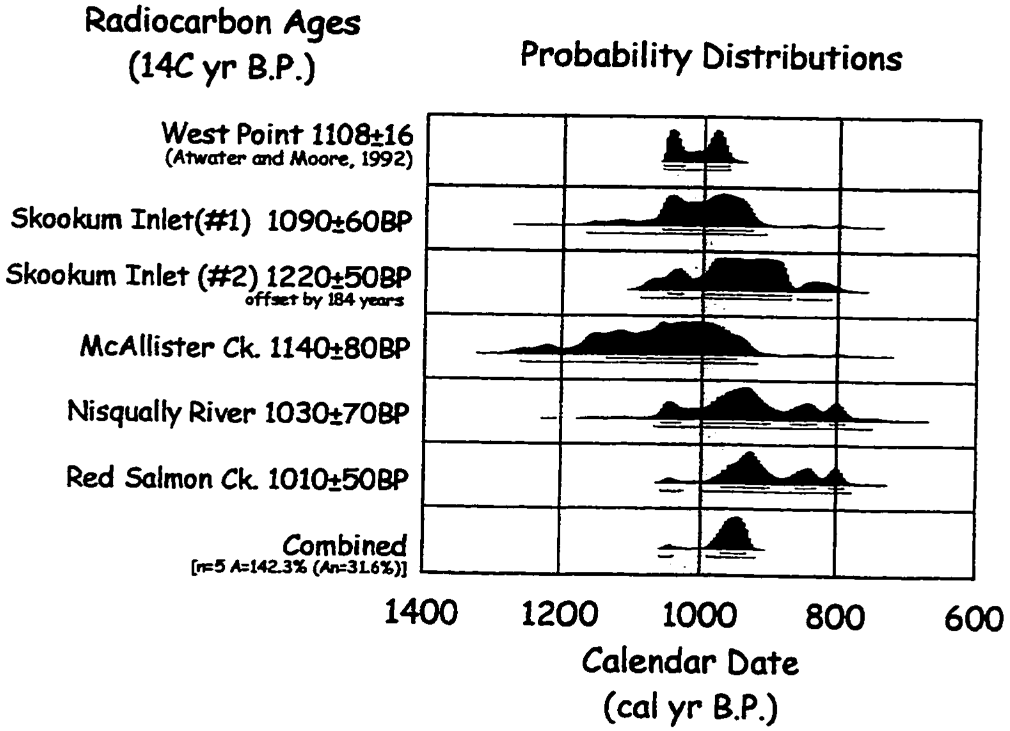


Figure 4-3. Probablity distributions for selected radiocarbon dates from sites in southern Puget Sound. The distribution at the top of the diagram shows the calibrated age range for the 1000-1100 year B.P. Seattle fault event (Atwater and Moore, 1992). The distribution at the bottom of the diagram is the age range (2 sigma, 95.4% confidence interval) for the combined probability distributions on samples from submerged trees and herbaceous plant remains from just above buried soils at sites in southern Puget Sound.

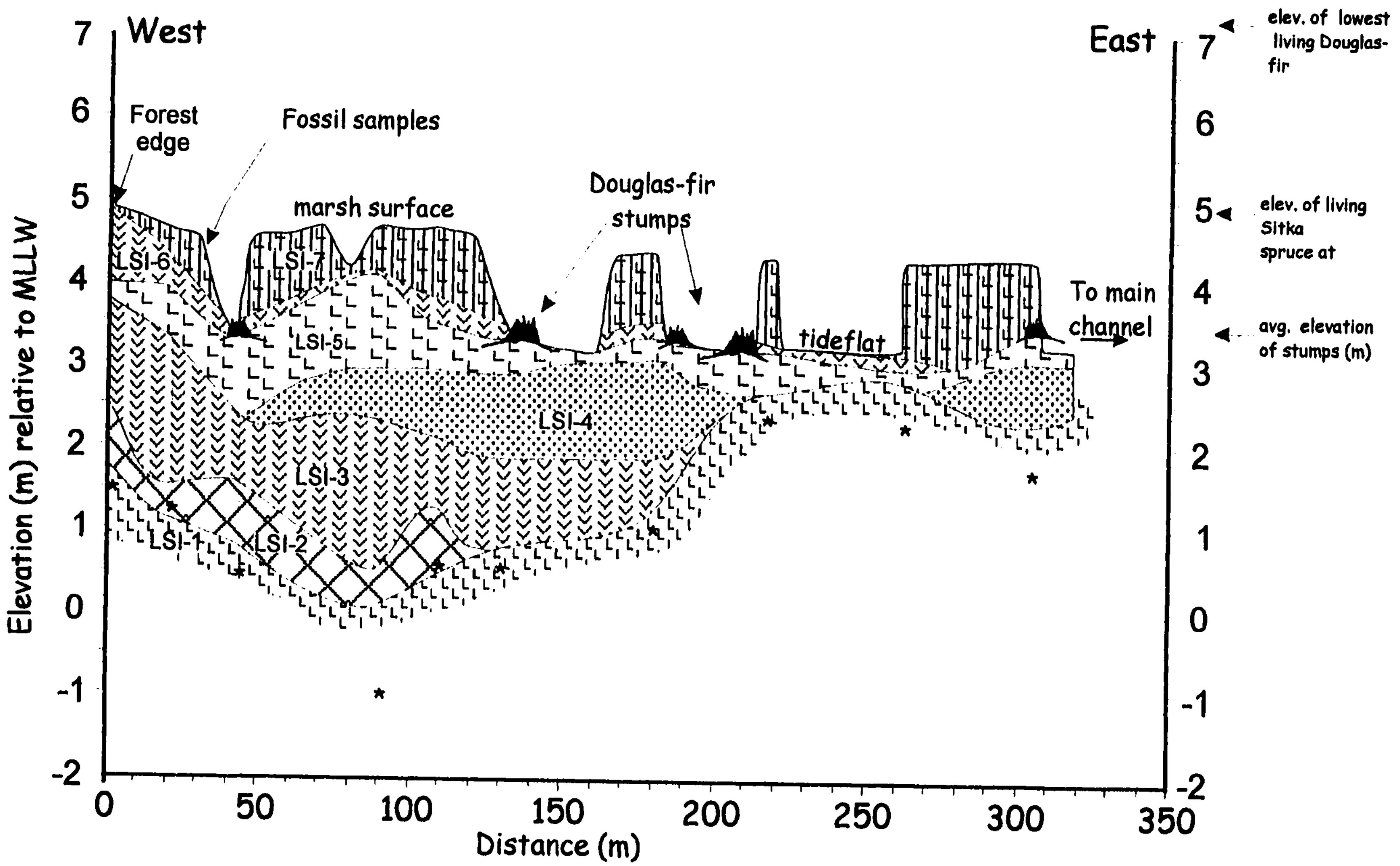


Figure 4-4. Stratigraphy of the Little Skookum Inlet locality.

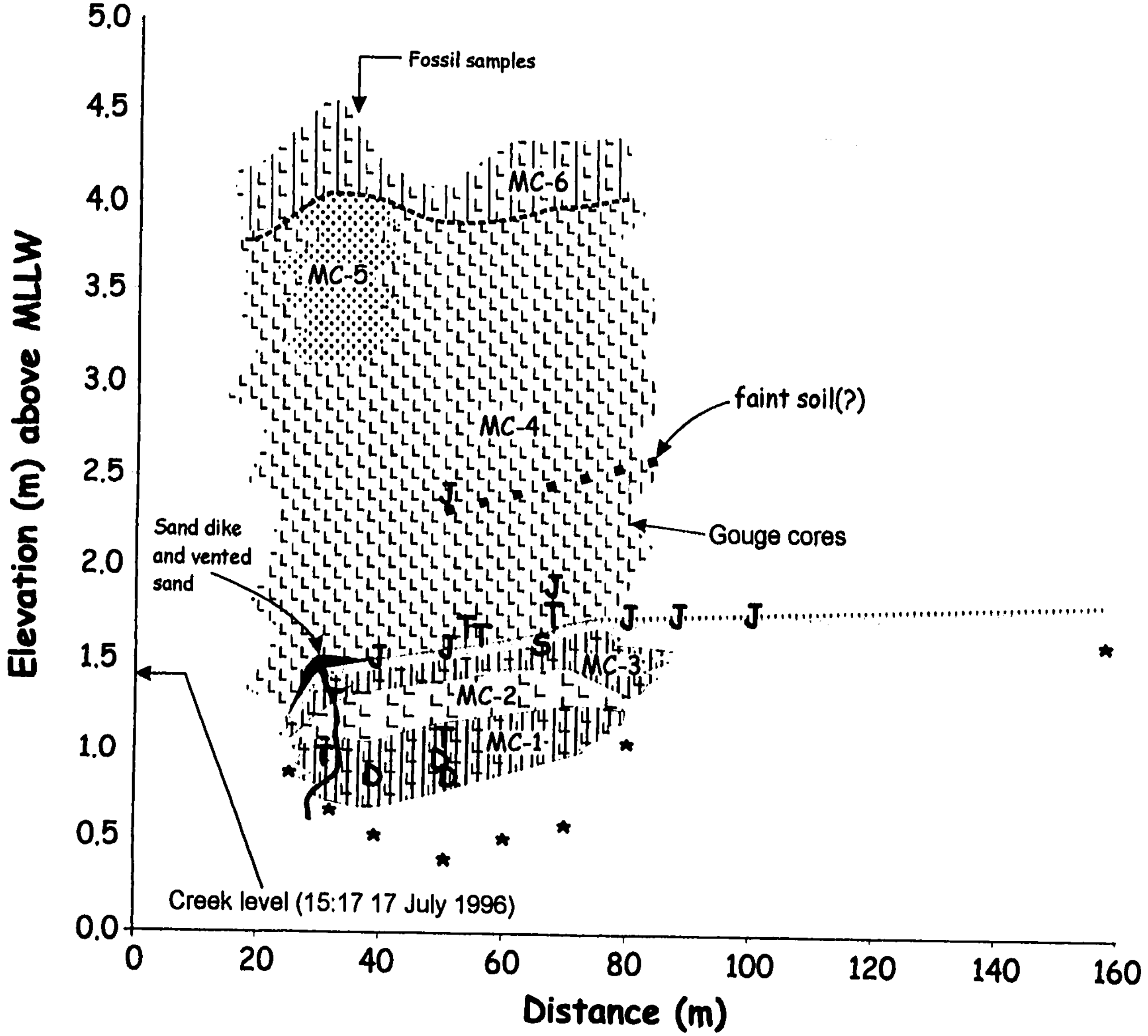


Figure 4-5. Stratigraphy of the McAllister Creek locality.

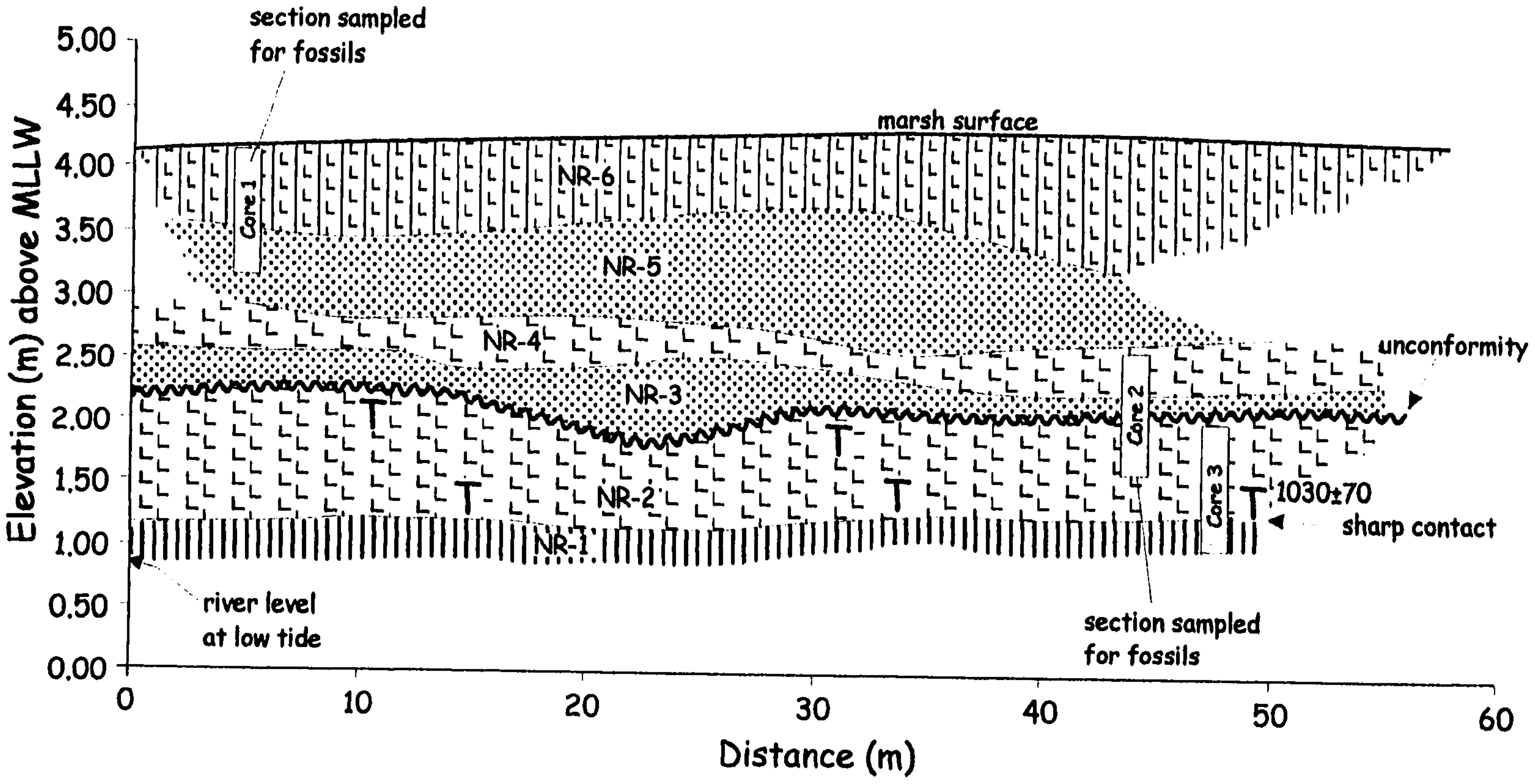


Figure 4-6. Stratigraphy of the Nisqually River locality.

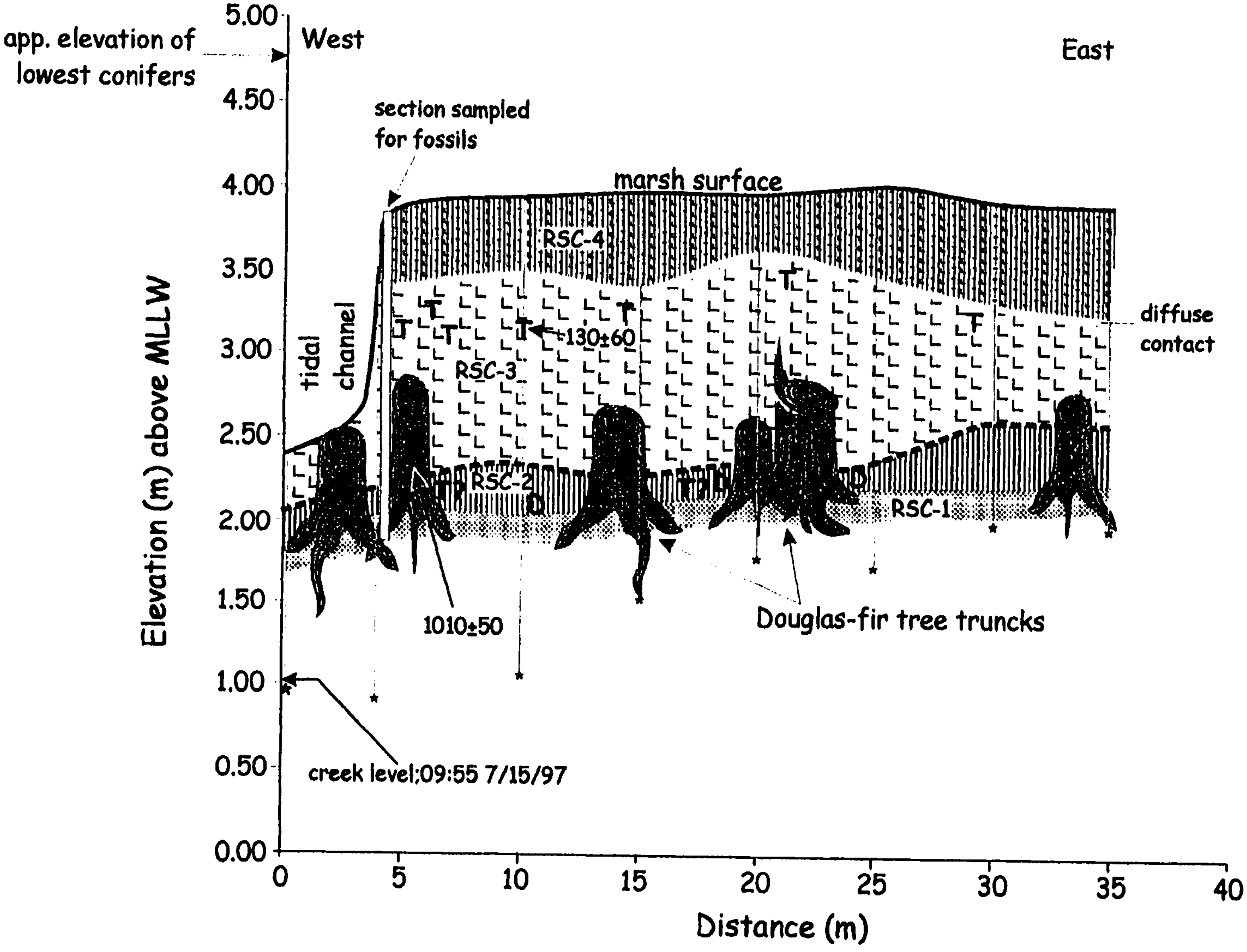


Figure 4-7. Stratigraphy of the Red Salmon Creek locality.

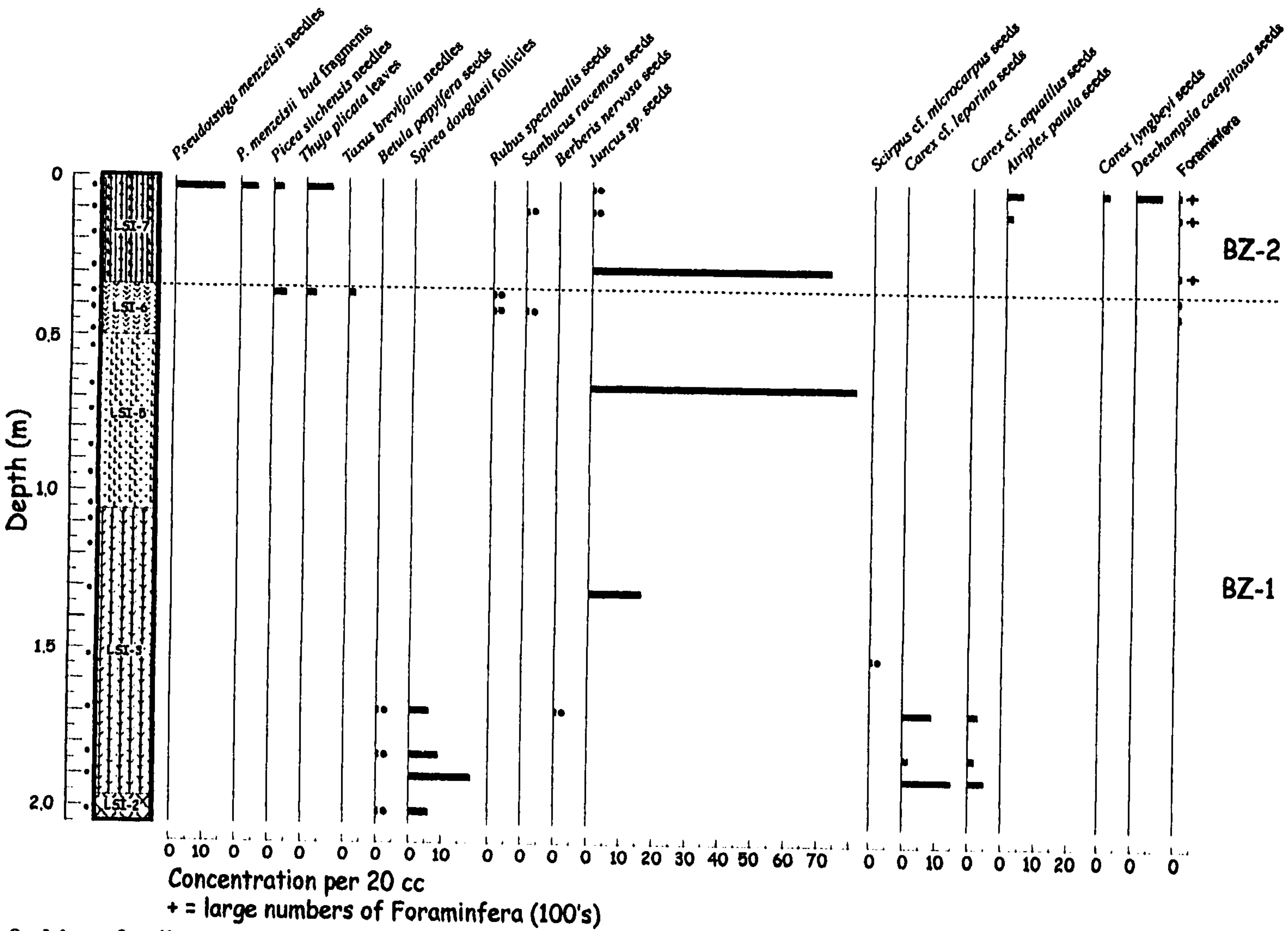


Figure 4-8. Macrofossils recovered from the Little Skookum Inlet locality, expressed as number of fossils per 20 cc of sediment. Biozones are labeled on right side.

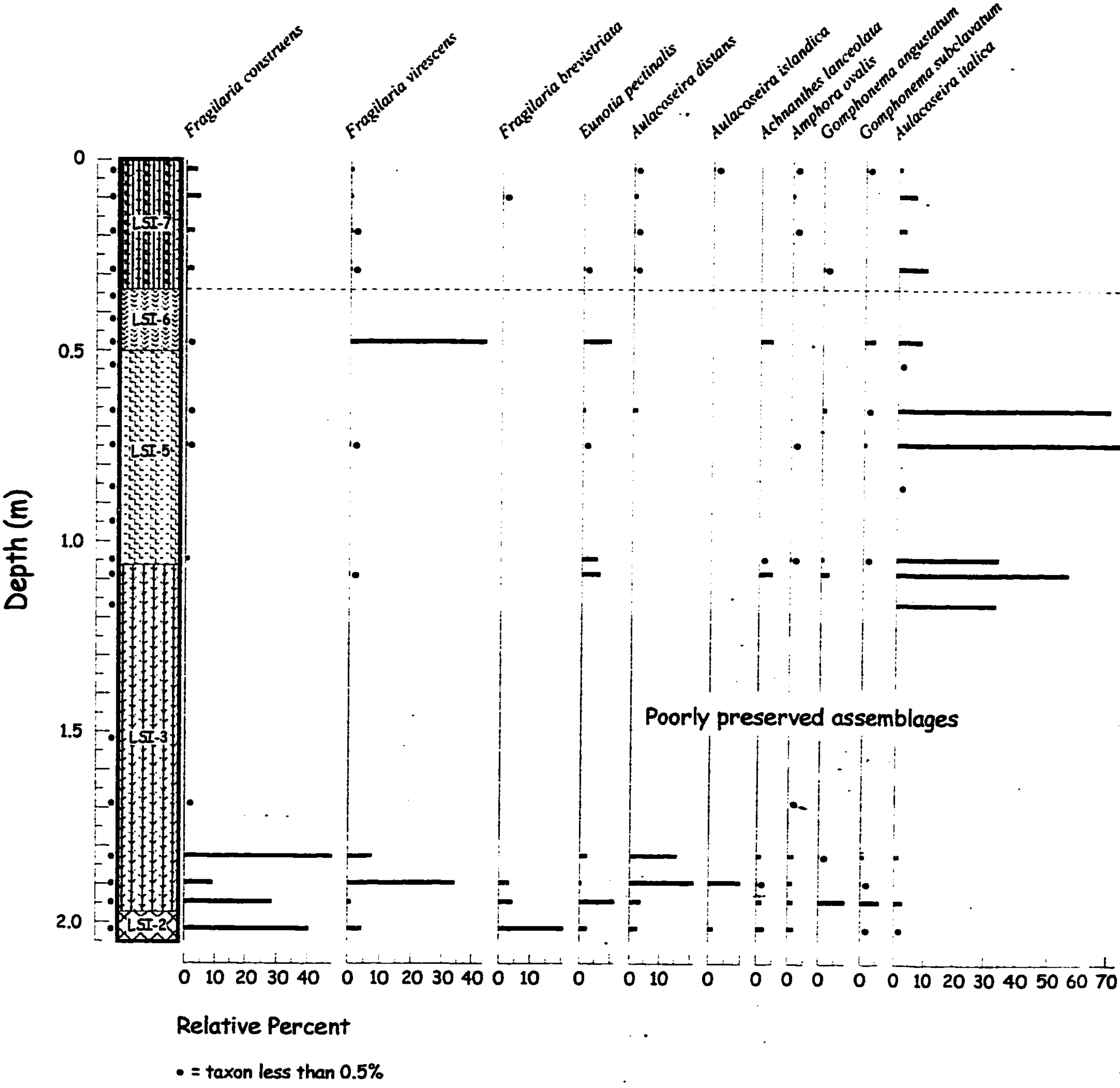
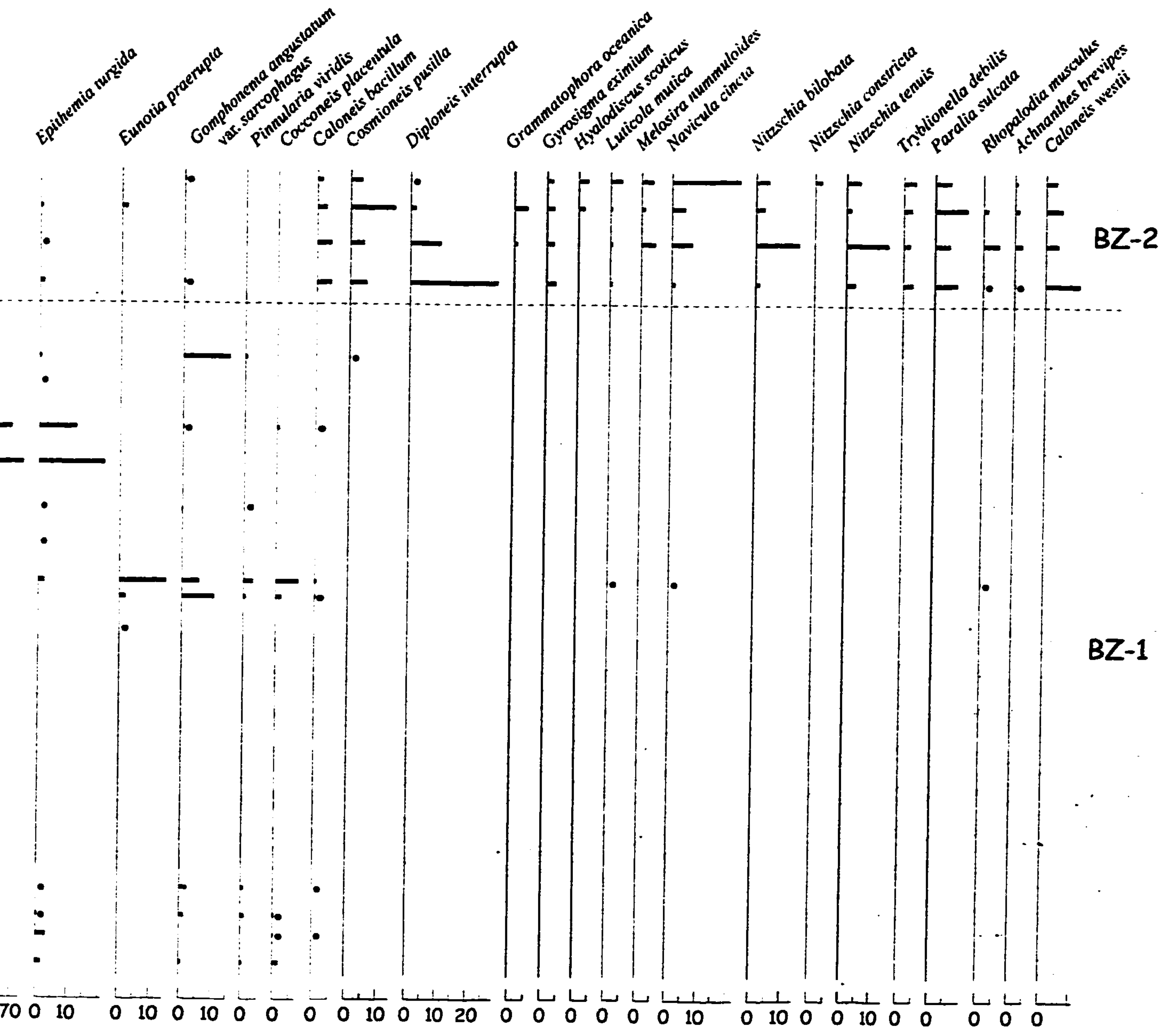


Figure 4-9. Relative abundance of fossil diatoms from the Little Skookum Inlet locality grouped accord
stratigraphic succession. Biozones are labeled on right side.


Epithemia turgida
Eunotia praerupta
Gomphonema angustatum var. sarcophagus
Pinnularia viridis
Cocconeis placentula
Caloneis bacillum
Cosmioneis pusilla
Diploneis interrupta
Grammatophora oceanica
Gyrosigma eximium
Hyalodiscus scoticus
Luticola mutica
Melosira nummuloides
Navicula cincta
Nitzschia bilobata
Nitzschia constricta
Nitzschia tenuis
Tryblionella debilis
Paralia sulcata
Rhopalodia musculus
Achnanthes brevipes
Caloneis westii
BZ-2
BZ-1
70 0 10 0 10 0 10 0 0 0 0 10 0 10 20 0 0 0 0 0 0 10 0 10 0 0 10 0 0 0 0 0

ording to

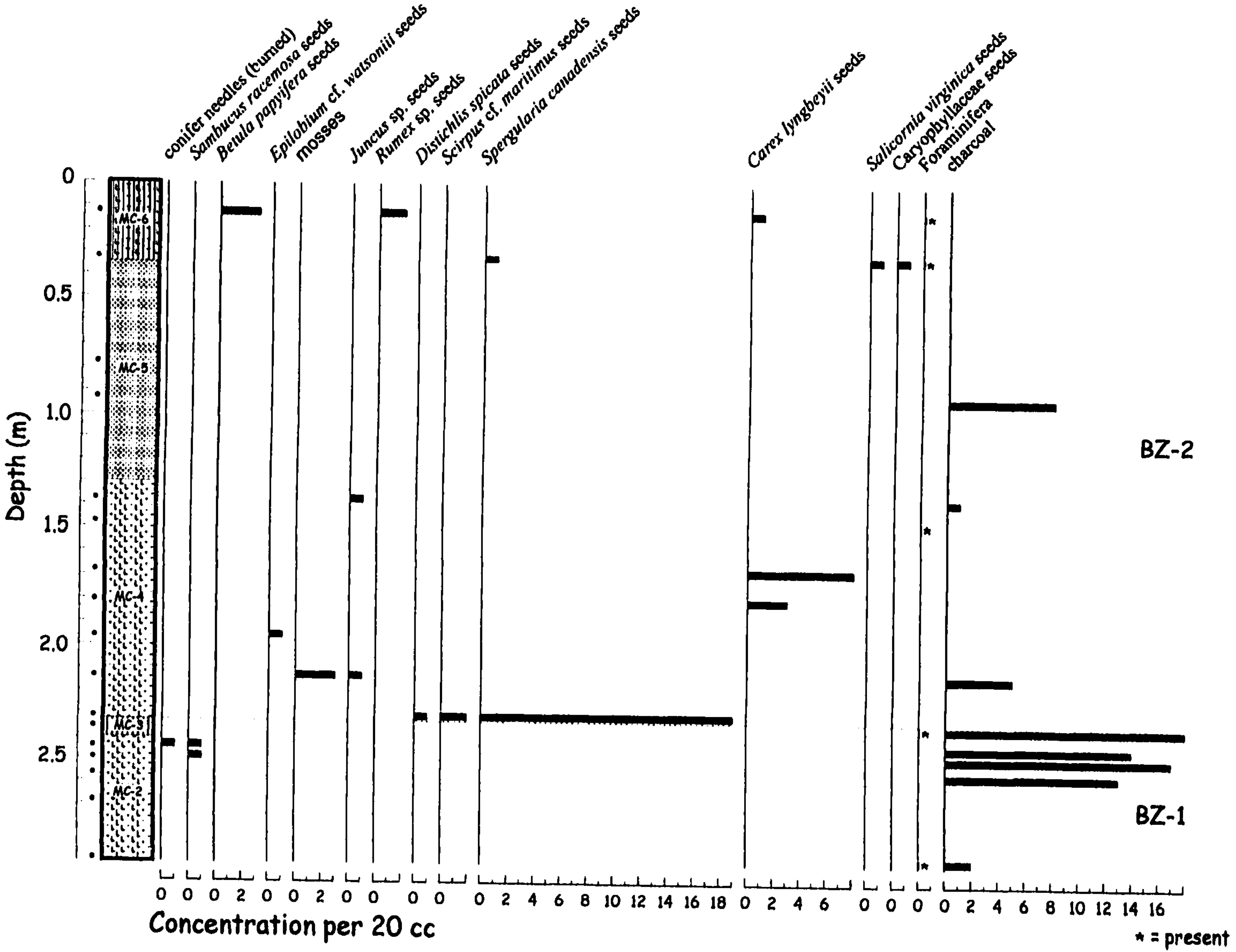


Figure 4-10. Macrofossils recovered from the McAllister Creek locality, expressed as number of fossils per 20 cc of sediment. Biozones are labeled on right side.

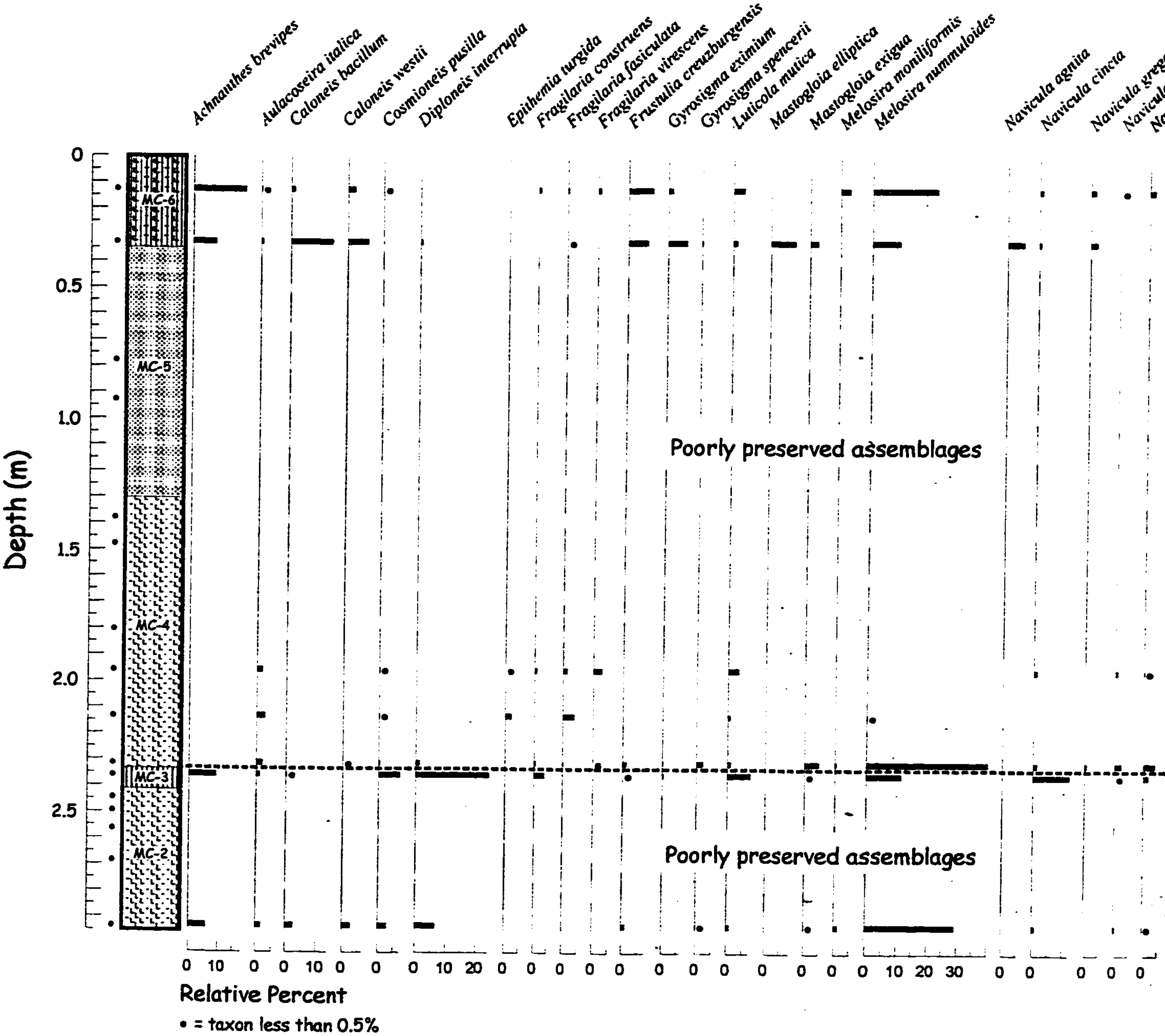
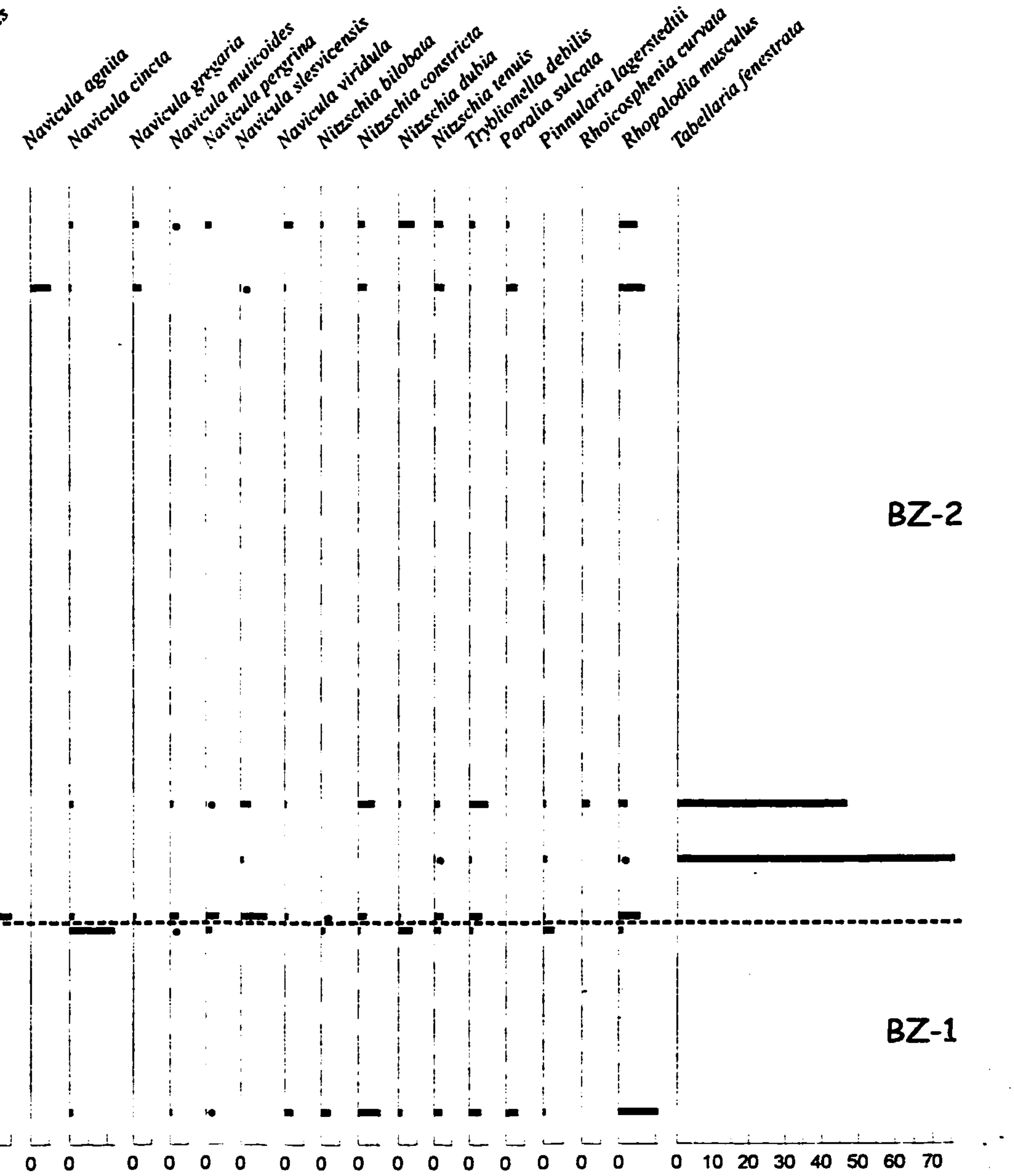


Figure 4-11. Relative abundance of fossil diatoms from the McAllister Creek locality, grouped according to stratigraphic succession. Biozones are labeled on right side.


Navicula agnita
Navicula cincta
Navicula gregaria
Navicula muticoides
Navicula pergrina
Navicula slesvicensis
Navicula viridula
Nitzschia bilobata
Nitzschia constricta
Nitzschia dubia
Nitzschia tenuis
Tryblionella debilis
Paralia sulcata
Pinnularia lagerstedtii
Rhoicosphenia curvata
Rhopalodia musculus
Tabellaria fenestrata
BZ-2
BZ-1
0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0
0 10 20 30 40 50 60 70

bed

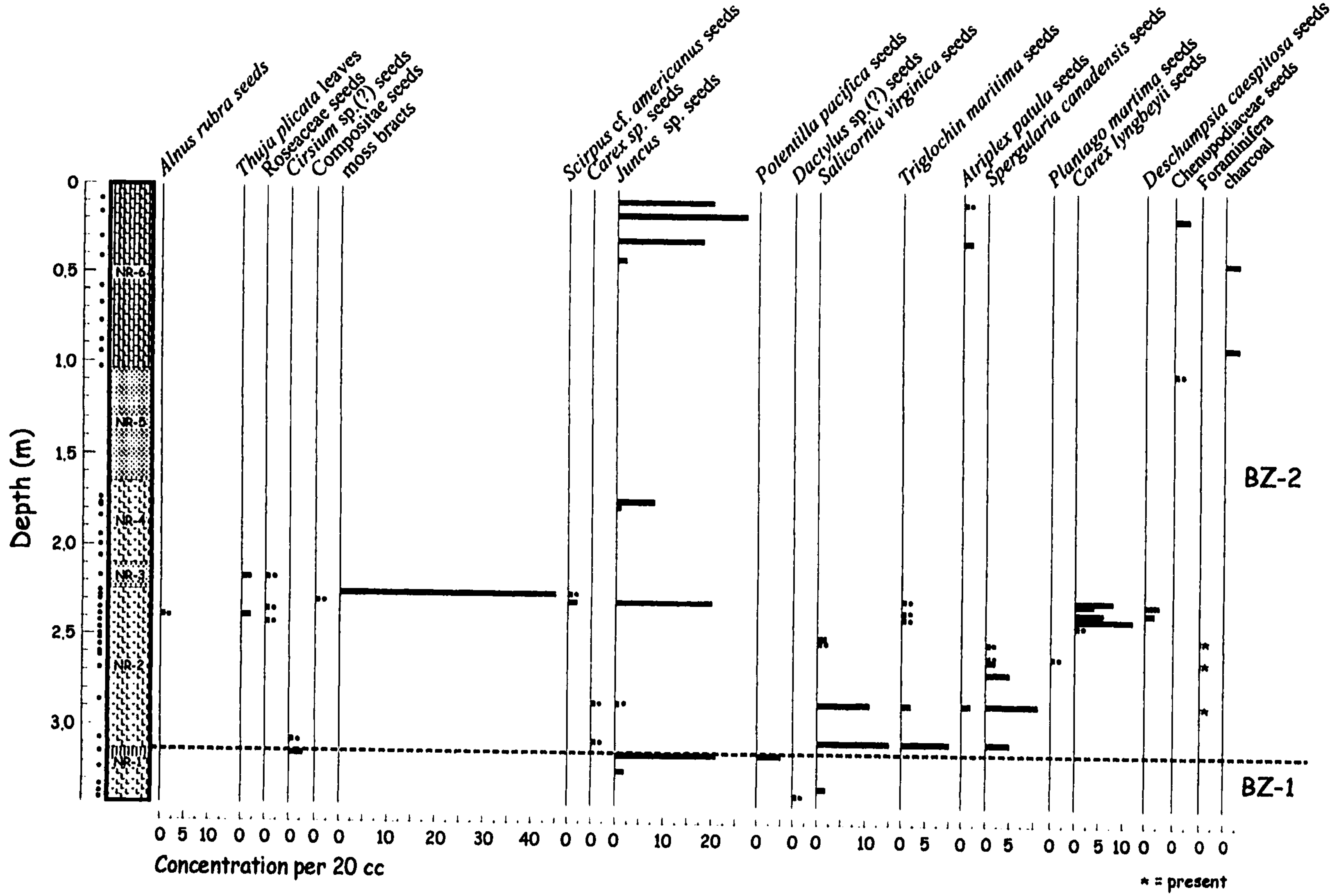


Figure 4-12. Macrofossils recovered from the Nisqually River locality, expressed as number of fossils per 20 cc of sediment. Biozones are labeled on right side.

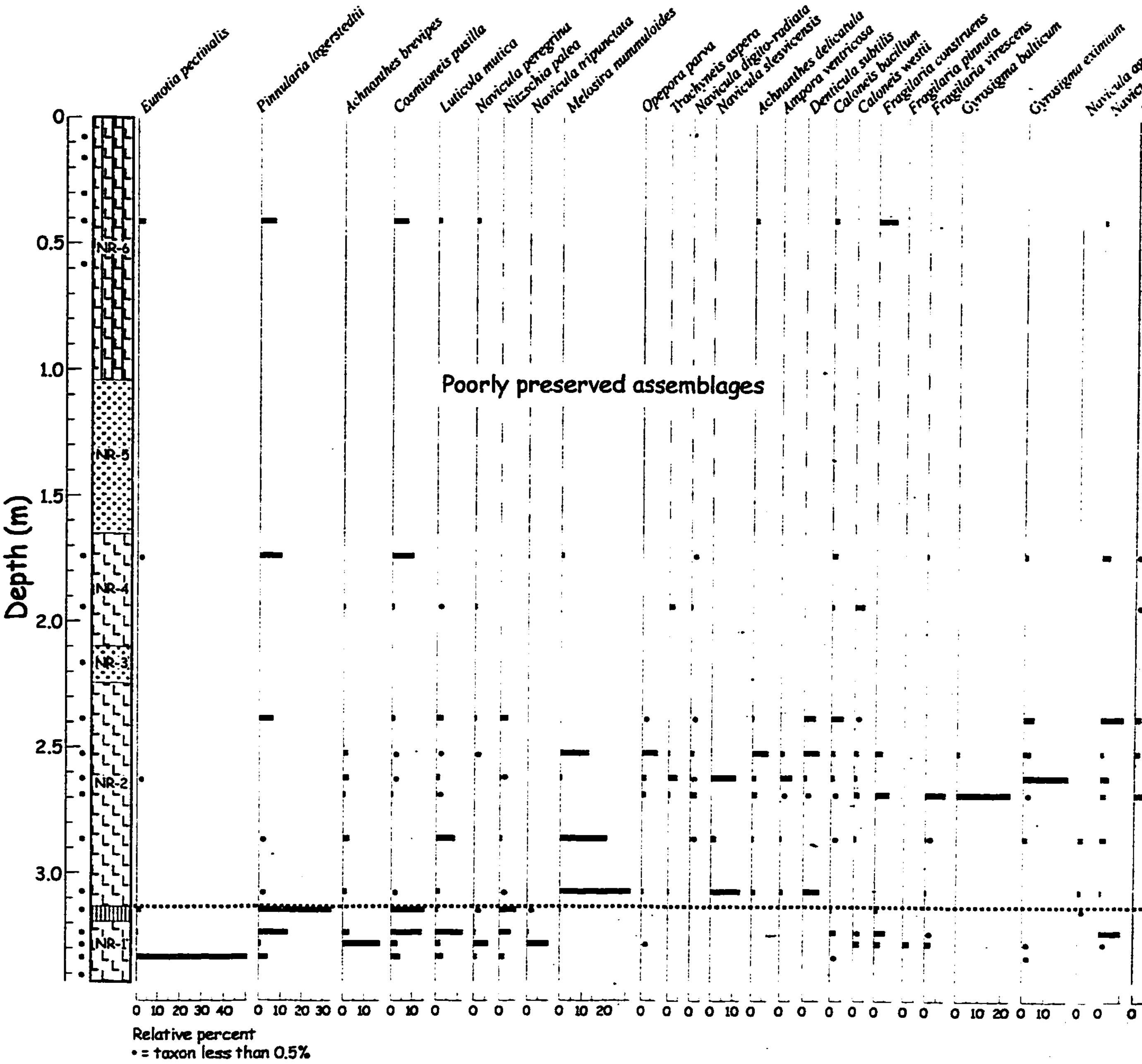
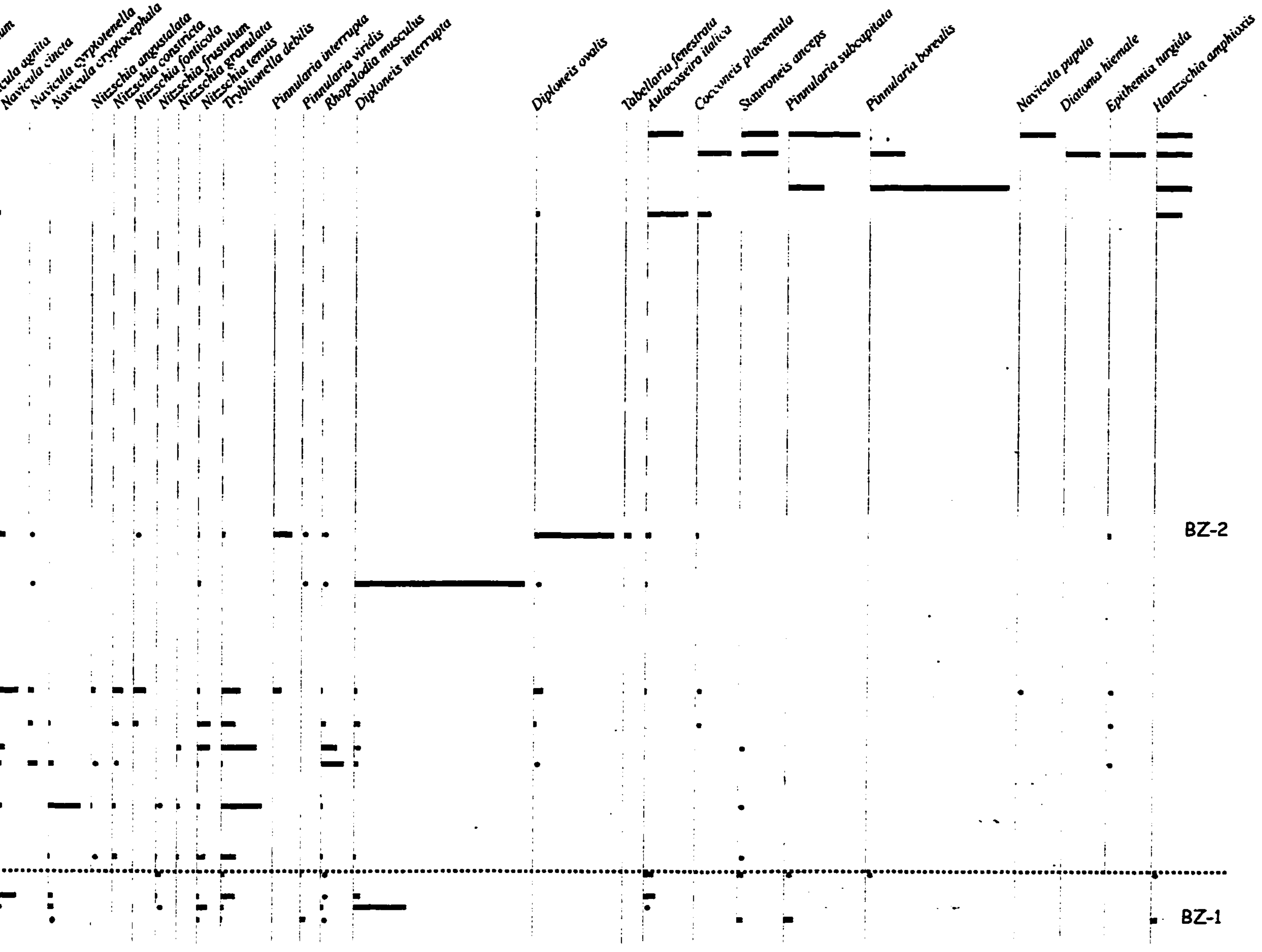


Figure 4-13. Relative abundance of fossil diatoms from the Nisqually River locality, grouped according to stratigraphic succession. Biozones are labeled on right side.


um
cula agnita
Navicula cincta
Navicula cryptotenella
Navicula cryptocephala
Nitzschia angustalata
Nitzschia constricta
Nitzschia fonticola
Nitzschia frustulum
Nitzschia granulata
Nitzschia tenuis
Tryblionella debilis
Pinnularia interrupta
Pinnularia viridis
Rhopalodia musculus
Diploneis interrupta
Diploneis ovalis
Tabellaria fenestrata
Aulacoseira italica
Cocconeis placentula
Stauroneis anceps
Pinnularia subcapitata
Pinnularia borealis
Navicula pupula
Diatoma hiemale
Epithemia turgida
Hantzschia amphioxis
BZ-2
BZ-1
0 0 10 0 0 0 0 0 0 0 10 0 0 0 0 10 20 30 40 50 60 70 0 10 20 30 0 0 10 0 10 0 10 0 10 20 30 0 10 20 30 40 50 60 0 10 0 10 0 10 0 10

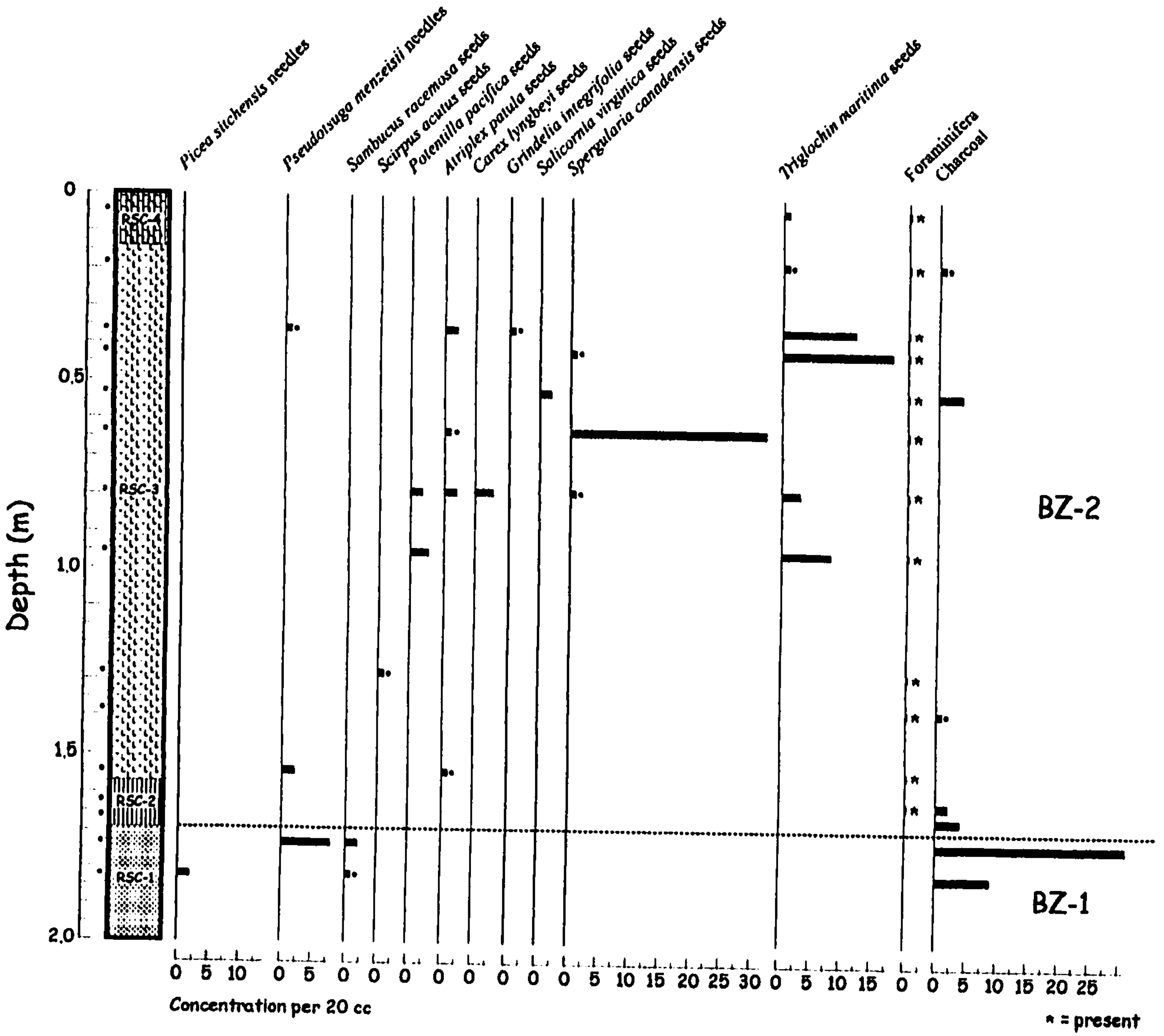


Figure 4-14. Macrofossils recovered from the Red Salmon Creek locality, expressed as number of fossils per 20 cc of sediment. Biozones are labeled on right side.

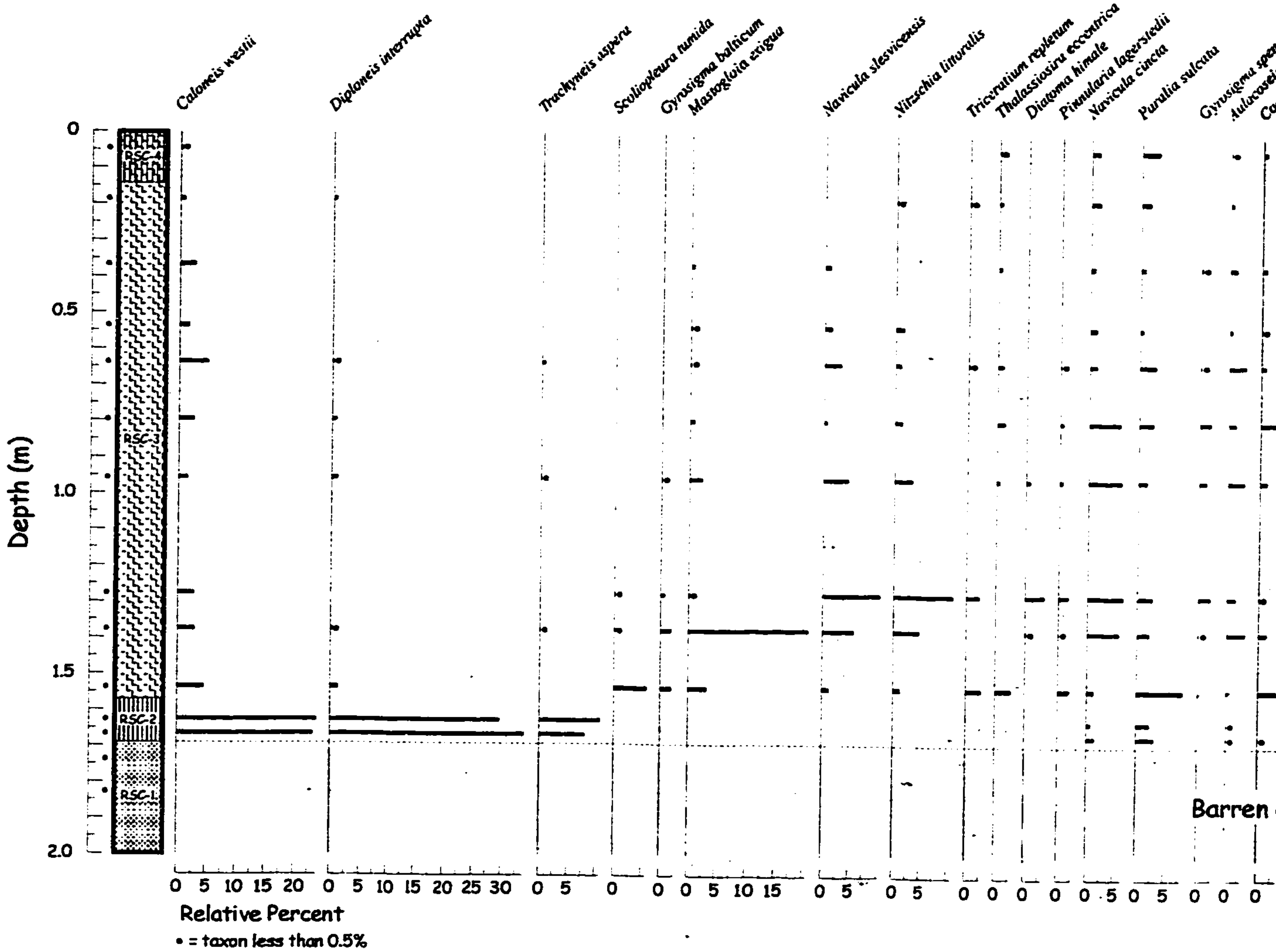
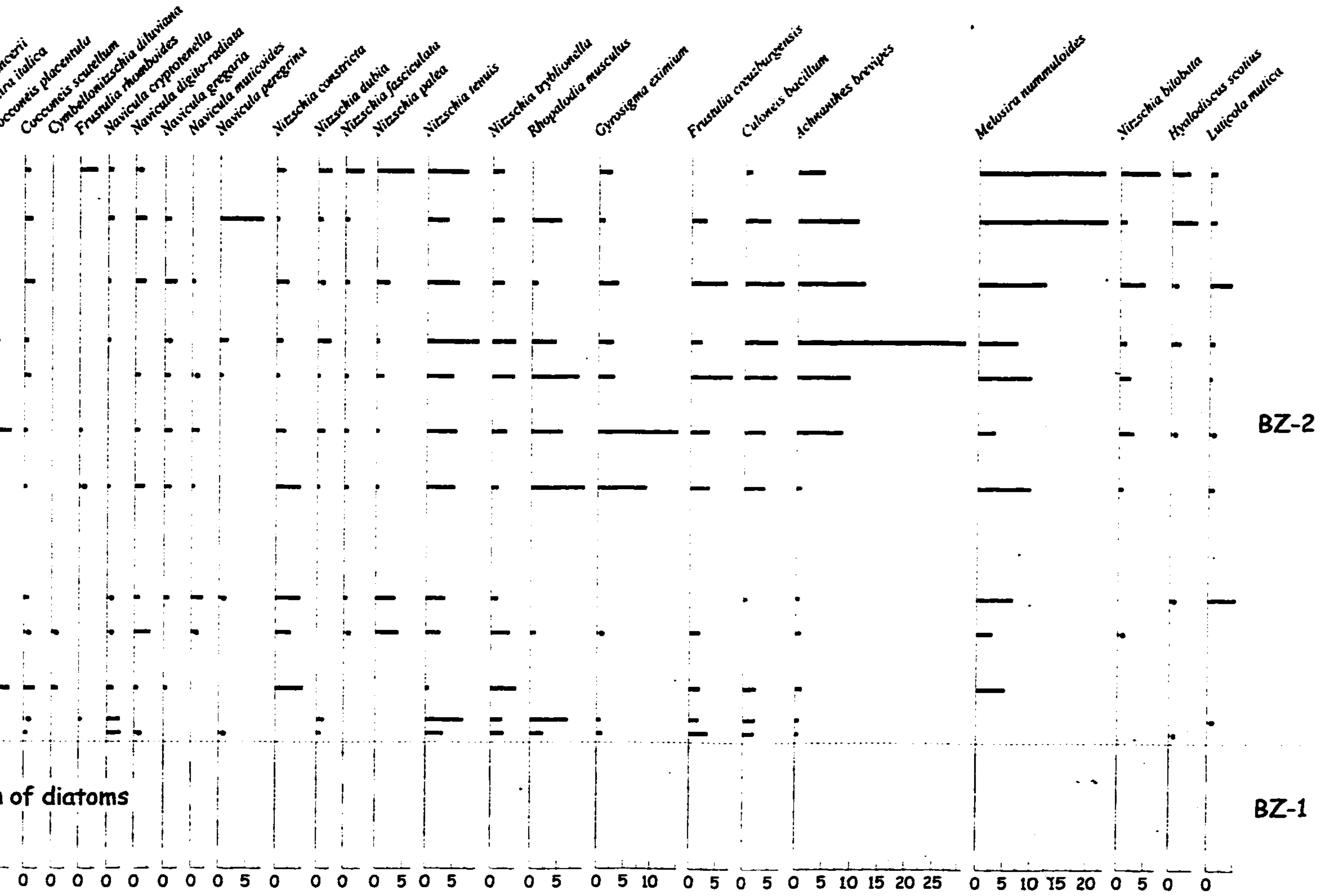


Figure 4-15. Relative abundance of fossil diatoms from the Red Salmon Creek locality, grouped according to stratigraphic succession. Biozones are labeled on right side.


ncerii
ra italica
occoneis placentula
Cocconeis scutellum
Cymbellonitzschia diluviana
Frustulia rhomboides
Navicula cryptotenella
Navicula digito-radiata
Navicula gregaria
Navicula muticoides
Navicula peregrina
Nitzschia constricta
Nitzschia dubia
Nitzschia fasciculata
Nitzschia palea
Nitzschia tenuis
Nitzschia tryblionella
Rhopalodia musculus
Gyrosigma eximium
Frustulia creuzburgensis
Caloneis bacillum
Achnanthes brevipes
Melosira nummuloides
Nitzschia bilobata
Hyalodiscus scotius
Luticola mutica
BZ-2
BZ-1
n of diatoms
0 0 0 0 0 0 0 0 5 0 0 0 0 5 0 5 0 0 5 0 5 10 0 5 0 5 0 5 10 15 20 25 0 5 10 15 20 0 5 0 0

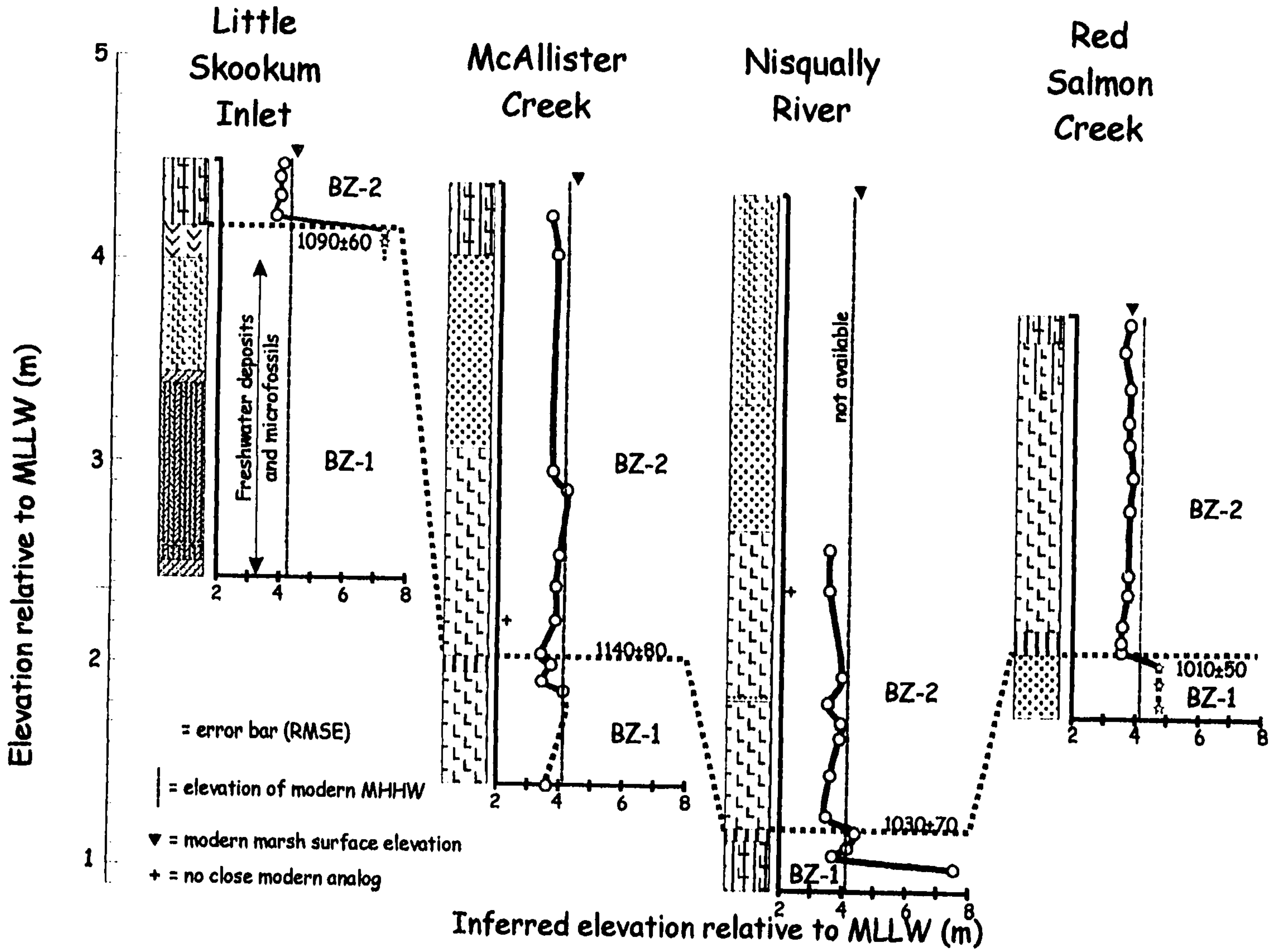


Figure 4-16. Inferred elevation changes from weighted averaging of fossil diatom assemblages. The horizontal dashed line correlates the buried soil at each locality, with selected radiocarbon dates shown. Note abrupt subsidence across contact of buried soil and overlying deposit.

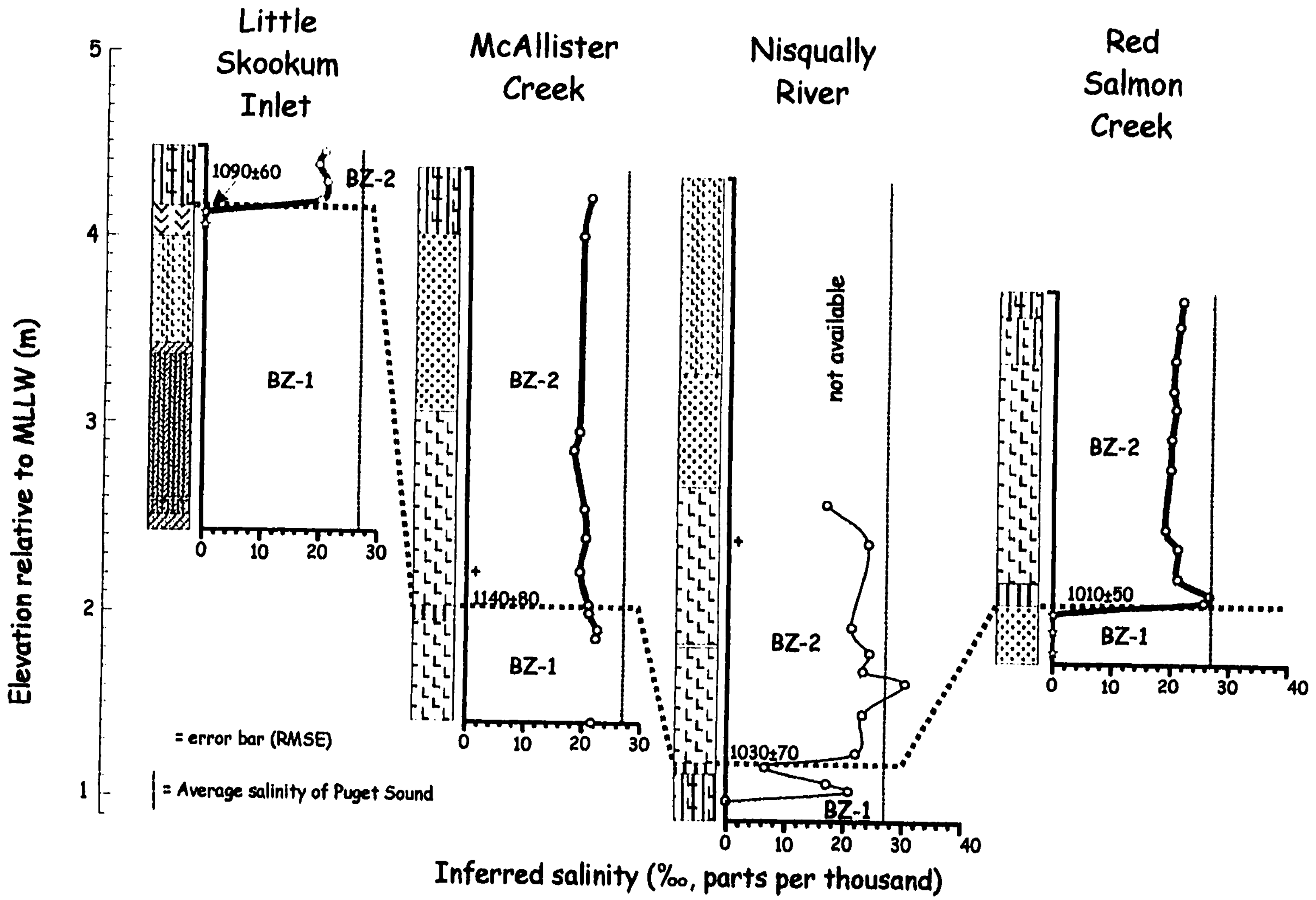


Figure 4-17. Inferred salinity changes from weighted averaging of fossil diatom assemblages. The horizontal dashed line correlates the buried soil at each locality, with selected radiocarbon dates shown. Vertical dashed line indicates value of average Puget Sound salinity.

Locality	Biozone	Lith. Unit	Depth (m)[1]	C14 Age[2]	Cal. Age[3]	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	1670 - 1950 AD	mudflat/tidal slough		
		RSC-2	1.57 - 0.38			low marsh		
	BZ-1	RSC-1	0.38 - 0	1010±50	890 - 1170 AD	Douglas-for forest	{-1.2 m	+ 26‰
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 sand (?)		
		NR-2	3.12 - 2.24	1030±70	880 - 1200 AD	mudflat		
	BZ-1	NR-1	3.18 - 3.12	(upper peat)		high marsh	{-0.9 m	+ 15‰
			3.23 - 3.18	(mud)		(?)		
			3.43 - 3.23	(lower peat)		high marsh	{-3.8 m (?)	+ 20‰
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	690 - 1030 AD	mudflat		
	BZ-1	MC-3	2.41 - 2.32			high marsh	{- <0.5 m	No change
		MC-2	2.53 - 2.41			(?)		
		MC-1	2.92 - 2.53			high marsh	{- 0.6 m	No change
Little Skookum Inlet	BZ-2	LSI-7	0.34 - 0	140±60	1660 - 1950 AD	low to high marsh		
	BZ-1	LSI-6	0.50 - 0.34	1090±60 1220±50	780 - 1040 AD 860 - 1150 AD	Douglas-for forest	{-3.4 m	+ 20‰
		LSI-5	1.06 - 0.50			freshwater lake	Above highest tide	freshwater
		LSI-4	not present			stream		
		LSI-3	1.90 -1.06	7030±70 7520±80	5980 - 5710 BC 6470 - 6180 BC	freshwater marsh		
		LSI-2	1.97 - 1.90			freshwater lake		
		LSI-1	2.05 - 1.97			late-glacial (?) lake		

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

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

[3] - calibrated radiocarbon age in calendar years AD/BC

Figure 4-18. Summary of stratigraphy, radiocarbon ages, biozones, and environmental interpretations for each locality. Inferred changes in elevation and salinity are indicated on right side.

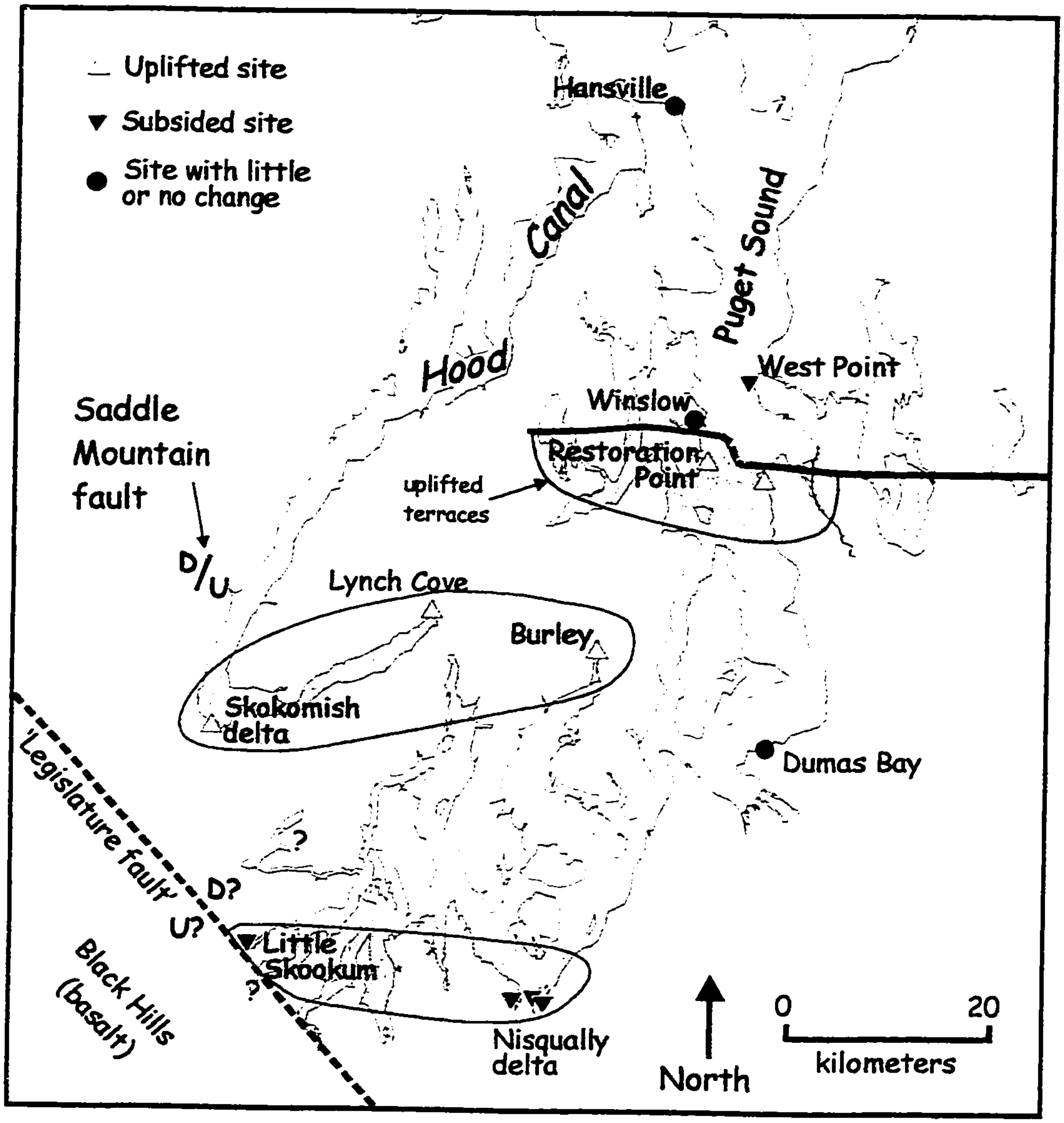


Figure 4-19. Map showing areas of uplift and subsidence that occurred between 1100 and 1000 years ago. Dashed lines shows location of Legislature fault.

CHAPTER 5. LATE HOLOCENE PALEOENVIRONMENTAL CHANGES AND EARTHQUAKES IN SOUTHERN PUGET SOUND, WASHINGTON.

ABSTRACT

Stratigraphic evidence from salt marshes and coastal geomorphology show several distinct areas of shoreline deformation in Puget Sound. In southern Puget Sound, abrupt subsidence occurred between 690 and 1200 years ago. High marsh soils or lowland forests were submerged at four widely-separated sites. Radiocarbon dates from either Douglas-fir stumps or rhizomes of *Triglochin maritima* show that submergence occurred between 1010±50 and 1140±80 ^{14}C years B.P. A combination of stratigraphic evidence and fossil-based elevation inferences indicates that the magnitude of submergence was between ~0.5 and ≥3.4 meters. Biostratigraphic and geomorphic evidence indicates that areas to the south of the Seattle fault were uplifted up to 7.5 meters about 1000 years ago.

The simplest fault configuration to explain the pattern of late Holocene coastal deformation implicates two or more faults, on which large earthquakes occurred at or about the same time. Movement on the Seattle fault resulted in 6.5 – 7 m of uplift to the south of the fault, and slight subsidence north of the fault. I hypothesize that movement on a fault in southern Puget Sound resulted in up to 3.4 m of subsidence. Candidate structures in southern Puget Sound include the Legislature fault near Olympia, Washington, and a small structure along the east side of the Nisqually delta.

INTRODUCTION

Astonishing things happened in Puget Lowland about 1000 years ago. There is evidence for large, enigmatic vertical displacements; a scarp on the Saddle Mountain East fault bordering the Olympic Mountains has over 3 m of vertical offset and a wave-cut platform near Seattle was uplifted between 6 and 7 meters (Bucknam et al., 1992). In addition, tsunamis swept through Puget Sound 1000 years ago (Atwater and Moore, 1992), and huge lahars poured off of Mt. Rainier and flowed northwards in river valleys to the outskirts of Seattle (Hoblitt et al., 1995). It was a truly catastrophic time in the Puget Lowland. This paper presents an equally astonishing finding for Puget Sound: lowland forest and marsh soils subsided into the intertidal zone about 1000 years ago, coincident with a large earthquake (Figure 5-1).

Large geologic structures developed in the Puget Lowland in response to north-south crustal compression. North-south compression is generated by oblique subduction of the Juan de Fuca plate beneath North America (Pratt et al., 1997). The oblique convergence can be visualized by tracking the advection of a particle of crust through time over long seismic cycles. During interseismic periods, the particle travels northeast but then quickly moves westward in quick jerks during earthquakes. The overall net advection is thus in a northward direction. To the north, Vancouver Island in British Columbia acts as a buttress, stopping the crustal advection and helping create the north-south compression. Large thrust faults and folds develop in response to this compression, of which the Seattle fault is an example. To the south of Seattle, a second large structure trends northwest-southeast and runs through Olympia, informally referred to as the "Legislature fault'. Geophysical studies suggest that this structure is either a fold in Eocene basalt underlying the area or a fault. Geologic studies have found evidence for other smaller faults in southern Puget Sound as well. Because of the proximity of geologic structures to highly urbanized areas, it is very important to understanding which structures are capable of producing large earthquakes. I employ stratigraphic studies of coastal marshes to detect past changes in land level associated with earthquakes.

Earlier studies showed that large magnetic and gravity anomalies occur in the Puget Lowland (Gower et al., 1985). Associated with these anomalies are clearly uplifted wavecut platforms. Gower et al. (1985) hypothesized that one of these magnetic anomalies was a large fault trending across Puget Sound, directly under downtown Seattle. Seismic surveys subsequently showed that this fault, the Seattle fault, has 4 east-west trending strands, with the northern-most strand being the most prominent feature of the fault zone (Johnson et al., 1994). A watershed of information on the Seattle fault was published 1992 and showed that this structure was the source of a large earthquake about 1000 years ago (Bucknam et al., 1992, Atwater and Moore, 1992, Shuster et al., 1992; Karlin and Abella, 1992; Jacoby et al., 1992).

GEOLOGIC EVIDENCE FOR EARTHQUAKES

Land deformation accompanies large earthquakes and results in dramatic changes to coastal environments. Uplift occurs on the upthrown block of thrust faults that rupture the surface or fold near-surface rocks (Ruegg et al., 1982). Subsidence also occurs along thrust faults on the downthrown block and results in abrupt submergence of coastal areas, causing burial of lowland soils by estuarine mud (Plafker and Kachadoorian, 1966; Atwater, 1996). Abrupt environmental changes occur when deformation lowers or raises coastal environments relative to sea level (Figure 5-2). Thelinius (1995) found that brackish marsh vegetation died and was replaced by lowland shrub vegetation following uplift of coastal marshes during the 1964 Alaska earthquake. Atwater (1987) observed former pastures buried by intertidal mud following submergence during the 1960 Chile earthquake. One of the principal geologic characteristics of the 1964 Alaska earthquake is the Placer River Silt (Ovenshine et al., 1976), a laminated silt deposited in intertidal areas created near Portage, Alaska during the 1964 Alaska earthquake. The Placer River Silt buries and preserves upright rooted stumps surrounded by a peat-bearing soil layer, preserving evidence of abrupt coseismic subsidence in the geologic record (Ovenshine et al., 1976). Preservation of abrupt environmental changes in stratigraphic records of coastal marshes provides a tool to investigate patterns of late Holocene tectonic deformation.

METHODS

I developed relative sea level histories at sites in Puget Sound using several sources of data to infer abrupt changes in land elevation possibly associated with past earthquakes. First, I mapped tidal creek bank exposures and described gouge cores from several sites to develop a stratigraphic context for sites in southern Puget Sound. I utilized fossil diatoms, seeds, and Foraminifera to reconstruct past environments at each site. Radiocarbon dates on samples from tree stumps and rhizomes of *Triglochin maritima* provide ages of former marsh and soil surfaces (Figure 5-3). I used weighted averaging of modern and fossil diatom assemblages to develop a transfer function for inferring past changes in elevation. In general, the weighted averaging method relates the occurrence of modern diatom species to environmental gradients, in this case elevation of the marsh surface. Once the species-environment relationships are known, a transfer function relates fossil diatom assemblages to past marsh elevation.

Paleoelevation of intertidal surfaces and forest soils were estimated using several techniques. I used transfer function results based on modern and fossil diatom assemblages to infer the elevation of former intertidal deposits at localities in central and southern Puget Sound. At sites with preserved Douglas-fir forest floors, I estimated the elevation of those surfaces using the lowest occurrence of modern Douglas-fir in forests adjacent to the areas with submerged trees. Published information concerning uplift and subsidence along the Seattle fault is also incorporated into this paper.

RESULTS

Evidence for late Holocene coastal deformation is found at several sites in southern Puget Sound. Information concerning submergence of lowland soils is derived from studies of intertidal marshes in southern Puget Sound and two locations along the

Seattle fault in central Puget Sound (Bucknam et al., 1992; Atwater and Moore, 1992). Uplift is summarized from measurements of uplifted wave-cut terraces along the Seattle fault (Bucknam et al, 1992; R. Bucknam, U.S.G.S., personal communication, 1998) and from biostratigraphy of raised intertidal deposits at Restoration Point.

COASTAL SUBMERGENCE AND UPLIFT

Lowland soils buried by estuarine deposits are found at several sites. At the McAllister Creek and Nisqually River localities in southern Puget Sound (Figure 5-1), high marsh soils with *Juncus* cf. *balticus* rhizomes are buried by ~3 m of laminated intertidal mud and massive sand (Figure 5-4). Former Douglas-fir forest floors are buried by low marsh peat at little Skookum Inlet and Red Salmon Creek (Figure 5-1). Both buried forest horizons contain abundant *in-situ* Douglas-fir stumps. Radiocarbon dates on wood from stumps and *Triglochin maritima* rhizomes indicate submergence occurred between 690-1200 years ago. A sand dike cutting across the buried soil, and vented sand on the former soil surface, attest for severe ground shaking at the time of submergence at McAllister Creek. A high marsh soil also underwent rapid submergence at West Point along the Seattle fault between 1000 and 1100 years ago, likely coincident with deposition of sand across the former marsh surface by a tsunami (Atwater and Moore, 1992).

Raised shoreline features along the Seattle fault in central Puget Sound attest to rapid uplift. An uplifted wavecut terrace just south of the Seattle fault records about 7 m of uplift; lack of intermediate shoreline features on the terrace suggest that the uplift was rapid (Bucknam et al., 1992). The elevation of the raised terrace remains about 6-7 m above present-day high tide line for several kilometers south of the Seattle fault, then abruptly decreases to about 1.5 m above high tide at Blake Island (Bucknam, R., U.S.G.S., personal communication, 1998). Biostratigraphic evidence from Restoration Point, just south of the Seattle fault, also suggests between 6-7.5 m of uplift sometime after 1500 years ago (Figure 5-4).

A marsh located near Federal Way, Washington lacks clear evidence for late Holocene vertical deformation. Deposits beneath the marsh at Dumas Bay are up to 6 m thick and consist primarily of sand and mud at the base of the section, overlain by fiberous peats. Rhizomes of *Distichlis spicata* and *Triglochin maritima* found in the mud and peat attest to an intertidal depositional environment for most of the deposits (Figure 5-5). A *Triglochin* leaf base from ~4.2 m below modern ground surface in muddy peat yielded a radiocarbon age of 1930±60 14C years B.P. (Beta-110745). A woody interval between 3.1 and 2.6 m lacks evidence for salt tolerant plants. Foraminifera extracted from sediment samples were dominated by four intertidal taxa; *Trochammina inflata, T. macrescens, Jadammina polystoma*, and *Miliammina fusca*. No Foraminifera were found in samples from 3.3 and 2.5 m in depth (Figure 5-5).

ELEVATION RECONSTRUCTIONS

Patterns of abrupt vertical deformation inferred from geologic evidence provide insight into the timing and location of past earthquakes in Puget Sound region. Changes in inferred elevation along an approximate N-S transect through Puget Sound (A-A' on Figure 5-1) show two distinct areas of subsidence, both bounded to the south by areas of net uplift (Figure 5-6). An earthquake on the Seattle fault between 1000 and 1100 years ago likely resulted in up to 1 m of subsidence to the north of the fault (at West Point and Winslow), and 6-7.5 m of uplift to the south of the fault (Restoration Point and Alki Point) (Bucknam et al., 1992; Atwater and Moore, 1992). This event resulted in up to 8.5 m of elevation change over the five kilometers distance between the areas of uplift and subsidence.

A second area of subsidence is located near Olympia, Washington (Figure 5-1). Inferred elevation changes in this area are variable and large, ranging from ~0.5 m to a minimum of 3.4 m (Figure 5-4). Subsidence is largest at Little Skookum Inlet adjacent to the Black Hills, an area of net uplift. Subsidence is less at three Nisqually Delta localities, ranging from ~0.5 m to a minimum of 1.2 m (Figure 5-4). Three factors indicate that the observed changes in elevation are the result of deformation during a large earthquake in southern Puget Sound between 690 and 1200 years ago.

1. Liquefaction coincided with submergence of a high marsh soil at McAllister Creek (Figure 5-1). Upward-directed sand was injected through subsurface deposits and breached the former marsh surface. Vented sand formed a small volcano directly above where the sand dike broke the surface. The sand is interpreted as extrusive rather than intrusive because laminations in the overlying estuarine mud appear to thin or disappear above the volcano rather than remain constant in thickness (as observed in areas where sand did not mantle the soil surface). This implies that the vented sand created topography on the former soils surface, causing laminations to thin out over high spots and thicken away from high areas.

2. Contacts between buried soils and overlying units are sharp (≤1mm), indicating abrupt rather than gradual change. Abrupt contacts produced by submergence of wetland and forest soils are described from large subduction zone earthquakes in Chile and Alaska (Plafker and Savage, 1970; Ovenshine et al., 1976; Atwater, 1992). Different vegetation communities and environments are associated with the abrupt environmental changes that occurred across these sharp contacts. Nelson (1992) argued that the case for coseismic subsidence is stronger when inferred subsidence involved several different vegetation types and environments across a wide area rather than just tidal wetlands.

3. The magnitude of environmental changes is large enough so that gradual processes capable of causing submergence can be ruled out. Fossil evidence indicates ~0.5 to a minimum of 3.4 m of abrupt submergence between 690 and 1200 years ago. Abrupt changes in macrofossils and fossil diatoms occurred across the upper contacts of buried soils, indicating rapid environmental changes rather than gradual changes. Gradual changes in microfossils across an upper contact of a buried soil suggests a gradual increase or decrease in marine influence (positive or negative sea level tendency) that is incompatible with subsidence during an earthquake (Nelson et al., 1996).

The Dumas Bay locality (Figure 5-1) is important because it lacks clear evidence for vertical land changes in the last ~1900 years. This site is situated between the area of subsidence near Olympia and the area of uplift along the Seattle fault, yet apparently did not participate in either uplift or subsidence. This could be due to lateral variation in deformation, or by deformation on different structures which did not affect Dumas Bay.

SOURCES OF EARTHQUAKES

There are several geologic structures in Puget Sound with potential for generating large earthquakes (M > 7). The lateral variability and large area of deformation suggests that more than one fault is responsible for the inferred late Holocene coastal deformation. capable of producing the observed land deformation. The Seattle fault is implicated by Bucknam et al. (1992) and Atwater and Moore (1992) for producing up to 8.5 m of elevation change (uplift + subsidence) across that structure about 1100 years ago (Figure 5-6). In southern Puget Sound, the largest structure nearest the area of subsidence about 1000 years ago between Olympia and Shelton is informally referred to as the Legislature fault. This structure was interpreted as a homocline by Gower et al. (1985) yet has a deformation pattern similar to the Seattle fault; net uplift to the south and evidence for subsidence to the north. The Legislature fault bounds Eocene basalt to the south and glacial deposits to the north. Similarity in deformation patterns across the Legislature faults and the Seattle fault leads me to speculate that the Legislature fault is a thrust fault rather than a fold. However, it is equally possible that the inferred subsidence observed to the north of the Legislature fault is from movement on some other structure in southern Puget Sound. A radiocarbon date from a single tree stump at Oyster Bay yielded an age of 1110±50 ^{14}C years B.P. (Beta-110745)(Figures 5-1 and 5-3). This age suggests that the trees at Oyster Bay died at about the same time as submergence in other areas of southern Puget Sound; however, evidence for submergence 1000 years ago at Oyster Bay site is not clear. Submergence of Oyster Bay about 1000 years ago would implicate movement on a structure other than the Legislature fault.

It is tempting to speculate that uplift in central Puget Sound and subsidence in southern Puget Sound are linked to movement on the Seattle fault because the deformation in both areas occurred over a relatively short period of time. However, this is unlikely because the submergence happened over 70 km to the south of the uplift along the Seattle fault, too distant to result from movement on just one structure (Figure 5-6). A simpler explanation invokes slip on the Seattle fault about 1100 years ago, and subsequent slip on a structure in southern Puget Sound at about the same time (within a decade to a century?). Other faults include the Legislature fault magnetic anomaly and a small scarp on the bottom of Puget Sound associated with a gravity anomaly along the east located along the east side of the Nisqually delta (Gower at al., 1985).

Uplift also occurred between 500 and 1700 years ago at Lynch Cove and Burley (Figure 5-1), about 20 km north of Nisqually delta and Little Skookum Inlet (Bucknam et al., 1992). This uplift occurred at about the same time as the Seattle fault event but lacks a clearly defined fault source. Sites located between the area of uplift centered around Lynch Cove and the band of subsidence in southern Puget Sound (Figure 4-19) do not show clear-cut evidence for either uplift or subsidence (Bucknam, R, U.S.G.S., personal communication, 1998). The distance separating the areas of uplift and subsidence again indicates that more than one structure is responsible for the pattern of late Holocene land deformation.

Submergence in southern Puget Sound is also temporally correlated to submergence of coastal wetlands along the Cascadia subduction zone, located about 100 km to the west (Atwater and Hemphill-Haley, 1997). Soil W of Atwater and Hemphill-Haley (1997) possibly corresponds to coseismic submergence along the Washington coast between 900 and 1300 years ago (Atwater, 1992). It is possible that some of the submergence in southern Puget Sound resulted from inland subsidence during a great subduction zone earthquake about 1000 years ago. However, no evidence for submergence has been found in other marshes throughout Puget Sound, suggesting a localized structure for the subsidence. Another equally plausible alternative is that earthquakes on faults in the North American plate were triggered by a great earthquake along the subduction zone about 1100 – 1000 years ago (Atwater and Hemphill-Haley, 1997; Clague, 1997).

CONCLUSIONS

1. Buried lowland soils in southern Puget Sound are significant in that they indicate coseismic subsidence between 690 and 1200 years ago, possibly up to 3.4 meters in places. The abruptness and magnitude of submergence, and observed liquefaction at the time of submergence, implies that a large earthquake in southern Puget Sound is responsible for the subsidence.
2. No known localized source for large earthquakes exists in southern Puget Sound. One possible source is the Legislature fault, define by a long, linear magnetic anomaly and previously interpreted as a fold in Eocene basalts underlying the southern Puget Lowland. If this is a fault, it is capable of producing M>7 earthquakes; sufficient to produce the inferred deformation in southern Puget Sound. Another possible fault is located along the east side of the Nisqually delta (Gower et al., 1985) but is likely too small to account for the inferred deformation.
3. Earthquakes in southern Puget Sound, in central Puget Sound along the Seattle fault, and the Cascadia subduction zone occurred either simultaneously or up to several hundred years apart based on radiocarbon ages. Temporal correlations between earthquakes at the subduction zone and earthquakes in the North American plate are loosely constrained at the present.

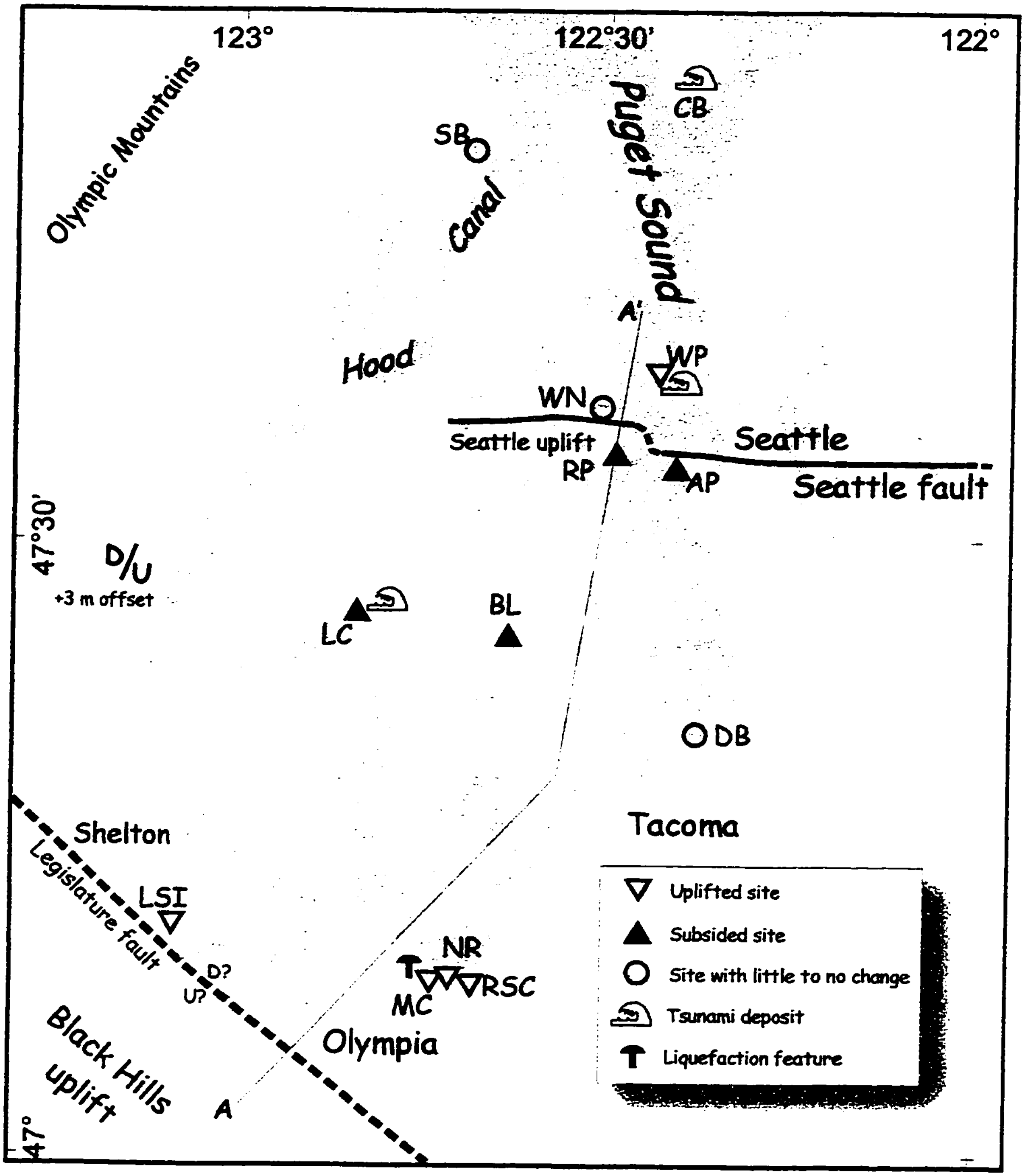


Figure 5-1. Map of Puget Sound showing locations of paleoseismic evidence. Site abbreviations are: LSI - Little Skookum Inlet; OB- Oyster Bay; MC - McAllister Creek; RSC - Red Salmon Creek; BL - Burley Lagoon; LC - Lynch Cove; Restoration Point; AP - Alki Point; WN - Winslow; WP - West Point; SB - Shine Bog; CB - Cultus Bay. Transect line A - A' is shown in Figure 5-6. Information on sites in central Puget Sound from Bucknam et al. (1992) and Atwater and Moore (1992).

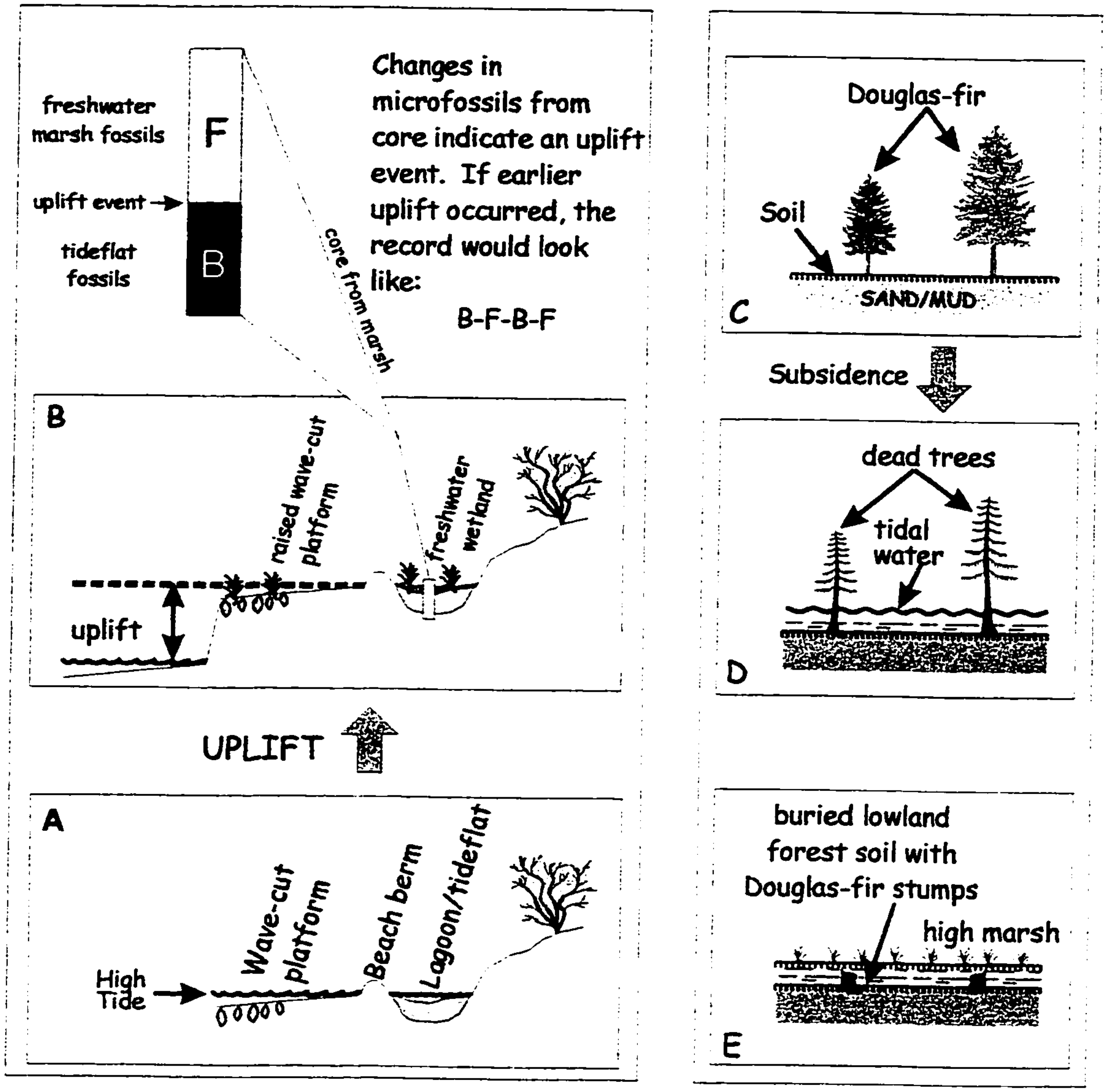


Figure 5-2. Geologic evidence used to infer uplift at a coastal site. A. Pre-uplift conditions at site, with wave-cut platform and molluscan infauna in intertidal zone. A small intertidal lagoon/mudflat exists behind gravel beach berm. B. Post-uplift site conditions, showing raised wave-cut platform, raised gravel beach berm, and small freshwater wetland occupying area of former lagoon. Core sediments from the wetland contain fossils indicative of a brackish water tideflats overlain by a freshwater wetland. Repitition of the brackish-freshwater couplet in earlier parts of the core suggests earlier episodes of uplift. Dates from core sediments help constrain timing of uplift events. Figure boxes C-E represents a conceptual model for subsidence of a forest soil into the intertidal zone in southern Puget Sound. C.. Forest soil with living Douglas-fir. D. Forest soil buried by intertidal deposits after subsidence during an earthquake. Trees were killed by submergence in salt water. E. High marsh soil develops over buried forest soil. Tree stumps rot of at level of sediment accumulation shortly after burial and are buried by accretion of salt marsh peat.

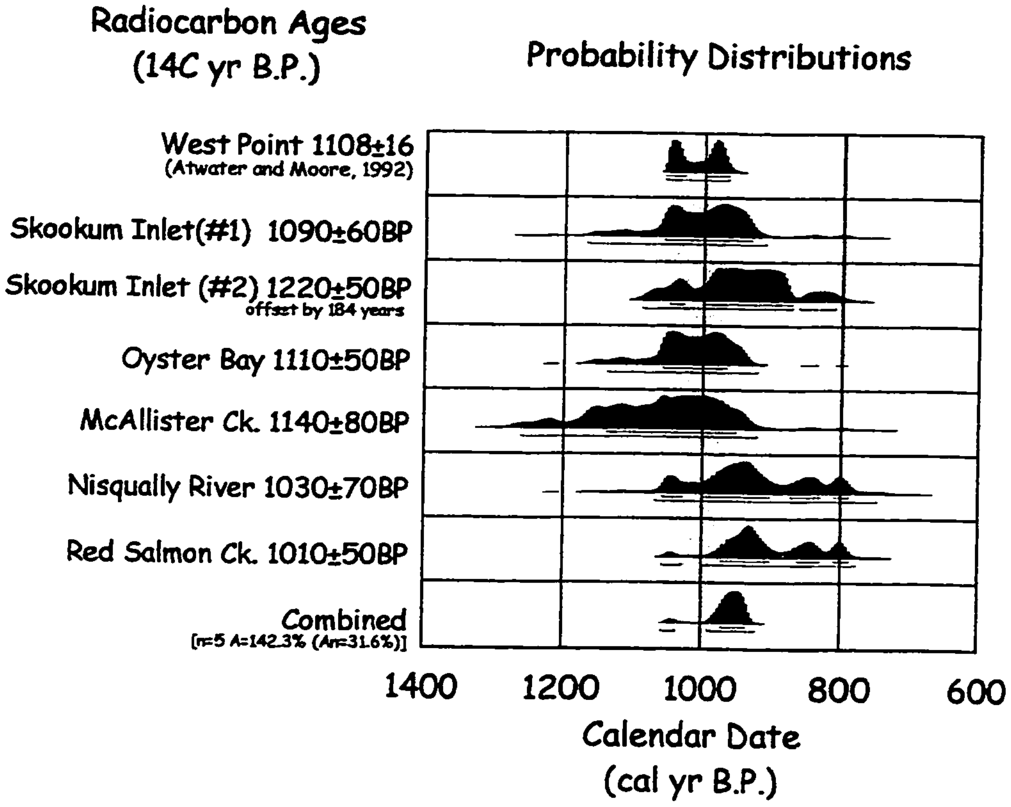


Figure 5-3. Probablity distributions for selected radiocarbon dates from sites in southern Puget Sound. The distribution at the top of the diagram shows the calibrated age range for the 1000-1100 year B.P. Seattle fault event (Atwater and Moore, 1992). The distribution at the bottom of the diagram is the age range (2 sigma, 95.4% confidence interval) for the combined probability distributions on samples from submerged trees and herbaceous plant remains from just above buried soils at sites in southern Puget Sound (does not include Oyster Bay sample).

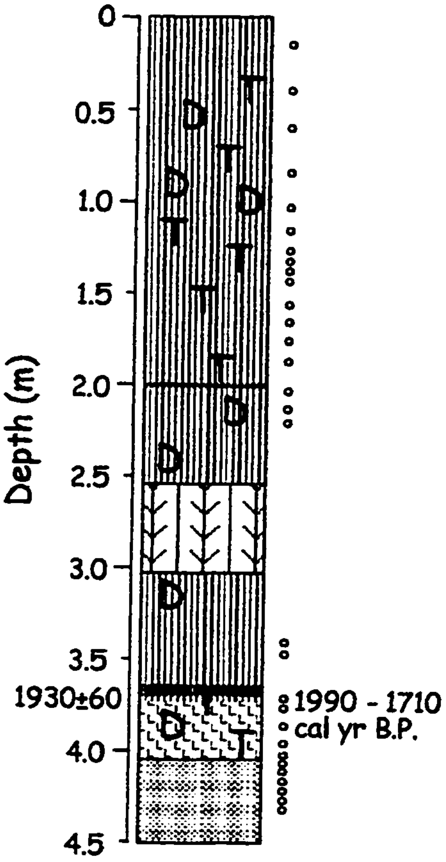


Figure 5-4. Dumas Bay locality stratigraphic section. Letters indicate positions of salt marsh plant rhizomes observed in 5-cm diameter piston core. Small circles indicate positions of samples that contained Foraminifera. Lithology follows Troells-Smith (1955).

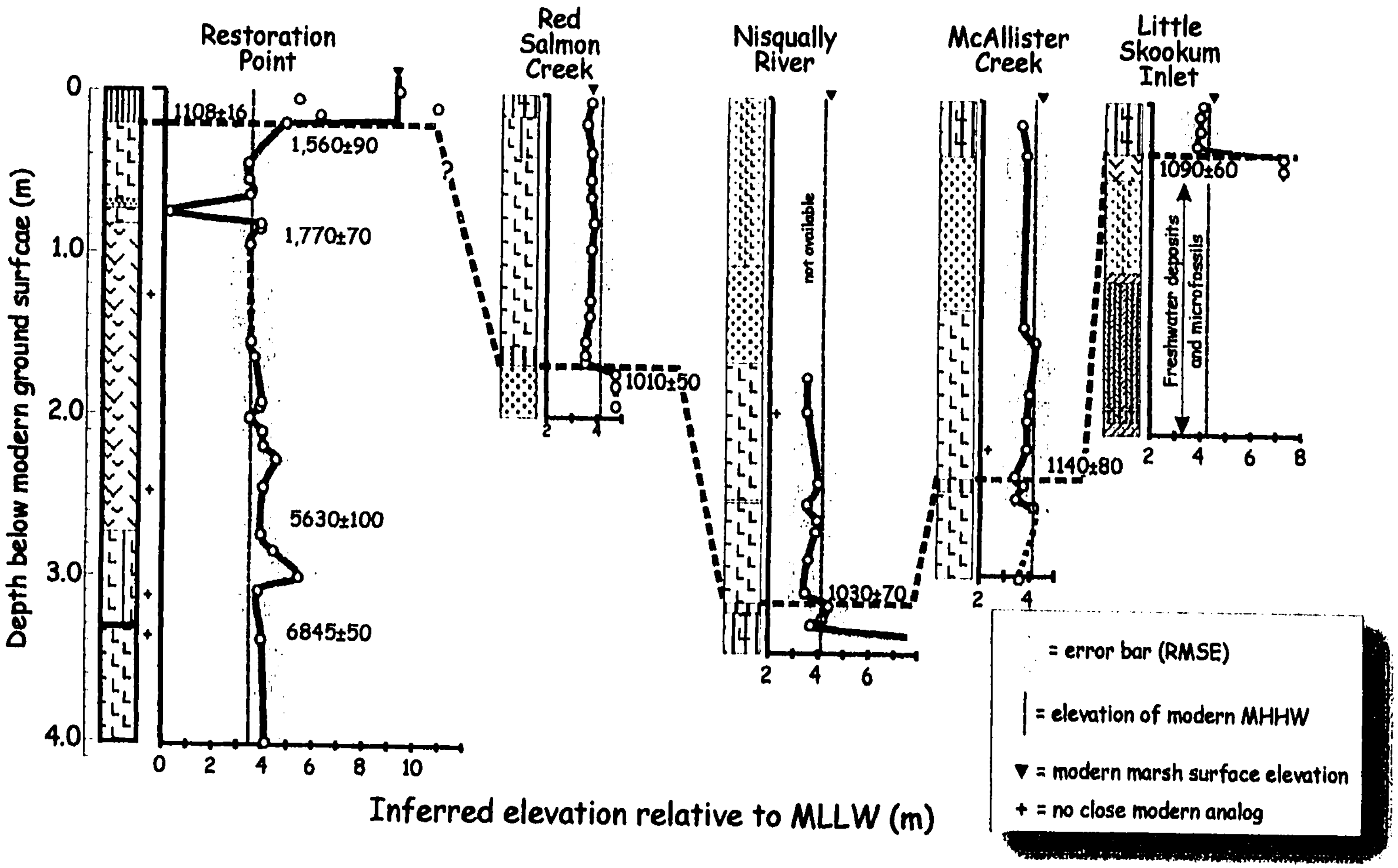


Figure 5-5. Elevation changes inferred from paleoecological evidence at sites in southern and central Puget Sound. The thick dashed line correlates the buried soil at southern Puget Sound localities with tideflat deposits at Restoration Point. Selected radiocarbon dates shown by each core diagram. Lithologic symbols in core diagrams follow Troells-Smith (1955). Note abrupt subsidence across contact of buried soil and overlying deposit in southern Puget Sound at about the same time as abrupt uplift at Restoration Point. All radiocarbon ages are quoted as C yr B.P. Ages from Restoration Point are from Bucknam et al. (1992)

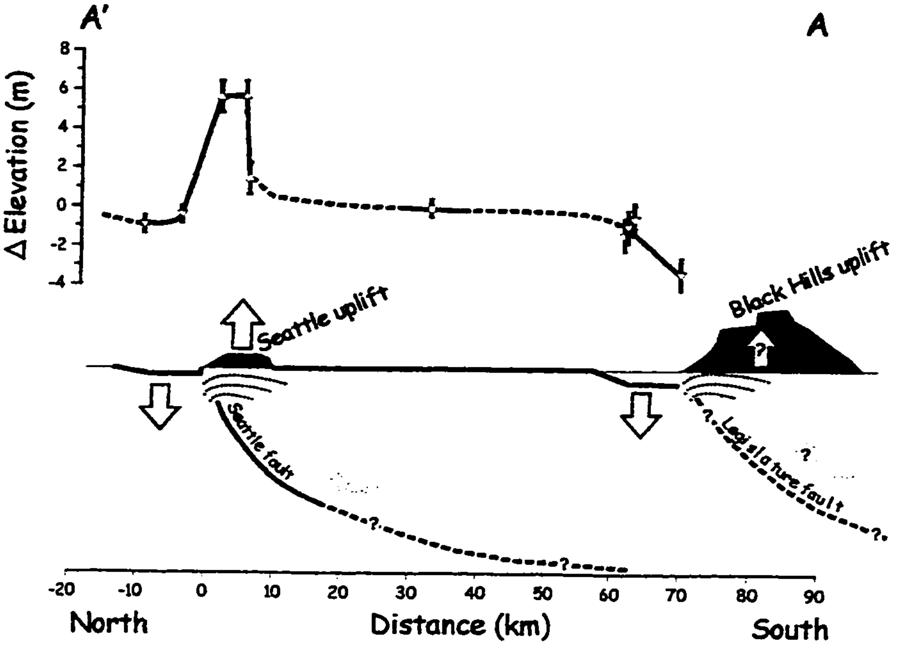


Figure 5-6. Change in elevation at coastal sites in Puget Sound between 690 and 1200 years ago. Site designations are the same as in Figure 5-1. A conceptual fault configuration showing the Seattle fault and Legislature fault is shown in the bottom half of the figure, and illustrates how movement on both structures could produce the inferred land level changes.

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APPENDIX A: SEED AND VEGETATION DATA

Seed and plant cover data used in the association index calculations in Chapter 2 is presented on the following pages.

Vegetation Cover Data used in Association Index Calculation

Meters	*Agropyron* sp.	*Agrostis alba*	*Alnus rubra*	*Anemone* sp.	*Aster* sp.	*Atriplex patula*	*Calamagrostis* sp.	*Carex lyngbyei*	Compositae
RSC2-0	0	0	0	0	0	0	0	0	0
RSC2-10	0	0	0	0	0	2	0	10	0
RSC2-20	0	0	0	0	0	0	0	0	0
RSC2-30	0	0	0	0	0	0	0	5	0
RSC2-40	0	0	0	0	0	0	0	2	0
RSC2-50	0	0	0	0	0	0	0	0	0
RSC2-60	0	0	0	0	0	0	0	0	0
RSC2-70	0	0	0	0	0	0	0	10	0
NISQ-B0	0	0	0	0	0	0	10	0	0
NISQ-B10	2	0	0	0	40	0	35	0	0
NISQ-B20	0	0	0	0	0	0	2	14	0
NISQ-B30	0	0	0	0	0	0	0	8	0
NISQ-B40	0	0	0	0	0	0	8	14	0
NISQ-B50	0	0	0	0	0	0	0	4	0
NISQ-B60	0	0	0	0	0	0	0	0	0
NISQ-B70	0	0	0	0	0	0	0	0	0
NISQ-B80	0	0	0	0	0	0	0	0	0
NISQ-B90	0	0	0	0	0	0	0	0	0
NISQ-B94	0	0	0	0	0	0	0	20	0
NISQ-B95	0	0	0	0	0	0	0	0	0
NISQ-B98	0	0	0	0	0	0	0	0	0
NS10	0	0	0	0	0	1	0	0	0
NS20	0	0	0	0	0	0	0	0	0
NS30	0	0	0	0	0	0	0	0	0
NS50	0	0	0	0	0	0	0	0	0
NS60	0	0	0	0	0	0	0	0	0
NS70	0	0	0	0	0	0	0	0	0
NS100	0	0	0	0	0	0	0	0	0
NS110	0	0	0	0	0	1	0	0	0
NS120	0	0	0	0	0	0	0	0	0
NS130	0	0	0	0	0	0	0	0	0
NS140	0	0	0	0	0	1	0	0	0
NS150	0	0	0	0	0	1	0	0	0
NS160	0	0	0	0	0	0	0	0	0
NS164	0	0	0	0	0	1	0	0	1
LC0	0	0	0	1	0	0	0	0	0
LC10	0	0	1	1	0	0	0	0	0
LC20	0	0	0	0	0	0	0	0	1
LC30	0	0	0	0	0	0	0	0	1
LC40	0	0	0	0	0	0	0	0	1
LC50	0	0	0	0	0	0	0	0	0
LC60	0	0	0	0	0	0	0	0	0
LC70	0	0	0	0	0	0	0	1	0
LC80	0	0	0	0	0	1	0	0	0
LC90	0	0	0	0	0	1	0	0	0
LC100	0	0	0	0	0	1	0	0	0
LC110	0	0	0	0	0	1	0	1	0
LC120	0	0	0	0	0	1	0	1	0
LC130	0	0	0	0	0	1	0	0	0
LC140	0	0	0	0	0	2	0	82	0
LC150	0	0	0	0	0	0	0	0	0
LC160	0	0	0	0	0	1	0	0	0
LC170	0	0	0	0	0	2	0	0	0
LC180	0	0	0	0	0	1	0	0	0
LC190	0	0	0	0	0	1	0	0	0
LC200	0	0	0	0	0	5	0	0	0
LC210	0	0	0	0	0	1	0	0	0
LC213	0	0	0	0	0	0	0	0	0
WIN01	0	0	0	0	0	0	0	0	0
WIN02	0	0	0	0	0	0	0	0	0
WIN03	0	75	0	0	0	0	0	0	0
WIN04	0	20	0	0	0	0	0	0	0
WIN05	0	0	0	0	0	4	0	0	0

e	*Cuscuta salina*	*Deschampsia caespitosa*	*Distichlis spicata*	*Festuca rubra*	*Festuca rubra*	*Galium* sp.	*Glaux* sp.	Graminaeae (undifferentiated)	*Grindelia integrifolia*	*Hordeum brachyantherium*	*Hordeum* sp.
	0	0	0	0	0	0	0	0	0	0	0
	0	0	66	0	0	0	4	0	0	0	0
	1	0	5	0	0	0	1	0	0	0	0
	0	0	60	0	0	0	2	0	0	0	0
	0	0	20	0	0	0	1	0	0	0	0
	0	0	30	0	0	0	8	0	0	0	0
	0	1	63	0	0	0	6	0	0	0	0
	0	0	13	0	0	0	8	0	0	0	0
	0	0	0	0	0	0	0	60	0	0	6
	0	0	3	0	0	0	0	0	0	0	0
	0	6	40	2	0	0	2	0	0	0	0
	0	12	60	2	0	0	3	0	0	0	0
	0	8	28	2	0	0	4	0	0	0	0
	0	8	32	2	0	0	4	0	0	0	4
	0	4	56	0	0	0	4	0	0	0	0
	0	8	46	0	0	0	4	0	0	0	4
	0	0	33	0	0	0	3	0	0	0	1
	0	0	42	0	0	0	2	0	0	0	0
	0	0	60	0	0	0	4	0	0	0	0
	0	0	0	0	0	0	0	0	0	0	0
	0	0	0	0	0	0	0	0	0	0	0
	0	0	1	0	0	0	0	0	0	0	0
	0	0	0	0	0	0	0	0	0	0	0
	0	0	0	0	0	0	0	0	0	0	0
	0	0	0	0	0	0	0	0	0	0	0
	0	0	0	0	0	0	0	0	0	0	0
	0	0	0	0	0	0	0	0	0	0	0
	0	0	10	0	0	0	0	0	0	0	0
	0	0	15	0	0	0	0	0	0	0	0
	0	0	25	0	0	0	0	0	0	0	0
	0	2	15	0	0	0	0	0	0	0	0
	0	1	29	0	0	0	0	0	0	0	0
	0	0	10	0	0	0	0	0	1	0	0
	0	0	5	0	0	0	0	0	0	0	0
	0	0	0	0	0	37	0	0	0	0	0
	0	0	0	0	0	0	0	0	0	0	0
	0	0	0	0	0	0	0	0	0	0	0
	0	0	0	0	0	0	0	0	0	0	0
	0	0	0	0	20	0	0	0	0	0	0
	0	0	0	0	20	0	0	0	0	0	0
	0	0	0	0	89	0	0	0	0	0	0
	0	0	0	0	95	0	0	0	0	0	0
	0	0	0	0	80	0	0	0	0	1	0
	0	0	55	0	29	0	0	0	0	15	0
	0	0	40	0	0	0	0	0	0	0	0
	0	0	50	0	10	0	0	0	0	2	0
	0	0	4	0	4	0	0	0	0	15	0
	0	0	0	0	0	0	0	0	2	0	0
	0	0	20	0	0	0	0	0	0	1	0
	0	0	0	0	0	0	0	0	10	0	0
	0	0	52	0	0	0	0	0	10	4	0
	0	0	39	0	0	0	0	0	0	1	0
	0	0	87	0	0	0	0	0	0	0	0
	0	0	74	0	0	0	0	0	0	0	0
	0	0	50	0	0	0	0	0	0	0	0
	0	0	20	0	0	0	0	0	0	0	0
	0	0	82	0	0	0	0	0	0	0	0
	0	0	80	0	0	0	0	0	0	0	0
	0	0	0	0	0	0	0	0	0	0	0
	0	0	0	0	0	0	0	0	0	0	0
	0	0	0	0	0	0	0	0	0	0	0
	0	0	0	0	0	0	0	0	0	0	0
	0	0	5	0	0	0	0	0	0	0	0

Vegetation Cover Data (Continued)

Meters	*Jaumea carnosa*	*Juncus balticus*	mosses	*Oenanthe sarmentosa*	*Plantago maritima*	*Potentilla pacifica*	*Rosa* sp.	*Rumex crispus*	*Salicorn virginic*
RSC2-0	0	0	0	0	0	0	0	0	0
RSC2-10	4	0	0	0	0	0	0	0	6
RSC2-20	23	0	0	0	34	0	0	0	28
RSC2-30	10	0	0	0	10	2	0	0	1
RSC2-40	8	0	0	0	25	10	0	0	4
RSC2-50	8	0	0	0	8	20	0	0	1
RSC2-60	6	0	0	0	0	20	0	0	0
RSC2-70	6	0	0	0	0	38	0	0	0
NISQ-B0	0	0	0	0	0	4	0	20	0
NISQ-B10	0	0	0	0	0	0	0	0	0
NISQ-B20	0	0	0	0	0	4	0	0	0
NISQ-B30	0	0	0	0	0	4	0	0	0
NISQ-B40	0	2	0	0	0	4	0	0	0
NISQ-B50	0	24	0	0	0	6	0	0	0
NISQ-B60	0	0	0	0	0	16	0	0	0
NISQ-B70	0	0	0	0	0	8	0	0	0
NISQ-B80	0	0	0	0	0	30	0	0	0
NISQ-B90	0	35	0	0	0	12	0	0	0
NISQ-B94	0	0	0	0	0	4	0	0	0
NISQ-B95	0	0	0	0	0	0	0	0	0
NISQ-B98	0	0	0	0	0	0	0	0	0
NS10	0	0	0	0	0	0	0	0	97
NS20	0	0	0	0	0	0	0	0	100
NS30	0	0	0	0	0	0	0	0	100
NS50	0	0	0	0	0	0	0	0	100
NS60	0	0	0	0	0	0	0	0	100
NS70	0	0	0	0	0	0	0	0	100
NS100	72	0	0	0	0	0	0	0	15
NS110	42	0	0	0	0	0	0	0	10
NS120	47	0	0	0	0	0	0	0	20
NS130	54	0	0	0	0	0	0	0	17
NS140	53	0	0	0	1	0	0	0	15
NS150	42	0	0	0	1	0	0	0	41
NS160	0	0	0	0	0	0	0	0	95
NS164	0	0	5	0	0	0	50	0	0
LC0	0	0	0	75	0	0	0	0	0
LC10	0	0	0	85	0	0	0	0	0
LC20	0	0	0	30	0	60	0	0	0
LC30	0	0	0	0	0	40	0	0	0
LC40	0	0	0	0	0	43	0	0	0
LC50	0	3	0	0	0	4	0	0	0
LC60	0	0	0	0	0	5	0	0	0
LC70	0	0	0	0	0	1	0	0	0
LC80	0	0	0	0	0	0	0	0	0
LC90	1	56	0	0	0	0	0	0	1
LC100	0	36	0	0	0	0	0	0	0
LC110	1	44	0	0	0	0	0	0	1
LC120	1	0	0	0	1	0	0	0	5
LC130	2	70	0	0	0	0	0	0	4
LC140	1	0	0	0	0	0	0	0	0
LC150	5	0	0	0	2	0	0	0	25
LC160	0	0	0	0	50	0	0	0	4
LC170	0	0	0	0	1	0	0	0	10
LC180	1	0	0	0	0	0	0	0	8
LC190	1	37	0	0	0	0	0	0	6
LC200	1	32	0	0	0	0	0	0	10
LC210	1	0	0	0	2	0	0	0	10
LC213	20	0	0	0	0	0	0	0	0
WIN01	0	0	0	5	0	50	5	0	0
WIN02	0	0	0	0	0	55	0	0	0
WIN03	0	0	0	0	0	10	0	0	0
WIN04	0	0	0	0	0	30	0	0	0
WIN05	0	0	0	5	0	0	0	0	0

Rumex crispus	*Salicornia virginica*	*Salix* sp.	*Scirpus acutus*	*Scirpus humifusa*	*Taraxicum officinale*	*Triglochin maritima*	*Typha latifolia*	"unknown mint"
0	0	0	0	0	0	0	0	0
0	6	0	0	0	0	8	0	0
0	28	0	0	0	0	8	0	0
0	1	0	0	0	0	10	0	0
0	4	0	0	0	0	30	0	0
0	1	0	0	0	0	25	0	0
0	0	0	0	0	0	4	0	0
0	0	0	0	0	0	25	0	0
20	0	0	0	0	0	0	0	0
0	0	0	0	0	20	0	0	0
0	0	0	0	0	0	30	0	0
0	0	0	0	1	0	10	0	0
0	0	0	0	0	0	30	0	0
0	0	0	0	0	0	16	0	0
0	0	0	0	0	0	20	0	0
0	0	0	0	0	0	30	0	0
0	0	0	0	0	0	33	0	0
0	0	0	0	1	0	8	0	0
0	0	0	0	0	0	12	0	0
0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0
0	97	0	0	0	0	0	0	0
0	100	0	0	0	0	0	0	0
0	100	0	0	0	0	0	0	0
0	100	0	0	0	0	0	0	0
0	100	0	0	0	0	0	0	0
0	100	0	0	0	0	0	0	0
0	15	0	0	0	0	3	0	0
0	10	0	0	0	0	25	0	0
0	20	0	0	0	0	8	0	0
0	17	0	0	0	0	12	0	0
0	15	0	0	0	0	0	0	0
0	41	0	0	0	0	0	0	0
0	95	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0
0	0	1	0	0	0	0	0	20
0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0
0	0	0	10	0	0	0	0	0
0	0	0	35	0	0	0	0	0
0	0	0	0	0	0	4	0	0
0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	17	0	0
0	0	0	0	0	0	0	0	0
0	1	0	0	0	0	1	0	0
0	0	0	0	0	0	1	0	0
0	1	0	0	0	0	0	0	0
0	5	0	0	0	0	88	0	0
0	4	0	0	0	0	1	0	0
0	0	0	0	0	0	5	0	0
0	25	0	0	0	0	0	0	0
0	4	0	0	0	0	0	0	0
0	10	0	0	0	0	0	0	0
0	8	0	0	0	0	16	0	0
0	6	0	0	0	0	5	0	0
0	10	0	0	0	0	32	0	0
0	10	0	0	0	0	4	0	0
0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	30	0
0	0	0	35	0	0	0	0	0
0	0	0	0	0	0	0	0	0
0	0	0	15	0	0	0	0	0
0	0	0	0	0	0	65	0	0

Seed data for Association Index calculation (0=absent, 1=present in sample)

Station	*Agropyron sp.*	*Agrostis alba*	*Alnus rubra*	*Anemone* sp.	*Angelica lucida*	*Aster* sp.	*Arbutus menzeisii*	*Atriplex patula*	*Cala*
RSC2-0	0	0	0	0	0	0	0	0	
RSC2-10	0	0	0	0	0	0	0	0	
RSC2-20	0	0	0	0	0	0	0	0	
RSC2-30	0	0	0	0	0	0	0	1	
RSC2-40	0	0	0	0	0	0	0	1	
RSC2-50	0	0	0	0	0	0	0	0	
RSC2-60	0	0	0	0	0	0	0	1	
RSC2-70	0	0	0	0	0	0	0	1	
NISQ-B0	0	0	0	0	0	0	0	1	
NISQ-B10	0	0	0	0	0	0	0	1	
NISQ-B20	0	0	0	0	0	0	0	1	
NISQ-B30	0	0	1	0	0	0	0	1	
NISQ-B40	0	0	0	0	0	0	0	0	
NISQ-B50	0	0	0	0	0	0	0	0	
NISQ-B60	0	0	0	0	0	0	0	1	
NISQ-B70	0	0	0	0	0	0	0	0	
NISQ-B80	0	0	0	0	0	0	0	0	
NISQ-B90	0	0	0	0	0	0	0	0	
NISQ-B94	0	0	0	0	0	0	0	1	
NISQ-B95	0	0	0	0	0	0	0	0	
NISQ-B98	0	0	0	0	0	0	0	0	
NS010	0	0	1	0	0	0	0	1	
NS030	0	0	1	0	0	0	0	0	
NS050	0	0	0	0	0	0	0	0	
NS060	0	0	0	0	0	0	0	0	
NS070	0	1	0	0	0	0	0	1	
NS080	0	0	1	0	0	0	0	0	
NS090	0	0	0	0	0	0	0	1	
NS100	0	0	0	0	0	0	0	0	
NS110	0	0	1	0	0	0	0	1	
NS120	0	1	0	0	0	0	0	1	
NS130	0	0	1	0	0	0	0	1	
NS140	0	1	1	0	0	0	0	0	
NS150	0	1	1	0	0	0	0	1	
NS160	0	0	0	0	0	0	0	0	
NS164	0	0	0	0	0	0	1	0	
LC0	0	0	1	0	1	0	1	0	
LC10	0	0	1	0	1	0	0	0	
LC20	0	0	0	0	1	0	0	0	
LC30	0	0	0	0	1	0	0	0	
LC40	0	0	0	0	0	0	0	0	
LC60	0	0	0	0	0	0	0	0	
LC80	0	1	0	0	0	0	0	0	
LC90	0	0	0	0	0	0	0	0	
LC110	0	0	0	0	0	0	0	1	
LC120	0	0	0	0	0	0	0	1	
LC130	0	0	0	0	0	0	0	0	
LC140	0	0	0	0	0	0	0	1	
LC160	0	0	0	0	0	0	0	1	
LC170	0	0	1	0	0	0	0	1	
LC200	0	1	0	0	0	0	0	1	
LC210	0	0	0	0	0	0	0	0	
WIN01	0	0	0	0	0	0	0	0	
WIN02	0	1	0	0	0	0	0	1	
WIN03	0	1	0	0	0	0	0	1	
WIN04	0	1	0	0	0	0	0	1	
WIN05	0	1	0	0	0	0	0	0	

Calamagrostis sp.	*Carex lyngbeyi*	Compositee	*Cuscuta cuscuta*	*Deschampsia caespitosa*	*Distichlis spicata*	Ericaceae	*Festuca rubra*	*Galium* sp.	*Gaultheria shalon*
0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0
0	1	0	0	0	0	0	0	0	0
0	1	0	0	0	0	0	0	0	0
0	1	0	0	0	0	0	0	0	0
0	0	0	0	0	1	0	0	0	0
0	0	0	0	1	1	0	0	0	0
0	1	0	0	1	0	0	0	0	0
0	1	0	0	1	0	0	0	0	0
0	1	0	0	1	1	0	0	0	0
0	1	0	0	1	1	0	0	0	0
0	1	0	0	1	1	0	0	0	0
0	1	0	0	1	1	0	0	0	0
0	1	0	0	1	1	0	0	0	0
0	1	0	0	0	0	0	0	0	0
0	0	0	0	1	1	0	0	0	0
0	0	0	0	1	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0
0	1	0	0	0	0	0	0	0	0
0	0	0	0	0	1	0	0	0	0
0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	1
0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	1	0	0	0	0
0	0	0	0	0	0	0	0	0	0
0	0	0	1	0	1	0	0	0	0
0	0	0	0	0	1	0	0	0	0
0	0	0	0	0	0	0	0	0	0
0	0	0	1	0	0	1	0	0	0
0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	1	0	0	0	0
0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	1	0	0	0	0
0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	1	0	0	0	0
0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0

Seed data (Continued)

Station	*Glaux* sp.	*Grindelia integrifolia*	*Holodiscus discolor*	*Hordeum* sp.	*Jaumea carnosa*	*Juncus balticus*	*Juncus effusus*	mosses
RSC2-0	0	1	0	0	0	0	0	0
RSC2-10	0	0	0	0	0	0	0	0
RSC2-20	0	1	0	0	0	0	0	0
RSC2-30	0	1	0	0	0	0	0	0
RSC2-40	0	1	0	0	1	0	0	0
RSC2-50	0	0	0	0	0	0	0	0
RSC2-60	0	0	0	0	1	0	0	0
RSC2-70	0	1	0	0	1	0	0	0
NISQ-B0	0	0	0	0	0	0	0	0
NISQ-B10	0	0	0	0	0	0	0	0
NISQ-B20	0	0	0	0	0	0	0	0
NISQ-B30	0	0	0	0	0	1	0	0
NISQ-B40	0	0	0	0	1	1	0	0
NISQ-B50	0	0	0	0	0	1	0	0
NISQ-B60	0	0	0	0	0	1	0	0
NISQ-B70	0	0	0	0	0	1	0	0
NISQ-B80	0	0	0	0	0	0	0	0
NISQ-B90	0	0	0	0	0	0	0	0
NISQ-B94	0	1	0	0	0	0	0	0
NISQ-B95	0	0	0	0	0	0	0	0
NISQ-B98	0	0	0	0	0	0	0	0
NS010	0	0	0	0	0	0	0	0
NS030	0	0	0	0	0	0	0	0
NS050	0	0	0	0	0	0	0	0
NS060	0	0	0	0	0	0	0	0
NS070	0	0	0	0	0	0	0	0
NS080	0	0	0	0	0	0	0	0
NS090	0	0	0	0	0	0	0	0
NS100	0	0	1	0	0	0	0	0
NS110	0	0	0	0	0	0	0	0
NS120	0	0	0	0	0	0	0	0
NS130	0	0	0	0	1	0	0	0
NS140	0	0	0	0	0	0	0	0
NS150	0	0	1	0	1	0	0	0
NS160	0	0	0	0	0	0	0	0
NS164	0	0	1	0	0	0	0	0
LC0	0	0	1	0	0	1	0	0
LC10	0	0	1	0	0	0	0	0
LC20	0	0	0	0	0	0	0	0
LC30	0	0	0	0	1	0	0	0
LC40	0	0	0	0	1	0	0	0
LC60	0	0	0	0	0	0	0	0
LC80	0	0	0	0	0	1	0	0
LC90	0	0	0	0	0	1	0	0
LC110	0	0	0	0	0	1	0	0
LC120	0	1	0	0	0	1	0	0
LC130	0	0	0	1	0	0	0	1
LC140	0	0	0	0	0	0	0	0
LC160	0	0	0	0	0	1	0	0
LC170	0	0	0	0	0	1	0	0
LC200	0	0	0	0	0	1	0	0
LC210	0	0	0	0	0	0	0	0
WIN01	0	0	0	0	0	0	0	0
WIN02	0	0	0	0	0	0	0	0
WIN03	0	0	0	0	0	0	0	0
WIN04	0	0	0	0	0	0	1	0
WIN05	0	0	0	0	0	0	0	0

Onenanthe sarmentosa	*Picea sitchensis*	*Plantago maritima*	*Plantago* sp.	*Potentilla pacifica*	*Prunus* sp.	*Pseudotsuga menzeisii*	*Ranunculus repens*	*Rosa* sp.	*Rubus* sp.
0	0	0	0	1	1	3	0	0	1
0	0	1	0	0	0	1	0	0	0
0	0	1	0	0	0	3	0	0	0
0	0	1	0	0	0	0	0	0	0
0	0	1	0	0	0	1	0	0	0
0	0	0	0	1	0	0	0	0	0
0	0	0	0	1	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0
1	0	1	0	1	0	0	0	0	1
0	0	0	0	0	0	0	0	0	0
1	0	1	0	1	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0
0	0	0	0	1	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0
0	0	0	0	1	0	0	0	0	0
0	0	0	0	1	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0
0	0	1	0	1	0	0	0	0	0
0	0	0	0	0	0	0	0	0	1
0	0	0	0	0	0	0	0	0	0
0	1	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	1
0	0	0	0	0	0	0	0	0	1
0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0
1	0	0	0	0	0	1	1	0	0
0	0	0	0	0	0	1	1	0	0
0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0
0	0	0	1	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0
1	0	0	0	1	0	0	0	1	0
1	0	0	0	1	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0
0	0	0	0	1	0	0	0	0	0
0	0	0	0	1	0	0	0	0	0

Seed data (Continued)

Station	*Rumex* sp.	*Salicornia virginica*	*Salix* sp.	*Scirpus acutus*	*Spergularia canadensis*	*Taraxcum officinale*	*Thuja plicata*	*Trifolium* sp.
RSC2-0	0	0	0	0	0	0	1	0
RSC2-10	0	0	0	0	0	0	0	0
RSC2-20	0	1	0	0	0	0	0	0
RSC2-30	0	0	0	0	0	0	0	0
RSC2-40	0	1	0	0	0	0	0	0
RSC2-50	0	1	0	0	0	0	0	0
RSC2-60	0	1	0	0	0	0	0	0
RSC2-70	0	0	0	0	0	0	0	0
NISQ-B0	1	1	0	0	0	0	0	0
NISQ-B10	1	0	0	0	0	0	0	0
NISQ-B20	0	0	0	0	0	0	0	0
NISQ-B30	0	0	0	0	0	0	0	0
NISQ-B40	0	1	0	0	0	0	0	0
NISQ-B50	0	0	0	0	0	0	0	0
NISQ-B60	0	0	0	0	0	0	0	0
NISQ-B70	0	1	0	0	0	0	0	0
NISQ-B80	0	1	0	0	0	0	0	0
NISQ-B90	0	0	0	0	0	0	0	0
NISQ-B94	0	1	0	0	0	0	0	0
NISQ-B95	0	1	0	0	0	0	0	0
NISQ-B98	0	0	0	0	0	0	0	0
NS010	0	1	0	0	1	0	0	0
NS030	0	1	0	0	0	0	0	0
NS050	0	1	0	0	0	0	0	0
NS060	0	0	0	0	1	0	0	0
NS070	0	1	0	0	1	0	0	0
NS080	0	0	0	0	0	0	0	0
NS090	0	1	0	0	0	0	0	0
NS100	0	1	0	0	1	0	0	1
NS110	0	1	0	0	1	0	0	0
NS120	0	1	0	0	1	0	0	0
NS130	0	1	0	0	1	0	0	0
NS140	0	0	0	0	1	0	0	0
NS150	0	1	0	0	1	0	0	0
NS160	0	1	0	0	1	0	0	0
NS164	0	0	0	0	1	0	0	0
LC0	0	0	0	0	0	0	0	0
LC10	0	0	0	0	0	0	1	0
LC20	0	0	0	0	0	0	0	0
LC30	0	0	0	0	0	0	0	0
LC40	0	0	0	0	0	0	0	0
LC60	0	0	0	0	0	0	0	0
LC80	0	0	0	0	0	0	0	0
LC90	0	0	0	0	0	0	0	0
LC110	0	1	0	1	1	0	0	0
LC120	0	0	0	0	1	0	0	0
LC130	0	0	0	0	1	0	0	0
LC140	0	0	0	1	0	0	0	0
LC160	0	1	0	0	1	0	0	0
LC170	0	1	0	0	1	0	0	0
LC200	0	1	0	0	1	0	0	0
LC210	0	0	0	0	0	0	0	0
WIN01	0	0	0	0	0	0	0	0
WIN02	0	0	0	0	0	0	0	0
WIN03	0	0	0	1	0	0	0	0
WIN04	0	0	0	0	0	0	0	0
WIN05	0	0	0	0	0	0	0	0

ja plicata	*Trifolium* sp.	*Triglochin maritima*	*Typha latifolia*	*Urtica dioica*
1	0	0	0	0
0	0	1	0	0
0	0	0	0	0
0	0	1	0	0
0	0	1	0	0
0	0	1	0	0
0	0	1	0	0
0	0	1	0	0
0	0	1	0	0
0	0	1	0	0
0	0	1	0	0
0	0	1	0	0
0	0	1	0	0
0	0	1	0	0
0	0	1	0	0
0	0	1	0	0
0	0	1	0	0
0	0	1	0	0
0	0	1	0	0
0	0	1	0	0
0	0	0	0	0
0	0	0	0	0
0	0	0	0	0
0	0	0	0	0
0	0	0	0	0
0	0	0	0	0
0	0	0	0	0
0	0	0	0	0
0	1	0	0	0
0	0	1	0	0
0	0	1	0	0
0	0	1	0	0
0	0	0	0	0
0	0	1	0	0
0	0	0	0	0
0	0	0	0	0
0	0	0	1	1
1	0	0	1	1
0	0	0	1	0
0	0	0	1	0
0	0	0	1	0
0	0	1	0	0
0	0	0	0	1
0	0	0	1	0
0	0	1	1	0
0	0	0	0	0
0	0	0	0	0
0	0	1	0	0
0	0	0	1	0
0	0	1	0	0
0	0	1	1	1
0	0	1	0	0
0	0	0	1	0
0	0	0	1	0
0	0	0	0	0
0	0	1	0	0
0	0	1	0	0

VITA

Brian L. Sherrod

University of Washington
1998

EDUCATION

- Ph.D., University of Washington, Department of Geological Sciences, 1998. Dissertation Title: Holocene paleoenvironments and earthquakes in southern Puget Sound (Chairperson: Estella B. Leopold, Ph.D.).
- M.S., Geology, University of Pittsburgh, Pittsburgh, Pennsylvania, 1989. Thesis Title: Paleolimnology of Alder Lake, Yellowstone National Park (Chairperson: Cathy Whitlock, Ph.D.).
- B.S. (2), Geology and Anthropology, James Madison University, Harrisonburg, Virginia, 1986.
- Certificate; Ground Water Resources, J. Sargent Reynolds Community College, Richmond, Virginia, 1983

PROFESSIONAL POSITIONS

1. *Geologist*, U.S. Geological Survey, Seattle, Washington. Intermittent appointment, September, 1994 - present. Duties: paleoseismology, coastal marsh/estuarine paleoecology, diatom and plant macrofossil analysis. Supervisor: Estella B. Leopold and Robert C. Bucknam (Golden, CO).

2. *Teaching Assistant*, University of Washington, Intermittent appointment, January, 1995 - present. Duties: teach introductory and upper level geology and Botany laboratories; lead a first year graduate student seminar on effective teaching. Supervisor: Bruce Nelson, Ph.D., Stanley Chernicoff, Ph.D., Estella B. Leopold, Ph.D.

3. *Geologist*, URS Consultants, Inc., Seattle, Washington, December, 1993 - September, 1994; March, 1990 - April, 1991. Duties: Task manager on multimillion dollar remedial investigation/feasibility studies at hazardous waste sites in the Pacific Northwest; data management coordination; database development within an Oracle-based data management group. Supervisor: David Mohr, P.E.

4. *Geologist*, Enviros, Inc., Kirkland, Washington. April, 1991 - December, 1993. Duties: Project management, hydrogeologic investigations, tidal monitoring of coastal aquifers. Supervisor: Kathleen Goodman, R.G.

5. *Research Assistant*, Carnegie Museum of Natural History, Pittsburgh, Pennsylvania. August, 1988 - December, 1989. Duties: pollen and macrofossil analyses; vertebrate fossil curation, lake coring, field stratigraphy, packrat midden excavation. Supervisor: Anthony D. Barnosky, Ph.D., and Cathy Whitlock, Ph.D.

6. *Lab Assistant*, University of Pittsburgh, Pittsburgh, Pennsylvania. August, 1986 - August, 1988. Duties: prepared petrographic samples and performed digital cartography using AutoCad. Supervisor: Jim Dwyer.

7. *Archaeologist*, James Madison University, Harrisonburg, Virginia. August, 1984 - August, 1986. Duties: directed excavations and field surveys, prepared project reports, artifact preparation and analysis. Supervisor: Clarence Geier, Ph.D.

TEACHING EXPERIENCE

Introduction to Geology (laboratory)
Geology of the Pacific Northwest (laboratory)
Stratigraphy (laboratory)
Effective Teaching Seminar (first year Geology TA's)
Origins of Modern Floras (laboratory)
Laboratory in Environmental Problems (both lecture and laboratory)

MEMBERSHIPS IN PROFESSIONAL ORGANIZATIONS

American Geophysical Union (student member)
International Diatom Society (student member)

AWARDS AND HONORS

- STAR award, U.S. Geological Survey, , 1998.
- Lead Teaching Assistant, Dept. of Geological Sciences, University of Washington, 1997.
- Best Paper, Geologic Section, Pacific Division, American Association for the Advancement of Science, Annual Meeting, Vancouver, British Columbia, 1995.
- Dean's Scholarship, University of Pittsburgh, 1988-1989.

- Graduating Geology Senior with Best Academic Year, James Madison University, 1986.

- Student Representative, National Water Well Association, J. Sargent Reynolds Community College, Richmond, Virginia, 1983.

PUBLICATIONS

Sherrod, B.L., in press, Gradient analysis of sedimentary diatom assemblages from a Puget Sound salt marsh. *Paleogeography, Paleoclimatology, Paleoecology.*

Sherrod, B.L., Rollins, H.B., and Kennedy, S.K., 1988, Subrecent intertidal diatoms from St. Catherine's Island, Georgia: Taphonomic implications. *Journal of Coastal Research*, vol. 5(4), pg. 665-677.

PAPERS PRESENTED AT MEETINGS

Sherrod, B. L., 1995. Salt marsh diatom taphonomy: Examples from the coast of Georgia and Puget Sound, Washington. *Geological Society of America*, Annual Meeting, v. 27(6), p. A-29.

Sherrod, B.L., and Leopold, E.B., 1995. Recurrent relative sealevel changes at Restoration Point, Washington: Tectonics or Eustasy? *Geological Society of America*, Annual Meeting, v. 27(6), p. A-365.

Sherrod, B.L., Bucknam, R.C, and Leopold, E.B., 1995. Holocene paleoenvironments at Restoration Point, Washington: Implications for prehistoric earthquakes in central Puget Sound. *American Association for the Advancement of Science*, Pacific Division, Annual Meeting, v. 14(1), p. 21.

Sherrod, Brian L., 1989. Postglacial diatom succession in Alder Lake, Yellowstone National Park. *X North American Diatom Symposium*, Abstract No. 30.

Sherrod, B.L., Rollins, H.B, and Kennedy, S.K., 1988. Subrecent intertidal diatoms from St. Catherine's Island, Georgia: Taphonomic implications. *Geological Society of America*, Annual Meeting, v. 20(6).

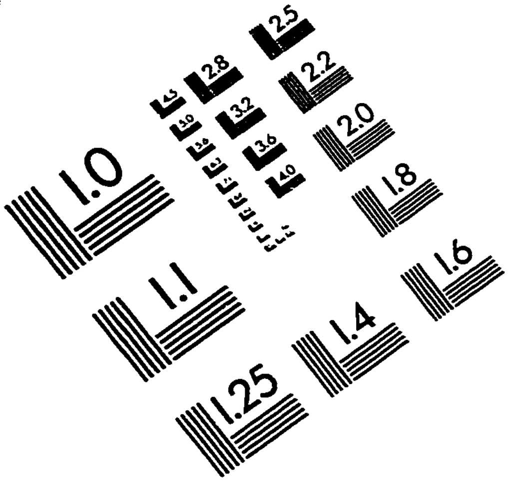
Sherrod, B.L., 1986. Sedimentology and depositional environments of the uppermost Martinsburg Formation and "Cub" sandstone at Catherine's Furnace. *Virginia Journal of Science*, v. 37(2), p. 108.

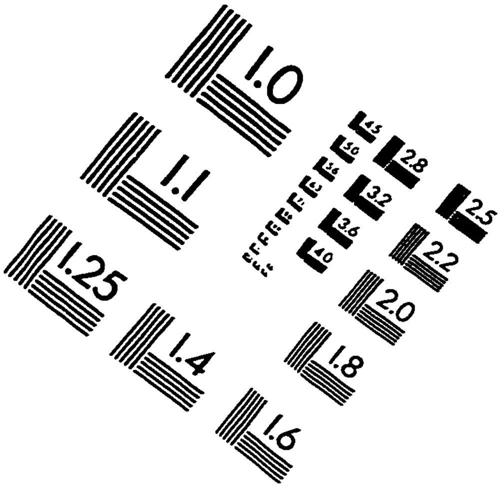
ABSTRACTS COAUTHORED

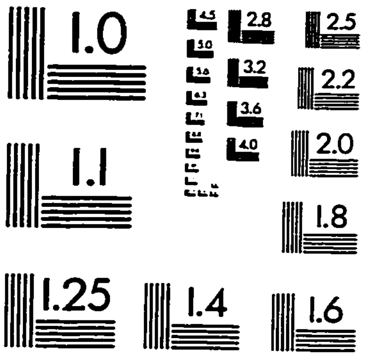
Bucknam, Robert C., Perkins, David M., and Sherrod, Brian L., 1997. Developing quantitative seismic hazard information from incomplete paleoseismic records - Examples from the Puget Sound region, Washington. *Geological Society of America*, Annual Meeting, v. 29(6).

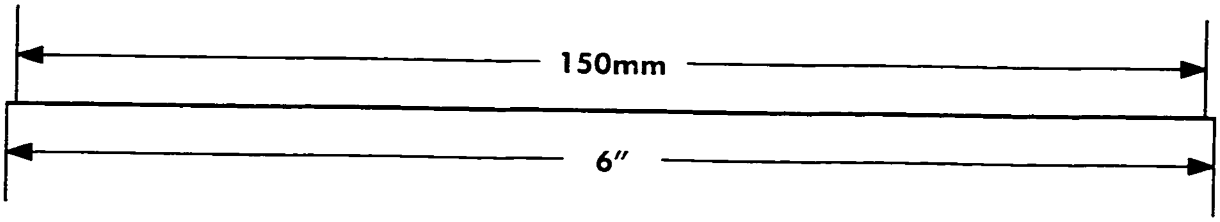
Bucknam, R.C., Sherrod, B.L., and Leopold, E.B., 1995. Late Holocene deformation along the Seattle fault and other areas of the Puget Sound region, Washington. *Geological Society of America*, Cordilleran Section, v. 28(5), p. 21.

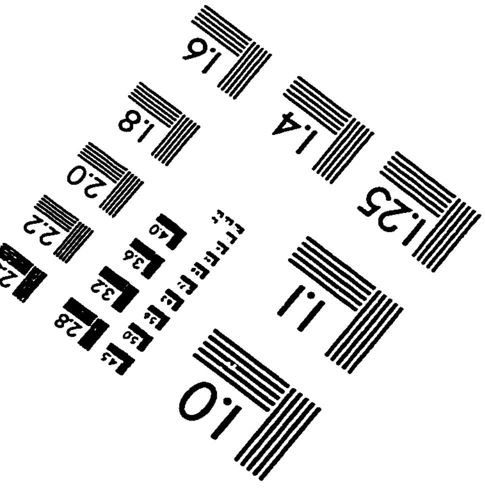
IMAGE EVALUATION
TEST TARGET (QA-3)

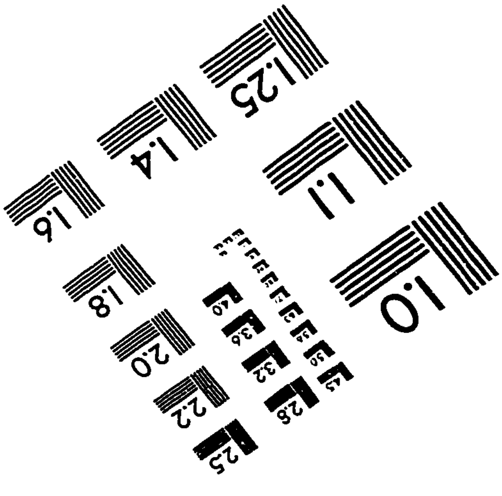












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