Applications of foraminifera to detecting land level change associated with great earthquakes along the west coast of North America

by

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ABSTRACT

Microfossils such as foraminifera, diatoms and pollen serve as proxy indicators of environmental change in tidal marsh environments. In this study, marsh foraminifera were used to estimate the magnitude of land-level change at Willapa Bay, Washington during repeated great (M>8) earthquakes at the Cascadia subduction zone. Tidal muds abruptly overlie buried high marsh soils in estuarine wetlands along the Pacific coast from northern California to central Vancouver Island. This stratigraphy records sudden submergence during great earthquakes.

A large brackish marsh along Niawiakum River at Willapa Bay was selected for this study because it contains buried soils that record the last seven great Cascadia earthquakes. The zonation of marsh foraminiferal species at Willapa Bay is closely related to elevation. Foraminiferal zonation in the modern marsh was determined by visually analysing, and applying cluster analysis to, surface samples collected along a transect across the marsh. Three zones were delimited: low marsh (1.30-2.23 m above MLLW), middle marsh (2.23-2.86 m above MLLW), and high marsh (2.86-3.06 m above MLLW). Modern foraminiferal assemblages were compared to fossil assemblages recovered from a vertical sediment monolith to estimate the paleoelevation of fossil samples. Amounts of coseismic subsidence of ~1 m were calculated using these estimates and a transfer function derived from partial least squares. Due to a limited sampling range for the modern analogue of the lowest marsh zone relative, these values are considered as minima. The values are similar to estimates of coseismic subsidence in other parts of coastal Washington, Oregon and British Columbia. This research complements similar diatom- and pollen-based studies at Willapa Bay and contributes to a multi-proxy assessment of the earthquake history of the area.

DEDICATION

To all those people who have been there for me: a family of support,
friendships that go the distance, and partners in crime.

For those who were there for the ride, and for those who are left in memory,
thanks for being a part of my journey.

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INTRODUCTION

Microfossils, such as diatoms, pollen and foraminifera, are important tools for reconstructing past environments. In many instances, a site's environmental and geological history can be inferred by comparing modern and fossil microfossil assemblages (Scott *et al.*, 2001). A number of studies have used foraminifera to interpret past environments due to their abundance in marine settings, their ability to react quickly to environmental change, and their relative ease of sampling. One relatively new use of foraminifera is in investigations of seismically induced coastal land movements (e.g. Guilbault *et al.*, 1995, 1996; Scott *et al.*, 2001; Shennan *et al.*, 1996, 1998, 1999). These investigations complement those done using pollen, diatoms and plant macrofossils, providing a multi-proxy approach for determining the pattern of coseismic deformation during large earthquakes in the past.

This study uses marsh foraminifera to estimate the magnitude of coastal land-level changes associated with past great earthquakes at the Cascadia subduction zone. A large tidal salt marsh at Niawiakum River, Willapa Bay, southwestern Washington, was chosen for this project, as it contains well-documented geologic evidence of large earthquakes during the late Holocene. Estimates of coseismic land-level change at this site are made by comparing fossil foraminiferal assemblages with modern assemblages of known elevation. The estimates are based on surveys and sampling of the present marsh, and lithostratigraphic logging of monoliths.

Background

Cascadia subduction zone earthquakes

Numerous very large earthquakes have occurred at the Cascadia subduction zone (CSZ) along the west coast of North America during the late Holocene. The CSZ extends offshore from the north end of Vancouver Island, British Columbia, to northern California, and marks the boundary between the subducting oceanic Juan de Fuca plate and the less dense continental North America plate (Figure 1). Part of the interface, or megathrust fault, separating the two plates is presently locked and accumulating a large amount of strain (Atwater *et al.*, 1995; Clague, 1997). This strain will ultimately be released in a 'great' ($M \geq 8$) earthquake. At least seven such earthquakes have occurred at 100-1000 year intervals over the past 3500 years (Atwater and Hemphill-Haley, 1997; Atwater *et al.*, 2004). Future similar earthquakes pose a significant hazard to the growing number of people who live in the Pacific Northwest.

There is abundant geologic evidence along the Pacific coast for repeated great earthquakes during the Holocene. This evidence includes buried marsh and forest soils and tsunami deposits beneath tidal marshes and estuarine wetlands (Atwater, 1987, 1992; Darienzo and Peterson, 1990; Atwater and Yamaguchi, 1991; Nelson, 1992; Clague and Bobrowsky, 1994; Atwater *et al.*, 1995; Atwater and Hemphill-Haley, 1997; Clague, 1997; Clague *et al.*, 1998), and tsunami deposits in coastal lakes (Hutchinson *et al.*, 1997, 2000; Kelsey *et al.*, 1998, Clague *et al.*, 1999). In most cases, the buried marsh soils (peat) are abruptly overlain by tidal muds. Such sharp contacts occur along passive coasts, but their abundance and areal extent in Cascadia, along with the tsunami sands that overlie some of them, argue for a seismic origin (Shennan *et al.*, 1996). The lithostratigraphic sequences are best explained by sudden submergence associated with coseismic subsidence during great earthquakes (Atwater *et al.*, 1995; Clague, 1997).

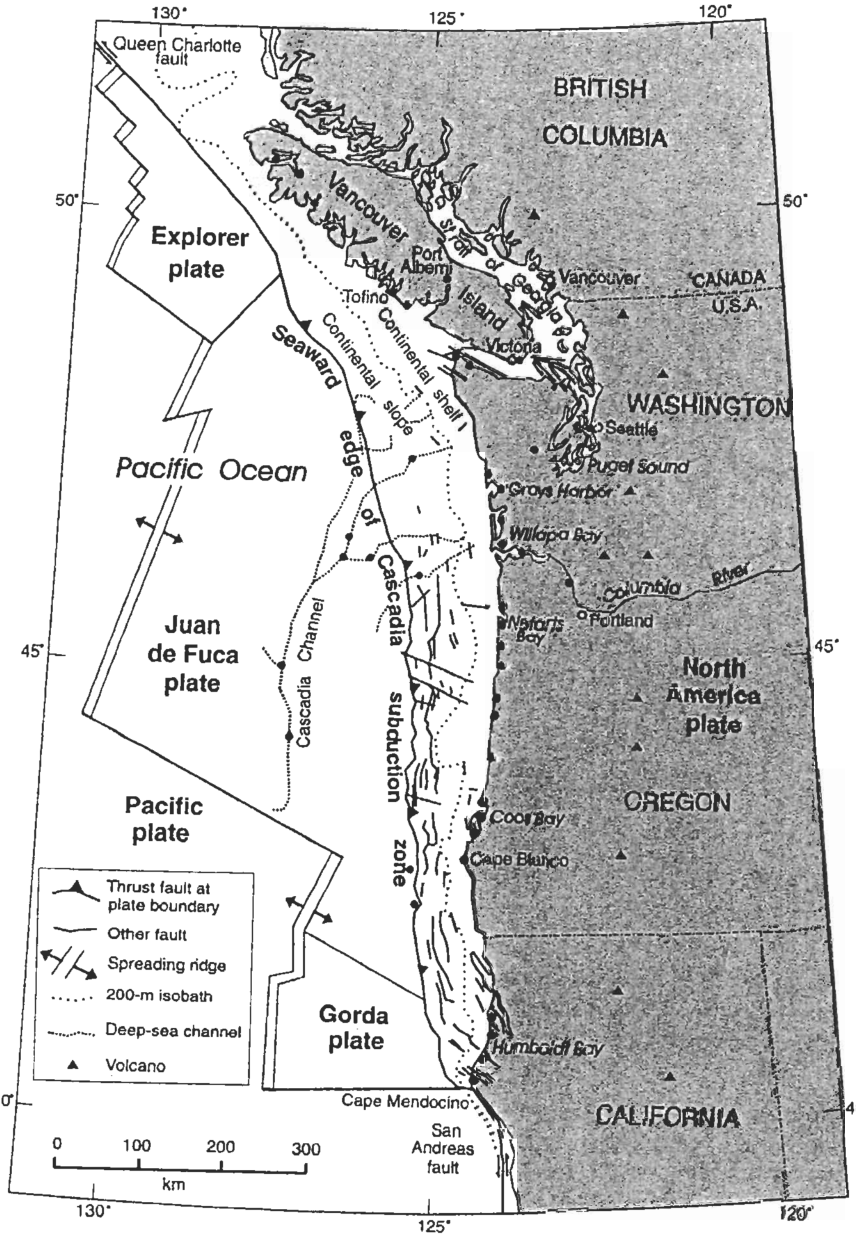

Figure 1. Location map of the Cascadia subduction zone (modified from Atwater *et al.*, 1995).

To confidently associate this kind of wetland stratigraphy with great earthquakes, researchers must demonstrate that: 1) the subsidence was sudden and large (generally >1 m); 2) submerged tidal wetland soils are laterally extensive; 3) tsunamis are coincident with subsidence; and 4) submergence events are synchronous at widely spaced sites (Nelson *et al.*, 1996a). Cycles of sudden submergence of wetlands, followed by gradual shoaling and development of new marshes are explained by a cycle of regional coseismic subsidence followed by aggradation and interseismic uplift (Atwater *et al.*, 1995; Nelson *et al.*, 1996a). This cycle has been termed the 'earthquake deformation cycle' (Figure 2; Dragert *et al.*, 1994).

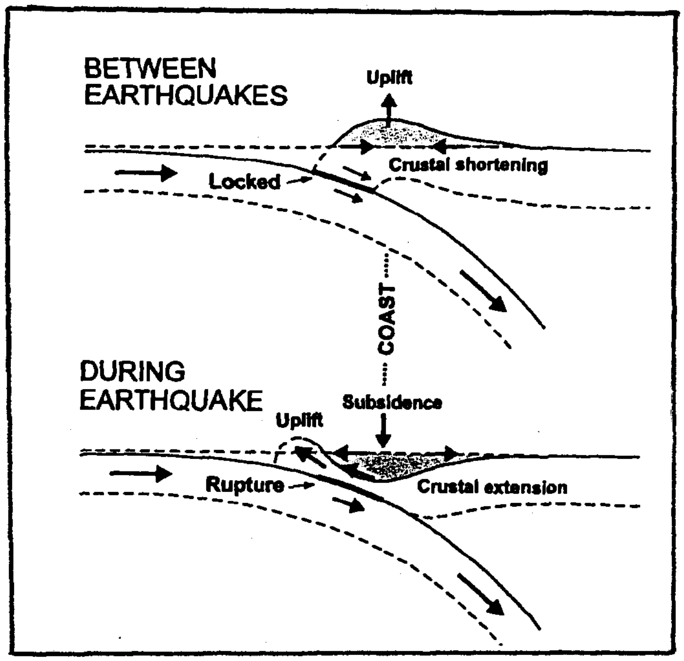

Figure 2. The great earthquake deformation cycle (modified from Dragert *et al.*, 1994).

Foraminifera as indicators of sea-level change

Foraminifera are one-celled marine microorganisms with shells (tests). The shells are commonly preserved as fossils in sediments. They provide information on the environmental history of a site in the absence of real-time physiochemical baseline data (Scott *et al.*, 2001). Foraminifera have been used as environmental proxies in several pollution studies, tracer and transport research, and studies of submarine slides and glacial-marine and fluvial transport (Scott *et al.*, 2001). They occur in large numbers in a wide variety of marine environments, and have restricted salinity and other environmental tolerances. A growing number of studies use foraminifera to reconstruct coastal marine palaeoenvironments. Examples of such studies include classification of estuaries and embayments, documentation of salinity and temperature fluctuations, and hurricane detection using estuarine sediments (Scott *et al.*, 2001). Foraminifera have also been recognized as important indicators of relative sea-level change caused by large storms, rapid climate change, seismic events, and other phenomena (e.g. Gayes *et al.*, 1992; Jennings *et al.*, 1995; Scott *et al.*, 1995a, 2001, 2003; Nelson *et al.*, 1996a).

Most marsh foraminifera are agglutinated, that is they have organic linings with tests composed of silt and sand grains that the organism collects from the substrate and cements together to make a rigid shell. The tests are resistant to low-oxygen and low-pH conditions, which characterize tidal marshes and are, therefore, well preserved in marsh sediments (Scott and Medioli, 1980a). In addition, local foraminiferal assemblages show a consistent vertical zonation within marshes. This characteristic underpins the application of foraminifera to sea-level studies. It allows recognition of distinct elevation zones in both modern and ancient sediments (Scott *et al.*, 2001). Marsh foraminifera have become an important tool for detecting relative sea-level change during the

Holocene, especially where the change is less than 1 m. Foraminiferal assemblages in tidal wetlands are commonly defined according to their elevation with respect to a tidal datum and include tidal flat, low marsh, middle marsh and high marsh assemblages (Patterson *et al.*, 2000).

Couplets of tidal mud and marsh peat separated by abrupt contacts have been described at numerous estuaries along the coast of the Pacific Northwest. The abrupt contacts between couplets have been attributed to episodic subsidence caused by CSZ earthquakes (Atwater, 1987; Atwater *et al.*, 1995; Shennan *et al.*, 1996; Nelson *et al.*, 1996b; Clague, 1997). Microfossils (diatoms, foraminifera and pollen) in these deposits record relative sea-level change and help determine whether the subsidence was sudden or gradual. Foraminiferal data increase the resolution of relative sea-level reconstructions (Nelson *et al.*, 1996a, b).

Importance of project

More precise estimates of coastal land-level change during great earthquakes allow geophysical modellers to better delineate the locked part of the CSZ and to estimate the magnitudes of the earthquakes. The objective of this study is to use marsh foraminifera to estimate amounts of coseismic subsidence during past great earthquakes at the CSZ and to track relative sea-level change between the earthquakes.

STUDY SITE

Physical environment

Willapa Bay, on the southwest coast of Washington state, comprises numerous estuaries that extend several kilometres inland and are protected from the open Pacific Ocean by a large barrier beach bar. Two major tidal arms extend landward from Willapa Bay and mark the mouths of Naselle and Willapa rivers. Niawiakum River, the location of this study, is just northeast of the Naselle arm (Figure 3). The northeastern part of Willapa Bay crosses the South Bend antiform (Figure 3), which is developed in an exposed core of the Crescent Formation – Eocene pillow basalt, basaltic breccia, and basaltic sedimentary rock. The South Bend antiform has been active in the Quaternary, as Pleistocene estuarine and shallow marine sediments crop out on its flanks (Atwater and Hemphill-Haley, 1997).

This study was conducted at the Oyster locality of Atwater and Hemphill-Haley (1997) on the northeast bank of Niawiakum River approximately 200 m upriver from US Highway 101 and 10 km north of Columbia River (Figure 4a). The bank is about 2 m high, and its top lies within the upper marsh above normal high tide level (>3 m) (Figure 4b). A nearby mudflat at the confluence of two tidal creeks tributary to the river is about 50 m wide and is inundated twice a day by tides. Extreme tides have a range of 4.5 m. Vascular plants in the marsh are typical of brackish-water wetlands and include tufted hair-grass (*Deschampsia caespitosa*), Baltic rush (*Juncus balticus*), Pacific silverweed (*Potentilla pacifica*), Seaside arrowgrass (*Triglochin maritimum*), and Lyngby's sedge (*Carex lyngbyei*). Pickleweed (*Salicornia virginica*) is common in saline parts of the high marsh and in the transition between the high and low marsh environment. Sitka spruce (*Picea sitchensis*) and western crabapple (*Pyrus fusca*) grow just above the extreme high tide level. The Oyster locality has been invaded by Atlantic-coast grass (*Spartina* sp.), which was introduced with oyster farming at Willapa Bay in the early 1980s (Atwater and Hemphill-Haley, 1997).

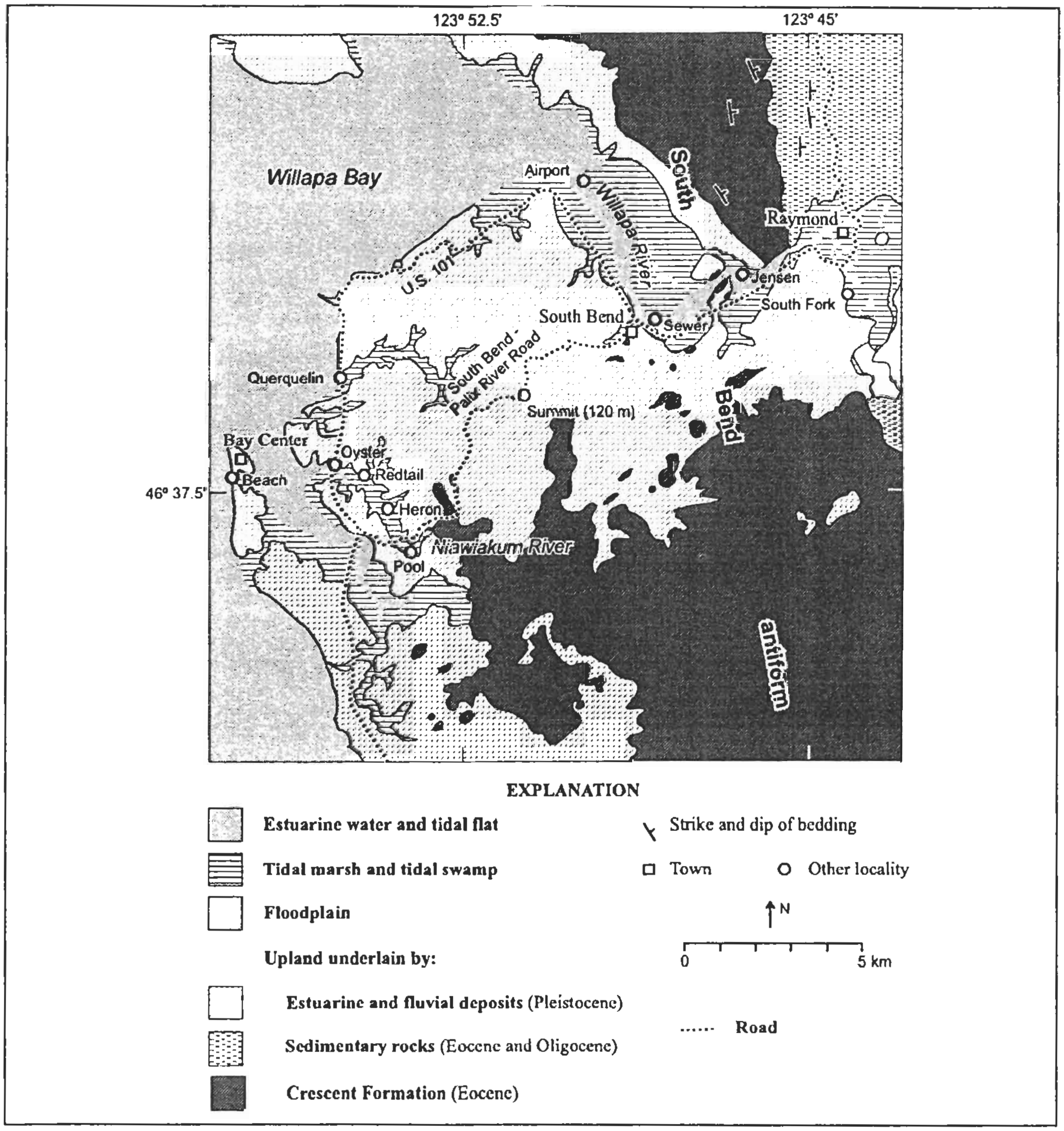

Figure 3. Map of northeastern Willapa Bay, southwestern Washington (after Atwater and Hemphill-Haley, 1997).

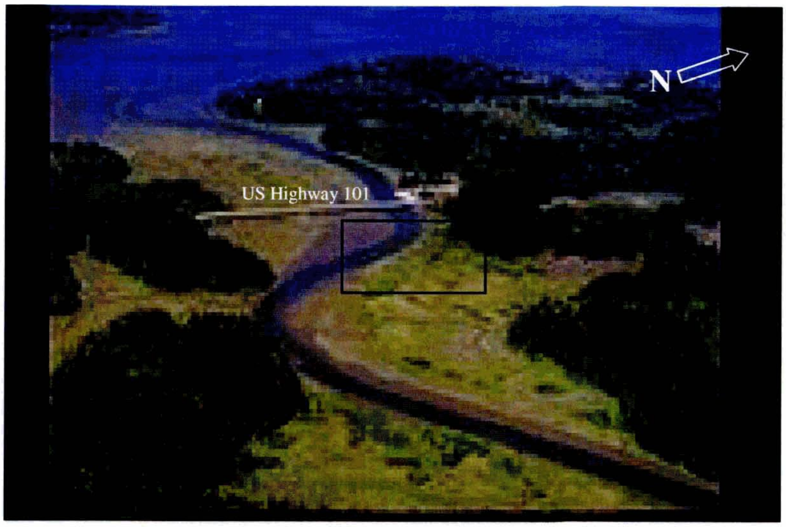

Figure 4a. Aerial photo of the Oyster locality along Niawiakum River at low tide. (Courtesy of the Washington State Department of Ecology, shoreline aerial photo #PAC0185, 5/11/97. www.ecy.wa.gov/programs/sea/SMA/atlas_home.html)

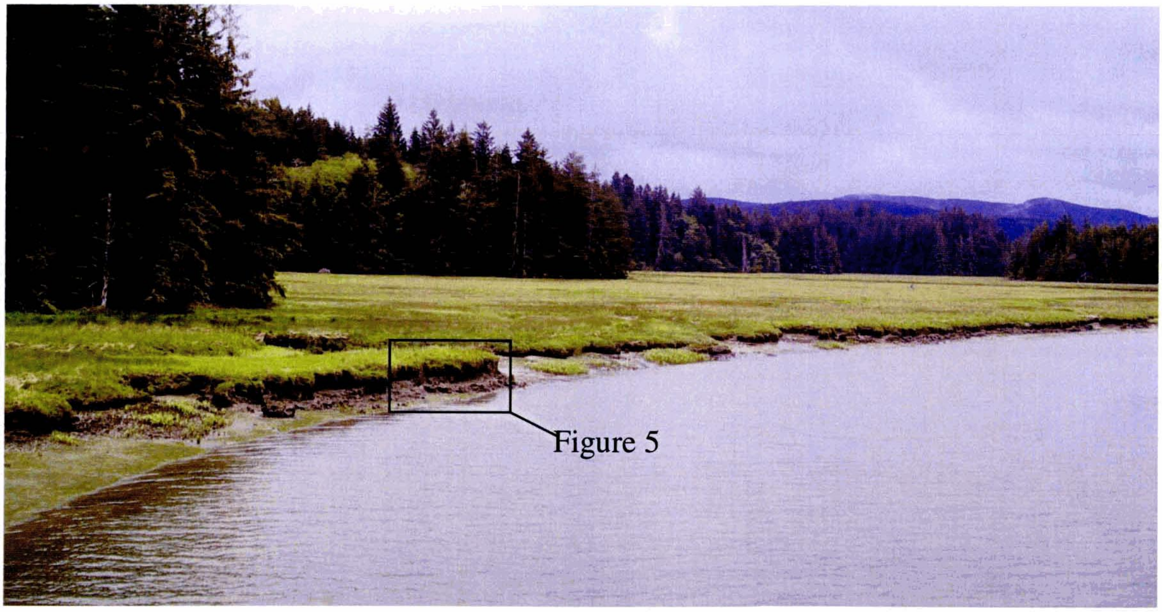

Figure 4b. Oyster locality at high tide, June 2001; view to the northeast.

Coseismic subsidence at Willapa Bay

Atwater and Hemphill-Haley (1997) conducted extensive litho- and biostratigraphic investigations at Willapa Bay, partly to determine the recurrence intervals of great earthquakes at this part of the CSZ. They surveyed and sampled outcrops along the banks of the rivers entering the bay and found evidence for seven great earthquakes in the area during the past 3500 years. They concluded that the earthquakes were plate-boundary events because the CSZ is the only recognized fault common to all areas having evidence for coseismic subsidence in southern Washington (Atwater and Hemphill-Haley, 1997).

The monolith that I analysed contains four buried soils, referred to as S, U, W and Y (oldest to youngest) by Atwater and Hemphill-Haley (1997). Figure 5 shows the two youngest soils (S and W) in the riverbank at the Oyster locality. Soils S and Y form prominent ledges along the tidal channels entering Willapa Bay, whereas soils U and W lack topographic expression, except on well washed, nearly vertical faces, from which they protrude a few centimetres. All of the soils are laterally extensive in the marshes. They have been radiocarbon dated at 1500-1700 years, 1130-1350 years ago, ~900 years ago, and about 300 years ago, respectively (Atwater and Hemphill-Haley, 1997). The work of Atwater and Hemphill-Haley (1997) is the foundation for this study, as it provides solid information on stratigraphy, vegetation and diatoms, as well as dates of the last four great earthquakes at the CSZ.

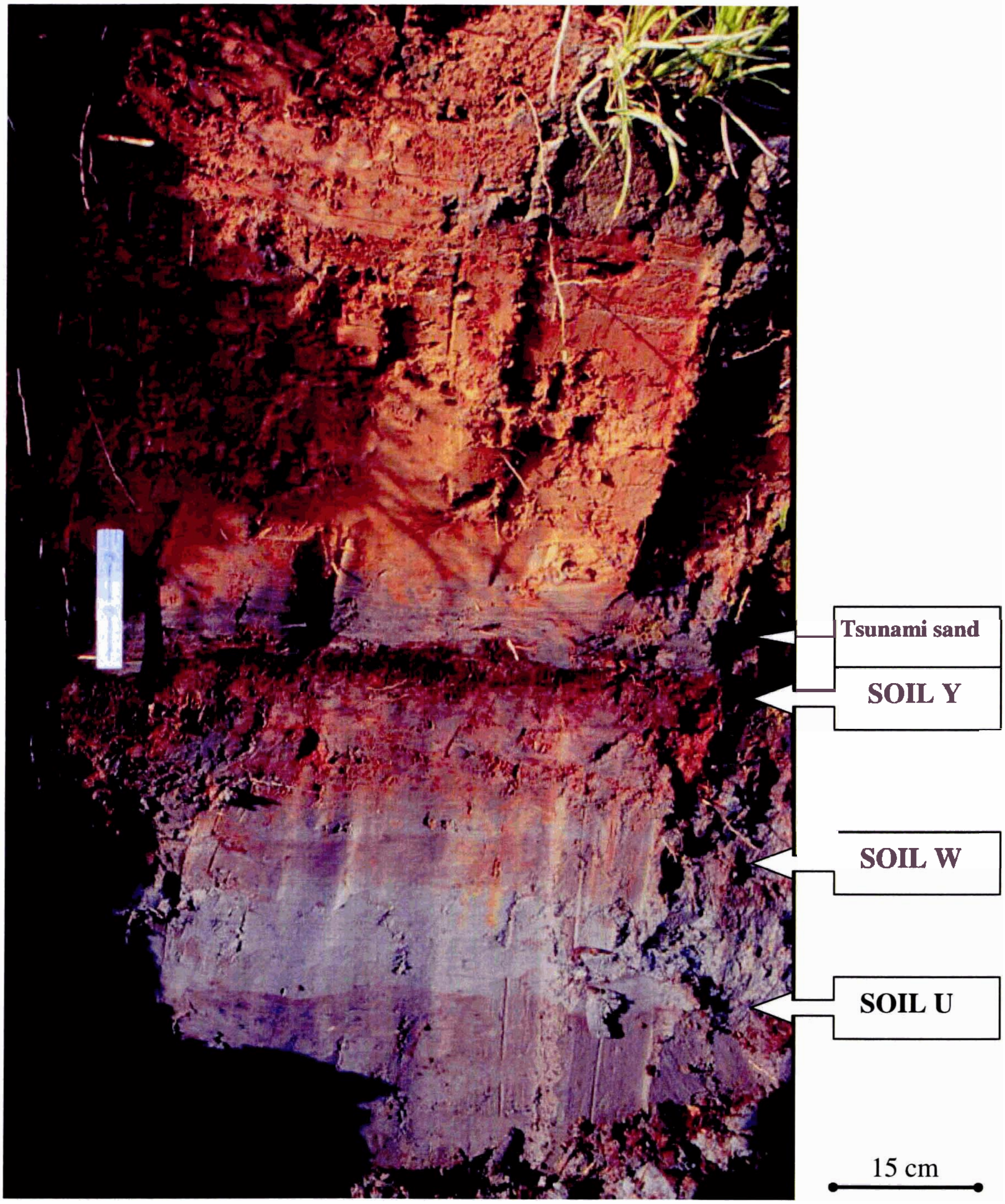

Figure 5. Riverbank outcrop at the Oyster locality showing soils S, W, and U.

PREVIOUS WORK

Microfossil evidence of sea-level change

A distinctive characteristic of most tidal marshes is the vertical zonation of plant communities (Chapman, 1960). Foraminifera also have a zonation within tidal marshes; knowing the elevational ranges of the foraminiferal species that constitute the zones, one can determine past elevations of the site from fossil foraminifera in sediments. A record of the changing elevation of the site through time can be obtained by analysing changes in the abundance of indicator species with depth in a sedimentary sequence (Patterson *et al.*, 2000; Scott *et al.*, 2001).

A set of agglutinated foraminiferal taxa typical of temperate tidal marshes includes *Ammotium salsum*, *Trochammina macrescens* (two formae), *Miliammina fusca*, *Tiphotrocha comprimata*, *Haplophragmoides* species and *Trochammina inflata* (Phleger, 1970, 1977; Murray, 1971; Scott *et al.*, 1996; Hutchinson *et al.*, 1998). Biogeography, local ecology and the discontinuous distribution of species introduce an element of variability in the vertical zonation of marsh foraminifera, but examination of high and low marsh fauna shows that these zones are marked by the same or similar groups of species over large areas (Sen Gupta, 1999). Jennings and Nelson (1992) summarized tidal data, floral zones, foraminiferal assemblages and faunal zones for four cool, humid areas in North America, demonstrating the relationship of marsh foraminifera to elevation. The summary of Pacific marsh foraminiferal faunas compiled by Scott *et al.* (1996) demonstrates the similarity among faunas around the Pacific Ocean (Table 1). The most noticeable features are the dominance of *T. macrescens* and *T. inflata* in high-marsh assemblages and the consistent occurrence of *M. fusca* in the low-marsh ones (Scott *et al.*, 1996). These species are important for relative sea-level studies. In Cascadia, buried peats in tidal marshes contain abundant *T. macrescens* (two formae), whereas muds are commonly dominated by *M. fusca* (Guilbault *et al.*, 1995, 1996). Major changes in marsh foraminiferal assemblages mark sudden changes in relative sea-level (Nelson *et al.*, 1996a).

Table 1. Common foraminifera in Pacific tidal marshes (modified from Scott *et al.* 1996).

Location	**High marsh**	**Low marsh**
Hokkaido	*Trochammina m.* f. *macrescens* *Haplophragmoides manilaensis* *Miliammina fusca*	*Miliammina fusca* *Trochammina m.* f. *macrescens* *(Trochammina inflata)*
British Columbia	*Trochammina m.* f. *macrescens* *Trochammina inflata*	*Miliammina fusca* *Ammonia beccarii* *Ammobaculites exiguus* *Elphidium spp.*
Washington State	*Trochammina m.* f. *macrescens* *Trochammina inflata* *Haplophragmoides wilberti* *Trochammina m.* f. *polystoma*	*Miliammina fusca* *Ammotium salsum*
Oregon	*Trochammina m.* f. *macrescens*	*Miliammina fusca* *Reophax nana* *Ammotium salsum* *Ammobaculites exiguus*
Northern California	*Trochammina m.* f. *macrescens* and f. *polystoma*	*Miliammina fusca* Calcareous spp.
Southern California	*Trochammina m.* f. *polystoma*	*Polysaccammina hyperhalina* *Miliammina fusca* Calcareous spp.
Chile	*Trochamminita salsa* *Haplophragmoides* spp. *Pseudothurammina limnetis*	*Milammina fusca*
New Zealand	*Trochammina inflata* *Trochamminata salsa* *Haplophragmoides wilberti* *Trochammina m.*f. *macrescens* *Miliammina obliqua*	*Elphidium* spp. *Haynesina depressulum* Other Calcareous spp.

Notes: Species are listed in order of importance. *Trochammina m.* f. refers to *Trochammina macrescens* f., either *macrescens* or *polystoma.*

Patterson *et al.* (2000) conducted a multi-proxy study of relative sea-level change at an intertidal marsh at Zeballos on northwestern Vancouver Island. They compared the vertical zonation of diatoms, foraminifera and vascular plants using Q-mode cluster analysis. The analysis yielded three, six and four, mostly elevation-controlled assemblage zones, respectively. Cluster analysis of the foraminifera dataset yielded three foraminiferal assemblages: high marsh (0.8-1.5 m above mean sea level, amsl), dominated by *Jadammina macrescens* and *Balticammina pseudomacrescens*; low marsh (0.4-0.8 m amsl), dominated by *B. pseudomacrescens*; and tidal flat (-0.2-0.4 m amsl), dominated by *Miliammina fusca.* Their study was one of the first to compare the zonation of three types of organisms across an intertidal marsh, and it demonstrated the value of a multi-proxy approach in relative sea-level studies. When applied to the fossil record at a site, this method allows even small sea-level changes to be detected, which is important in the Pacific Northwest where coseismic land-level changes of only a few tens of centimetres are probably common (Patterson *et al.*, 2000).

More generally, studies from different tidal wetlands around the world have shown the value of marsh foraminifera in studies of sea-level change: in the UK (Edwards and Horton, 2000), Greece (Cundy *et al.*, 2000), Chile (Jennings *et al.*, 1995) Japan (Scott *et al.*, 1995b), New Zealand (Hayward *et al.*, 1999), eastern Canada (Scott and Medioli, 1980b), and the US (de Rijk and Troelstra, 1997).

Microfossil studies of coseismic subsidence in the Pacific Northwest

Tidal marshes are sensitive recorders of relative sea-level change and thus have become favoured sites for paleoseismic investigations, especially along the Pacific coast (Jennings *et al.*, 1995; Guilbault *et al.*, 1995, 1996; Scott *et al.*, 2001).

Western British Columbia

One of the first paleoseismic studies in British Columbia to incorporate microfossil data was done by Mathewes and Clague (1994) at tidal wetlands near

Vancouver. They inferred two large earthquakes from plant fossils recovered from buried soils. The two events were radiocarbon dated at approximately 3400 and 2000 ^{14}C years ago. At one site, a fossil forest is sharply overlain by silt and sand containing brackish-water diatoms (Mathewes and Clague, 1994).

Tidal marshes at Tofino and Ucluelet on western Vancouver Island contain one to two buried marsh soils. A sheet of tsunami sand overlies the upper soil. On the basis of stratigraphic and geochronological data, Clague and Bobrowsky (1994) concluded that the upper soil was a former marsh surface that subsided suddenly during the last earthquake at the CSZ about 300 years ago.

Guilbault *et al.* (1995) conducted a foraminiferal study at the Tofino study site of Clague and Bobrowsky (1994) ('cemetery site'). They compared fossil foraminiferal assemblages in sediments below the modern marsh with those of the modern marsh. The modern samples were grouped into four biofacies based on visual examination: tidal flat; lower marsh, dominated by *Miliammina fusca*, but also including *Ammobaculites exiguus*, *Ammotium salsum* and *Eggerella advena*; middle marsh, dominated by *Jadammina macrescens*; and upper marsh, dominated by *J. macrescens* and *Haplophragmoides wilberti*. Visual examination of the modern and fossil foraminiferal assemblages indicated 0.50-0.95 m of coseismic subsidence during the earthquake about 300 years ago. Guilbault *et al.* (1995) also used transfer functions to estimate the amount of coseismic subsidence at Tofino. Q-mode factor analysis was performed on 16 modern samples with 22 taxonomic categories. The analysis produced three factors that explain 96.7% of the data variance. The first factor was designated 'higher high marsh' and was dominated by *J. macrescens*. The second factor, the 'low marsh', was dominated by *M.*

fusca. The third factor was termed the 'lower high marsh' and was dominated by *H. wilberti* and, secondarily, *T. inflata*. Stepwise multiple regression analysis was then done to obtain a regression equation (the transfer function) that gives elevation as a function of species composition. The transfer function was then applied to the fossil data to calculate paleoelevations of the samples. This analysis of the fossil data yielded values of 0.20-0.94 m of coseismic subsidence. Guilbault *et al.* (1995) also used the assemblage approach of Jennings and Nelson (1992), obtaining extreme subsidence values of 0.0 m and 1.33 m.

Guilbault *et al.* (1996) did similar work at a site on Meares Island near Tofino. At that site, the pre-earthquake succession begins with a tidal flat and lower marsh assemblage and changes upward into a middle marsh assemblage, followed by an upper marsh assemblage. Above the tsunami sand, there is a brief middle marsh interval, followed by an upper marsh assemblage that extends to the top of the section. Data from the modern transects revealed three biofacies: tidal flat and lower marsh, dominated by *M. fusca*, with some *A. exiguus*, *A. salsum* and *Polysaccamina hyperhalina*; the upper marsh, dominated by *J. macrescens* and *T. salsa*; and the supratidal zone, dominated by arcellacea. Guilbault *et al.* (1996) developed a transfer function to test their visual interpretations. Factor analysis yielded three factors that explain 96.8% of the variance in the Meares Island data. Factor 1 (75.2% of the variance) characterizes the upper marsh, as it is dominated by *J. macrescens* and *T. salsa*. Factor 2 (18.6% of the variance) is dominated by adult *M. fusca* and represents the lower marsh. Factor 3 (3.0% of the variance) is dominated by *H. wilberti*. The mean estimate of subsidence is 55 cm (Guilbault *et al.*, 1996).

Another study was conducted in the tidal marshes near Tofino by Hughes *et al.* (2002). They obtained estimates of coseismic subsidence using pollen and vascular plants. The relationship between the modern and fossil data sets was established using four transfer functions: partial least squares (PLS); weighted averaged PLS; simple weighted averaging (WA); and WA with the tolerance of abundant taxa downweighted (WA(tol)). Four marsh zones were delimited by the vascular plants: low (2.0-2.9 m amsl); middle (2.8-3.5 m amsl); high (3.2-3.9 m amsl); and forest-edge transition (3.7-4.2 m amsl). WA(tol) provided a mean estimate of coseismic subsidence of 0.61 +/- 0.3 m, which was in agreement with estimates derived from the foraminiferal studies (Hughes *et al.*, 2002). This study demonstrated that pollen from subsurface sediment, when combined with modern pollen and plant distributions, can contribute to high-resolution sea-level reconstructions.

Washington State

The southwestern coast of Washington has extensive estuarine tidal marshes that have been extensively studied by many scientists. Several types of evidence were presented by Atwater (1987, 1992) and Atwater and Yamaguchi (1991) to support the hypothesis that the uppermost buried soil in tidal marshes along Niawiakum River had dropped during a great subduction earthquake. First, they documented the abruptness of the upper contact of the buried soil, with *in situ* tree roots and other plants preserved along it. Second, below-ground rhizomes of *Triglochin maritimum*, a low-marsh plant, were found in mud a few tens of centimetres above the contact, suggesting that submergence was long-lived, rather than temporary due to a storm or another ephemeral phenomenon. Atwater and Yamaguchi (1991) estimated the amount of submergence at

0.5-2 m, based on the stratigraphic position of fossil plants and their modern counterparts. Finally, they reported anomalous fine sand layers directly above the buried soil that became finer and thinner up-valley. They interpreted these layers as the deposit of the tsunami generated by the last great earthquake about 300 years ago.

Hemphill-Haley (1995) used diatom evidence to infer the amount of relative sea-level rise during the most recent great earthquake in southwestern Washington. Diatom assemblages from four stratigraphic sections at Niawiakum River showed a sudden drop in marsh and forest surfaces that were near or above high tide, followed by a change to mud flat and low marsh environments. The latter were gradually replaced by a high marsh. Based on known elevations of modern diatom assemblages, Hemphill-Haley (1995) estimated the amount of coseismic subsidence required to explain the abrupt change in fossil assemblages above and below the buried marsh surface. The estimates range from a minimum of 0.8-1.0 m to a maximum of 3.0 m. A tsunami origin for the sand sheet overlying the buried peat was supported by diatom evidence. The sand contains diatom species that are found on the modern sand flats of Willapa Bay, indicating a bayward source. In a later study, Atwater and Hemphill-Haley (1997) presented a detailed analysis of the past seven great earthquakes and their recurrence interval, based on surveys of numerous outcrops throughout Willapa Bay.

Shennan *et al.* (1996) tested the ‘earthquake deformation cycle’ in Cascadia by applying the methods and scientific framework common to sea-level investigations in northwest Europe to a sequence of peat-mud couplets in southern Washington. Intertidal sediments at the estuary of Johns River include eight peat-mud couplets that record coastal submergence over the past 5000 years. The study of these deposits incorporated lithologic, pollen, diatom and foraminiferal data obtained from samples collected along surface transects and tidal channel exposures. Multivariate statistical methods were employed on the large data set to reconstruct paleoelevations. One of the eight events had approximately 1.5 m of submergence, four events had 1 +/- 0.5 m of submergence, and three events had <0.5 m of submergence. The upper contact of each peat horizon is abrupt, and the pollen and diatom data show changes from vegetated marsh to mudflat. Two of the eight events were preceded by non-seismic relative sea-level rise. Shennan *et al.* (1996) note that a lack of a modern analogue representative of immediate post-submergence environments limited the precision of their subsidence estimates.

Oregon

The late Holocene estuarine record along the Oregon coast is more difficult to interpret than that of southwestern Washington, because there are few good exposures and coring at some sites indicates differing styles of late Holocene relative sea-level rise - uniform in some sites, jerky in others. Nelson and Jennings (1988) recognized that marsh foraminifera are sensitive to changes in sea level and analysed samples along surface transects at several Oregon marshes. They identified three informal assemblage zones: a high-marsh zone, dominated by *T. macrescens* and *T. inflata*, with lesser values of *M. fusca* and *H. wilberti*; an upper-low-marsh zone, dominated by *M. fusca*, with subordinate *T. macrescens* and *T. inflata*; and a low-marsh to mudflat zone, dominated by *M. fusca* and *A. salsum*, with calcareous species increasing in abundance with decreasing elevation. Based on their preliminary findings, Nelson and Jennings (1988) argued that sudden changes in sea level of about 0.5-1.0 m could, in theory, be identified at Oregon estuaries.

Darienzo and Peterson (1990) conducted a detailed study of late Holocene relative sea-level change at a small marsh bordering Netarts Bay. They reported six buried marsh surfaces, five of which have sharp, non-erosional upper contacts with either anomalous sand layers, interpreted to be tsunami deposits, or tidal flat mud. In contrast, the marsh peats grade downward into underlying intertidal muds, indicating progressive uplift and development of the marsh over time. Darienzo and Peterson (1990) used percent organic matter, diatom assemblages and percent eolian sand to estimate the paleoelevations of the buried soils. They reported subsidence of 1-1.5 m, followed by gradual uplift of 0.5-1.0 m, which they attributed to coseismic strain release followed by interseismic strain accumulation associated with great earthquakes.

After completing their first project in southwestern Washington, Shennan and co-workers turned their attention to Netarts Bay, using tidal marsh stratigraphy, diatoms and pollen to reconstruct relative sea-level change. Three main floral zones were identified in the modern marsh: mudflat (0.0-0.3 m above mean tide level); low marsh (0.3-1.2 m); and high marsh (1.3-1.5 m), with a mixed community of vegetation comprising both low- and high-marsh species between 1.05 and 1.35 m (Shennan *et al.*, 1998). The multivariate statistical analysis techniques that had been used successfully by Shennan *et al.* (1996) at Johns River were not successful in this study. Certain pollen and diatom species were grouped as outliers at Netarts Bay, representing distinctive assemblages with only a small overlap between contemporary and fossil samples. Nevertheless, their quantitative comparison of the contemporary and fossil microfossil data provided limits on the magnitude of submergence during great earthquakes at Netarts Bay (Shennan *et al.*, 1998).

Jennings and Nelson (1992) studied foraminifera distributions in three Oregon tidal marshes and developed assemblage zones that they linked to marsh floral zones and elevation. Discriminant analysis was used to distinguish three foraminiferal zones: the high marsh; low marsh; and mudflat (Table 2). They observed that boundaries between modern zones are gradational, especially that between the low and high marsh, due to the low gradients of the middle parts of the marshes they studied. They found their results to be similar to those from other mid-latitude, cool-temperature coastal marshes, but noted that the large vertical ranges of the marsh zones in Oregon limited the precision with which they could estimate amounts of relative sea-level change using foraminiferal assemblages.

Table 2. Vascular plant and foraminiferal zones in three Oregon tidal marshes (modified from Jennings and Nelson, 1992).

Zone	Plants	Foraminifera
Mudflat	*Zostera nana,* *Zostera marina*	*Miliammina fusca,* *Reophax nana,* *Ammotium salsum*
Low Marsh	*Carex lynbyei,* *Triglochin maritimum,* *Salicornia virginica,* *Distichlis spicata,* *Deschampsia caespitosea*	*Miliammina fusca,* *Lilaeopsis occidentalis,* *Trochammina macrescens* f. *macrescens,* *Trochammina inflata,* *Haplophragmoides* sp., *Ammotium salsum*
High Marsh	*Deschampsia caespitosea,* *Carex lynbyei,* *Distichlis spicata,* *Agrostis alba,* *Potentilla pacifica,* *Triglochin maritimum* *Salicornia virginica,* *Atriplex patula*	*Trochammina macrescens* f. *macrescens,* *Miliammina fusca,* *Trochammina inflata,* *Haplophragmoides sp.*

Note: Species are listed in order of abundance.

One of the challenges in using estuarine stratigraphy to infer the size and rate of late Holocene relative sea-level change is that both seismic and nonseismic processes can produce peat-mud contacts. Nelson *et al.* (1996a) studied changes in lithology and microfossil assemblages at a protected tidal marsh at Coos Bay, Oregon, to determine which of the ten abrupt contacts at the site are the result of sudden coseismic subsidence. Fossil foraminifera and diatom assemblages across peat-mud contacts in one core were compared with modern assemblages previously studied along transects elsewhere in Coos Bay (Jennings and Nelson, 1992). Using discriminant function analysis, they showed that two of the ten contacts, dating to approximately 1700 and 2300 years ago, record at least 0.5 m of sudden subsidence.

Kelsey *et al.* (2002) documented eleven plate-boundary earthquakes over the past 6000 years in coastal wetland sediments at Sixes River valley in south-coastal Oregon. Diatom assemblages indicate that the land subsided abruptly at least 0.5 m in each event. Sand layers on top of buried soils demonstrate coincidence of coseismic subsidence and tsunami inundation. Witter *et al.* (2003) conducted similar research at the Coquille River estuary in southern Oregon and identified peat-mud couplets dating to the last 6700 years. Diatom assemblages indicate 1.2-3.0 m of submergence during each event.

Alaska

A challenge in studying relative sea-level change associated with great earthquakes in the Pacific Northwest is the lack of historical events. In contrast, Alaska has experienced a great subduction earthquake in historic time. On March 27, 1964, a great earthquake submerged forest and tidal marshes bordering Turnagain Arm near Anchorage. Coseismic subsidence decreased from a maximum of 2 m at Portage to approximately 1 m around Anchorage.

Peat layers are sharply overlain by clastic sediments at tidal marshes at Portage and Girdwood Flats. The stratigraphy is similar to that at tidal marshes on Vancouver Island and along the Pacific coasts of Washington and Oregon. What makes the Alaskan stratigraphy different is that the times of coseismic subsidence and post-seismic recovery at Girdwood Flats are known with precision, thus data from this site can provide insights that help in interpreting the pre-earthquake stratigraphy of Cascadia. Shennan *et al.* (1999) hypothesized four phases of relative sea-level change at Girdwood Flats using diatom, pollen, foraminifera and thecamoebian data. Uplift during the first phase was caused by slow strain accumulation along the locked portion of the Aleutian subduction zone. It is manifested in the development of a freshwater swamp above high marsh sediments. The second phase, which is recorded by a change in all three microfossil groups in the uppermost 2 cm of peat, is interpreted to be subsidence. The third phase is instantaneous subsidence during the March 1964 earthquake, which initiated intertidal silt deposition on the marsh peat. The final phase is post-seismic uplift, recorded by colonization of the mudflat by salt marsh communities. These observations raise the question whether the relative sea-level rise prior to the 1964 earthquake is a precursor signal (Shennan *et al.*, 1999).

METHODS

Sample collection

The sampling strategy was to establish the overall pattern of foraminiferal assemblages in the modern marsh and their relation to tide levels (Shennan *et al.*, 1996). Samples were collected in June 2000 along transect JS1, perpendicular to Niawiakum River (Figure 6). Marsh foraminifera are commonly discussed in terms of 'low', 'middle' and 'high' or 'upper' marsh zones. This usage has become accepted in studies of the distribution of foraminifera in marshes to informally denote position and elevation in the marsh (Scott and Medioli, 1978, 1980b; Patterson *et al.*, 2000). The transect was chosen to sample low, middle and high marsh ecologic zones and to traverse plant and microfossil communities (Nelson *et al.*, 1996b).

The 320-m-long transect extended from the forest edge (highest high marsh) to the river's edge at lower low tide (lowest low marsh). Tide tables were consulted to determine the best time to collect samples from the lower part of the tidal zone. Ten cubic centimetre samples of surface sediment were collected at stations along the transect with a garden bulb planter. Only the top 1 cm of the material was used in this study. The local flora was recorded along the transect. Salinity was not recorded along the transect, as the marsh surface was too dry at the time of sampling.

Differences in elevation of the marsh surface were measured with a surveying level and are accurate to within 1 cm. Vertical levels were referenced to a temporary benchmark in the marsh, which in turn was tied to a geodetic benchmark. The elevation datum is mean lower low water (MLLW), the average of the two daily tides. MLLW is a standard datum for nautical charts in the western United States. Horizontal distances from the upland forest to the river were determined with a measuring tape.

Most salt marshes in the world have a vertical zonation of plants (Chapman, 1960), and marsh foraminiferal populations have a similar zonation. Therefore, only 36 of the 47 surface samples were selected for foraminiferal analysis. They were chosen to provide continuous 10-cm vertical coverage of the marsh, as this is the limit of resolution of tidal marsh foraminiferal assemblages (Scott and Medioli, 1980b). Other samples were collected where significant changes in vegetation were observed, irrespective of elevation. No attempt was made to establish the direct influence of other factors that can affect the distribution of microfossils, such as salinity, nutrient status, seasonal changes and sedimentation rates.

A series of vertical sediment monoliths were collected by Jonathan Hughes and Brian Atwater in 1997 along a freshly exposed cutbank at the Oyster locality, several tens of metres from surface transect JS1 (Figure 6), and within 0.5 m of Hemphill-Haley's monolith collection site (at horizontal coordinate 165 m in the outcrop sketch of Atwater and Hemphill-Haley's (1997) Figure 18, p. 44). The monoliths were removed from the outcrop in several overlapping (10 x 10 x 50 cm) blocks, to a depth of 330 cm, using a flat-faced spade and knife. They were stored in a cold room at SFU until the start of this project. Transect JS1 was located near the monolith site to minimize differences in tidal range and species variability within the marsh.

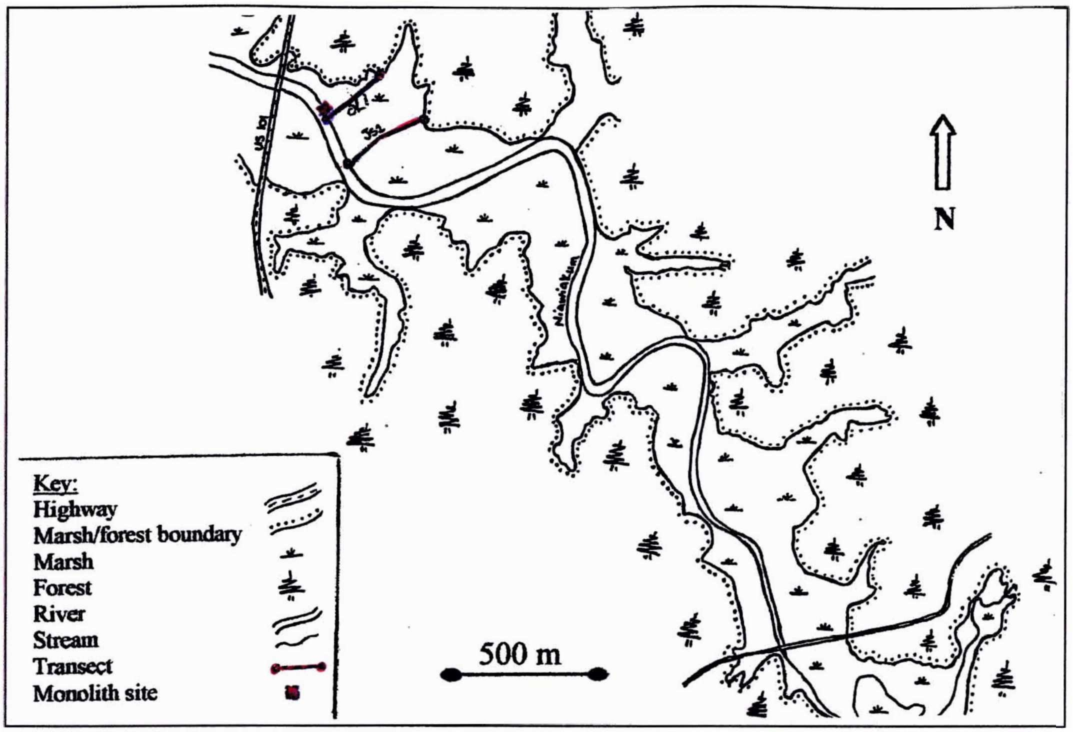

Figure 6a. Map of the Oyster locality, showing transects JS1 and OL1 and the monolith sample site.

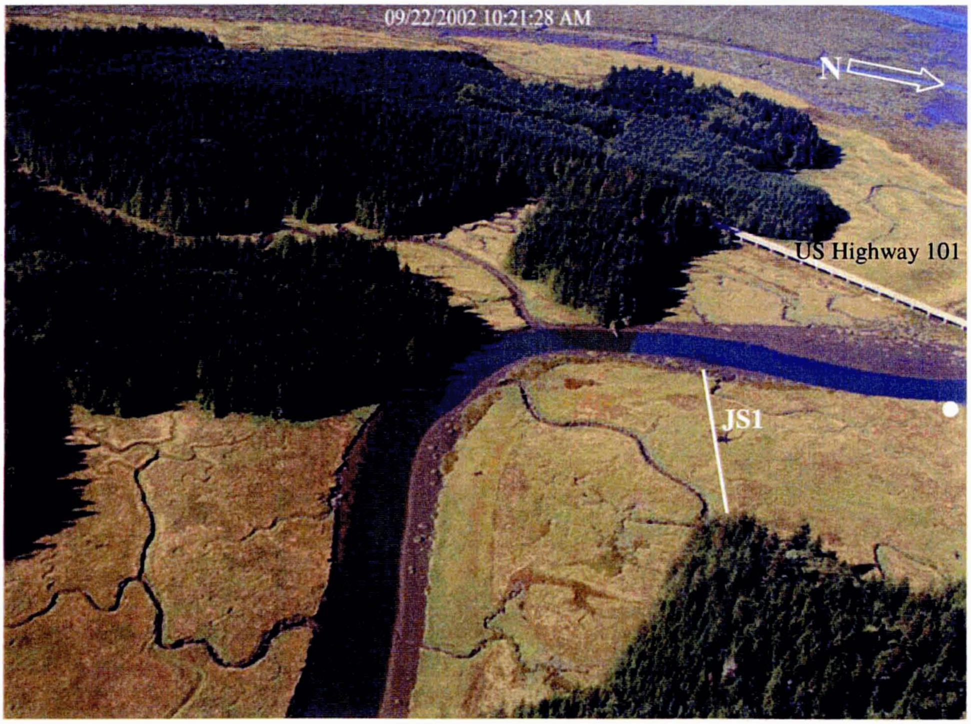

Figure 6b. Aerial photograph of the Oyster locality at low tide; view to the southwest. Transect JS1 is shown as a solid line; the monolith site is shown as a dot. (Courtesy of the Washington State Department of Ecology, shoreline aerial photo #0209221021_073; www.ecy.wa.gov/programs/sea/SMA/atlas_home.html)

Sample preparation

The surface samples were refrigerated at Simon Fraser University upon return from the field. At the time of processing, the monoliths were removed from cold storage and photographed with a digital camera. They were then correlated with the aid of stratigraphic notes and photographs supplied by Jonathan Hughes. Ten-cubic-centimetre samples were extracted from the monoliths at a 1-cm interval to obtain a continuous 330-cm sediment sequence similar to a core.

Surface samples were treated with buffered formalin to kill any living foraminifera. The monolith and surface samples were wet-sieved through 500 μm and 63 μm screens to eliminate large debris and silt and clay particles, respectively. The residue retained on the 63 μm screen included sand, plant detritus and foraminifera. Each sample was then rinsed in water, preserved in diluted ethanol, and stored in air-tight containers prior to examination. Residues were split into eight equal parts using a settling column splitter (Figure 7; Scott and Hermelin, 1993).

The organic content of the monolith samples was determined by Pacific Soils Analysis Inc. (Richmond, B.C.) by the loss-on-ignition (LOI) method. Each 5 cc subsample was weighed, dried, ashed in a muffle furnace at 500 °C for sixteen hours, and weighed again to calculate the organic content of the sediment.

Data analysis

Split subsamples were examined in liquid under a binocular stereoscope at magnifications of 20-40x to find, identify and count the foraminifera present (total number of individuals, total number of species and total number of individuals per species). Phleger (1960) first suggested that 300 foraminifera per 10 cc sample are an adequate number to count to obtain statistically significant data, and this has been the standard since (Scott *et al.*, 2001). Values in split subsamples were multiplied by eight to give a representative value for the entire 10 cc sample.

For the purposes of this study, two taxa mentioned under different names in the section on previous work (pp. 12-24) will be referred to from this point forward as follows: *Jadammina macrescens* and *Trochammina macrescens* f. *macrescens* will be referred to as *Trochammina macrescens*, and *Jadammina macrescens* f. *polystoma* will be referred to as '*Trochammina macrescens* f. *polystoma*' (Appendix 2).

Counts were entered into Excel spreadsheets and recalculated as percentages. Percentage values were then entered into a paleontologic plotting program called 'psimpoll' (Bennett, 2003). Microfossil figures and graphs, displaying population percentages vs. depth or horizontal distance, were generated using ©CorelDraw10. Statistical analysis was performed on raw, percentage and logarithm ($\log_{10}$) values.

Multivariate statistical analysis was used to extract a qualitative assessment of the foraminiferal assemblages and the within-group variance and groupings. Three stages of statistical analysis were performed on both the modern and fossil data sets to determine species zonation and paleoelevations for the subsurface samples (steps outlined in Figure 8).

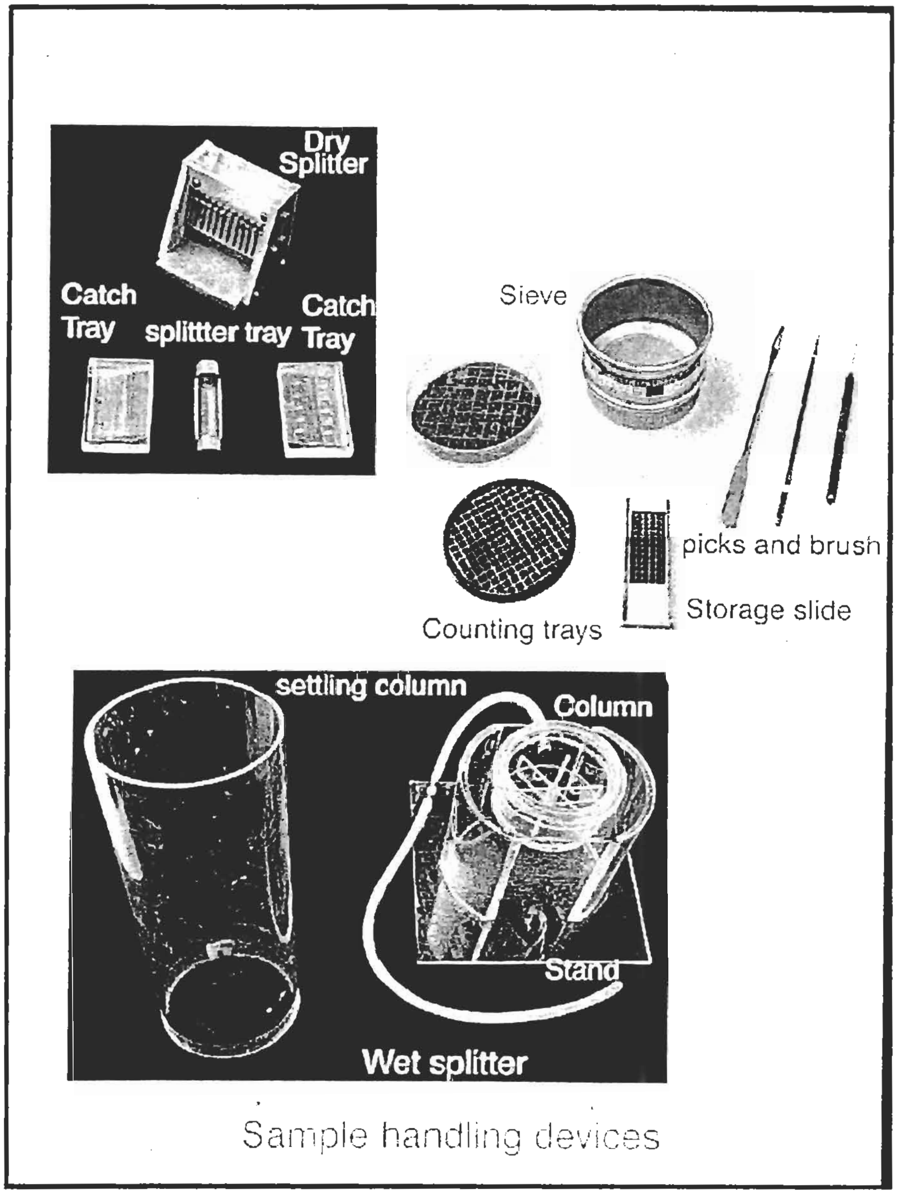

Figure 7. Laboratory tools used to process and examine foraminifera (modified from Scott *et al.*, 2001).

The data sets were considered in several different forms to account for the natural variability within the environment. Both the original modern and fossil data sets were analysed in three forms: raw abundances, percentages, and logarithms ($\log_{10}$). Raw abundances use the actual counts, which is appropriate if the samples are equivalent in some way (i.e., equal volume). However, analogues based on raw counts may be biased by total abundances, which can fluctuate greatly within a marsh environment and may not necessarily be representative of external forces. The raw counts were recalculated as percentages of the total abundance in each sample. Percentage data are constrained to a sum of 100%, thus an increase in the percentage of one organism must be balanced by a decrease in the percentage of another. This is problematic because, in such a scenario, it is possible that both organisms may increase in absolute abundance. Analyses based on log counts avoid some of these problems. Logarithms also take into account abundance because ratios reflect powers of absolute numbers. The choice of data form depends on the environmental conditions that influenced the species in the analysed samples, as well as the project's objective.

Principal component analysis (PCA) and cluster analysis (CA) were used on the correlation matrix to reduce the large data sets to a more manageable size while maintaining as much of the underlying structure in the data as possible (Orwin and Smart, 2003). PCA, a type of factor analysis, was first run on the separate data sets using ©SPSS 9.0 for Windows. This method organizes sampling entities (e.g., number of species per sample) along meaningful gradients (i.e., principal components), which are linear combinations of the original values that describe maximum variation among the individual sampling entities (McGarigal *et al.*, 2000). In this case, the principal components define the environmental variables that have the greatest influence on species distribution.

Cluster analysis (CA) was then performed on the modern data using ©SPSS 9.0. Samples with similar distributions were grouped using Ward's hierarchical clustering method. This method, also known as minimization of within-group dispersion, creates clusters by minimizing a squared distance between variance weighted by cluster size (McGarigal *et al.*, 2000). It produces the smallest increase in the within sum-of-squares, maintaining the within-group variability to a minimum (see Fishbein and Patterson, 1993, for methodology).

A cluster dendrogram can then be plotted, aiding in the visual identification and interpretation of the various clusters. Descriptive titles, in this case marsh zones, can be assigned using the data represented by each cluster (Orwin and Smart, 2003). By combining the results from PCA and CA, one can identify patterns and interpret environmental factors controlling those patterns.

When PCA and CA were run on the entire modern data set, it became clear that several uncommon foraminifera (i.e. *Eggerella advena*, *T. comprimata* and *T. ochracea*) were not key indicator species and were consequently ignored in the statistical analysis of the surface samples.

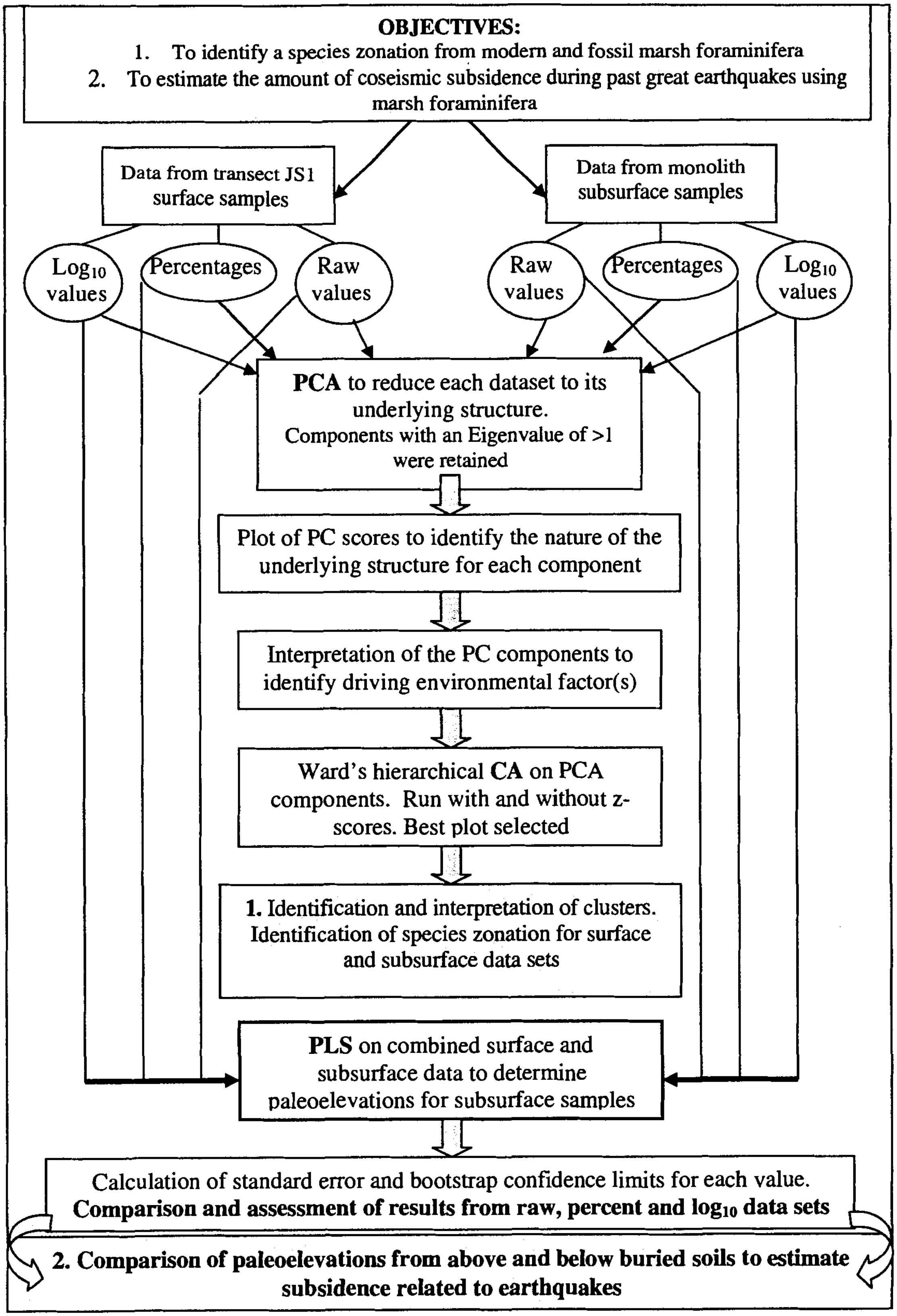

Figure 8. Flowchart of steps used in multivariate statistical analysis.

Data obtained from the monolith were also analysed using CA, and a species zonation was determined from the clusters based on fossil distribution with depth. CA was first run on the entire data set, but due to the size of the dataset and the amount of variability of the foraminiferal assemblages over the 2000-year length of the record, the results showed poor association. The fossil record was therefore divided into five different groups, using the marker soils (S, U, W and Y) as boundaries, and the groups were individually analysed using CA. This analysis produced much better associations. Samples grouped using this method can be considered to be representative of a particular environment or biofacies (Patterson *et al.*, 1999). PCA and CA results provided a species zonation for the modern marsh based on measured elevations. A species zonation was then established for the fossil record based on CA and species assemblages alone.

The relationship between elevation and species composition was examined using partial least squares (PLS) in ©JMP5.1. The PLS method, a form of multiple regression analysis, is suitable when the number of x-variables exceeds the number of samples. PLS develops a model based on factors that explain both response and predictor variation, and works in three stages.

The modern and the fossil data sets are first run through a factor analysis to determine successive linear combinations of *predictors*, called factors (also known as *latent variables* or *components*) from the original set of variables (i.e. the foraminiferal data). The second step involves determining the number of factors to extract, based on the data. Too many factors can result in over-fitting (i.e., tailoring the model too much to the data). The PLS platform enables the user to choose the number of extracted factors by *cross validation*, that is by fitting the model to part of the data and minimizing the prediction error for the unfitted part (JMP5.1, 2002). PLS produces *x-loadings,* which show what the factors are, and *scores,* which are the values of the factors. The user must decide how many of the predictors are relevant to the analysis based on what species are represented by the different factors. For example, the first factor may extract foraminiferal species that are known to prefer higher marsh settings (e.g. *T. macrescens, T. inflata*), whereas a second factor might extract species that are more common in a low marsh environment (e.g. *M. fusca*).

Lastly, PLS runs a regression on the scores to develop an equation that predicts elevation (y_2) based on species composition. In this study, each of the modern samples has a known elevation relative to MLLW (y_1), based on level measurements in the field and known species abundance at each elevation (x_1). Each fossil sample also has known species abundance (x_2), but its elevation prior to burial (y_2) is unknown. PLS develops an equation to predict y_2.

Standard error was calculated in ©SASS for paleoelevations predicted by PLS in ©JMP5.1, and by applying the bootstrap method using a 95% confidence interval. The bootstrap technique estimates uncertainty of an estimated statistic (x_s) of a population parameter (θ) by repeatedly resampling a portion of the population. The resample size is the same as the original sample size, and a total of B resamples is generated. The statistic x_s* is calculated for each sample, where * denotes a bootstrap estimate. Standard errors or confidence limits for x_s can be constructed to describe the uncertainty of x_s as a predictor of θ, based on the variability of x_s* (Politis, 1998). The analysis was run using 500 bootstrap samples. The 2.5th, 50th and 97.5th percentiles were computed. The 2.5th and 97.5th percentiles correspond to the 95% confidence interval.

RESULTS

Modern record

Marsh setting

The Niawiakum River marsh is part of a large temperate tidal marsh that forms a discontinuous fringe around Willapa Bay. At the Oyster locality, the marsh rises from 1.2 m above MLLW to approximately 1.8 m above MLLW over a short distance near the river, and then slopes gently inland to approximately 3.2 m above MLLW at the forest edge (Figure 9). It is interrupted, however, by several tidal channels and depressions. Slump blocks occur at the boundary between the marsh and the mud flat. An old tidal channel near the forest edge was filled with dead wrack at the time of the survey. The marsh is underlain by a thick dark rooty peat, which grades downward into organic-rich mud. Vegetation along the transect is similar to that described by Hughes (unpublished) (Figure 10).

Foraminifera

Fourteen benthic foraminiferal species were observed in the top 1 cm of the samples collected from the modern marsh: *Ammobaculites dilatatus, A. exiguus, Eggerella advena, Elphidium excavatum, Haplophragmoides manilaensis, H. wilberti, Miliammina fusca, Tiphotrocha comprimata, Trochammina inflata, T. macrescens, T. macrescens* f. *polystoma, T. ochracea, Trochamminata salsa*, and inner linings (Appendix 1). Only the four most common species are present in all of the samples: *T. macrescens*, *H. manilaensis*, *T. inflata,* and *M. fusca*. Figure 11 summarizes the counts, plotted against the horizontal distance along the transect.

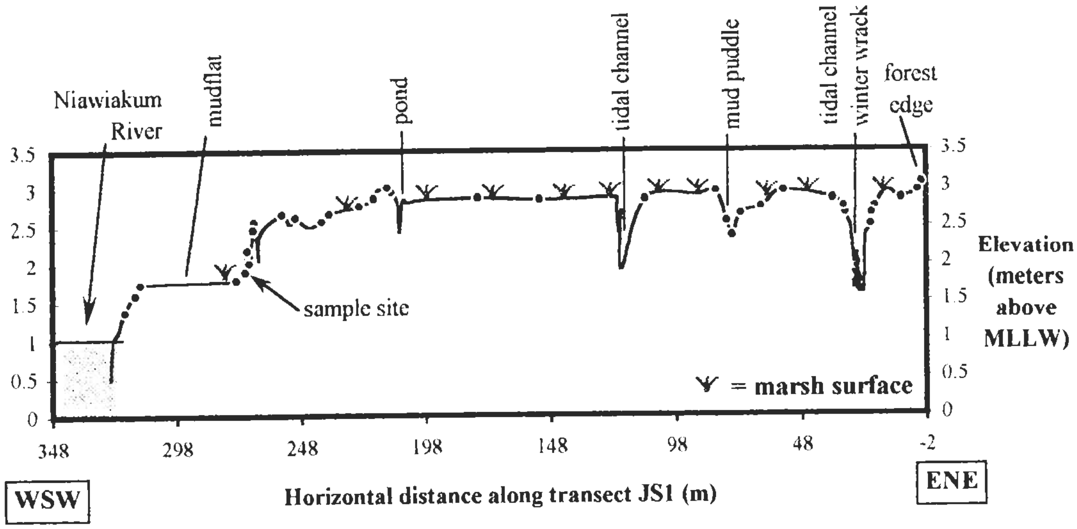

Figure 9. Profile of marsh surface along transect JS1 (see Figure 6 for location).

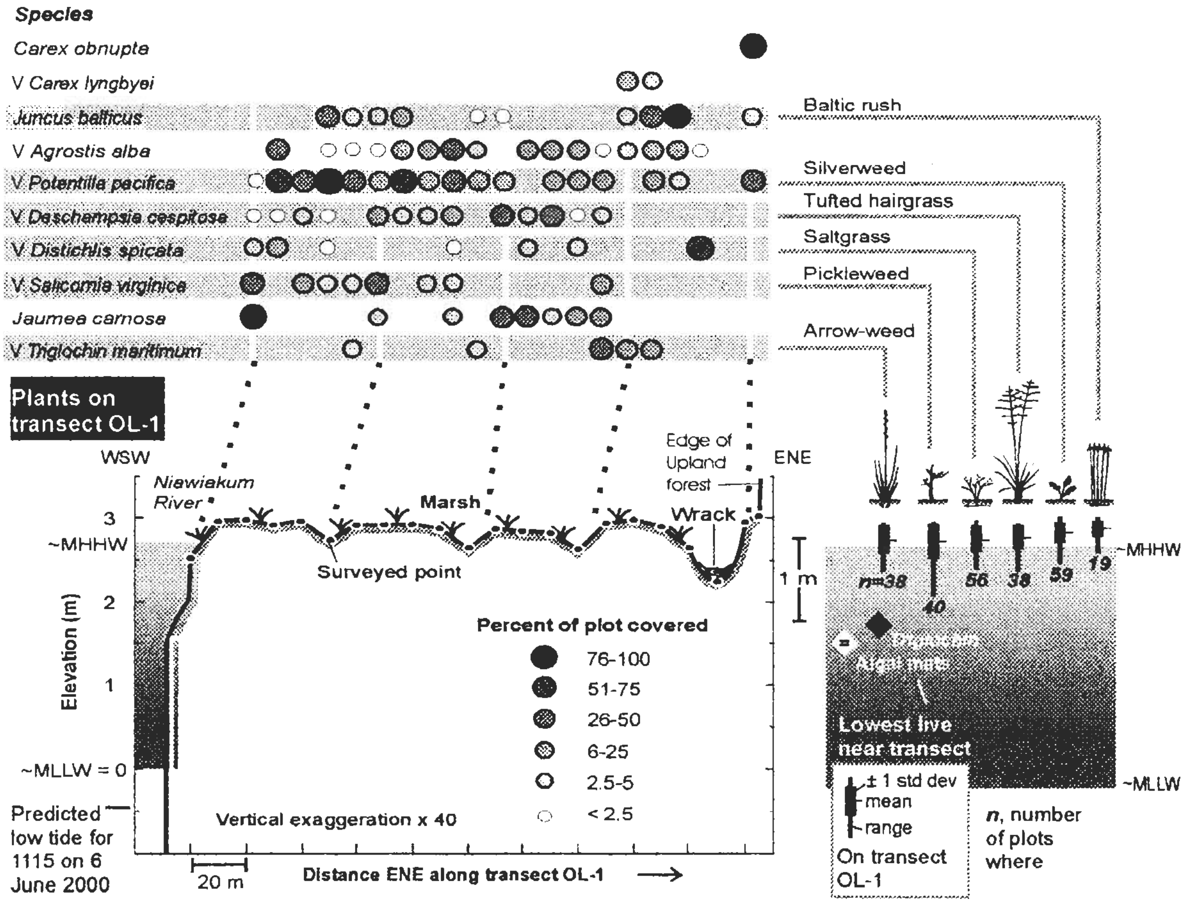

Figure 10. Vegetation distribution along surface transect OL-1, which is within 100 m of transect JS1 (see Figure 6 for location) (Hughes, unpublished).

Visual interpretation of Figures 9 and 11 shows a change in marsh environment along transect JS1, with the appearance and disappearance of different groups of species and changes in total abundance. From the river's edge to approximately 1.7 m above MLLW, the samples contain relatively low total numbers of tests (< 700/10 cc) and species, and the dominant species are *M. fusca* (60%), *A. dilatatus* (~25%) and *A. exiguus* (~10%). These species characterize the lower portion of the marsh and the mudflat.

Assemblages change markedly, and total numbers of individuals and number of species increase, as the marsh surface rises sharply, first over a slump block, and then more consistently along a steep gradient. Both forms of *Ammobaculites* disappear, and *M. fusca* declines to less than 20%, as *H. manilaensis*, *T. macrescens* and *T. inflata* increase. These changes mark the transition from the low marsh to a higher marsh setting at approximately 2 m above MLLW. At the crest of the steep rise up from the low marsh (~220 m in Figure 9 and 11), *T. macrescens* increase to about 70%, followed by a peak in *H. manilaensis* at about 55%. The two species are co-dominant from about 180 m to the first large tidal channel (at about 50% and 40% respectively). *Haplophragmoides manilaensis* is nearly replaced by *T. inflata* at about 100 m to the forest edge.

The marsh surface rises inland of a tidal channel at approximately 90 m. This change is reflected in the foraminiferal assemblages, with a brief rise in *T. inflata*, *H. manilaensis*, *M. fusca*, and *T. macrescens* f. *polystoma*, and a decline in *T. macrescens*. A similar change occurs inland of a second tidal channel at ~30 m, where *H. wilberti* appears for the first time in trace amounts.

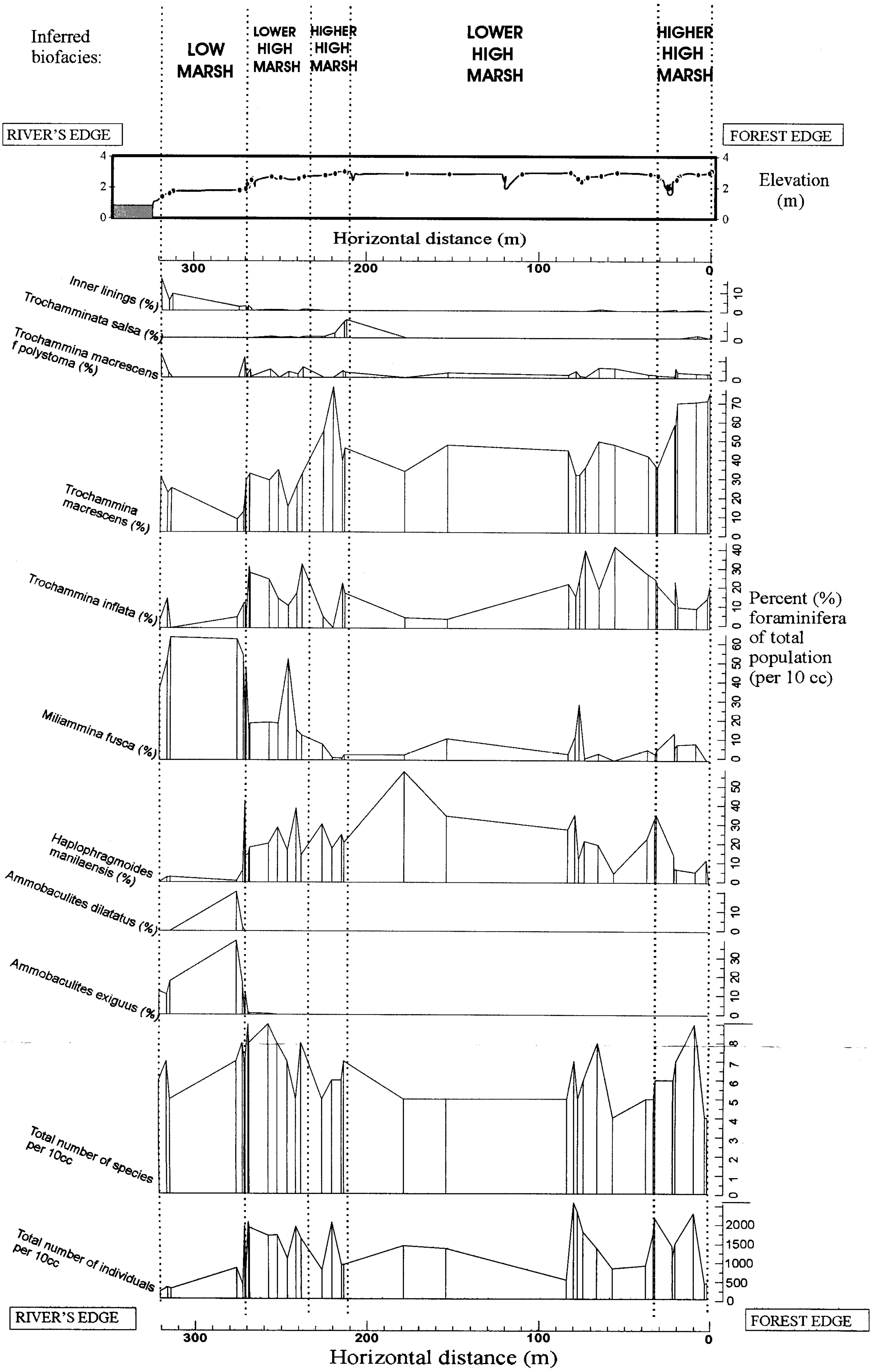

Figure 11. Distribution of total and percent foraminifera along transect JS1 at the Oyster locality. Total number of individuals in 10 cc of sediment, total number of species in 10 cc of sediment, and percentages of species in total population are plotted against horizontal distance along the transect. Thin vertical lines represent samples. Dashed vertical lines represent biofacies inferred from visual analysis.

Inner linings are present only in small amounts (< 10%) in the lower marsh and mudflat. *Trochammina ochracea*, *T. comprimata* and *H. wilberti* occur only in trace amounts along the transect. *Haplophragmoides wilberti* is largely restricted to higher elevations, and *T. salsa* to the area where the marsh rises most steeply. *Trochammina macrescens* f. *polystoma*, although present throughout most of the marsh above 2 m above MLLW, nowhere exceeds 10%.

Species diversity is lower where the marsh surface is flat than where it is undulating or steep. The total number of individuals is highest above 2 m above MLLW near the river edge (at 240-270 m) and in the upper marsh, where the surface rises to almost 3 m (at ~10 m). Samples near the forest edge showed a significant drop in diversity and total numbers, and *T. macrescens* and *T. inflata* are dominant, at 74% and 25%, respectively.

Three zones were identified in the modern marsh at the Oyster locality based on visual interpretations alone (Figure 11): 1) the mudflat and low marsh (~1.3–2 m above MLLW), dominated by *M. fusca* and *Ammobaculites* sp.; 2) the lower high marsh (~2–2.8 m above MLLW), dominated by *T. macrescens* and *H. manilaensis*, and including *T. inflata*; and 3) the higher high marsh (>2.8 m above MLLW), dominated by *T. macrescens* and *T. inflata*, but with low total number of individuals.

Statistical analysis

Clusters obtained from the modern data expressed as raw abundances, percentages and logarithms are presented in Figure 12, plotted along transect JS1. In each case, two to three marsh foraminiferal zones were identified relative to elevation.

Absolute (raw) values

PCA of the raw modern data yielded three factors that account for 66% of the total variance. The first factor accounts for 31% of the variance and is dominated by *T. macrescens*. The second factor accounts for 20% of the variance and is dominated by *M. fusca* and *T. inflata*. The third factor accounts for 15% of the variance and is dominated by *H. wilberti* and *T. macrescens*. The unexplained variance is partly due to the low gradient of the marsh surface at the Oyster locality. Only small sections span the low marsh-high marsh transition, limiting the total variability in foraminiferal assemblages in the sample population.

Ward's CA was run on the raw data from the modern surface samples. Two main clusters were identified, along with four smaller groupings, with z-scores. The clusters, when associated with individual samples, demonstrate that the distribution of species is largely controlled by one variable, elevation. There are two primary marsh zones, and one of the two zones is divisible into two sub-zones: zone 1, 1.30-2.18 m above MLLW (low marsh); zone 2a, 2.02-2.88 m above MLLW (lower high marsh); zone 2b, 2.77-3.06 m above MLLW (higher high marsh). A species zonation for the modern marsh based on analysis of the raw data is shown in Figure 12a.

Percentages

PCA of the modern data expressed as percentages yielded four factors that account for 75% of the total variance. The first factor accounts for 36% of the variance and is dominated by *A. exiguus*, *M. fusca* and inner linings. The second factor accounts for 16% of the variance and is dominated by *T. macrescens* f. *polystoma*. The third factor accounts for 14% of the variance and is dominated by *H. wilberti* and *T. macrescens*.

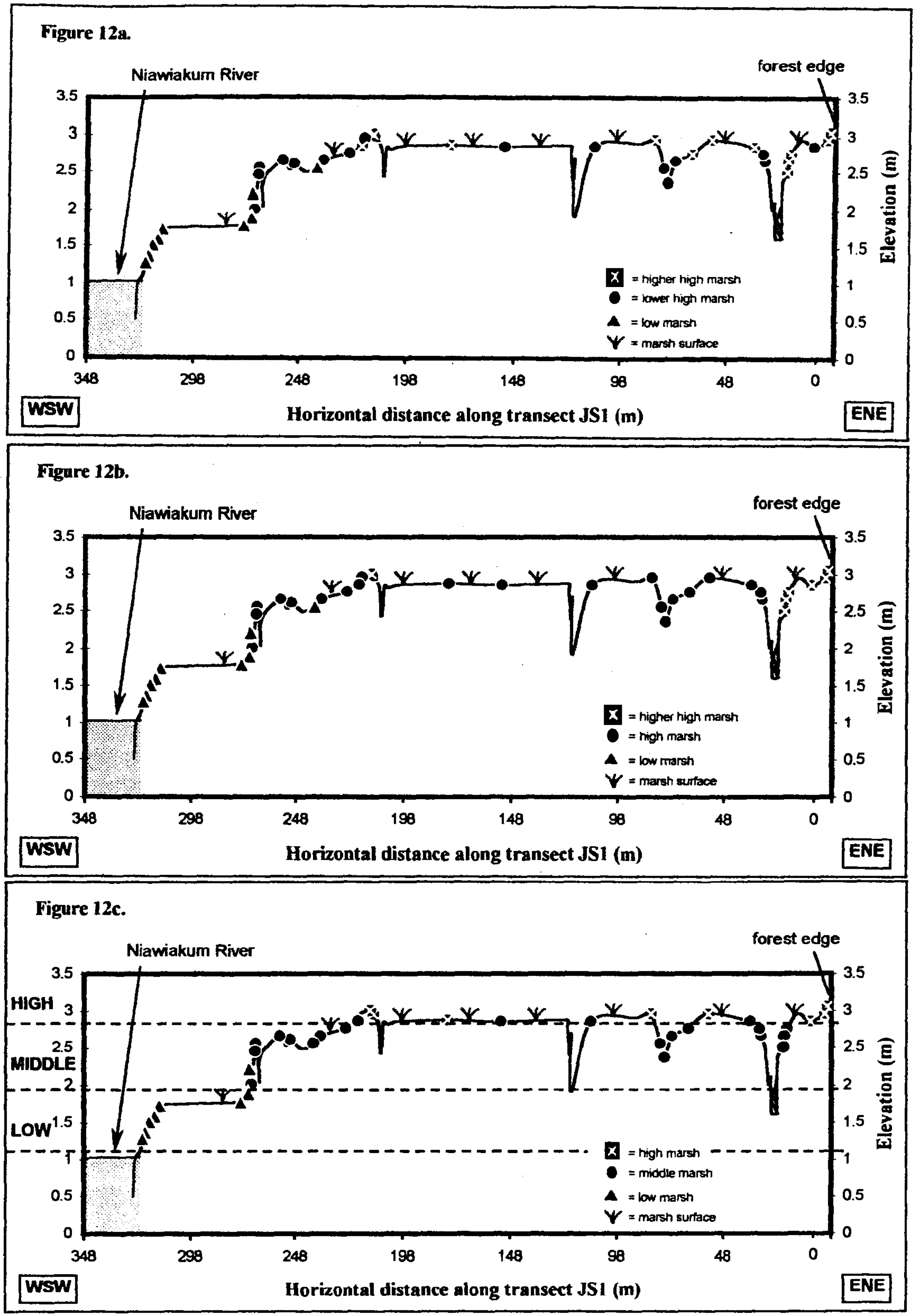

Figure 12. Profile of marsh along transect JS1. Marsh zones are depicted by black triangles, dots and squares. a) Results of cluster analysis (CA) of raw abundances. b) Results of CA of percentages. c) Results of logarithms. Dashed lines represent biofacies inferred from CA of logarithms.

The fourth factor accounts for only 11% of the variance and is dominated *T. salsa*, a species that appears in very small amounts and can be considered an outlier.

Ward's CA method was next run on the modern surface data expressed as percentages. The same results were obtained when all species were considered and when outlier species were removed. Three main clusters were identified without the use of z-scores. Again, the clusters, when associated with individual samples, demonstrate that the distribution of foraminiferal species is controlled by one dominant variable, elevation. There are three marsh zones: zone 1, 1.30-2.23 m above MLLW (low marsh); zone 2, 2.23-2.91 m above MLLW (high marsh); and zone 3, 2.86-3.06 m above MLLW (higher high marsh). The elevation ranges of zones 2 and 3 overlap (Figure 12b).

Logarithms

PCA of the modern data expressed as logarithms ($\log_{10}$) yielded three factors that account for 69% of the total variance. The first factor accounts for 40% of the variance and is dominated by *T. macrescens*, *H. manilaensis* and *T. inflata*. The second factor accounts for 17% of the variance and is dominated by *M. fusca*. The third factor accounts for 12% of the variance and is characterized by low abundances of *H. wilberti* and *T. salsa*. There is a weak association between elevation and the species represented by the second and third factors.

Ward's CA was run on the modern data expressed as logarithms. A species zonation for the modern marsh is provided by the results of CA with z-scores (Figure 12c). There are three distinct marsh zones: zone 1, 1.30-2.23 m above MLLW (low marsh); zone 2, 2.23-2.86 m above MLLW (middle marsh); zone 3, 2.86-3.06 m above

MLLW (high marsh). The clusters determined from the data expressed as logarithms best represent the species zonation in the modern marsh relative to elevation.

Fossil record

Lithostratigraphy

The 330-cm monolith from the Oyster locality contains soils Y, W, U and S, at depths of 101 cm, 132 cm, 182 cm and 270 cm, respectively (Figure 13). Each of the buried soils has a sharp contact with overlying mud, although soils W and U are fainter than soils Y and S.

- **Bottom of monolith to soil S (330 to 270 cm).** The lowest part of the sequence consists of 24 cm of dark gray, organic-rich mud with abundant plant macrofossils. The mud grades upward into grayish brown marsh peat marking soil S.

- **Soil S to soil U (270 to 182 cm).** The upper boundary of soil S is sharp and very irregular. It was eroded before overlying sediment was deposited. Sediment directly above soils S is silt and sand with abundant plant fragments. This minerogenic sediment grades upward into massive, dark gray, organic-rich mud. Algal rhythmites occur between 238 and 230 cm. The mud between 230 and 195 cm is light gray. *Triglochin maritimum* rhizomes were observed at 205 cm. The light gray mud grades upward into 13 cm of marsh peat marking soil U.

- **Soil U to soil W (182 to 132 cm).** The upper boundary of soil U is sharp and irregular. A thin (2 cm) layer of sand and silt rests on soil U. It is overlain by dark gray, organic-rich mud. The mud grades into dark grayish brown marsh peat at 138 cm. The marsh peat, soil W, is 6 cm thick.

- **Soil W to soil Y (132 to 101 cm).** The upper contact of soil W is sharp, but is the least distinct of the four peat-mud contacts and lacks sand, silt and plant fragments. However, it marks a significant change in sediment type. About 10 cm of dark gray, organic-rich mud overlies soil W and grades upward into dark gray muddy peat over a distance of 2 cm between 112 and 110 cm. The muddy peat, in turn, grades into 10 cm of marsh peat riddled with vertical stringy rootlets. *Triglochin maritimum* rhizomes were noted at the base of the marsh peat.

- **Soil Y to surface (101 to 0 cm).** The upper boundary of soil Y is very sharp and is overlain by 6 cm of laminated sand, silt and mud, containing plant detritus including cones and twigs. The laminated sediments are overlain, at 95 cm, by 10 cm of dark gray, organic-rich mud, which grades into mottled, dark gray muddy peat at 85 cm. *Triglochin maritimum* rhizomes are present at 65 and 57 cm. The colour of the organic-rich mud changes upward from dark gray to mottled brown. Above 30 cm, the brown mud grades into dark grayish brown marsh peat. The uppermost peat (18 cm to surface) contains abundant roots of the modern marsh vegetation.

Foraminifera

Fourteen species of benthic foraminifera were found in the sediment samples from the monolith. Twelve species occur in numbers that are statistically significant (>1 %, or >100/10 cc of sediment) and thus were considered in the analysis: *A. exiguus, A. dilatatus, Elphidium excavatum, E. advena, H. manilaensis, H. wilberti, M. fusca, T. comprimata, T. inflata, T. macrescens, T. macrescens* f. *polystoma*, *T. ochracea*, *T. salsa* and inner linings. The four most common species in the fossil record are *T. macrescens, T. macrescens* f. *polystoma*, *T. inflata* and *Miliammina fusca*. The foraminiferal results are presented in five sections, corresponding to the five peat-mud couplets and starting with the oldest couplet first.

- **Bottom of monolith to soil S (330 to 270 cm).** The section starts with very low numbers of individuals (< 500/10 cc), but concentrations increase upward (Figure 14). *Haplophragmoides manilaensis* increases to ~10% in the lower part of the section before disappearing at 300 cm. *Miliammina fusc*a also disappears by 300 cm and is replaced by *T. inflata,* which gradually increases to ~60% by 295 cm before dropping back to ~20%. *Trochammina macrescens* increases upward through the section to a maximum of ~80% at 290 cm. Inner linings are present in trace amounts (<10%) to ~280 cm, at which level they drop off to zero. Values of *T. macrescens* and *T. inflata* fluctuate between 290 and 270 cm, and *T. macrescens* f. *polystoma* is consistently present in small amounts (<15%). The total number of individuals rises to 10,000–14,000/10 cc near the top of the section, the highest values in the fossil record (Figure 14).
- **Soil S to soil U (270 to 182 cm).** The number of foraminifera decreases drastically at the contact between soil S and the base of the overlying mud, from >11,000 to <600/10 cc (Figures 14 and 15). Values remain very low to 208 cm, but then increase to 2000-4000/10 cc. The dominant species in the lowest 10 cm of the section between soil S and soil U are *T. macrescens* (>50%), *T. inflata* (<15%), *A. exiguus* (<10%) and inner linings (<10%). The assemblage changes at 260 cm. *Trochammina macrescens* and *T. inflata* are replaced by *T. macrescens* f. *polystoma* and *M. fusca*, which are tolerant of more saline conditions. *Miliammina fusca* increases from <5% just above soil S to 30% at 240 cm and then decreases to 0% by

220 cm. *Ammobaculites exiguus* ranges from ~15% to >20%, but disappears at 200 cm. *Trochammina inflata* increases to >35%, and *T. macrescens* replaces *T. macrescens* f. *polystoma*, above 208 cm. Inner linings, which reach 20% in the lower part of the section, decrease to <5% by 205 cm. *Haplophragmoides manilaensis* appears just below the top of soil U, reaching 14% at 185 cm.

- **Soil U to soil W (182 to 132 cm).** The total number of foraminifera begins to decline just below the top of soil U and continues to do so above it, with values of <200/10 cc at 180 cm. Values remain low to 168 cm, increase to 1000/10 cc at ~164 cm, drop again, and then increase to ~8000/10 cc at 135 cm. The foraminiferal assemblages reflect these fluctuations (Figure 14). *Trochammina macrescens*, *T. macrescens* f. *polystoma* and inner linings are dominant just above soil U, but decrease as *M. fusca* increases from 0% to 50% at ~170 cm. *Trochammina inflata* appears at 170 cm, but only reaches 20% when *M. fusca* disappears at 160 cm. *Trochammina macrescens* f. *polystoma*, *T. macrescens* and *T. inflata* increase above 160 cm, and, at 150 cm, *T. macrescens* f. *polystoma* is the dominant species. *Trochammina macrescens* replaces *T. macrescens* f. *polystoma*, and *T. inflata* increases, at 140 cm.

- **Soil W to Soil Y (132 to 101 cm).** The total number of individuals drops from >2,000/10 cc to 10/10 cc at 132 cm. Inner linings attain their highest concentration in the monolith (>60%) at 131 cm, but drop to <15% as *T. macrescens* returns to high values at 128 cm. *Trochammina inflata* peaks at ~45% at 111 cm, and then declines to <20% at the top of the section as it is replaced by *Trochammina macrescens*, which peaks at >75% below the top of soil Y. *Elphidium excavatum*, a calcareous species that is rare in the monolith, is present in small amounts above soil W. It accompanies large numbers of inner linings, but disappears with an increase of *H. manilaensis* and the first occurrence of *H. wilberti.* The latter species does not appear anywhere else in the monolith in significant amounts. *Trochammina comprimata* occurs in trace amounts just below soil Y.

- **Soil Y to surface (101 to 0 cm).** The total number of individuals is low just above soil Y (<2,000/10 cc), but slowly increases to 55 cm, where values are greatest. *Miliammina fusca* is the dominant species (>50%) at 97 cm, where it is accompanied by inner linings and *T. macrescens* (Figure 14). It declines, however, to <20% at 90 cm, where it is briefly replaced by *T. inflata*, *T. macrescens*, *T. macrescens* f. *polystoma* and trace amounts of *H. wilberti* before rising again to >80% at 80 cm, its highest concentration in the monolith. *Miliammina fusca* disappears at 60 cm, where it is replaced by *T. macrescens* f. *polystoma.* The latter peaks at 70% for several centimetres and then declines to ~30%, accompanied by increases in *T. inflata*, *T. macrescens* and, eventually, *H. manilaensis.* Inner linings are present in significant amounts only in the lower part of the section.

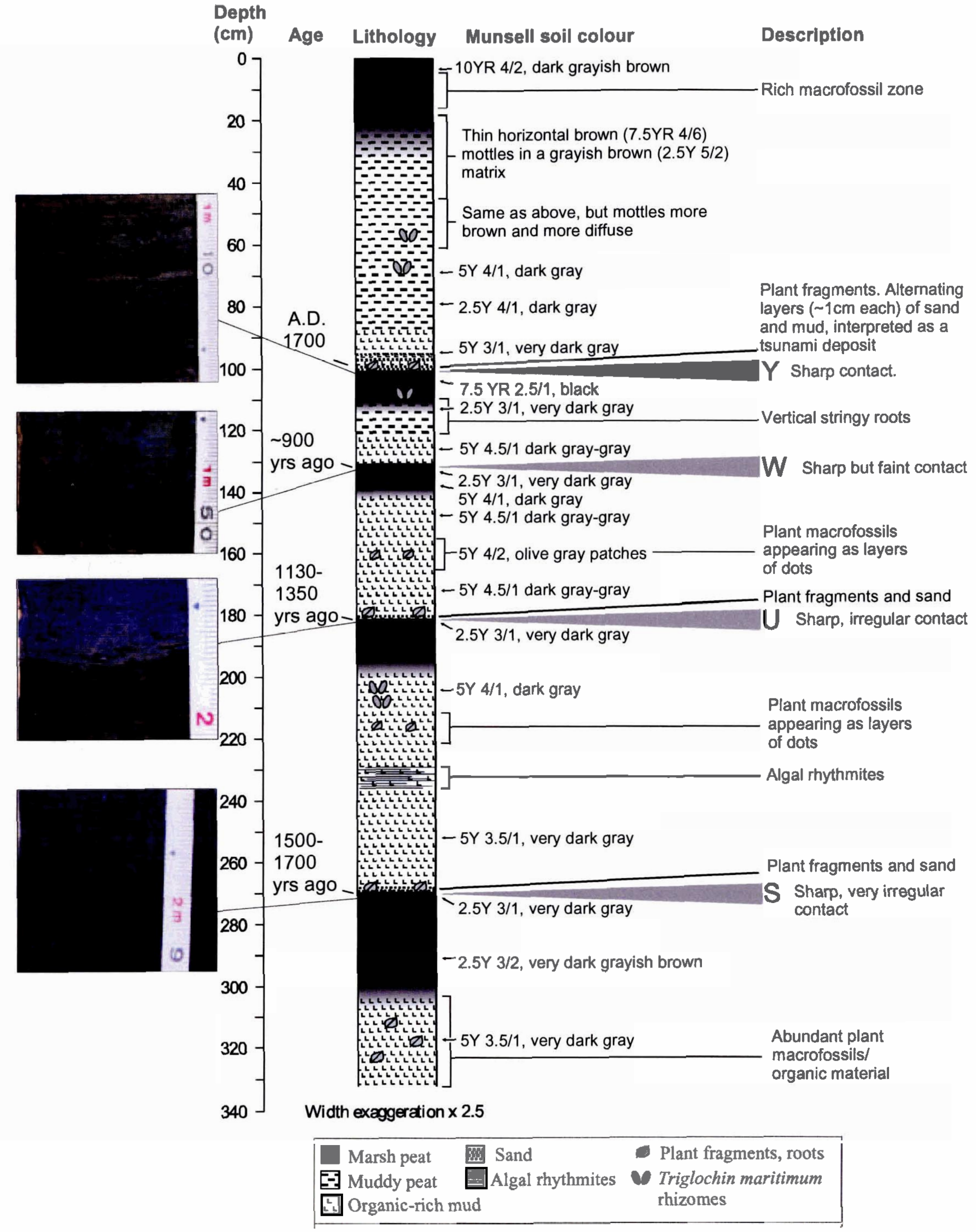

Figure 13. Lithostratigraphy of the sediment monolith sequence (modified from notes of J. Hughes), and photographs of soil contacts.

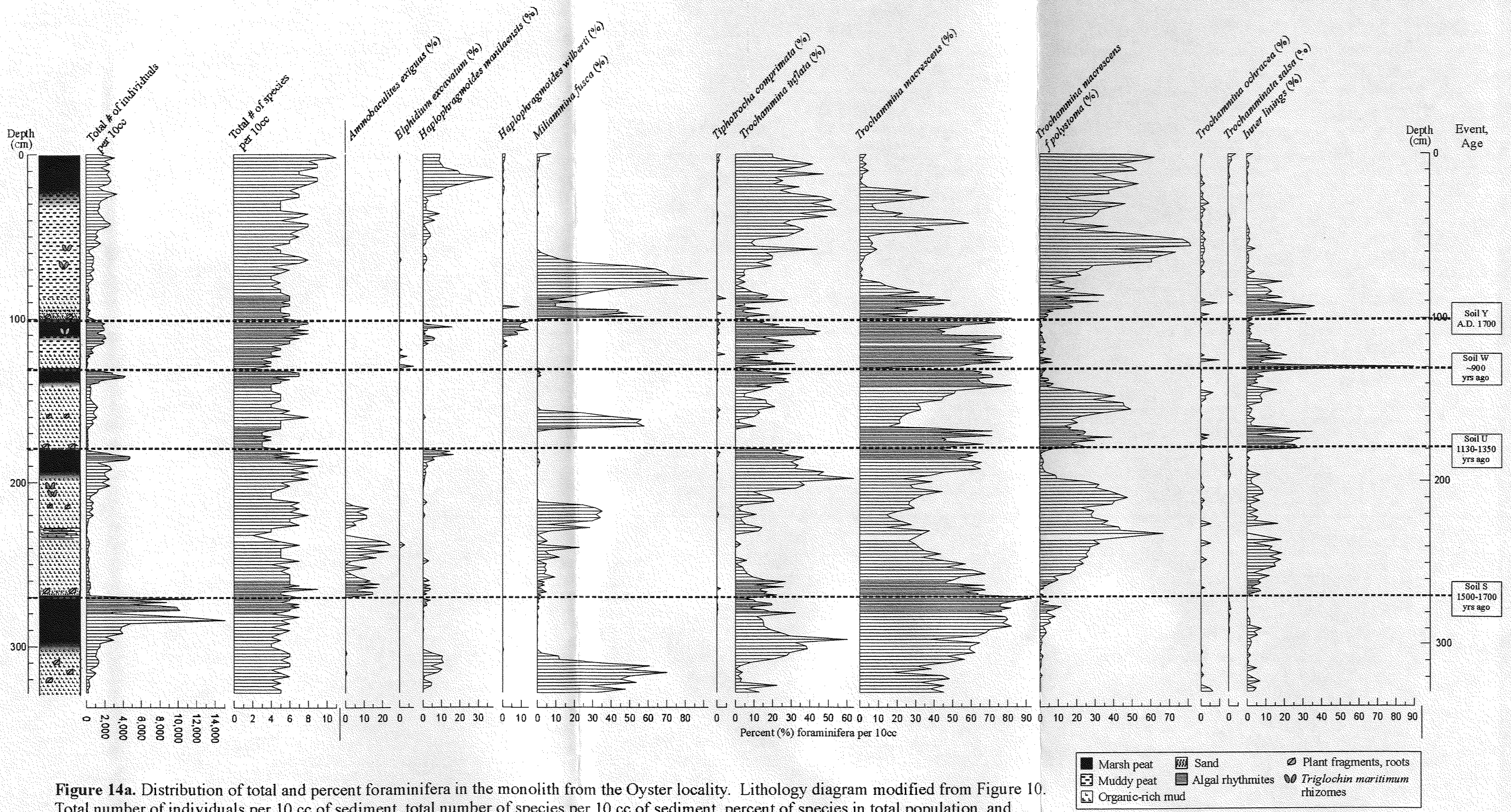

Figure 14a. Distribution of total and percent foraminifera in the monolith from the Oyster locality. Lithology diagram modified from Figure 10. Total number of individuals per 10 cc of sediment, total number of species per 10 cc of sediment, percent of species in total population, and calibrated radiocarbon ages (Atwater and Hemphill-Haley, 1997) are plotted against depth. Thin horizontal lines represent sub-samples (10 cc at 1 or 2 cm intervals); thick dashed lines represent earthquake horizons.

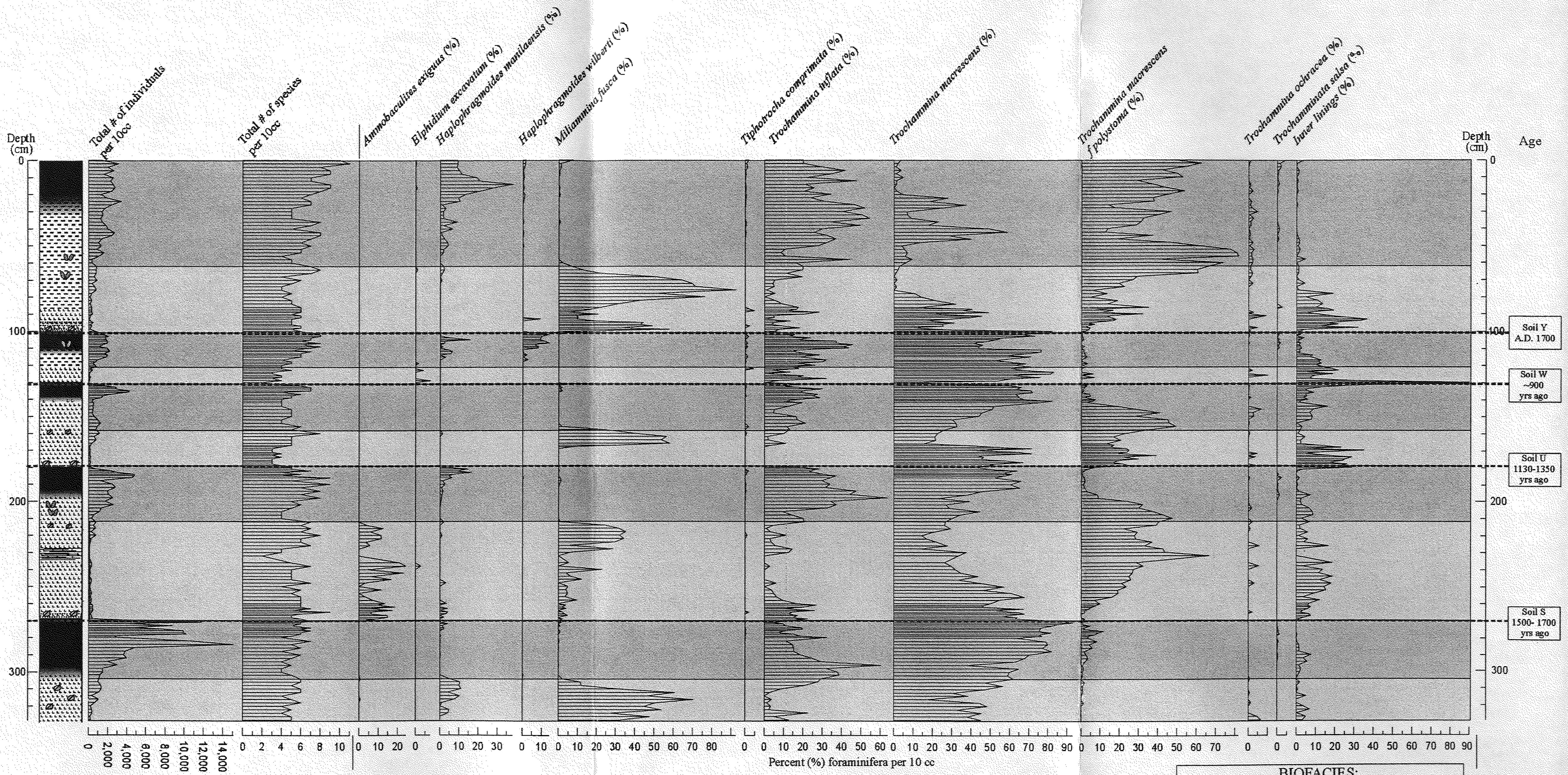

Figure 14b. Distribution of total and percent foraminifera in the monolith from the Oyster locality. Lithology diagram modified from Figure 10. Total number of individuals per 10 cc of sediment, total number of species per 10 cc of sediment, and percent of species in total population are plotted against depth. Thin horizontal lines represent sub-samples (10 cc at 1 or 2 cm intervals); thick dashed lines represent earthquake horizons. Shaded bars represent biofacies inferred from cluster analysis (CA) of data expressed as logarithms (dark grey = upper marsh, light grey = lower marsh).

Loss on ignition

Soils S and Y have the highest LOI values in the sequence (28% and 25%, respectively) (Figure 15). Values are lowest (<10%) above each soil and gradually increase upward to a peak of 15 - 25% just below each peat-mud contact. LOI values drop from 23% to 6% across soil S, 16% to 8% across soil U, 10% to 3% across soil W, and 25% to 6% across soil Y.

Statistical analysis

Several unsuccessful attempts were made to analyse the fossil data in their entirety. Better results were achieved by dividing the record into five parts, separated by soils S, U, W and Y. The data were also analysed in three forms, as absolute (raw) values from the original counts, as percentages, and as logarithms ($\log_{10}$).

Principal component analysis is an inappropriate method to analyse the monolith data, as the fossil samples cannot be tied to a known elevation at the time of deposition. Elevation is the dominant environmental control on species distribution in the modern marsh, but there are too many other factors that affect the monolith samples for PCA to extract this element alone. Therefore, only results from the cluster analysis are included in this section.

Ward's hierarchical CA method (without z-scores) was successful in all cases, and samples clustered into two general marsh foraminiferal zones: those representative of the lower marsh, and those representative of the middle to high marsh (referred to here as 'upper marsh'). The best CA results were obtained from data expressed as logarithms (Figure 14b), but all three forms of data produced similar clusters associated with lower and upper marsh foraminifera species.

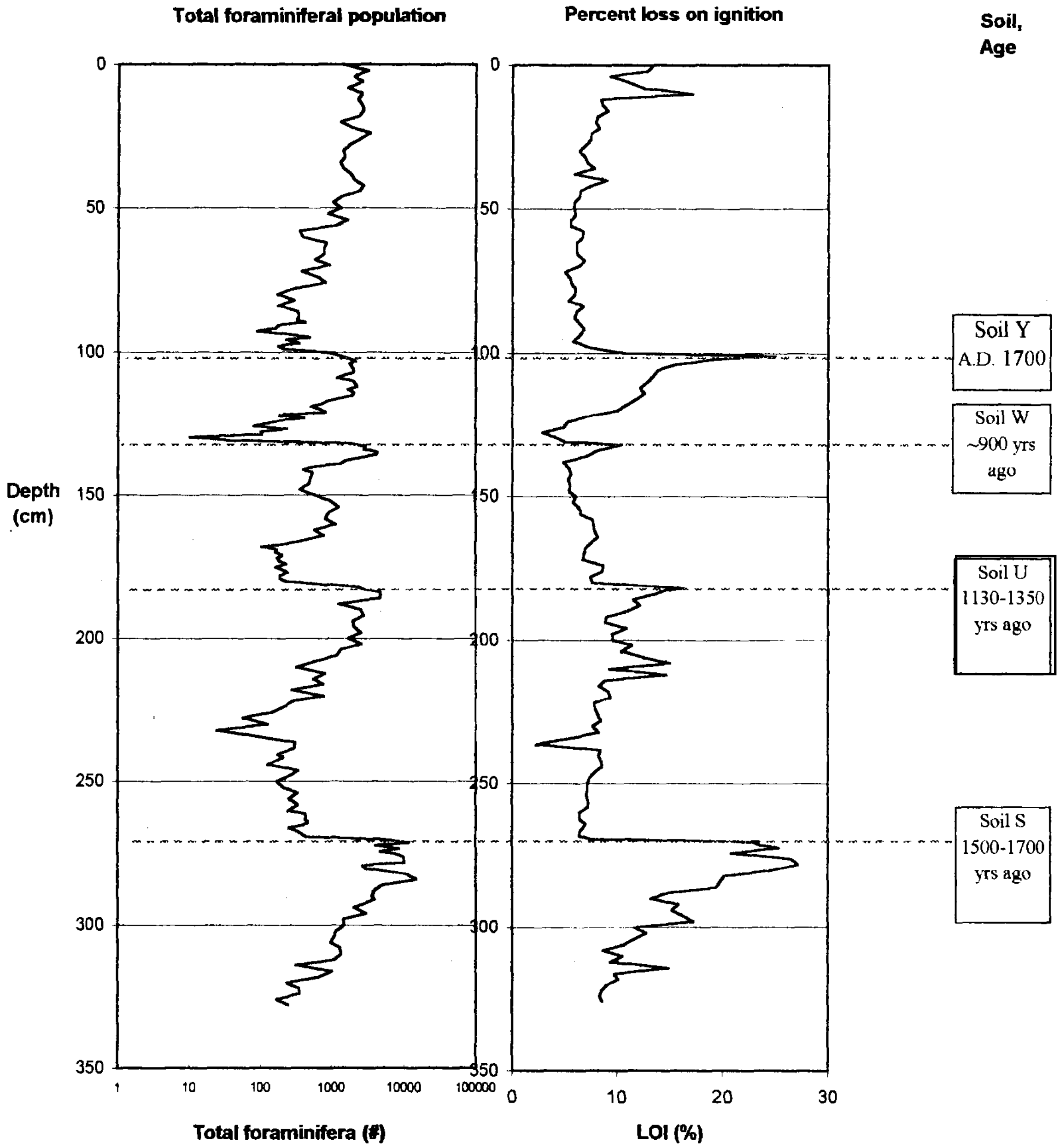

Figure 15- Total number of foraminifera (logarithmic scale), percent loss on ignition, and calibrated radiocarbon ages (Atwater and Hemphill-Haley, 1997) plotted against depth below marsh surface. Dashed horizontal lines represent buried soils.

Absolute (raw) abundances

- **Bottom of sequence to soil S (330 to 270 cm).** Ward's hierarchical CA produced two distinct clusters (Table 3), one of low marsh species (*M. fusca*) and one of upper marsh species (*T. macrescens* and *T. inflata*). When applied to the monolith, CA indicates a change from low marsh to upper marsh at ~280 cm, with three brief low marsh intervals in the upper part of the interval.

- **Soil S to soil U (270 to 182 cm).** Ward's CA method produced two clusters (Table 3), which represent the upper and lower to middle marsh zones. The lower to middle marsh, represented by *M. fusca*, *A. exiguus* and *T. macrescens*, is replaced by the upper marsh, dominated by *T. inflata* and *T. macrescens*, at ~210 cm.

- **Soil U to soil W (182 to 132 cm).** Ward's CA method yielded two clusters (Table 3). Much of this part of the sequence is lower marsh, dominated by *M. fusca*, inner linings and *T. macrescens*. The lower marsh is replaced by upper marsh at ~140 cm, near the top of this interval.

- **Soil W to soil Y (132 to 101 cm).** Ward's CA yielded two clusters (Table 3). The clusters record an upper marsh zone dominated by *T. inflata* and *T. macrescens,* and a second zone, which is difficult to classify as it lacks *M. fusca* but contains low total number of individuals and the highest peak of inner linings seen in the monolith.

- **Soil Y to surface (101 to 0 cm).** Ward's CA extracted two clusters (Table 3) representative of the low and upper marsh zones. This part of the sequence alternates between low marsh, dominated by *M. fusca*, and upper marsh, dominated by *T. macrescens f. polystoma* and *T. inflata*. It begins in the low marsh and ends, near the surface, in a higher marsh.

Percentages

- **Bottom of sequence to soil S (330 to 270 cm).** Ward's hierarchical CA produced two clusters (Table 3), one of low marsh species (*M. fusca*) and one of upper marsh species (*T. macrescens* and *T. inflata*). There is a change from low marsh to upper marsh at ~305 cm.

- **Soil S to soil U (270 to 182 cm).** Ward's CA method produced two clusters (Table 3): a low marsh zone, including *M. fusca* and *A. exiguus*, which, at 200 cm, is replaced by an upper marsh zone, dominated by *T. macrescens* and *T. inflata.*

- **Soil U to soil W (182 to 132 cm).** Ward's CA yielded two main clusters (Table 3), one of which can be divided into two units. The lower part of this section is low marsh, dominated by *M. fusca.* It is followed by a brief middle marsh zone, dominated by *T. macrescens* f. *polystoma*, and then an upper marsh zone, dominated by *T. inflata* and *T. macrescens.*

- **Soil W to soil Y (132 to 101 cm).** Ward's CA yielded two clusters (Table 3). A lower zone lacks *M. fusca,* but contains the highest peak in inner linings seen in the monolith. An upper marsh zone occurs above 110 cm.

- **Soil Y to surface (101 to 0 cm).** Ward's CA extracted two clusters (Table 3), representative of the low and upper marsh zones. This part of the sequence alternates between low marsh and upper marsh. Low marsh, dominated by *M. fusca*, occurs up to 90 cm and is followed by two brief upper marsh intervals between 90 and 80 cm. There is a low marsh interval above this, which is replaced by an upper marsh zone, dominated by *T. macrescens* f. *polystoma* and *T. inflata* at ~68 cm. The upper marsh zone extends up to the surface.

Logarithms

- **Bottom of sequence to soil S (330 to 270 cm).** Ward's hierarchical CA produced two clusters (Table 3), one of low marsh fauna (*M. fusca*) and another of upper marsh fauna (*T. macrescens* and *T. inflata*). A low marsh zone extends to ~305 cm and is followed by an upper marsh zone that continues to the top of the interval (Figure 14b).

- **Soil S to soil U (270 to 182 cm).** Ward's CA method produced two clusters (Table 3) for this section. A lower marsh zone, dominated by *M. fusca* and *T. macrescens* f. *polystoma*, is replaced by an upper marsh zone, dominated by *T. macrescens*, and *T. inflata*, at ~211 cm (Figure 14b).

- **Soil U to soil W (182 to 132 cm).** Ward's CA yielded two clusters (Table 3). A low marsh zone, dominated by *M. fusca* and inner linings, is replaced by an upper marsh zone, dominated by *T. macrescens* and *T. inflata*, at ~160 cm (Figure 14b).

- **Soil W to soil Y (132 to 101 cm).** Ward's CA yielded two clusters (Table 3). A lower zone lacks the low-marsh species *M. fusca*, but contains the highest number of inner linings in the monolith. This zone changes to an upper marsh zone, represented by *T. macrescens* and *T. inflata*, at ~120 cm (Figure 14b).

- **Soil Y to surface (101 to 0 cm).** Ward's CA extracted two clusters (Table 3), representative of the low and upper marsh zones in this section. A low marsh zone, dominated by *M. fusca*, is replaced by the upper marsh, dominated by *T. macrescens* f. *polystoma* and *T. inflata*, at ~60 cm (Figure 14b).

Table 3. Results of cluster analysis of the monolith data sets.

Soil	Interval (cm)	Ward's hierarchical clusters					
		Raw numbers		Percentages		Logarithms ($\log_{10}$)	
		Cluster 1 (cm)	Cluster 2 (cm)	Cluster 1 (cm)	Cluster 2 (cm)	Cluster 1 (cm)	Cluster 2 (cm)
S	330-270	270-271 273-274 275-279 282-286	272-273 274-275 279-282 286-330	270-303	304-330	270-305	306-330
U	270-182	181-182 208-270	182-207	181-199 256-257 260-261 269-270	200-254 258-259	182-212	214-269
W	182-132	132-140	141-182	133-143	144-180	132-156	158-180
Y	132-101	101-116	117-132	102-111	112-132	102-121	122-131
---	101-surface	0-57 62-67	58-61 68-101	0-67, 86-87, 89-90, 100-101	68-85 87-89 90-91 99-100	0-63	64-101

Transfer functions

A transfer function was developed based on partial least squares (PLS), multiple regression analysis to predict paleoelevations of monolith samples. PLS analysis was performed on the entire dataset (both the modern and the fossil data) expressed separately as raw abundances, percentages and logarithms. Three species were treated as outliers and not included in the analysis: *E. excavatum*, *H. wilberti* and inner linings.

Absolute (raw) abundances

PLS results from the data expressed as absolute (raw) abundances are skewed by the total abundances of foraminifera and were not considered representative of the marsh environment and former land level changes.

Percentages

PLS results obtained from the data expressed as percentages (Figure 16) show a trend representative of changes in foraminiferal assemblages at different elevations over time. PLS x-loadings and x-scores are shown in Table 4. One factor was selected through cross-validation, based on the x-loadings, which show a strong contrast between lower marsh and higher marsh species. The following prediction equation (transfer function) was used to determine the unknown elevations (y_2) of fossil samples expressed as percentages:

Elevation (m above MLLW) (y_2) =

$$\left(\begin{array}{l}
\;\;(-3.8952048509451) * \text{percent\_}\textit{A. exiguus} \\
+ (0.995456548811995) * \text{percent\_}\textit{H. manilaensis} \\
+ (-1.7199021985525) * \text{percent\_}\textit{M. fusca} \\
+ (20.5360880852835) * \text{percent\_}\textit{T. comprimata} \\
+ (1.26813787028555) * \text{percent\_}\textit{T. inflata} \\
+ (1.25939497276459) * \text{percent\_}\textit{T. macrescens} \\
+ (-4.2574333302244) * \text{percent\_}\textit{T. macrescens}\text{ f. }\textit{polystoma} \\
+ (12.0772807766741) * \text{percent\_}\textit{T. ochracea} \\
+ (5.42491188176893) * \text{percent\_}\textit{T. salsa}
\end{array}\right)
\begin{array}{l} * \; 0.42997908880168 \\ + \; 2.3468404511686 \end{array}$$

Paleoelevations predicted from the percentage data (Table 5, Figure 16) show sudden subsidence just above soils U and Y (~0.86 m over 2 cm, and ~1.02 m over 1 cm). Results from soil S indicate a smaller sudden drop (~0.4 m over 2 cm), followed by a more gradual drop (~2 m over 40 cm). There is no apparent subsidence associated with soil W. Above soils S, U and Y, there is a gradual drop, followed by a gradual rise. Data were bootstrapped with the 95 percent confidence interval and showed an asymmetric distribution within the central range, indicating a slightly skewed set of results.

Table 4. Partial least squares results from fossil data expressed as percentages and as logarithms.

PLS x-loadings			PLS x-scores		
Species	**Percentages**	**Logarithms**	Sample	**Percentages**	**Logarithms**
Ammobaculites exiguus	-5.1877004	-5.1972231	JS1-01	0.141561	-0.013619
			JS1-02	0.11955	0.01445991
Haplophragmoides manilaensis	2.62230987	4.34008511	JS1-03	0.095132	0.14629415
			JS1-04	0.087686	0.06938528
M. fusca	-5.4703626	-2.0651663	JS1-05	0.055231	0.06702583
			JS1-06	0.052597	0.04663376
Tiphotrocha comprimata	1.48024165	0.33081854	JS1-08	0.087624	0.12902467
			JS1-09	0.096943	0.12820818
Trochammina inflata	2.53580084	3.62082375	JS1-10	0.086	0.05793518
			JS1-11	0.093	0.08535333
Trochammina macrescens	3.93328882	5.15401711	JS1-12	0.082051	0.11454073
			JS1-13	0.142257	0.15801148
T. macrescens f. *polystoma*	-1.7992185	1.78516287	JS1-14	-0.03468	0.05568022
			JS1-15	0.033514	0.11434259
Trochammina ochracea	0.51956359	1.134 e-30	JS1-16	0.098784	0.0268708
			JS1-19	.0.40896	0.04722286
Trochamminata salsa	1.94351797	2.16929924	JS1-20	0.100916	0.07578065
			JS1-23	0.200851	0.16139694
			JS1-24	0.160983	0.19364073
			JS1-26	0.165983	0.14923267
			JS1-27	0.092721	0.01165059
			JS1-28	0.035207	0.09678702
			JS1-29	0.021256	0.06926394
			JS1-30	-0.15803	-0.0802242
			JS1-31	0.087822	0.05518509
			JS1-33	0.00033	0.08168306
			JS1-34	0.046843	0.01592818
			JS1-35	0.010099	0.01419522
			JS1-37	-0.22531	-0.2598933
			JS1-38	-0.02712	-0.0291267
			JS1-39	-0.37365	-0.3358622
			JS1-40	-0.48373	-0.4904074
			JS1-41	-0.34378	-0.3751732
			JS1-42	-0.25647	-0.2990503
			JS1-44	-0.33308	-0.3023767

Notes: X-loadings are shown for each of the foraminiferal species used, and x-scores are shown for the modern analogue.

Table 5. Estimated paleoelevations and coseismic subsidence for soils obtained by partial least squares analysis of foraminiferal data expressed as percentages.

Soil	**Age**[1]	**Paleoelevation before event (m)**	**Paleoelevation after event (m)**	**Estimated subsidence (m)**
Soil Y **(101 cm)**	A.D. 1700	3.05	2.03	**1.02**
Soil W **(132 cm)**	~900 years ago	N/A	N/A	N/A
Soil U **(182 cm)**	1130-1350 years ago	3.02	2.16	**0.86**
Soil S **(270 cm)**	1500-1700 years ago	2.87	2.47	**0.4**

Notes: Error ranges are shown in Figure 16.

[1] Calibrated radiocarbon ages from Atwater and Hemphill-Haley (1997).

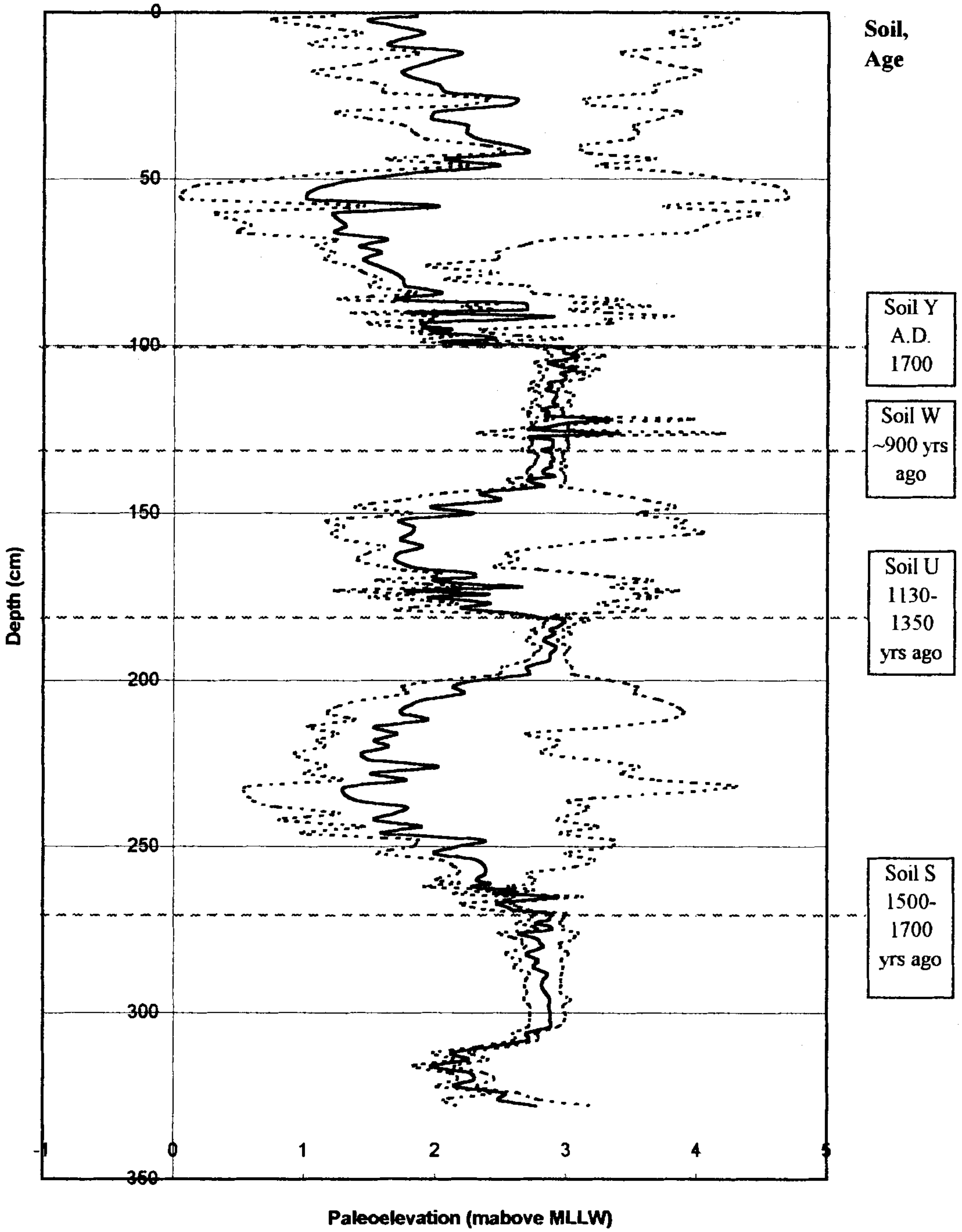

Figure 16. Predicted paleoelevations from fossil data expressed as percentages, plotted against depth. Data were bootstrapped with the 95 percent confidence interval. Dashed vertical lines represent the 95 percent central range. Dashed horizontal lines represent buried soils. Calibrated radiocarbon ages from Atwater and Hemphill-Haley (1997).

Logarithms

PLS results obtained from the data expressed as logarithms (Figure 17) provide paleoelevations representative of changes in marsh environment and foraminiferal species assemblages at different elevations over time. PLS x-loadings and x-scores are shown in Table 4. One factor was selected through cross-validation, based on the x-loadings, which show a strong contrast between lower marsh and higher marsh species. The following transfer function was used to determine the unknown elevations (y_2) of fossil samples expressed as logarithms:

Elevation (m above MLLW) (y_2) =

$$\left(\begin{array}{l} (-0.7539412407864) * \log_{10}\_\textit{A. exiguus} \\ + (0.29870488857607) * \log_{10}\mathrm{log}\_\textit{H. manilaensis} \\ + (-0.3298859710621) * \log_{10}\_\textit{M. fusca} \\ + (0.103356956936716) * \log_{10}\_\textit{T. comprimata} \\ + (0.3030592487865) * \log_{10}\_\textit{T. inflata} \\ + (0.65657311353166) * \log_{10}\_\textit{T. macrescens} \\ + (0.10186568243546) * \log_{10}\_\textit{T. macrescens}\ \text{f.}\ \textit{polystoma} \\ + (-3.981206159\text{e-}16) * \log_{10}\_\textit{T. ochracea} \\ + (0.41522496497852) * \log_{10}\_\textit{T. salsa} \end{array}\right) \begin{array}{l} * 0.42997908880168 \\ + 1.62234208162211 \end{array}$$

Paleoelevations predicted from the logarithm data rise gradually towards each buried soil, with small fluctuations near the top of the soil. Samples above the four buried soils indicate abrupt subsidence of ~1 m in each case (Table 6). Data were bootstrapped with the 95 percent confidence interval and showed a symmetric distribution within the central range (dashed vertical lines in Figure 17), with much smaller ranges of error from the mean than those obtained with percentage data.

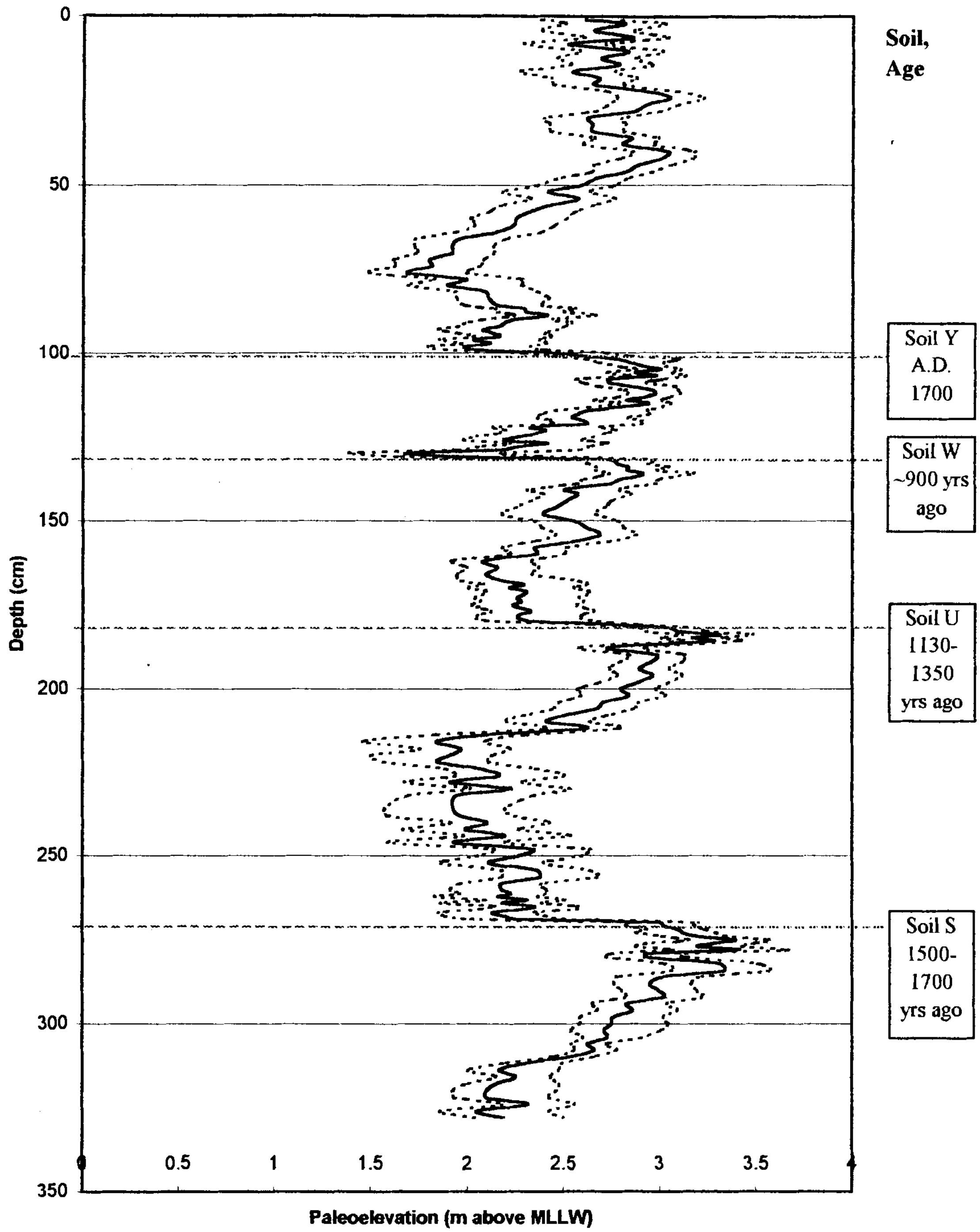

Figure 17. Predicted paleoelevations from fossil data expressed as logarithms, plotted against depth. Data were bootstrapped with the 95 percent confidence interval. Dashed vertical lines represent the 95 percent central range. Dashed horizontal lines represent buried soils. Calibrated radiocarbon ages from Atwater and Hemphill-Haley (1997).

Table 6. Estimated paleoelevations and coseismic subsidence for soils obtained by partial least squares analysis of foraminiferal data expressed as logarithms.

Soil	Age[1]	Paleoelevation before event (m)	Paleoelevation after event (m)	Estimated subsidence (m)
Soil Y (101 cm)	A.D. 1700	3.00	1.97	**1.03**
Soil W (132 cm)	~900 years ago	2.77	1.66	**1.11**
Soil U (182 cm)	1130-1350 years ago	3.32	2.26	**1.06**
Soil S (270 cm)	1500-1700 years ago	3.12	2.13	**0.99**

Notes: Error ranges are shown in Figure 17.

[1] Calibrated radiocarbon ages from Atwater and Hemphill-Haley (1997).

DISCUSSION

Foraminiferal evidence for earthquakes

This study has provided foraminiferal evidence for sudden and lasting submergence during the last four great earthquakes at the Cascadia subduction zone, and for tsunami deposition during two of the events. Submergence during the earthquakes was about 1 m.

Sudden submergence is marked with an abrupt change from high-marsh to low-marsh foraminiferal assemblages at the upper contact of each of the four buried soils (S, U, W and Y). This change is apparent from both visual interpretation of the foraminiferal assemblages and multivariate statistical analysis. The marsh environment recovers slowly following each abrupt submergence. Low-marsh species such as *M. fusca* colonize the tidal flat produced by the earthquake and are gradually replaced by upper-marsh species, including *T. macrescens* and *T. inflata.* No offshore foraminifera were observed within sandy sediment overlying some of the buried soils, but the total number of individuals declines markedly and tests show signs of wear not observed elsewhere in the sequence. The estimate of ~1 m of coseismic subsidence is on the low side of independent estimates made by other researchers working in coastal Washington and Oregon (Darienzo and Peterson, 1990; Hemphill-Haley, 1995; Nelson *et al.*, 1996a; Shennan *et al.*, 1996; Kelsey *et al.*, 2002; Witter *et al.*, 2003), and is considered a minimum value. The lowest modern sample in this study imposes an artificial maximum limit on the computed subsidence.

Foraminifera as indicator species

Studies of modern marsh foraminiferal assemblages show that some species have a narrow elevational range (Scott and Medioli, 1986; Scott and Leckie, 1990). *Trochammina inflata* and *T. macrescens* are common at higher elevations in tidal marshes, whereas *M. fusca* is more abundant at lower elevations. *Miliammina fusca*, however, is not restricted to the low marsh in Willapa Bay, as it tolerates a range of salinities. It is the occurrence of *Ammobaculites* sp. with high numbers of *M. fusca* that defines the low marsh environment at this site.

Haplophragmoides may be more responsive to changes in salinity than elevation, but it is characteristic of low-salinity high marsh areas around the world (Scott and Medioli, 1980b; Scott *et al.*, 1990, 1991; de Rijk and Troelstra, 1997). Guilbault *et al.* (1996) concluded that *H. wilberti* and *T. inflata* are high-marsh species at tidal marshes near Tofino on western Vancouver Island. *Haplophragmoides wilberti* is associated with brackish conditions, whereas *T. inflata* tolerates higher salinities in the high-marsh zone.

Some species, such as *E. excavatum*, are present in Willapa Bay samples both sporadically and in low concentrations and thus were not included in the statistical analysis. It is nevertheless important to consider what these species might contribute to the overall analysis. From the visual analysis, it is clear that, where these species are present, other, more common species are not. For example, *E. excavatum* peaks directly above soil W but does not occur elsewhere in the monolith. As discussed below, environmental conditions that follow submergence of soil W appear to be different from those that followed submergence of the three other soils.

Paleoelevation

The relationship between elevation and foraminiferal species assemblage was examined using two different forms of data sets: percentages and logarithms. The two sets of inferred paleoelevations show differences related to the statistical analysis. Nelson *et al.* (1996b) argue that researchers should not depict changes in sea level with a single line on plots of age or depth vs. elevation. They recommend that results be displayed with a band to reflect uncertainties in the analysis. Accordingly, both data sets were bootstrapped using the 95 percent confidence interval, including the central range of the 2.5th and 97.5th percentiles.

The percentage data yield a trend that shows changes in species assemblages relative to one another (Figure 16). The changes may reflect biological transitions between marsh environments over time. Figure 16 shows that foraminifera colonize a subsided marsh surface after an earthquake, indicating that the earthquake resets the marsh. There is an abrupt drop in land level above soils U and Y, but the drop is subtler above soil S and is followed by a gradual, further drop. The analysis fails to show subsidence of soil W, due to missing low marsh indicator species at this level of the monolith. No analogue of this assemblage was sampled in the modern marsh.

Percentage values fail to register the significant drops in total number of foraminifera that follow each earthquake. In contrast, logarithmic data show relationships between species over time as well as the influence of total numbers of foraminifera (Figure 17). Estimates of coseismic subsidence are likely more accurate in this case, as the earthquake not only affects the ratio between low- and high-marsh species, but also drastically and instantaneously reduces the total population. The sudden submergence would drown the living high-marsh species, and deposition of intertidal muds following the earthquake would reduce the environment from a healthy high marsh to an uncolonized tidal flat (Dave Scott, personal communication, 2004). Over time, as sedimentation rates drop back to normal, and once the accommodation space created by the coseismic subsidence is filled, the tidal flat would be colonized by low-marsh species and the marsh would slowly rebuild.

The ordinate in Figures 16 and 17 is a depth scale, not a linear time-scale. Deposition of sediment immediately after each earthquake would likely occur more rapidly than accretion of the marsh later during the post-seismic uplift. In Alaska, rates of uplift and sedimentation declined exponentially following the 1964 earthquake (Shennan *et al.*, 1999; Atwater *et al.*, 2001). Changes in rates of uplift and sedimentation could be different for each earthquake depending on the amount of subsidence, the time between events and the level attained by the marsh prior to the succeeding event. The reset time required to rebuild a widespread, stable, high marsh is poorly known, but has been estimated to be less than 150 years at Willapa Bay (Atwater and Hemphill-Haley, 1997). Because of these uncertainties, it is not possible to date sample-based changes in elevation of the marsh between earthquakes at the Oyster locality.

A limitation of using PLS to estimate paleoelevation in all cases (raw abundances, percentages, logarithms) is that estimates at both ends of the elevation spectrum are constrained by the single modern transect used in this study, with its limited elevation range of 1.28-3.06 m above MLLW. Past marsh surfaces may have been different from the modern surfaces documented in this study. A consequence of this is that estimates of coseismic subsidence are minima.

Growth-position, vascular plant fossils are an important component of the monolith collected at the Oyster locality. At the top of soils S, U and Y are stems and leaves of high-marsh plants that were buried at the time of the earthquake. In contrast, rhizomes in the organic-rich mud below each soil are dominantly of the low-marsh species *Triglochin maritimum*. These observations are in agreement with those of Atwater and Hemphill-Haley (1997). They report that fossil *T. maritimum* rhizomes at Willapa Bay record a position near the lowest growth limit of the species.

The plant macrofossils help pinpoint the levels of the marsh before and after each earthquake. For example, algal rhythmites above soil S, at ~235 cm depth in the monolith, may correspond to modern day algal mats on mudflats below the lowest *T. maritimum* at the Oyster locality. The algal mats form about 1.0-1.5 m below the level of the high marsh in this area (Figure 18, p. 44, Atwater and Hemphill-Haley, 1997; the lower *Triglochin* limit is labelled "T" and upper algal limit is labelled "a"). The position of the algal mats in the monolith is consistent with foraminiferal-based estimates of paleoelevation.

The aftermath of a fifth large earthquake (event N of Atwater and Hemphill-Haley, 1997) appears to be recorded in sediments below soil S (i.e., below 330 cm) (Figure 17). These sediments record gradual change from low marsh to high marsh.

The microfossil record indicates that there has been little net relative sea-level change at the Oyster locality over the last 2000 years. Eustatic sea-level rise has been offset by gradual accretion of the marsh. Following each submergence event, post-seismic rebound and sediment accretion restore the marsh to near the same elevation it had prior to the earthquake.

Soil W couplet

There are only 30 cm of sediment between soils U and W, yet these sediments represent about 700 years of aggradation. Some of the results presented in this thesis do not indicate coseismic subsidence of soil W. An example is the PLS analysis performed on the percentage data. This result likely is due to the absence of *M. fusca* and *Ammobaculites* sp. in mud above soil W, because the modern analogue delineates the low marsh based on the presence of these indicator species. When the total number of individuals is incorporated into the analysis (e.g. logarithmic data set), an abrupt drop in land level is apparent. The logarithmic results are more reliable in this instance, as percentages of low total numbers mean little. However, the amount of subsidence of soil W indicated by the logarithmic results (~1.11 m) is greater than that of the other three buried soils, which disagrees with other lines of evidence. This result may be invalid because key low-marsh indicator foraminiferal species are missing from the mud directly above soil W. Nevertheless, a low-marsh diatom species makes a brief appearance in the mud above soil W near the monolith collection site (Figure 20, p. 49, Atwater and Hemphill-Haley, 1997).

The large number of inner linings above soil W is noteworthy, although these forms are also common above soils Y and U. The linings may indicate the former presence of calcareous foraminifera. They are fragile, thus some are lost during or after deposition or during sample preparation. Their numbers underestimate the calcareous foraminiferal contribution to the assemblage (Edwards and Horton, 2000). Why, then, are there so many more inner linings above soil W than at any other level in the sequence? Perhaps conditions in the marsh favoured their preservation just after earthquake W. The inner linings at Willapa Bay, however, may not be derived from calcareous species, but rather from poorly preserved, agglutinated foraminifera that were degraded by oxygen introduced by roots from soil Y (Jonathon Hughes, personal communication, 2003).

Missing tsunami deposits (soil U and W)

Soils U and W are not overlain by tsunami sand. The form of the large spit that protects Willapa Bay from the open ocean (Figure 1) has changed over the last several thousand years due to longshore drift, eustatic sea level rise and storms. This begs the question as to whether the environmental setting at present is the same as at the time of the earthquakes that buried soils U and W. It is possible that the configuration of the spit prevented tsunamis from reaching the Oyster locality during some earthquakes. It is also possible that the earthquakes were smaller (M<9), or occurred on a part of the Cascadia subduction zone that was farther away from Willapa Bay. In either case, a smaller tsunami may have been generated, or there may have been no tsunami along this part of the coastline.

Loss on ignition

Organic matter of a variety of compositions and textures affects benthic foraminifera in estuarine systems. It may create anoxic conditions, which are harmful to most marine fauna (Scott *et al.*, 2001), although some foraminifera thrive where organic matter is abundant (Williamson, 1999). In this study, the LOI curve mimics that of the total number of foraminifera (Figure 15). High LOI values record a brackish high marsh, in which foraminifera are abundant.

Four sharp drops in organic carbon correspond to the four earthquake horizons (Figure 15). The sharp drops are followed by gradual increases in organic carbon, reflecting post-seismic rebound and reestablishment of the marsh. LOI values are highest directly below each earthquake horizon. The results demonstrate that LOI is a useful method for documenting coseismic land level change in some tidal marshes.

Precursor events

Paleoelevations of samples below the four buried soils display noteworthy fluctuations over a short period of time (Figure 17). At least 10 cm of submergence occurred shortly before each of the four earthquakes. As well, the amount of organic matter (Figure 15) appears to drop slightly prior to a final peak below buried soils S and U. These may be the 'precursor events' hypothesized by Shennan *et al.* (1999) based on their research on the deposits of the 1964 Alaska earthquake. Their data indicate a rise in relative sea level prior to the 1964 Alaska earthquake. Alternatively, the fluctuations may reflect small changes in eustatic sea level or may be noise in the data. The data are otherwise consistent with the expected trends implicit in the 'earthquake deformation cycle', with cycles of sudden submergence of wetlands followed by gradual shoaling and development of new marshes.

Implications of measured coseismic subsidence

The results of this study reinforce the usefulness of foraminifera for paleoseismic studies. Comparison of the modern and fossil foraminiferal record allows identification and quantification of sudden and long-term land level change. The four soils analysed in this study are laterally extensive and record sudden submergence (Atwater and Hemphill-Haley, 1997). Two of the four soils (S and Y) are overlain by silt and sand that are best explained as tsunami deposits coincident with the submergence. These observations meet four of the five criteria for coseismic subsidence suggested by Nelson *et al.* (1996b). The fifth criterion is the amount of submergence, which has been successfully documented in this study by analysing foraminifera distributions in the marsh. The paleoelevation trends produced by PLS show cycles of sudden submergence of upper marsh peat, followed by gradual shoaling and development of new marsh surfaces. These cycles reflect regional coseismic subsidence followed by interseismic uplift and marsh accretion (Atwater *et al.*, 1995; Nelson *et al.*, 1996a), and are consistent with recurrent great earthquakes along the Pacific Northwest coast (Figure 18).

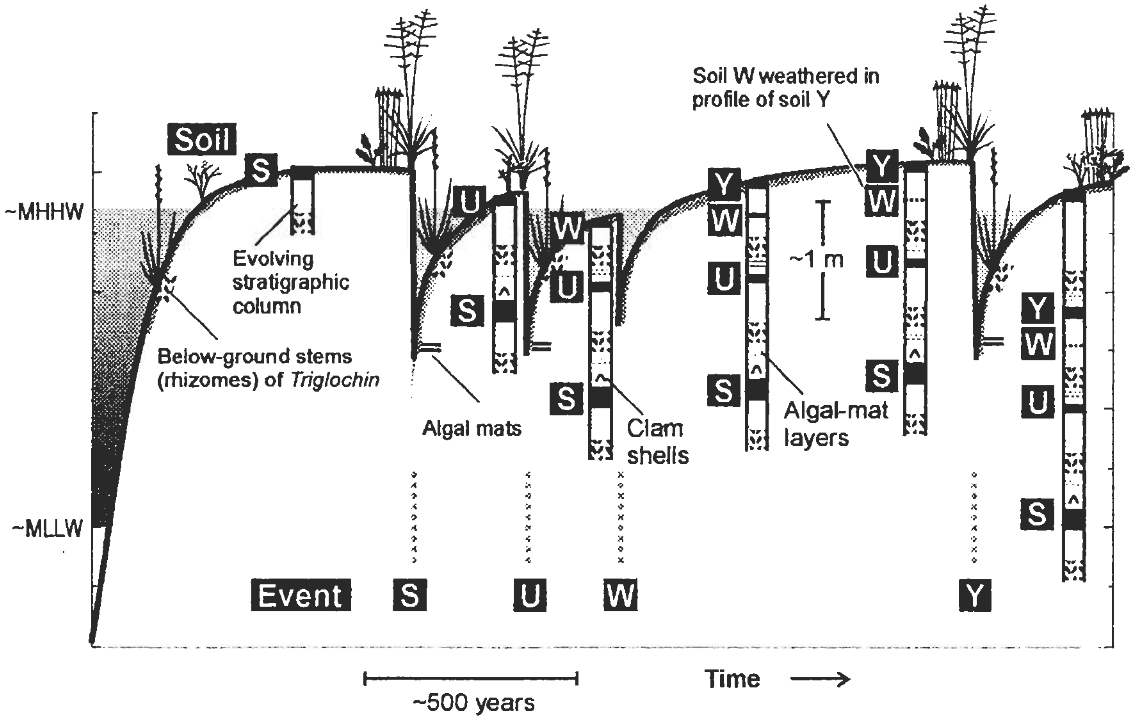

Figure 18. Inferred land-level change over time at the Oyster locality (modified from Atwater *et al.*, 2004).

Limitations of study

Modern assemblages may not provide a good analogue for environments immediately after earthquakes. Post-subsidence tidal prisms following submergence of soils S and Y transformed the Niawiakum River valley into a wall-to-wall tidal flat with salinities greater than those of today (Brian Atwater, personal communication, 2003). The large peak in *M. fusca* and inner linings above soil Y may have resulted from an increased tidal prism after the earthquake.

Tsunamis may also complicate interpretations of foraminiferal assemblages. The thin sand and silt laminae directly above soil S contain high concentrations of *T. inflata* and *T. macrescens* f. *polystoma*, even though the total number of foraminifera is low. It is likely these foraminifera were eroded from the underlying marsh peat by the tsunami that followed the earthquake, as Shennan *et al.* (1999) hypothesize happened in a marsh in Alaska following the 1964 earthquake.

The monolith location is within 100 m of transect JS1, where the surface samples were collected. It was expected, therefore, that the foraminiferal assemblage of the top few centimetres of the monolith would be similar to those of transect samples at the same elevation. Both contain similar amounts of *T. inflata* and *H. manilaensis*, but they differ in their abundance of *T. macrescens* and *T. macrescens* f. *polystoma*. *Trochammina macrescens* f. *polystoma* is almost completely absent from the modern record, but is abundant throughout the fossil record. The monolith was collected close to the river's edge, and its top, although technically in the upper marsh, was more strongly influenced by tidal ebb and flow than samples at sites along the modern transect at the same elevation but more distant from the river. *Trochammina macrescens* f. *polystoma* is known to be more tolerant of salt than *T. macrescens* (Scott and Medioli, 1980b), which may explain its greater abundance in the uppermost monolith samples than in samples collected farther from the river. The differences between the two sets of data may also result from the considerable spatial variability that exists in foraminiferal assemblages in tidal marshes.

Future studies of this type should include several surface transects to obtain a more detailed representation of the spatial distribution of foraminifera in modern marshes.

The reliability of subsidence estimates may be limited by other factors. Guilbault *et al.* (1995) point out that both long-term and coseismic compaction of water-logged marsh sediments produces an apparent rise in sea level. Long-term compaction does not compromise estimates of coseismic subsidence, but coseismic compaction (as documented by Plafker, 1969, for the 1964 Alaska earthquake) would result in anomalously high subsidence estimates (Guilbault *et al.*, 1995). Unrecorded postseismic rebound is also a concern. Guilbault *et al.* (1995) suggest that rebound may begin before sediments start to accumulate on the subsided marsh surface. This potential problem is minimized by sampling the lowest sediment above the peat, as was done in this study.

Multivariate statistical techniques were used to explore the underlying structure of the large foraminiferal data sets. The data sets were reduced by eliminating uncommon species, which carries some risk. A tidal marsh is an extremely sensitive environment, and the distribution of foraminifera is controlled by a large number of environmental factors. The sampling scheme was designed to establish the overall pattern of microfossil assemblages and their relation to elevation, but the statistical analysis included more species than those whose distributions are primarily controlled by elevation (*T. macrescens*, *T. inflata* and *M. fusca*). This approach was used to provide a more accurate representation of the marsh environment, whose foraminiferal assemblages are controlled by many factors, which may not be independent of one another and, therefore, cannot be ignored.

The lowest samples from transect JS1 were higher than MLLW, thus imposing an artificial limit on the analogue that was used to compute the values of coseismic subsidence. Hemphill-Haley's (1995) estimates of coseismic subsidence for the 1700 earthquake in Willapa Bay range from 0.8 m to ~3.0 m. The estimates are based on diatom assemblages from samples that span a greater vertical interval between MLHW and MLLW than the interval samples in this study (Figure 3, p. 370, Hemphill-Haley, 1995).

CONCLUSIONS

A foraminiferal study was conducted at Willapa Bay on marsh sediments that record the last four great earthquakes at the Cascadia subduction zone. The four earthquakes are manifested in the marsh sediments by abrupt contacts between peats and overlying tidal muds. *In situ* plant macrofossils, tsunami sands, a sharp drop in organic matter, and changes in foraminiferal assemblages demonstrate that the contacts record subsidence during earthquakes.

Foraminiferal assemblages in samples from the modern marsh at the Oyster locality provide a species zonation against which the fossil record can be compared to estimate elevations of the marsh over the last 2000 years. Three marsh zones were identified: low marsh (1.3 –2.23 m above MLLW), dominated by *M. fusca* and *Ammobaculites* species; middle marsh (2.23–2.86 m above MLLW), dominated by *T. macrescens, Haplophragmoides* species, and *T. inflata*; and upper marsh (2.86–3.06 m above MLLW), dominated by *T. macrescens and T. inflata.*

A transfer function was created using partial least squares, a multivariate statistical method. It was applied to modern marsh foraminiferal assemblages to estimate paleoelevations of fossil samples. The calculated paleoelevations are most reliable for samples containing key foraminiferal indicator species that are common in the modern marsh. Each of the earthquakes appears to have caused about 1 m of subsidence. The lower elevation limit of the modern analogue sets an artificial maximum limit on the computed subsidence, thus the subsidence estimates are minima. Cluster analysis defined high-marsh and low-marsh biofacies and showed that, during each earthquake, a high marsh dropped to a low marsh position. Tsunamis sands were deposited on two of the four buried soils, further strengthening evidence for coseismic activity. These findings support the hypothesis that the buried soils record great earthquakes at the Cascadia subduction zone.

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APPENDIX 1:

Foraminiferal data

Table A1-1. Foraminifera in modern samples collected from transect JS1 at the Oyster locality, Willapa Bay.

Transect JS1 surface samples, Oyster locality, Willapa Bay																		
Station #	**JS1-01**	**JS1-02**	**JS1-03**	**JS1-04**	**JS1-05**	**JS1-06**	**JS1-08**	**JS1-09**	**JS1-10**	**JS1-11**	**JS1-12**	**JS1-13**	**JS1-14**	**JS1-15**	**JS1-16**	**JS1-19**	**JS1-20**	**JS1-23**
Elevation (m)	3.06	2.96	2.86	2.76	2.66	2.51	2.66	2.76	2.86	2.96	2.76	2.66	2.37	2.56	2.96	2.86	2.88	2.96
No. of species	4	4	9	7	6	6	6	5	5	4	8	6	5	7	5	5	5	7
No. of individuals per 10cc (total)	432	400	2272	1464	1128	1400	2152	1720	888	808	1352	1784	2312	2544	512	1344	1416	912
Ammobaculites dilatatus (%)	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Ammobaculites exiguus (%)	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Eggerella advena (%)	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Haplophragmoides manilaensis (%)	0.00	12.00	5.63	7.10	7.09	14.86	35.69	33.95	23.42	4.95	20.12	21.97	12.46	35.85	28.13	35.12	58.76	21.05
Haplophragmoides wilberti (%)	0.00	0.00	1.41	1.09	0.71	0.00	0.74	0.00	0.00	0.00	0.59	0.00	0.00	0.31	0.00	0.00	0.56	0.00
Miliammina fusca (%)	0.00	0.00	8.80	8.20	6.38	14.29	5.20	3.26	5.41	0.00	3.55	0.90	29.41	12.58	3.13	11.31	2.82	2.63
Tiphotrocha comprimata (%)	0.00	0.00	0.35	0.55	0.00	0.00	0.00	0.00	0.00	0.00	0.59	0.45	0.00	0.31	0.00	0.00	0.00	0.88
Trochammina inflata (%)	22.20	16.00	10.56	11.48	24.82	12.57	23.05	26.05	28.83	43.56	20.71	41.70	26.30	16.98	23.44	4.76	5.65	18.42
Trochammina macrescens (%)	74.00	70.00	69.37	68.85	56.03	57.14	34.20	35.35	40.54	46.53	48.52	34.53	30.80	30.50	43.75	46.43	32.20	44.74
Trochammina macrescens f. *polystoma* (%)	1.90	2.00	2.11	2.73	4.96	0.57	1.12	1.40	1.80	4.95	5.33	0.45	1.04	3.46	1.56	2.38	0.00	2.63
Trochammina ochracea (%)	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Trochamminata salsa (%)	1.90	0.00	1.41	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	9.65
Inner linings (%)	0.00	0.00	0.35	0.00	0.00	0.57	0.00	0.00	0.00	0.00	0.59	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Station #	**JS1-24**	**JS1-26**	**JS1-27**	**JS1-28**	**JS1-29**	**JS1-30**	**JS1-31**	**JS1-33**	**JS1-34**	**JS1-35**	**JS1-37**	**JS1-38**	**JS1-39**	**JS1-40**	**JS1-41**	**JS1-42**	**JS1-44**	
Elevation (m)	3.01	2.87	2.77	2.67	2.57		2.62	2.67	2.57	2.46	2.02	2.18	1.9	1.79	1.74	1.6	1.38	
No. of species	6	6	5	8	5	7	8	9	8	9	7	7	8	7	5	7	6	
No. of individuals per 10cc (total)	912	2040	776	1600	1920	1080	1696	1680	1888	2048	672	1936	376	816	272	304	192	
Ammobaculites dilatatus (%)	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.41	2.13	20.59	0.00	0.00	0.00	
Ammobaculites exiguus (%)	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.48	0.85	1.17	11.90	1.24	17.02	39.22	17.65	10.53	12.50	
Eggerella advena (%)	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.42	0.39	0.00	0.00	0.00	0.00	0.00	0.00	0.00	
Haplophragmoides manilaensis (%)	25.44	18.04	30.93	14.50	39.17	17.04	29.25	20.48	18.64	15.23	14.29	43.39	6.38	0.98	2.94	2.63	0.00	
Haplophragmoides wilberti (%)	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	
Miliammina fusca (%)	0.88	1.18	8.25	13.00	15.83	53.33	19.34	20.00	19.49	15.63	48.81	21.49	55.32	63.73	64.71	52.63	37.50	
Tiphotrocha comprimata (%)	0.00	0.39	0.00	0.50	0.00	0.74	1.42	0.48	0.85	0.39	0.00	0.00	0.00	0.00	0.00	0.00	0.00	
Trochammina inflata (%)	23.68	0.39	6.19	34.00	18.33	11.85	15.57	25.71	29.24	32.81	5.95	13.64	12.77	5.88	0.00	15.79	4.17	
Trochammina macrescens (%)	37.72	77.25	53.61	31.00	25.00	13.33	33.02	27.62	30.93	30.47	27.38	19.01	10.64	6.86	23.53	21.05	29.17	
Trochammina macrescens f. *polystoma* (%)	3.51	0.00	0.00	5.50	1.67	2.96	0.00	4.29	0.42	4.30	1.19	2.07	10.64	0.00	0.00	2.63	12.50	
Trochammina ochracea (%)	0.00	0.00	0.00	0.00	0.00	0.00	0.47	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	
Trochamminata salsa (%)	8.77	2.75	1.03	1.00	0.00	0.74	0.47	0.95	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	
Inner linings (%)	0.00	0.00	0.00	0.50	0.00	0.00	0.47	0.48	0.00	0.78	2.38	0.00	2.13	1.96	8.82	5.26	16.67	

Notes: The elevation of each sample in meters above MLLW, the total number of species per 10 cc of sediment, the total number of individuals per 10cc of sediment, and percentages of the total population are shown.

Table A1-2. Foraminifera in monolith samples (depths 0-97 cm) collected from the Oyster locality, Willapa Bay.

Monolith samples, Oyster locality, Willapa Bay																		
Depth (cm)	0-1cm	2-3cm	4-5cm	6-7cm	8-9cm	10-11cm	12-13cm	14-15	16-17	18-19	20-21	22-23	24-25	26-27	28-29	30-31	32-33	34-35
Total # of species per 10 cc of sediment	10	11	8	9	9	7	7	9	9	8	7	6	7	7	5	5	5	5
Total # of indivduals per 10 cc of sediment	1440	3144	2016	2632	1616	2616	2288	2584	2720	2376	1304	1904	3400	2448	1712	1408	1488	1280
Ammobaculites exiguus (%)	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Elphidium excavatum (%)	0.00	50.89	0.00	0.00	0.00	0.00	0.00	0.00	0.59	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Haplophragmoides manilaensis (%)	9.44	941.48	8.73	10.03	11.39	18.96	20.63	38.08	27.65	20.54	13.50	9.66	10.35	0.98	2.80	1.70	1.61	1.88
Haplophragmoides wilberti (%)	1.67	127.23	1.19	0.30	0.50	0.92	0.35	0.31	0.88	0.00	1.23	0.84	0.71	0.00	0.00	0.00	0.00	0.00
Miliammina fusca (%)	7.22	101.78	1.19	0.30	0.50	0.00	0.00	0.00	0.29	0.00	0.61	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Trochammina comprimata (%)	1.67	76.34	1.19	0.30	0.50	0.31	0.00	0.31	0.59	0.34	0.61	0.42	0.24	0.33	0.00	0.00	0.00	0.00
Trochammina inflata (%)	20.00	2035.62	29.76	41.64	34.65	22.02	47.55	21.05	25.59	20.54	34.36	23.95	30.59	46.41	51.87	40.34	50.54	54.38
Trochammina macrescens (%)	3.33	203.56	1.19	3.65	0.99	4.59	1.40	1.24	0.00	1.68	4.29	27.73	18.59	37.25	25.70	6.82	6.99	8.75
Trochammina macrescens f. polystoma (%)	48.33	6234.10	54.76	41.95	50.00	52.91	29.02	36.84	43.53	53.54	45.40	37.39	37.88	14.05	17.76	46.59	40.32	32.50
Trochammina ochracea (%)	1.11	50.89	0.00	0.00	0.00	0.00	0.00	0.93	0.59	2.36	0.00	0.00	1.65	0.65	1.87	4.55	0.54	2.50
Trochamminata salsa (%)	3.89	152.67	1.98	0.61	0.50	0.31	0.35	0.93	0.00	0.34	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Inner Linings (%)	3.33	25.45	0.00	1.22	0.99	0.00	0.70	0.31	0.29	0.67	0.00	0.00	0.00	0.33	0.00	0.00	0.00	0.00

Depth (cm)	36-37	38-39	40-41	42-43	44-45	46-47	48-49	50-51	52-53	54-55	56-57	58-59	60-61	62-63	64-65	66-67	68-69	70-71
Total # of species per 10 cc of sediment	8	7	5	8	8	7	6	7	6	6	4	5	5	7	8	7	4	6
Total # of indivduals per 10 cc of sediment	1432	1792	1992	2688	2416	1344	1024	1320	880	1624	1104	344	392	840	768	776	576	920
Ammobaculites exiguus (%)	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Elphidium excavatum (%)	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	1.04	0.00	0.00	0.00
Haplophragmoides manilaensis (%)	0.09	1.79	6.43	0.60	0.99	2.38	3.91	4.24	1.82	1.48	0.00	0.00	0.00	1.90	2.08	1.03	0.00	0.87
Haplophragmoides wilberti (%)	0.01	0.00	0.00	0.60	0.33	0.00	0.00	0.61	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Miliammina fusca (%)	0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	2.04	6.67	12.50	22.68	50.00	64.35
Trochammina comprimata (%)	0.01	0.45	0.00	0.60	0.33	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Trochammina inflata (%)	0.34	49.55	30.12	25.60	32.12	36.90	32.03	27.88	10.91	8.37	10.87	44.19	16.33	20.00	19.79	11.34	19.44	5.22
Trochammina macrescens (%)	0.23	17.86	49.00	58.63	28.15	39.88	14.06	4.24	5.45	6.90	5.80	9.30	6.12	2.86	2.08	1.03	0.00	1.74
Trochammina macrescens f. polystoma (%)	0.31	28.57	13.65	12.50	37.09	18.45	46.09	61.82	77.27	80.79	81.88	39.53	73.47	86.67	60.42	60.82	29.17	26.96
Trochammina ochracea (%)	0.01	1.34	0.00	0.89	0.66	0.60	2.34	0.61	2.73	1.48	1.45	2.33	2.04	0.95	1.04	2.06	1.39	0.00
Trochamminata salsa (%)	0.00	0.45	0.80	0.60	0.00	0.60	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Inner Linings (%)	0.00	0.00	0.00	0.00	0.33	1.19	1.56	0.61	1.82	0.99	0.00	4.65	0.00	0.95	1.04	1.03	0.00	0.87

Depth (cm)	72-73	74-75	76-77	78-79	80-81	82-83	84-85	86-87	87-88	88-89	89-90	90-91	91-92	92-93	93-94	94-95	95-96	96-97
Total # of species per 10 cc of sediment	5	4	4	5	4	5	5	6	6	6	6	5	6	6	5	5	5	5
Total # of indivduals per 10 cc of sediment	368	640	816	296	168	296	176	320	336	336	312	424	176	160	88	240	488	224
Ammobaculites exiguus (%)	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Elphidium excavatum (%)	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Haplophragmoides manilaensis (%)	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Haplophragmoides wilberti (%)	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	9.09	0.00	0.00	0.00
Millammina fusca (%)	0.70	71.25	92.16	51.35	76.19	43.24	31.82	22.50	16.67	11.90	5.13	20.75	9.09	10.00	9.09	20.00	44.26	42.86
Trochammina comprimata (%)	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	2.38	4.76	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Trochammina inflata (%)	0.04	5.00	0.98	5.41	0.00	5.41	9.09	17.50	16.67	11.90	28.21	20.75	4.55	5.00	0.00	13.33	4.92	3.57
Trochammina macrescens (%)	0.00	1.25	0.00	10.81	14.29	21.62	31.82	12.50	40.48	35.71	48.72	16.98	45.45	40.00	27.27	16.67	31.15	25.00
Trochammina macrescens f. polystoma (%)	0.20	22.50	5.88	13.51	4.76	18.92	13.64	35.00	7.14	16.67	10.26	32.08	13.64	15.00	18.18	16.67	3.28	7.14
Trochammina ochracea (%)	0.02	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	2.56	0.00	9.09	5.00	0.00	0.00	0.00	0.00
Trochamminata salsa (%)	0.00	0.00	0.00	0.00	0.00	0.00	0.00	2.50	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Inner Linings (%)	0.04	0.00	0.98	18.92	4.76	10.81	13.64	10.00	16.67	19.05	5.13	9.43	18.18	25.00	36.36	33.33	16.39	21.43

Notes: The depth of each sample in centimeters, the total number of species per 10 cc of sediment, the total number of individuals per 10cc of sediment, and percentages of the total population are shown.

Table A1-3. Foraminifera in monolith samples (depths 98-161 cm) collected from the Oyster locality, Willapa Bay.

Monolith samples, Oyster locality, Willapa Bay																		
Depth (cm)	97-98	98-99	99-100	100-101	101-102	102-103	103-104	104-105	105-106	106-107	107-108	108-109	109-110	110-111	111-112	112-113	113-114	114-115
Total # of species per 10 cc of sediment	6	6	5	6	7	8	8	7	7	6	8	6	8	7	5	7	6	6
Total # of indivduals per 10 cc of sediment	344	176	208	800	1208	1632	2072	1728	1848	1960	1952	1440	1168	1960	2088	2200	1656	1968
Ammobaculites exiguus (%)	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Elphidium excavatum (%)	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Haplophragmoides manilaensis (%)	0.00	0.00	0.00	0.00	0.66	0.00	0.77	5.56	15.58	2.45	2.46	0.00	1.37	0.41	4.98	6.55	5.80	0.00
Haplophragmoides wilberti (%)	0.00	0.00	0.00	0.00	5.30	13.73	10.42	9.72	9.09	11.43	13.93	6.11	8.22	8.16	0.00	0.36	0.48	2.44
Miliammina fusca (%)	0.49	31.82	57.69	8.00	2.65	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Trochammina comprimata (%)	0.02	0.00	0.00	0.00	1.32	0.49	1.93	1.39	0.00	0.41	1.23	0.56	1.37	0.82	0.00	0.36	0.00	0.81
Trochammina inflata (%)	0.09	18.18	7.69	5.00	8.61	15.69	12.74	23.61	17.32	37.14	37.30	45.56	41.10	43.27	17.24	14.55	21.26	28.46
Trochammina macrescens (%)	0.26	9.09	26.92	82.00	80.13	66.18	72.97	55.09	53.68	47.76	40.98	46.11	43.84	44.08	76.25	76.36	71.50	58.13
Trochammina macrescens f. polystoma (%)	0.02	4.55	3.85	2.00	0.00	0.49	0.39	0.93	1.30	0.00	0.00	0.00	1.37	0.00	1.15	1.09	1.93	2.03
Trochammina ochracea (%)	0.00	4.55	0.00	1.00	0.00	0.49	0.39	0.00	0.00	0.00	0.41	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Trochamminata salsa (%)	0.00	0.00	0.00	0.00	0.00	0.98	0.39	0.00	0.87	0.41	1.64	0.56	0.68	0.82	0.00	0.00	0.00	0.00
Inner Linings (%)	0.12	31.82	3.85	2.00	1.32	1.96	0.00	3.70	2.16	0.41	2.05	1.11	2.05	2.45	1.53	1.82	0.97	8.13
Depth (cm)	115-116	117-118	118-119	119-120	120-121	121-122	122-123	123-124	124-125	125-126	126-127	127-128	128-129	129-130	130-131	131-132	132-133	133-134
Total # of species per 10 cc of sediment	6	4	5	5	4	4	4	5	3	3	4	4	3	4	2	3	6	7
Total # of indivduals per 10 cc of sediment	1888	904	716	504	704	808	180	408	184	128	80	232	100	104	10	36	1768	2920
Ammobaculites exiguus (%)	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Elphidium excavatum (%)	0.00	0.00	0.00	1.59	0.00	0.00	0.00	3.92	0.00	0.00	0.00	0.00	0.00	7.69	0.00	0.00	0.00	0.00
Haplophragmoides manilaensis (%)	0.03	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Haplophragmoides wilberti (%)	0.00	2.65	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Miliammina fusca (%)	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	2.78	0.00	1.64
Trochammina comprimata (%)	0.01	0.00	0.56	0.00	0.00	0.00	4.44	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.45	0.55
Trochammina inflata (%)	0.18	31.86	30.17	17.48	26.14	13.86	17.78	3.92	13.04	0.00	20.00	17.24	32.00	7.69	0.00	19.44	10.41	16.99
Trochammina macrescens (%)	0.71	53.10	57.54	68.25	62.50	72.28	60.00	68.63	82.61	81.25	60.00	75.86	60.00	53.85	10.00	22.22	60.63	66.03
Trochammina macrescens f. polystoma (%)	0.03	0.00	0.56	3.17	1.14	1.98	0.00	0.00	0.00	6.25	0.00	6.90	0.00	0.00	0.00	0.00	2.71	1.64
Trochammina ochracea (%)	0.00	0.00	0.00	0.00	0.00	0.00	0.00	1.96	0.00	0.00	10.00	0.00	0.00	0.00	0.00	0.00	0.45	0.27
Trochamminata salsa (%)	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Inner Linings (%)	0.07	12.39	11.17	12.70	10.23	13.86	17.78	21.57	4.35	18.75	10.00	6.90	8.00	30.77	90.00	55.56	25.34	12.88
Depth (cm)	134-135	135-136	136-137	137-138	138-139	139-140	140-141	141-142	142-143	144-145	146-147	148-149	150-151	152-153	154-155	156-157	158-159	160-161
Total # of species per 10 cc of sediment	7	7	4	6	5	5	4	4	4	4	5	5	5	4	4	6	5	8
Total # of indivduals per 10 cc of sediment	2800	4304	4072	2400	1528	1336	544	400	536	496	472	352	584	952	1240	904	800	1128
Ammobaculites exiguus (%)	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Elphidium excavatum (%)	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Haplophragmoides manilaensis (%)	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	1.42
Haplophragmoides wilberti (%)	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Miliammina fusca (%)	0.01	2.04	0.20	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	1.77	24.00	40.43
Trochammina comprimata (%)	0.00	0.37	0.00	0.33	0.52	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	1.77	0.00	0.71
Trochammina inflata (%)	0.30	19.70	19.06	27.33	25.13	28.74	19.12	10.00	19.40	12.90	5.08	4.55	16.44	16.81	21.29	11.50	13.00	9.93
Trochammina macrescens (%)	0.63	71.00	71.91	63.00	64.40	64.67	67.65	82.00	76.12	51.61	50.85	45.45	43.84	30.25	32.26	32.74	26.00	22.70
Trochammina macrescens f. polystoma (%)	0.01	1.30	0.00	4.33	4.71	1.80	7.35	6.00	2.99	19.35	28.81	40.91	28.77	45.38	45.81	49.56	35.00	23.40
Trochammina ochracea (%)	0.00	0.19	0.00	0.33	0.00	1.20	0.00	0.00	0.00	0.00	6.78	2.27	2.74	0.00	0.65	0.00	0.00	0.71
Trochamminata salsa (%)	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Inner Linings (%)	0.05	5.39	8.84	4.67	5.24	3.59	5.88	2.00	1.49	16.13	8.47	6.82	8.22	7.56	0.00	2.65	2.00	0.71

Notes: The depth of each sample in centimeters, the total number of species per 10 cc of sediment, the total number of individuals per 10cc of sediment, and percentages of the total population are shown.

Table A1-4. Foraminifera in monolith samples (depths 161-251 cm) collected from the Oyster locality, Willapa Bay.

Monolith samples, Oyster locality, Willapa Bay																		
Depth (cm)	162-163	164-165	166-167	167-168	168-169	169-170	170-171	171-172	172-173	173-174	174-175	175-176	176-177	177-178	178-179	179-180	180-181	181-182
Total # of species per 10 cc of sediment	5	5	5	5	4	3	3	3	4	3	4	3	3	3	3	4	5	5
Total # of indivduals per 10 cc of sediment	568	776	360	232	104	168	160	200	168	184	224	160	200	240	184	184	224	760
Ammobaculites exiguus (%)	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Elphidium excavatum (%)	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Haplophragmoides manilaensis (%)	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	3.57	14.74
Haplophragmoides wilberti (%)	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Miliammina fusca (%)	0.56	53.61	57.78	31.03	7.69	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Trochammina comprimata (%)	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Trochammina inflata (%)	0.01	2.06	11.11	3.45	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	17.86	28.42
Trochammina macrescens (%)	0.21	21.65	15.56	37.93	53.85	71.43	40.00	64.00	71.43	43.48	46.43	45.00	56.00	66.67	52.17	47.83	42.86	50.53
Trochammina macrescens f. polystoma (%)	0.17	20.62	13.33	17.24	15.38	23.81	25.00	24.00	19.05	39.13	21.43	30.00	20.00	16.67	21.74	26.09	7.14	3.16
Trochammina ochracea (%)	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	4.76	0.00	3.57	0.00	0.00	0.00	0.00	4.35	0.00	0.00
Trochamminata salsa (%)	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Inner Linings (%)	0.04	2.06	2.22	10.34	23.08	4.76	35.00	12.00	4.76	17.39	28.57	25.00	24.00	16.67	26.09	21.74	28.57	3.16

Depth (cm)	182-183	183-184	184-185	185-186	186-187	188-189	190-191	192-193	194-195	196-197	198-199	200-201	202-203	204-205	206-207	208-209	210-211	212-213
Total # of species per 10 cc of sediment	7	4	6	4	9	5	9	6	8	6	8	5	6	5	4	4	4	7
Total # of indivduals per 10 cc of sediment	2352	2912	4736	4768	4544	1216	2480	2768	1952	2048	2528	1720	2584	1328	1168	560	320	808
Ammobaculites exiguus (%)	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Elphidium excavatum (%)	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Haplophragmoides manilaensis (%)	0.09	16.48	6.76	4.70	6.34	1.32	2.58	0.87	1.64	1.17	0.95	0.47	0.31	0.00	0.00	0.00	0.00	1.98
Haplophragmoides wilberti (%)	0.00	0.00	0.00	0.00	0.70	0.00	0.32	0.00	0.41	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Miliammina fusca (%)	0.00	0.00	0.00	0.00	0.70	1.32	0.32	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.99
Trochammina comprimata (%)	0.02	1.10	0.68	0.00	0.00	0.00	0.65	0.29	0.41	0.00	0.32	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Trochammina inflata (%)	0.23	25.55	30.41	36.91	34.51	29.61	33.87	31.50	47.54	44.14	63.61	34.42	37.15	32.53	9.59	14.29	20.00	20.79
Trochammina macrescens (%)	0.64	56.87	60.81	57.72	52.11	65.79	60.32	65.32	45.49	37.89	22.78	39.07	26.93	28.92	44.52	34.29	30.00	26.73
Trochammina macrescens f. polystoma (%)	0.01	0.00	0.68	0.67	1.41	1.97	0.97	1.73	2.87	8.59	9.18	24.19	32.20	30.12	37.67	42.86	47.50	40.59
Trochammina ochracea (%)	0.00	0.00	0.00	0.00	0.70	0.00	0.00	0.00	0.00	0.00	0.32	0.00	0.62	1.81	0.00	0.00	0.00	1.98
Trochamminata salsa (%)	0.00	0.00	0.68	0.00	2.11	0.00	0.32	0.29	0.41	1.17	0.32	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Inner Linings (%)	0.01	0.00	0.00	0.00	1.41	0.00	0.65	0.00	1.23	7.03	2.53	1.86	2.79	6.63	8.22	8.57	2.50	6.93

Depth (cm)	214-215	216-217	218-219	220-221	222-223	224-225	226-227	228-229	230-231	232-233	236-237	238-239	240-241	242-243	244-245	246-247	248-249	250-251
Total # of species per 10 cc of sediment	6	7	6	8	6	6	7	4	4	2	5	7	5	5	5	5	7	4
Total # of indivduals per 10 cc of sediment	552	760	272	776	280	216	144	56	128	24	304	296	176	208	128	336	264	168
Ammobaculites exiguus (%)	0.04	12.63	5.88	11.34	11.43	3.70	5.56	0.00	0.00	0.00	21.05	24.32	4.55	23.08	6.25	16.67	3.03	0.00
Elphidium excavatum (%)	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	2.70	0.00	0.00	0.00	0.00	0.00	0.00
Haplophragmoides manilaensis (%)	0.00	0.00	0.00	1.03	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	3.03	0.00
Haplophragmoides wilberti (%)	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Miliammina fusca (%)	0.25	31.58	35.29	31.96	34.29	29.63	5.56	28.57	6.25	0.00	5.26	0.00	22.73	3.85	6.25	11.90	0.00	4.76
Trochammina comprimata (%)	0.00	0.00	0.00	1.03	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Trochammina inflata (%)	0.04	1.05	2.94	11.34	2.86	3.70	5.56	14.29	12.50	0.00	0.00	2.70	0.00	0.00	0.00	0.00	6.06	0.00
Trochammina macrescens (%)	0.26	29.47	20.59	14.43	17.14	22.22	27.78	14.29	37.50	33.33	26.32	29.73	31.82	34.62	43.75	33.33	45.45	57.14
Trochammina macrescens f. polystoma (%)	0.39	22.11	29.41	27.84	28.57	37.04	33.33	42.86	43.75	66.67	28.95	32.43	27.27	26.92	25.00	26.19	21.21	23.81
Trochammina ochracea (%)	0.00	1.05	0.00	0.00	0.00	0.00	5.56	0.00	0.00	0.00	0.00	5.41	0.00	0.00	0.00	0.00	3.03	0.00
Trochamminata salsa (%)	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Inner Linings (%)	0.01	2.11	5.88	1.03	5.71	3.70	16.67	0.00	0.00	0.00	18.42	2.70	13.64	11.54	18.75	11.90	18.18	14.29

Notes: The depth of each sample in centimeters, the total number of species per 10 cc of sediment, the total number of individuals per 10cc of sediment, and percentages of the total population are shown.

Table A1-5. Foraminifera in monolith samples (depths 252-320 cm) collected from the Oyster locality, Willapa Bay.

Monolith samples, Oyster locality, Willapa Bay																		
Depth (cm)	252-253	254-255	256-257	258-259	260-261	261-262	262-263	263-264	264-265	265-266	266-267	267-268	268-269	269-270	270-271	271-272	272-273	273-274
Total # of species per 10 cc of sediment	6	5	6	6	6	6	6	7	5	9	6	5	5	6	7	6	6	5
Total # of indivduals per 10 cc of sediment	208	328	248	336	240	416	432	416	464	392	248	328	376	432	5696	11776	4080	8736
Ammobaculites exiguus (%)	0.12	0.00	3.23	7.14	13.33	9.62	18.52	5.77	17.24	6.12	6.45	14.63	14.89	9.26	0.00	0.00	0.00	0.00
Elphidium excavatum (%)	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Haplophragmoides manilaensis (%)	0.00	0.00	0.00	0.00	3.33	0.00	0.00	3.85	0.00	4.08	3.23	0.00	2.13	0.00	0.42	0.27	4.12	1.10
Haplophragmoides wilberti (%)	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Miliammina fusca (%)	0.04	4.88	3.23	9.52	0.00	3.85	1.85	3.85	0.00	2.04	3.23	4.88	0.00	1.85	0.28	1.36	0.20	0.73
Trochammina comprimata (%)	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	2.04	0.00	0.00	0.00	0.00	0.14	0.27	0.00	0.00
Trochammina inflata (%)	0.04	4.88	6.45	9.52	16.67	26.92	20.37	9.62	25.86	14.29	12.90	17.07	14.89	22.22	11.94	4.62	9.80	10.99
Trochammina macrescens (%)	0.46	60.98	67.74	54.76	50.00	46.15	46.30	67.31	51.72	65.31	67.74	56.10	63.83	62.96	86.80	92.66	84.90	82.42
Trochammina macrescens f. polystoma (%)	0.19	19.51	16.13	7.14	10.00	7.69	5.56	3.85	1.72	2.04	0.00	0.00	0.00	1.85	0.28	0.82	0.78	4.76
Trochammina ochracea (%)	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	2.04	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Trochamminata salsa (%)	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.20	0.00
Inner Linings (%)	0.15	9.76	3.23	11.90	6.67	5.77	7.41	5.77	3.45	2.04	6.45	7.32	4.26	1.85	0.14	0.00	0.00	0.00
Depth (cm)	274-275	275-276	276-277	277-278	278-279	279-280	280-281	282-283	284-285	286-287	288-289	290-291	292-293	294-295	296-297	298-299	300-301	302-303
Total # of species per 10 cc of sediment	7	6	7	6	6	5	4	7	5	6	4	6	5	4	5	4	4	5
Total # of indivduals per 10 cc of sediment	4696	7808	9888	9920	10176	2664	2960	10688	15040	4864	3888	3664	3960	2032	3016	1448	1496	1176
Ammobaculites exiguus (%)	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Elphidium excavatum (%)	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Haplophragmoides manilaensis (%)	0.02	2.05	0.32	0.00	0.00	0.60	0.00	0.30	0.00	0.00	0.00	0.22	0.00	0.00	0.00	0.00	0.00	0.00
Haplophragmoides wilberti (%)	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.68
Miliammina fusca (%)	0.00	0.00	0.65	0.65	0.00	0.00	0.00	0.30	0.00	0.16	0.00	0.00	0.00	0.00	0.27	0.00	0.00	0.00
Trochammina comprimata (%)	0.00	0.41	0.32	0.65	0.63	0.00	0.27	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Trochammina inflata (%)	0.19	19.67	10.68	7.10	15.09	18.62	32.43	11.38	14.68	15.13	15.43	18.78	24.65	29.53	60.21	32.04	37.97	38.78
Trochammina macrescens (%)	0.76	75.82	75.73	81.61	75.47	76.88	63.51	78.74	79.79	77.14	81.89	70.09	67.88	62.99	37.67	64.64	59.89	59.18
Trochammina macrescens f. polystoma (%)	0.01	1.64	11.65	9.35	7.23	3.60	3.78	8.38	4.26	5.92	1.44	2.84	3.43	1.97	0.53	1.10	0.53	0.68
Trochammina ochracea (%)	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Trochamminata salsa (%)	0.00	0.41	0.65	0.65	1.26	0.00	0.00	0.60	0.21	0.16	0.00	0.44	0.40	0.00	0.00	0.00	0.00	0.00
Inner Linings (%)	0.00	0.00	0.00	0.00	0.31	0.30	0.00	0.30	1.06	1.48	1.23	7.64	3.64	5.51	1.33	2.21	1.60	0.68
Depth (cm)	304-305	306-307	308-309	310-311	312-313	314-315	316-317	318-319	320-321	322-323	324-325	326-327	328-329					
Total # of species per 10 cc of sediment	6	6	5	6	6	4	5	6	4	5	4	5	5					
Total # of indivduals per 10 cc of sediment	1096	984	1288	1360	1120	312	1024	664	232	344	352	168	248					
Ammobaculites exiguus (%)	0.01	0.00	0.00	0.00	0.00	0.00	0.78	0.00	0.00	0.00	0.00	0.00	0.00					
Elphidium excavatum (%)	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00					
Haplophragmoides manilaensis (%)	0.05	10.57	9.94	11.18	4.29	10.26	7.81	1.20	0.00	4.65	4.55	0.00	0.00					
Haplophragmoides wilberti (%)	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00					
Miliammina fusca (%)	0.02	11.38	11.80	31.76	60.71	46.15	70.31	50.60	44.83	53.49	27.27	47.62	32.26					
Trochammina comprimata (%)	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00					
Trochammina inflata (%)	0.29	27.64	21.12	8.82	2.86	0.00	3.91	1.20	3.45	2.33	22.73	4.76	12.90					
Trochammina macrescens (%)	0.62	47.15	56.52	47.06	30.71	38.46	17.19	44.58	48.28	32.56	45.45	38.10	45.16					
Trochammina macrescens f. polystoma (%)	0.00	1.63	0.62	0.59	0.71	0.00	0.00	1.20	0.00	0.00	0.00	0.00	0.00					
Trochammina ochracea (%)	0.01	0.00	0.00	0.00	0.71	0.00	0.00	1.20	0.00	0.00	0.00	4.76	6.45					
Trochamminata salsa (%)	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00					
Inner Linings (%)	0.00	1.63	0.00	0.59	0.00	5.13	0.00	0.00	3.45	6.98	0.00	4.76	3.23					

Notes: The depth of each sample in centimeters, the total number of species per 10 cc of sediment, the total number of individuals per 10cc of sediment, and percentages of the total population are shown.

APPENDIX 2: Taxonomy of benthic foraminifera

The classification of foraminiferal genera listed here is in accordance with Scott *et al.* (2001). The following list includes all species of benthic foraminifera mentioned in the thesis. Taxa are listed in alphabetical order by genus.

Ammobaculites dilatatus (Cushman and Brönnimann)

Ammobaculites dilatatus Cushman and Brönnimann, 1948, p. 39, pl.7, figs. 10,11; Scott *et al.*, 1991, p. 384.
Ammobaculites c.f. *foliaceus* (Brady). Parker, 1952, p. 444, pl. 1, figs. 20, 21.
Ammobaculites foliaceus (Brady). Scott and Medioli, 1980b, p. 35, pl. 1, figs. 6-8.

Remarks: Test, agglutinated, initially planispirally coiled, then two to several uniserial chambers with a single terminal aperture. This species lives typically in low marsh and shallow upper estuarine environments where salinities do not exceed 20‰. It appears to have a worldwide occurrence (Scott *et al.*, 2001).

Ammobaculites exiguus (Cushman and Brönnimann)

Ammobaculites exiguous Cushman and Brönnimann, 1948, p. 38, pl. 7, figs. 7, 8; Scott *et al.*, 1991, p. 384; Scott *et al.*, 1995b, p. 292, Figure 6.1.
Ammobaculites dilatatus Cushman and Brönnimann; Scott et al., 1977, p. 1578, pl. 2, Figure 6; Scott and Medioli, 1980b, p. 35, pl. 1, figs. 9, 10.

Remarks: Test agglutinated, initially planispirally coiled, then several chambers uniserial; similar to *A. dilatatus*, but much narrower in outline. When broken it can be confused with *Ammotium salsum*. Its occurrence is similar to *A. dilatatus* (Scott *et al.*, 2001).

Eggerella advena (Cushman)

Verneuilina advena Cushman, 1922, p. 141.
Eggerella advena (Cushman). Cushman, 1937, p. 51, pl. 5, figs. 12-15; Phleger and Walton, 1950, p. 277, pl. 1, figs. 16-18; Scott *et al.*, 1977, p. 1579, pl. 2, fig. 7; Scott and Medioli, 1980a, p. 40, pl. 2, fig. 7; Scott *et al.*, 1991, p. 385, pl. 2, figs. 1, 2.

Remarks: Test finely agglutinated, chambers triserial, roughly triangular in cross-section; aperture is a small slightly protruding slit at the base of the last chamber. This species occurs worldwide in outer estuaries (Scott *et al.*, 2001).

Elphidium excavatum (Terquem)

Polystomella escavata Terquem, 1876, p. 429, pl. 2, fig. 2.
Elphidium excavatum (Terquem) formae Miller *et al.*, 1982, (all).

Haplophragmoides manilaensis (Anderson)

Haplophragmoides manilaensis Anderson, 1953, p. 22, pl. 4, Scott *et al.*, 1990, p. 730, pl. 1, figs. 9a, b; Scott *et al.*, 1991, p. 385, pl. 1, figs. 18, 19; Scott *et al.*, 1995b, p. 292, pl. 1, figs. 3, 4.

Haplophragmoides bonplandi Todd and Brönnimann, 1957, p. 23, pl. 2. Scott and Medioli, 1980b, p. 40, pl. 2, figs. 4, 5.

Remarks: Test agglutinated, planispirally coiled. This species is characteristic of low-salinity high marsh areas worldwide (Scott *et al.*, 2001).

Haplophragmoides wilberti (Anderson)

Haplophragmoides wilberti Anderson, 1953, p. 21, pl. 4, Figure 7; Boltovsky and Vidarte, 1977, p. 39, pl. 3, Figure 3; Zaninettie *et al.*, 1977, pl. 1, figs. 12, 13.

Miliammina fusca (Brady)

Quinqueloculina fusca Brady, 1870, p. 286, pl. 11, figs. 2, 3.

Miliammina fusca (Brady) Phleger and Walton, 1950, p.280, pl.1, figs. 19a, b; Phleger, 1954, p. 642, pl. 2, figs. 22, 23; Scott *et al.*, 1977, p. 1579, pl. 2, figs.8, 9; Schafer and Cole, 1978, p. 28, pl. 12, fig. 2; Scott and Medioli, 1980a, p. 40, pl. 2, figs. 1-3; Scott *et al.*, 1991, p. 386, pl. 1, fig. 14.

Remarks: Test agglutinated, coiled in a "quinqueloculine" pattern. This species occurs almost worldwide in low-salinity low marsh and upper estuarine areas (Scott *et al.*, 2001).

Tiphotrocha comprimata (Cushman and Brönnimann)

Trochammina comprimata Cushman and Brönnimann, 1948, p. 41, pl. 8, figs. 1-3; Phleger, 1954, p.646, pl.3, figs.20, 21.

Tiphotrocha comprimata (Cushman and Brönnimann). Saunders, 1957, p. 11, pl. 4, figs. 1-4; Scott *et al.*, 1977, p. 1579, pl. 4, figs. 3, 4; Scott and Medioli, 1980a, p. 44, pl. 5, figs. 1-3; Scott *et al.*, 1990, pl. 1, figs. 10a, b; Scott *et al.*, 1991, p. 388, pl. 2, figs. 5, 6.

Remarks: Test agglutinated, trochospiral, ventral side somewhat concave. This species is distinguished from *Trochammina* by a siphon-like extension of the aperture in the umbilical area. It is common in middle and high marsh environments and in brackish areas, except in the Pacific basin (Scott *et al.*, 2001).

Trochammina inflata (Montagu)

Nautilas inflatus Montagu, 1808, p. 81, pl. 18, fig. 3

Rotalina inflata Williamson, 1858, p. 50, pl. 4, figs. 93, 94.

Trochammina inflata (Montagu). Parker and Jones, 1859, p. 347; Phleger, 1954, p. 646, pl. 3, figs. 22, 23; Scott *et al.*, 1977, p. 1579, pl. 4, figs. 6, 7; Scott and Medioli, 1980a, p. 44, pl. 3, figs. 12-14; pl. 4, figs. 1-3; Scott *et al.*, 1990, p. 733, pl. 1, figs. 3a, b; Scott *et al.*, 1991, p. 388, pl. 2, figs. 7, 8; Scott *et al.*, 1995b, p. 294, figs. 6.10-17.

Remarks: Test agglutinated, trochospiral; chambers rather inflated, increasing in size gradually; aperture a low arch with a bordering lip. This is the type species of the genus *Trochammina*. It is perhaps the best known and most distinctive of the endemic marsh species, and is one of the first foraminifera species ever described. It characterizes high marsh environments worldwide (Scott *et al.*, 2001).

Trochammina macrescens (Brady)

(forma *macrescens* and forma *polystoma*)

Trochammina inflata (Montagu) var. *macrescens* Brady, 1870, p. 290, pl. 11, fig. 5; Scott, 1976, p. 320, pl. 1, figs. 4-7; Scott *et al.*, 1977, pl. 4, figs. 6-7.

Jadammina polystoma Barenstein and Brand, 1938, p. 381, figs. 1, 2.
Trochammina macrescens Brady. Parker, 1952, p. 460, pl. 3, fig. 3; Phleger, 1954, p. 646, pl. 3, fig. 24; Scott and Medioli, 1980a, p. 44, pl. 3, figs. 1-12; Scott *et al.*, 1990, p.733, p l.1, figs. 1a, b, 2a-c; Scott *et al.*, 1991, p. 388, pl. 2, figs. 10, 11; Scott *et al.*, 1995b, p. 294, p. 294, figs. 6-8.

Remarks: This species was first listed as a variety of *T. inflata,* from which it differs in being more compressed and limited to somewhat lower salinity conditions. A high salinity ecophenotype, *T. polystoma*, commonly occurs with *T. inflata*. This high salinity form is sometimes called *Jadammina polystoma*. In high numbers *T. macrescens* forms occur as a narrow zone near higher high water. (Scott *et al.*, 2001)

“All the specimens designated as *T. macrescens* here would be *T. macrescens* forma *macrescens* (the low salinity forma of Scott and Medioli, 1980a). Brönnimann and Whittaker (1984) went back to Brady’s (1870) original collection of what he called *T. inflata* var. *macrescens* and discovered that all of the specimens in his syntypic material had supplementary apertures, which are characteristic of *J. polystoma* Bartenstein and Brand. Based on these observations they re-designated Brady’s species as *Jadammina* macrescens (Brady) which is perfectly valid without the emendation of the genus *Trochammina* mentioned above to accommodate supplementary apertures. However because we view all these “species” as forma, we prefer to use “*polystoma*” (the Bartenstein and Brand species) forma as the higher salinity variant. Brönnimann and Whittaker (1984) subsequently divided other forms of this species into a different genus, *Balticammina,* based on whether or not the umbilicus was open or not. A relatively recent presentation was given by Gehrels (1997) regarding the taxonomy of this species and the relevance to the study of former sea levels, which was subsequently published in Gehrels and van de Plassche (1999). The most surprising aspect of the presentation given by Gehrels (1997) was that the plate that he used to show three *genera* was the very one used in 1980 by Scott and Medioli (1980a, pl. 3, figs. 1-12) to show that all these “formae” were one species using one of the most complete intragradational series ever assembled. Medioli and Scott (1978) pioneered the use of the intragradational series as a technique to illustrate foraminiferal variability within species. This is a technique previously suggested as a legitimate means to illustrate intraspecific variability by Mayr *et al.* (1953), a group of taxonomists that may be the most distinguished taxonomists of our time. The erection of these new species and genera for what we have already proven is one species adds undue confusion to a problem that is not taxonomic but one of recognizing ecophenotypes and what they mean. Gehrels and van de Plassche (1999) saw few forms of what we would call *T. macrescens* forma *macrescens*; mostly they saw what they would call *Jadammina (Trochammina) macrescens,* which is what we would call *T. macrescens* forma *polystoma* (the high salinity forma with supplementary apertures). Just with this one example it is already clear what the problems are going to be with a series of different names all in the literature. If only the species *T. macrescens* is used as the species with formae *macrescens*(the low salinity form) and *polystoma* (the high salinity form) then the confusion is reduced significantly and it is also taxonomically correct since the formae fall outside the ICZN. As for the new genus/species *Balticammina pseudomacrescens*, this to us is the end member of the series (pl 3, figs. 1-3, Scott and Medioli, 1980a); if it is useful as a paleo-indicator then by all means it can be used but not as a new species and genus but as a forma (*T. macrescens* forma *pseudomacrescens).* The group of authors on our paper may have looked at more specimens of this individual species than everyone else put together (> 10,000 samples with an average of 1000 counted per sample even with a splitter) and obviously we can see the many variations and we could erect many “new species” but this would be spurious and would be counterproductive to the goal which is to use these forms as sea-level indicators. If the formae can be shown to be useful ecophenotypes then they should be delineated but as informal names, not species." (Tobin *et al.*, unpublished manuscript)

Trochammina ochracea (Williamson)

Rotalina ochracea Williamson, 1858, p. 55, pl. 4, fig. 112, pl. 5, fig. 113.
Trochammina squamata Parker and Jones, 1865, p. 407, pl. 15, figs. 30, 31; Scott and Medioli, 1980a, p. 45, pl. 4, figs. 6, 7.
Trochammina squamata Parker and Jones, 1859, and related species. Parker, 1952, p. 460, pl. 3, fig. 5.
Trochammina ochracea (Williamson). Cushman, 1920, p. 75, pl. 15, fig. 3; Scott and Medioli, 1980a, p. 45, pl. 4, figs. 4, 5.

Remarks: *Trochammina ochracea* is distinguished from the previous two species of *Trochammina* by being very flat and concave ventrally. It occurs in a wide variety of places, including high marsh areas in Tierra del Fuego and Alaska, upper estuarine areas in Nova Scotia, and reefs in Bermuda. This species is believed to be opportunistic (Scott *et al.*, 2001).