The application of intertidal foraminifera to reconstruct coastal subsidence during the giant Cascadia earthquake of AD 1700 in Oregon, USA

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ABSTRACT

Changes in species assemblages of intertidal foraminifera can be used to estimate the amount of earthquake-related subsidence during plate-boundary earthquakes at the Cascadia subduction zone. The accuracy and precision of foraminiferal methods in paleoenvironmental reconstruction is underpinned by the relations between contemporary taxa and their environment, which are used to calibrate fossil foraminiferal assemblages in sediment sequences. A contemporary training set of surface sediment samples from five intertidal marshes along the Oregon coast was used to determine foraminiferal distributions and prevailing environmental control(s) along elevational transects. Dominant taxa include *Balticammina pseudomacrescens*, *Trochamminita irregularis*, *Haplophragmoides wilberti*, *Trochammina inflata*, *Jadammina macrescens* and *Miliammina fusca*. Unconstrained cluster analysis and detrended correspondence analysis was used to identify two elevation-dependent faunal zones: Faunal Zone I (upland, high marsh, middle marsh) dominated by *Balticammina pseudomacrescens*, *Haplophragmoides wilberti* and *Trochammina inflata*, and Faunal Zone II (low marsh and tidal flat) dominated by *Miliammina fusca*. Site-specific differences in assemblages at three marshes enabled further subdivision of Faunal Zone I. Zone Ia is based on one or more of *Balticammina pseudomacrescens*, *Trochammina inflata*, *Trochamminita irregularis* and *Haplophragmoides* sp., and Zone Ib on *Jadammina macrescens*, *Haplophragmoides* sp., *Trochammina inflata* and *Miliammina fusca*. Canonical correspondence analysis (CCA) and partial CCA of the training set from the Nehalem River marsh transect was used to infer that the zonation of foraminifera is elevation-dependent (39% of explained variance).

A transfer function was developed to reconstruct sudden changes in relative sea-level during plate-boundary earthquakes in Oregon. The results indicate a robust performance of the transfer function ($r^2_{jack} = 0.82$) with the error estimate ($RMSEP_{jack} = 0.20$ m) comparable to local and regional transfer functions from other temperate marshes. To illustrate the potential of the technique, the transfer function was applied to reconstruct subsidence during the AD 1700 earthquake using at Alsea Bay, Oregon. The reconstruction (0.18 ± 0.20 m) is less than half the subsidence estimate of Nelson et al. [2008. Great-earthquake palogeoesy and tsunamis of the past 2000 years at Alsea Bay, central Oregon coast, USA. Quaternary Science Reviews, 27, 747–768] using their foraminiferal transfer function, perhaps because of differences in taxonomy and the species relationship to elevation.

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1. Introduction

Along coasts of the Cascadia subduction zone of western North America, stratigraphic sequences archive evidence of some of the greatest earthquakes (magnitude 8–9) and tsunamis of the late Holocene (e.g., Darienzo and Peterson, 1995; Nelson et al., 1996a, 2006; Atwater and Hemphill-Haley, 1997; Clague, 1997; Kelsey et al., 2002; Witter et al., 2003). As inferred from couplets of interbedded peaty and muddy sediment beneath tidal wetlands, Darienzo and Peterson (1995) found evidence for subsidence during six great (magnitude 8–9) earthquakes since 3 ka along the northern Oregon coast. Similarly, Nelson et al. (1996b, 1998) identified 10 episodes of rapid submergence since 5 ka in southern Oregon, but inferred earthquake origins for only three. Atwater and

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Hemphill-Haley (1997) documented subsidence for seven great earthquakes in southwest Washington since 3.5 ka. Kelsey et al. (2002) and Witter et al. (2003) described similar evidence for 11–12 great earthquakes since 7 ka in southern Oregon. Nelson et al. (2006) summarized Cascadia coastal stratigraphy, concluding that eight great earthquakes ruptured much of the central and southern subduction zone since 5 ka.

Many estimates of the amount of coseismic subsidence at Cascadia are too imprecise to distinguish, for example, differences in amounts of subsidence or uplift from one earthquake cycle to the next (Nelson et al., 2008). Estimates based on changes in lithology or diagnostic plant macrofossils generally have error ranges greater than 0.5 m (e.g., Atwater and Hemphill-Haley, 1997; Peterson et al., 2000; Leonard et al., 2004). Furthermore, most previous efforts to reconstruct subsidence at Cascadia using microfossils, such as pollen, diatoms, or foraminifera, were either semi-quantitative and/or relied on differences between intertidal floral and faunal zones with broad ranges (e.g., Nelson and Kashima, 1993; Darienzo et al., 1994, 1995; Hemphill-Haley, 1995, 1996; Nelson et al., 1996b; Shennan et al., 1996; Atwater and Hemphill-Haley, 1997; Williams and Hutchinson, 2000; Scott et al., 2001; Hawkes et al., 2005).

More recently, the application of transfer function techniques to microfossil assemblages has increased the precision of relative sea-level (RSL) reconstructions on many coasts including Cascadia's (e.g., Guilbault et al., 1995, 1996; Horton et al., 1999; Gehrels et al., 2001, 2005, 2008; Hughes et al., 2002; Hamilton et al., 2005a, 2005b; Horton and Edwards, 2006; Nelson et al., 2008). To reconstruct former sea-levels transfer functions develop relations between species relative abundance and elevation, which is the primary control on the degree of exposure to brackish water in tidal wetland environments. Because different species vary in their sensitivity to elevation, species assemblages of these groups often reflect precise ecological niches within the intertidal environment (Horton and Edwards, 2006). Transfer functions use regressions to model the relations between elevation and the relative abundance of microfossil taxa. Calibration is then used to reconstruct the elevations of former buried marshes from microfossil assemblages in fossil sediment samples. When combined with lithostratigraphic data, the resulting RSL reconstructions typically have precisions in the ±0.1–0.3 m range (e.g., Edwards et al., 2004; Gehrels et al., 2005, 2008; Hamilton and Shennan, 2005a, b; Horton and Edwards, 2006).

This paper presents a foraminiferal-based transfer function from an extensive set of contemporary foraminiferal data from five Oregon tidal marshes. As an example of using such data in sea-level reconstruction, the transfer function is used to estimate the amount of coastal subsidence during the giant earthquake of AD1700. A requirement of the transfer function technique is that the foraminiferal assemblages in the contemporary training set must be systematically related to the environmental variable(s) to be reconstructed (in this case, elevation). Scott and Medioli (1980), Horton (1999), Horton and Edwards (2006) and others found that the principal environmental variable controlling foraminiferal species distribution within the intertidal environment was elevation, a surrogate for the duration and frequency of tidal exposure (Gehrels et al., 2001). In contrast, Jonasson and Patterson (1992), de Rijk (1995b) and Goldstein and Watkins (1998) argued that salinity was the primary control on the distribution of intertidal foraminifera on North America's Atlantic Coast. This paper describes the distribution of the foraminiferal assemblages with respect to elevation at the five study sites. Subsequently, the relations between the relative abundance of contemporary foraminiferal species and elevation together with several other important environmental variables (clay-silt fraction, loss on ignition, vegetation cover, pH and pore-water salinity) are clarified.

The success of the transfer function technique depends to a large degree on the investigators' ability to collect a high-quality training set comprised of contemporary species assemblages and associated environmental variables from the full range of intertidal environments likely to be encountered in fossil datasets (Birks, 1995). Jennings and Nelson (1992) and Nelson et al. (2008) compiled a contemporary foraminiferal training set from four marshes along the Oregon coast. The resulting transfer function was used to reconstruct subsidence during four plate-boundary earthquakes at Alsea Bay (Fig. 1; Nelson et al., 2008). Reconstructions were, however, compromised by a lack of contemporary analogue assemblages for some fossil assemblages and uncertainties in taxonomy. This research expands and improves the training set of contemporary intertidal foraminifera in Oregon and adds a wider range of environmental data for marshes at five estuaries (Fig. 1). The training set of 91 samples better represents the likely range of foraminiferal assemblages in former intertidal environments. Collecting contemporary and fossil foraminifera samples from the same sites helps minimize potential environmental changes. The reconstructions also benefit from the application of a consistent taxonomy, nomenclature, sampling strategy, and sample analysis of both contemporary and fossil assemblages.

2. Study area

Contemporary foraminifera were identified and environmental variables measured along five intertidal transects across marshes at five drowned river-mouth estuaries along 400 km of the Oregon coast (Figs. 1a,b). Shore-normal transects bisect up to five vertical floral zones defined by vascular plant species (tidal flat, low marsh, middle marsh, high marsh and upland; Eilers, 1975).

Although large areas of former marsh in the lower Nehalem River estuary have been diked and converted to pastures, coastal marshes on the northern side of the river cover 2 km² (Fig. 1c). The 167-m-long transect extends from the tidal flat below 0.40 m mean sea-level (MSL), through a sporadic *Zostera nana* vegetated low marsh (0.40–1.02 m MSL). The low marsh grades into a fully vegetated *Carex lyngbyei* and *Triglochin maritima* middle marsh between 1.02 m and 1.20 m MSL. High marsh communities of *Carex lyngbyei, Triglochin maritima*, *Deschampsia caespitosa*, *Eleocharis acicularis*, and *Aster subspicatus* (1.20–1.75 m MSL) are replaced in the upland by *Picea sitchensis*, *Alnus rubra*, *Jaumea carnosa* and *Galium trifidum* above 1.75 m MSL.

Dikes built for cattle grazing along the lower Salmon River estuary in the 1960s were breached in the late 1970s to encourage restoration of intertidal environments, which now cover 2.5 km² (Mitchell, 1981; Fig. 1d). The 99-m-long transect extends across the tidal flat below 0.50 m MSL, which grades into a *Zostera nana* – and *Salicornia virginica*-vegetated low marsh between 0.50 m and 1.20 m MSL. *Juncus balticus* and *Deschampsia caespitosa* dominate the middle marsh between 1.20 m and 1.50 m MSL and an *Atriplex patula*, *Juncus balticus*, and *Potentilla palustris* community covers the high marsh (1.50–1.85 m MSL). The upland above 1.85 m MSL includes *Picea sitchensis*, *Alnus rubra*, *Jaumea carnosa* and *Galium trifidum*.

The intertidal environment along the Siuslaw River covers an area of 2.7 km² (Fig. 1e). The 63-m-long transect extends from the tidal flat below 0.20 m MSL onto low marsh between 0.20 m and 0.50 m MSL with sparse *Zostera nana*. *Juncus balticus* and *Carex lyngbyei* dominate the extensive middle marsh (0.50–0.85 m MSL). The high marsh (0.85–1.40 m MSL) flora includes *Deschampsia caespitosa*, *Potentilla palustris*, *Juncus balticus*, *Distichlis spicata* and *Jaumea carnosa*. Upland floras above 1.40 m MSL include *Oenanthe sarmentosa*, *Jaumea carnosa*, *Potentilla palustris*, *Cytisus scoparius* and *Atriplex patula*.
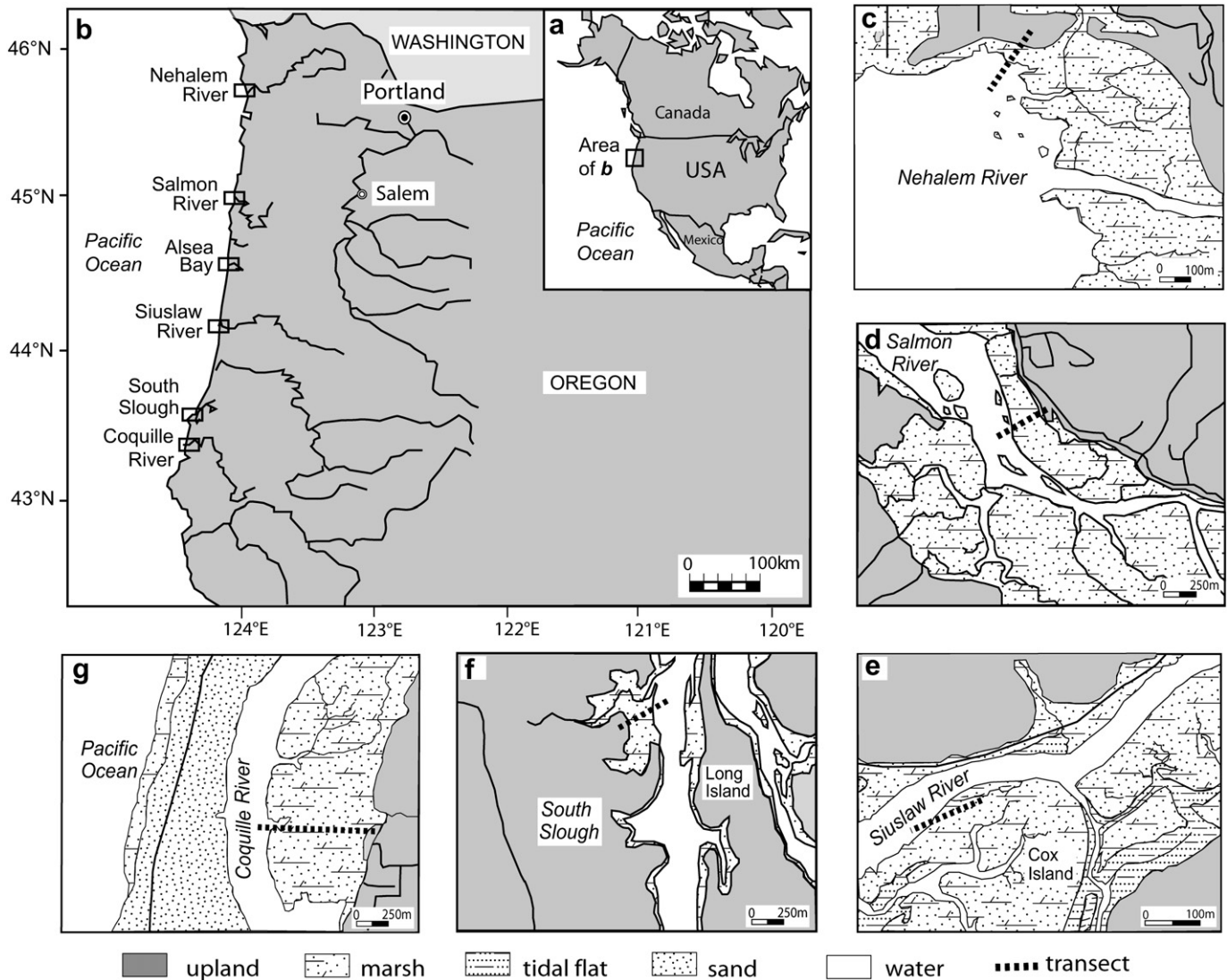
Fig. 1. Location map of: (a) Oregon; (b) study sites in the marshes of five Oregon estuaries; (c) Nehalem River marsh site; (d) Salmon River marsh site; (e) Siuslaw River marsh site; (f) South Slough marsh site; and (g) Coquille River marsh site. Dashed lines mark the location of elevational transects across the marshes.

The South Slough arm of the large Coos Bay estuary is protected as part of the National Estuarine Research Reserves System, and so marshes here have had less human impact than the other studied marshes (Rumrill and Cornu, 1995). Intertidal environments cover 1.5 km^2 (Fig. 1f). A 288-m-long transect begins in the tidal flat that lies below 0.40 m MSL and continues into the low marsh where *Zostera nana* and *Salicornia virginica* are predominant between 0.40 m and 0.65 m MSL. *Carex lyngbyei*, *Juncus balticus*, and *Triglochin maritima* dominate its middle marsh (0.65–1.00 m MSL). The high marsh (1.00–1.40 m MSL) is composed of *Scirpus americanus*, *Eleocharis acicularis*, *Potentilla palustris*, *Deschampsia caespitosa*, *Juncus balticus* and *Distichlis spicata*. The upland above 1.40 m MSL includes *Picea sitchensis*, *Alnus rubra*, *Acer macrophyllum*, *Tsuga heterophylla*, *Atriplex patula* and *Potentilla palustris*.

Jetties that secured the position of the Coquille River-mouth in the 1890's facilitated the development of extensive tidal flat and low marsh areas (covering 2 km^2), which are commonly bisected by smaller meandering channels (Fig. 1g). The 732-m-long transect extends from tidal flat, across low marsh, middle marsh, and then continues into low marsh (a channel meander) and then on into high marsh and upland. The tidal flat lies below 0.15 m MSL. The low marshes along the transect contain sparse *Zostera nana* and

coverage between 0.15 m and 0.40 m MSL and the middle marsh is composed of *Carex lyngbyei*, *Juncus balticus* and *Salicornia virginica* (0.40–1.00 m MSL). High marsh and upland communities above 1.00 m MSL include *Jaumea carnosa*, *Alnus rubra* and *Potentilla palustris*.

Subsidence during the AD 1700 earthquake was reconstructed using data collected at Alsea Bay by Nelson et al. (2008). Core V1 was collected from the northeast side of the bay near the high marsh–middle marsh boundary. Although marshes in the area were widened and deepened in the early twentieth century this site is mostly undiked and predominantly undisturbed (see Nelson et al., 2008 Figs. 2 and 3 for site maps). A west–east transect of ten detailed core descriptions corroborate the continuous stratigraphy from the low marsh through the upland (Figs. 4 and 7 for stratigraphy).

3. Materials and methods

3.1. Contemporary field sampling, leveling, and tidal range

Samples of the upper 1-cm of surface sediment were collected from between 14 and 23 stations along the five transects from the
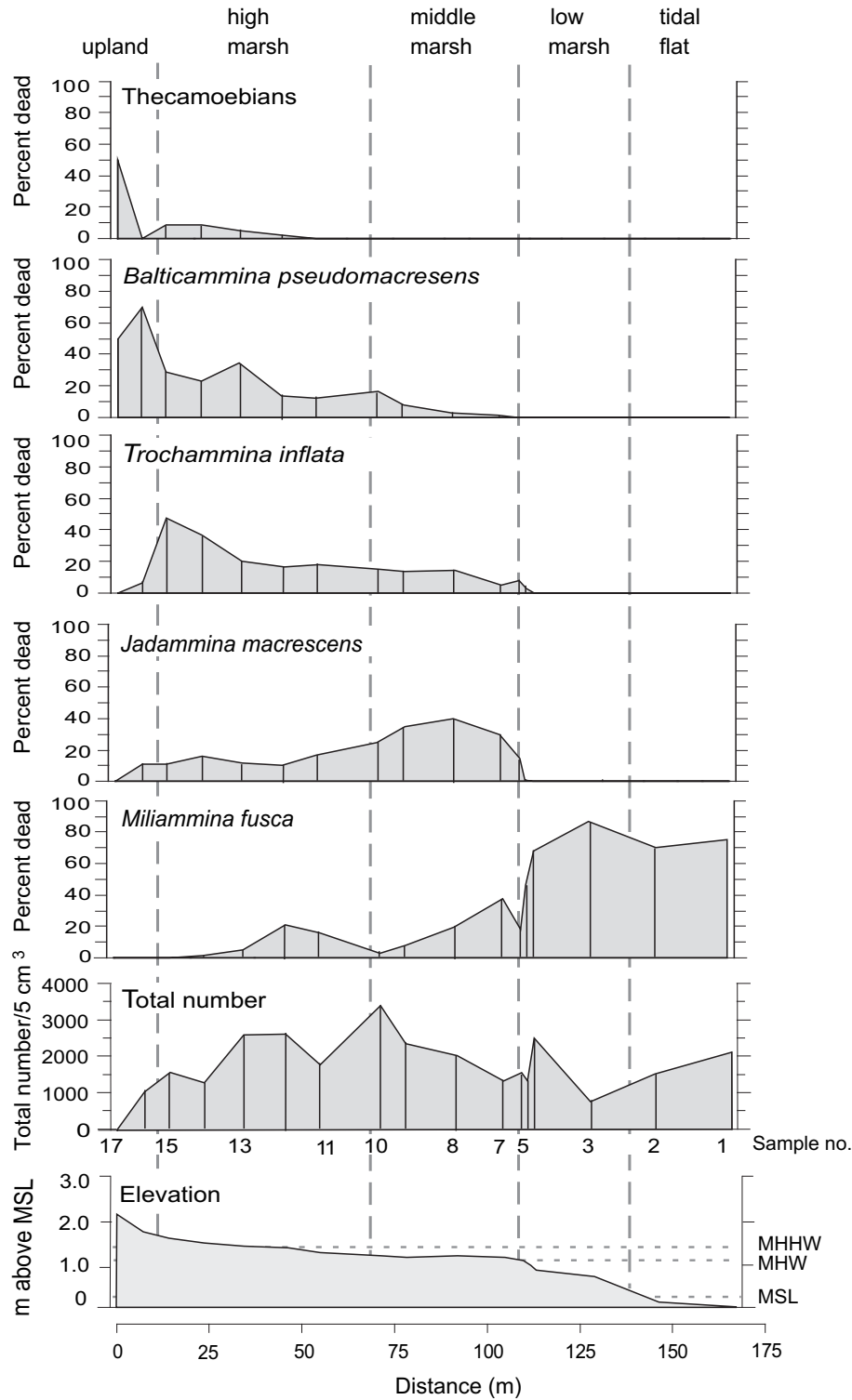
Fig. 2. Percent of the five most dominant species in the death assemblages from the Nehalem River transect (45° 39′ 30″N, 123° 32′ 49″W). Concentration of foraminifera (per 5 cm³), elevation, tidal levels, and floral zones are shown.

tidal flat to upland. The samples were taken in the fall to minimize seasonal variability (i.e., reproduction blooms) in foraminiferal assemblages, which are most pronounced in the spring and summer due to environmental factors (e.g., Buzas, 1965; Jones and Ross, 1979; Alve and Murray, 1999; Horton and Edwards, 2003; Horton and Murray, 2006, 2007). At each station, a 5-cm³ forami-nifera sample and a 10-cm³ sample were collected for

environmental analyses, measured elevation, and estimated vege-tation cover. Environmental samples were collected for clay-silt fraction, organic content (loss of ignition (LOI)), pore-water salinity and pH. The samples were placed in sealed bags and refrigerated. Foraminifera samples were placed in vials with a calcium carbonate chip, treated with rose Bengal (a protein staining agent), preserved in a 30% ethanol 70% distilled water solution, and also refrigerated.
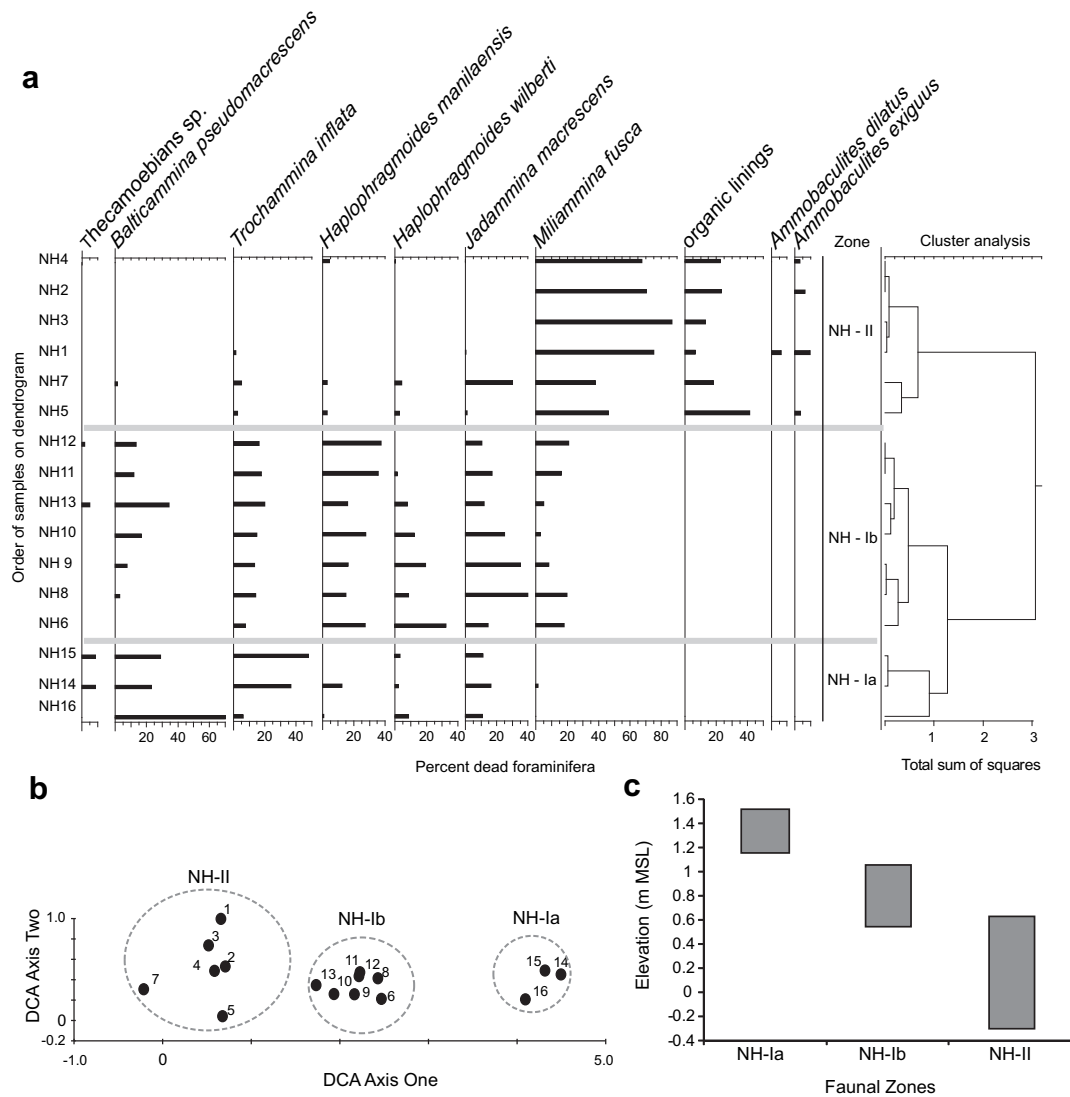
Fig. 3. (a) Unconstrained cluster analysis (unweighted Euclidean distance) diagram showing groupings of samples (b) plot of samples showing detrended correspondence analysis where samples with similar assemblages plot closer together and (c) vertical zonation of foraminiferal death assemblages (%) from Nehalem River. Only samples with counts greater than 100 individuals and species that contribute 5% of the dead assemblage are included.

Rose Bengal differentiates living from dead foraminifera (e.g., Murray, 1991) because it stains the protoplasm bright red whereas test walls and organic linings are either unstained or lightly stained. Foraminifera with stain in their last few chambers are recorded as living at the time of sample collection (e.g., Murray and Alve, 2000). Bernhard (2000) debated the efficacy of rose Bengal as a staining agent, but the value of alternative methods is uncertain (Murray, 2000). Assemblages of dead foraminifera were analyzed to minimize the seasonal fluctuations commonly recorded in live populations. Dead surface assemblages most accurately reflect subsurface assemblages indicating that taphonomic processes are minimal (Culver and Horton, 2005).

Intertidal foraminifera are known to live infaunally (see Culver and Horton, 2005, for a brief summary) and thus may change the composition of fossil assemblages. Studies from the Atlantic coast of North America have recorded intertidal foraminifera as "live" (i.e., rose Bengal stained) from 60 cm depth in marsh sediments of Delaware (Hippensteel et al., 2002) and 30 cm depth in Georgia marshes (Goldstein and Harben, 1993). In contrast, investigations of North Carolina (Culver and Horton, 2005), New Brunswick, Canada (Patterson et al., 2004) and the UK (Horton, 1997; Horton and

Edwards, 2006) have shown live foraminifera restricted to the top few centimeters of salt marsh sediments. Clearly, the depth that marsh foraminifera live in the sediment varies considerably from location to location (and, probably, from time to time) presumably due to local environmental conditions and chance bioturbation (Culver and Horton, 2005). The influence of infaunal foraminifera in the marshes of Oregon is assumed to be negligible based on a pilot core from the Nehalem River marsh; live foraminifera are predominantly found in the surface assemblage (0–1 cm) and are only present to depths of 5 cm (Hawkes, 2008).

To determine the elevations of contemporary samples, sampling stations along each transect were leveled to a temporary benchmark using a total station. At sites with no nearby geodetic benchmark to provide an absolute elevation, sample elevation was related to MSL by continually measured water levels with respect to the temporary benchmark at each transect over at least two successive high tides (precision ~0.05 m). Because there are only five continuously monitored tide gauges along the ~500 km Oregon coast (Astoria, Garibaldi, South Beach, Charleston and Port Orford; Table 1), a model of tide levels for every ~3 km (nodes) of coast was developed. Tidal simulations were conducted using ADCIRC (Luettich and Westerink,
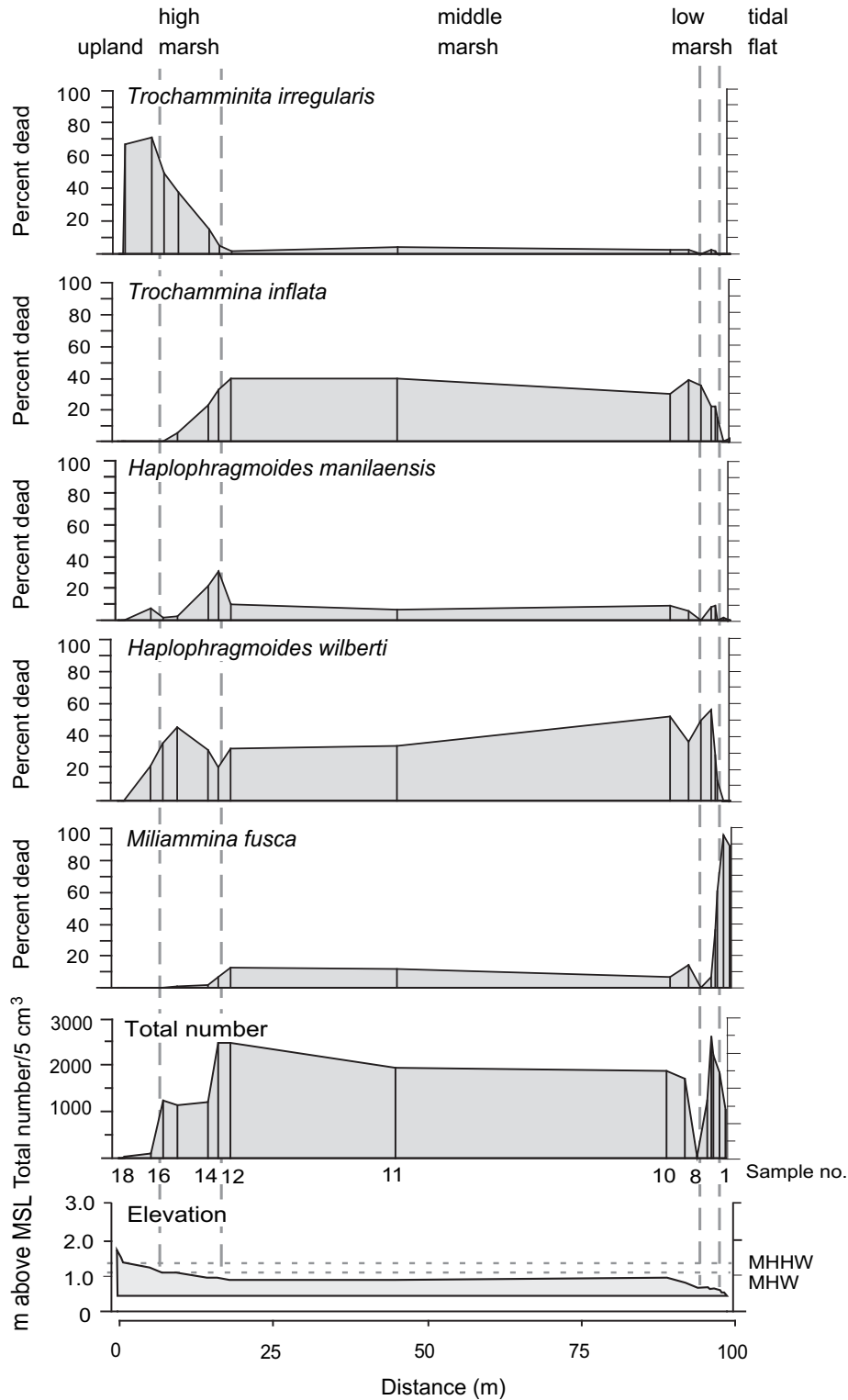
Fig. 4. Percent of the five most dominant species in death assemblages from the Salmon River transect (45° 02′ 21″N, 123° 59′ 09″W). Concentration of foraminifers (per 5 cm³), elevation, tidal levels, and floral zones are shown.

1991), a two-dimensional, depth-averaged, fully non-linear hydro-dynamic circulation model, which solves the equations of motion on an unstructured finite-element mesh, allowing for accurate representation of complex coastlines. The Eastern North Pacific Ocean (ENPAC) 2003 grid (Mark et al., 2003), which extends into deep water curving along the coast of North America from Unimak Island, Alaska to Chamela, Mexico, was used. The open boundary was forced

with four diurnal and four semi-diurnal tides, with amplitude and phase data drawn from the TXPO global ocean tide model from Oregon State University (Egbert et al., 1994). Model runs were carried out for 60 days (model time), with an initial spin-up period of 15 days needed to prevent transients and reflections in the domain. To compute tidal datums along the Oregon coast, time series of elevation (15 min intervals) were requested at all model nodes along

Table 1
Summary of differences in tidal levels between NOAA tide gauges and modeled tidal nodes.

NOAA tide gauge	Measurements (m MSL)	MHHW	MHW	MTL	MSL	MLW	MLLW
Astoria	Tide gauge	1.25	1.05	0.01	0.00	−1.02	−1.37
	Model	1.27	1.03	0.00	0.00	−1.03	−1.45
	Difference	0.01	−0.01	−0.01	0.00	−0.01	−0.08
Garibaldi	Tide gauge	1.14	0.92	−0.01	0.00	−0.94	−1.35
	Model	1.25	1.02	0.01	0.00	−1.00	−1.43
	Difference	0.11	0.11	0.02	0.00	−0.06	−0.08
South Beach	Tide gauge	1.18	0.97	0.02	0.00	−0.94	−1.36
	Model	1.23	1.00	0.01	0.00	−0.98	−1.41
	Difference	0.05	0.03	−0.01	0.00	−0.04	−0.05
Charleston	Tide gauge	1.08	0.88	0.01	0.00	−0.86	−1.24
	Model	1.15	0.92	0.01	0.00	−0.90	−1.32
	Difference	0.07	0.05	0.00	0.00	−0.04	−0.07
Port Orford	Tide gauge	1.02	0.81	0.01	0.00	−0.78	−1.20
	Model	1.10	0.88	0.01	0.00	−0.86	−1.27
	Difference	0.07	0.07	0.00	0.00	−0.07	−0.07
	Average difference (m)	0.06	0.05	0.00	0.00	−0.05	−0.07

Tidal levels are in meters above MSL. MHHW, mean high high water; MHW, mean high water; MTL, mean tide level; MSL, mean sea-level; MLW, mean low water; and MLLW, mean low low water.

the boundary and interrogated directly to determine datums. In a comparison of the modeled data with tide gauge data from the five NOAA gauges (Table 1) the average error was 0.04 m among tidal datums with a maximum error of 0.11 m.

3.2. Foraminiferal analysis

Preparation of foraminifera followed de Rijk (1995a) and Horton and Edwards (2006). Foraminifera were concentrated by washing 5 cm^3 of sediment through 500 μm and 63 μm sieves. A wet splitter was used to subdivide samples into smaller fractions for ease of counting (Scott and Hermelin, 1993). Up to 300 dead tests were wet-counted in the 63–500 μm size fraction (data in Appendix I). Foraminifera (Plate I) were identified using the National Collection of Foraminifera, Smithsonian National Museum of Natural History and the taxonomies of Gehrels and van de Plassche (1999), Debenay et al. (2002), Edwards et al., (2004) and Horton and Edwards (2006). This taxonomy differs from that of Scott and Medioli (1980) by its separation of individuals formerly grouped as *Trochammina macrescens*, into the separate species *Balticammina pseudomacrescens* and *Jadammina macrescens* (Alve and Murray, 1999). Gehrels and van de Plassche (1999) demonstrated that *B. pseudomacrescens* and *J. macrescens* exhibit different relationships with elevation relative to mean high water (MHW) and that their separation increases the amount of sea-level information that may be extracted from fossil foraminiferal assemblages in Maine. Such taxonomic issues surrounding the differentiation of genus, species or ecophenotype do not influence the use of foraminifera as modern analogues in transfer function studies, provided that 'species' or forms are identified consistently (Edwards et al., 2004). Organic linings (e.g., Murray and Alve, 1999; Edwards and Horton, 2000) and thecamoebians (e.g., Scott and Medioli, 1980; Lloyd and Evans, 2002) are included as additional groups.

In order to reconstruct the amount of subsidence during the AD 1700 earthquake at Alsea Bay using the foraminiferal data of Nelson et al. (2008), it was necessary to modify their taxonomy. Following the suggestions of Alve and Murray (1999) and Gehrels and van de Plassche (1999) *J. macrescens* was used for *T. macrescens* as described by Nelson et al. (2008), and *B. pseudomacrescens* for *T. salsa*. *T. salsa* was abundant throughout the fossil dataset of Nelson et al. (2008), but was only found in high marsh and upland zones in their contemporary data. This species is absent in other contemporary

datasets along the west coast of North America (e.g. Jennings and Nelson, 1992; Patterson et al., 2005), but present in Sabean (2004) and Guilbault et al. (1995, 1996). *T. salsa* may have been misidentified in the fossil samples of Nelson et al. (2008). The considerable taxonomic discrepancies among *T. irregularis, T. salsa, B. pseudomacrescens, J. macrescens, T. macrescens cf. macrescens, T. macrescens cf. polystoma* and in the above referenced literature and the absence of foraminiferal plates in Nelson et al. (2008) precludes a thorough reassessment of their taxonomy and warrants further investigation.

3.3. Environmental analysis

Six environmental variables were recorded at the Nehalem River transect: elevation; pH; pore-water salinity; clay-silt fraction; vegetation cover; and loss on ignition (LOI; a measure of the percentage of organic matter; Fig. 8). pH and pore-water salinity were measured following the methods of Woodroffe et al. (2005), using a hand-held pH and conductivity meter on equal amounts of sediment and distilled water. Clay-silt fractions were measured using a Beckman Coulter laser particle size analyzer with pre-treatment to remove organic carbon following Hawkes et al. (2007). Sediment for LOI was weighed, dried at 105 °C for 12 h, weighed, baked at 550 °C for 4 h, and weighed again to measure the percent of organic carbon per sample (Ball, 1964). The percentage of vascular plant cover in a 4.0 m^2 area around each sampling station was assessed, and the areal dominance of common plant species estimated with reference to Cooke (1997).

3.4. Statistical analysis of contemporary data

Two multivariate statistical methods (unconstrained cluster analysis and detrended correspondence analysis, DCA) were used to identify, describe and classify the distribution of foraminiferal species along each transect (Fig. 10). Unconstrained cluster analysis based on unweighted Euclidean distance (with no transformation or standardization of percentage data) is used to classify contemporary samples into homogeneous faunal zones (clusters). DCA, an ordination technique, is used to represent samples as points in multidimensional space where similar samples are located close together and dissimilar samples are farther apart. Cluster analysis is successful at grouping the samples according to the similarities of their foraminiferal assemblages, whereas DCA provides further information about the patterns of variation within and between groups. The complementary nature of the two techniques was stressed by Birks (1986, 1992). The elevation range of clustered samples is used to establish the elevational range for each faunal zone. CANOCO was used for DCA runs (ter Braak and Smilauer, 1997–2003) and CONNISS for the unconstrained cluster analysis (Grimm, 2004). Results for Nehalem River are in Figs. 3, 9 and 10; results for other sites are in Fig. 10 (DCA analyses) and Appendix I.

Canonical correspondence analysis (CCA; CANOCO program of ter Braak and Smilauer, 1997–2003) of the Nehalem River data was used to relate foraminiferal distribution to elevation and other environmental parameters, and to test the statistical significance of the observed relations (Fig. 9; ter Braak, 1986, 1988, 1990; ter Braak and Verdonschot, 1995). The degree of independence and relative strength of the major environmental gradients (with forward selection in partial CCAs; Boccard et al., 1992) separated the total variation of foraminiferal data into components representing: the unique contributions of single environmental variables; the contribution of covariance between variables; and the unexplained variance. The statistical significance of partial CCA is determined using a Monte Carlo permutation test. For most analyses, samples with foraminiferal concentrations of less than 100 individuals and all species groups contributing less than 5% relative abundance of

any assemblage (Patterson and Fishbein, 1989; Horton and Edwards, 2006) were not considered. However, following Patterson and Fishbein (1989) and Fatela and Taborda (2000), two samples with concentrations under 100 individuals were included because their assemblages include indicator species having a relative abundance of 50% or greater.

4. Results

4.1. Distribution of contemporary foraminifera

A total of 18 species were identified in the dead assemblages in 91 samples from the five transects. The dominant species are *Balticammina pseudomacrescens*, *Haplophragmoides manilaensis*, *Haplophragmoides wilberti*, *Jadammina macrescens*, *Miliammina fusca*, *Trochammina inflata*, and *Trochamminita irregularis* (Figs. 3 and 5–8). The relative abundance (%) of dominant species is described below. Species concentration varied between seven and 12,304 individuals per 5 cm^3.

4.1.1. Nehalem River

At Nehalem River, 10 species were identified in 17 samples spaced along the transect (Fig. 2). Thecamoebian species and *B. pseudomacrescens* (50% each) dominate the landward edge of the upland. *B. pseudomacrescens* increases to a maximum of 70% at the lower upland edge. In the high marsh, *T. inflata* increases to 50% replacing *B. pseudomacrescens*, which decreases to 12%. The middle marsh is dominated by *J. macrescens*, which reaches 40%. The low marsh and tidal flat are dominated by increasing relative abundances of *M. fusca* (18–75%). The concentration (total number) of foraminifera is highest at the landward edge of the middle marsh with 3400 individuals per 5 cm^3 and lowest at the landward edge of the upland with only 16 individuals per 5 cm^3.

Multivariate analyses identified three faunal zones at Nehalem River (Figs. 3 and 10). Zone NH-Ia is dominated by *B. pseudomacrescens* and *T. inflata*, which reaches a maximum of 70% and 50%, respectively, with a near absence of *M. fusca*. The elevational range of NH-Ia is between 1.55 m and 1.17 m MSL. Zone NH-Ib is dominated by *H. manilaensis*, with >15% in all samples, and by *J. macrescens*, with a maximum of 40%. NH-Ib occupies the elevation between 1.06 m and 0.54 m MSL. Zone NH-II has an elevation range between 0.65 m and −0.26 m MSL and is dominated by *M. fusca* (>18% in all samples), with organic linings reaching a maximum (40%) in one sample.

4.1.2. Salmon River

From the Salmon River transect, nine species were identified in 18 samples (Fig. 4). *T. irregularis* dominates the upland (≤71%) whereas the high marsh is dominated by *H. wilberti* with relative abundances between 20% and 45%. From the upper to lower edge of the high marsh *T. irregularis* rapidly decreases from 50% to 5% and is replaced by *T. inflata*, which increases to 30%. The middle marsh and low marsh are dominated by *H. wilberti* (≤56%) and *T. inflata* (≤36%). The nearly monospecific tidal flat assemblage consists of *M. fusca* (>96% in all samples) with concentrations above 1000 individuals per 5 cm^3. The concentration of foraminifera is highest in the low marsh with 2600 individuals per 5 cm^3 and lowest at the landward edge of the upland (eight per 5 cm^3; Fig. 4).

Multivariate analyses identified three faunal zones at Salmon River (Figs. 10 and A1). Zone SR-Ia is dominated by *T. irregularis* (>40%) and *H. wilberti* (>20% in all samples). Zone SR-Ib is dominated by *T. inflata* and *H. wilberti* (>20% in all samples within the elevation range between 1.51 m and 1.08 m MSL). Zone SR-II is dominated by *M. fusca* (>35% in all samples).

4.1.3. Siuslaw River

At Siuslaw River, eight species were identified in 14 samples (Fig. 5). The very low concentration upland sample is dominated by a monospecific assemblage of *T. inflata* (seven per 5 cm^3). The high marsh is dominated by *H. wilberti* (≤49%). *M. fusca* (>44%) dominates the middle marsh, low marsh and tidal flat zones with lesser amounts of *J. macrescens*, *T. inflata*, and *H. wilberti* in the middle marsh. *M. fusca* reaches 91% in the low marsh and tidal flat with concentrations of ∼2000 individuals per 5 cm^3. The concentration of foraminifera reaches a maximum of 3808 individuals per 5 cm^3 in the middle marsh (Fig. 5).

Multivariate analyses identified two faunal zones at Siuslaw River (Figs. 10 and A2). Zone SI-I is dominated by *H. wilberti* (>20%), *T. inflata* (>17%), and *B. pseudomacrescens* (>10% in all samples) and occupies the elevation range between 1.35 m and 0.96 m MSL. Zone SI-II, found at elevations between 0.91 m and 0.21 m MSL, is dominated by *M. fusca* (>44% in all samples).

4.1.4. South Slough

At South Slough, nine species were identified in 23 samples (Fig. 6). The upland edge is dominated by *T. irregularis* (>50% in all samples). *T. inflata* decreases from 41% to 16%, respectively, from the landward to seaward edge of the high marsh, and is replaced by *J. macrescens*, which increases from 14% to 50%. Middle marsh assemblages consist of *J. macrescens* (≤52%) and *M. fusca* (>20% in all samples). The low marsh and tidal flat are dominated by *M. fusca* (61–89%). In the middle marsh concentrations vary from 6300 per 5 cm^3 to 876 per 5 cm^3, respectively.

Multivariate analyses identified three faunal zones at South Slough (Figs. 10 and A3). Zone SS-Ia is dominated by maximum relative abundances of *T. irregularis* (54%), *T. inflata* (40%), *H. wilberti* (27%) and *B. pseudomacrescens* (21%). SS-Ia occupies the elevation range between 1.52 m and 1.27 m MSL. Additionally, there is a near absence of *M. fusca* (<10% in all samples). Zone SS-Ib is dominated by *J. macrescens* (>25% in all samples) and *M. fusca* (20–60%) and is found at elevations between 1.20 m and 0.78 m MSL. Zone SS-II is dominated by *M. fusca* (61–89%). SS-II is found at elevations between 0.73 m and 0.04 m MSL.

4.1.5. Coquille River

At Coquille River, nine species were identified in 19 samples from an undulating transect (Fig. 7). The upland and high marsh assemblage is dominated by *T. irregularis*, *H. wilberti* and *B. pseudomacrescens* with maximum relative abundances of 45%, 25% and 16%, respectively. The low marsh and tidal flat are dominated by *M. fusca* (>48% in all samples). The low concentration tidal flat assemblage is monospecific (21 and 26 individuals of *M. fusca* per 5 cm^3). The middle marsh is dominated by *J. macrescens* (32%), *T. inflata* (31%) and *H. wilberti* (22%). Concentrations vary with the greatest number of individuals (12,304 per 5 cm^3) at the seaward edge of the low marsh.

Despite the irregular elevation along the transect, multivariate analyses identified two faunal zones at Coquille River (Figs. 10 and A4). Zone CQ-I is dominated by *T. irregularis* (45%), *T. inflata* (31%), *B. pseudomacrescens* (16%) and *H. wilberti* (25%) and occupies the elevation range between 1.32 m and 0.59 m MSL. Additionally, CQ-I has a near absence of *M. fusca*. Zone CQ-II found at elevations between 0.54 m and −0.53 m MSL is dominated by *M. fusca* (48–91%).

4.2. Environmental variables

Six environmental variables (elevation, loss of ignition (LOI), clay-silt fraction, pH, pore-water salinity and vegetation cover) were measured along the Nehalem River transect (Fig. 8). LOI measurements decrease rapidly in the upland from 71% to 26% and
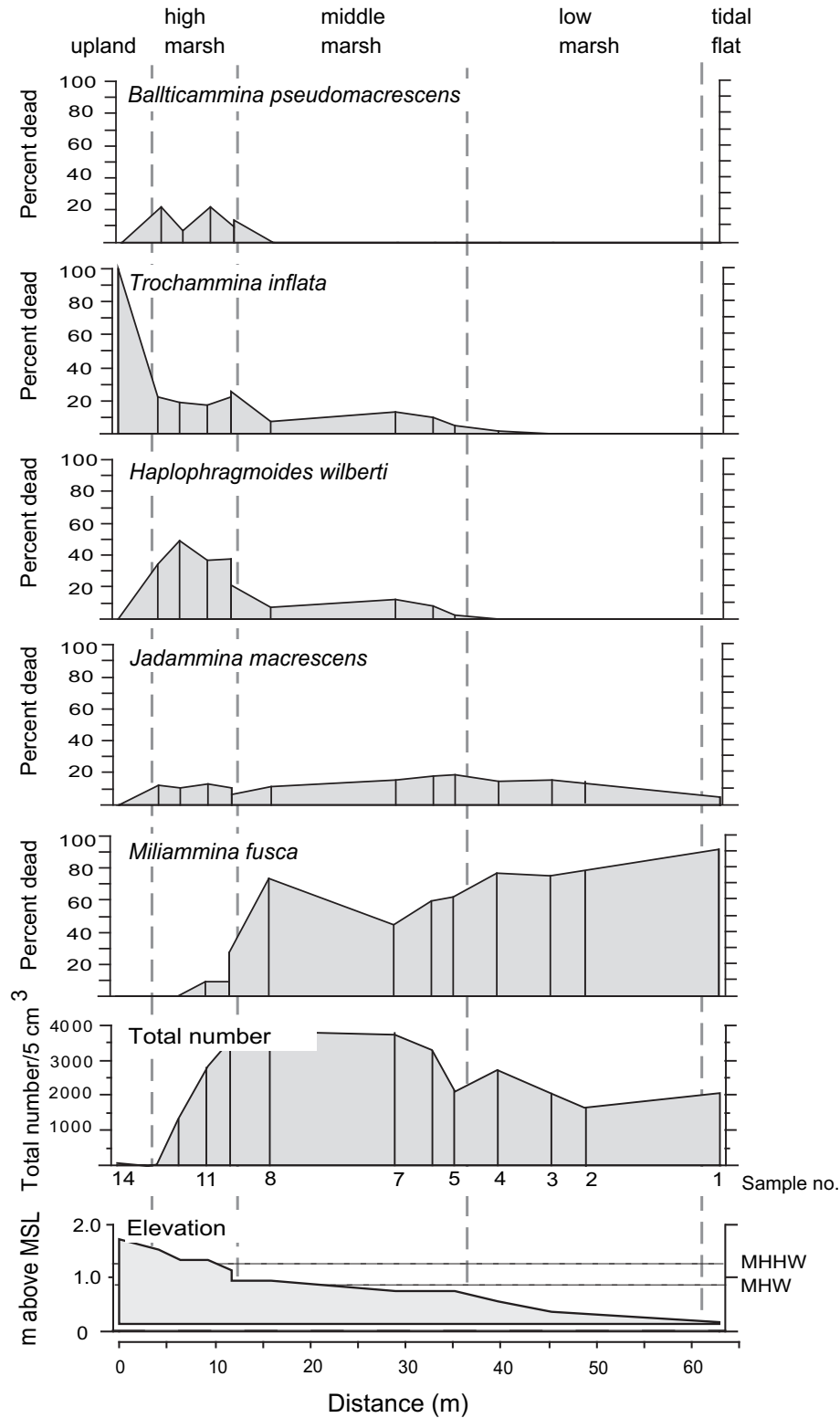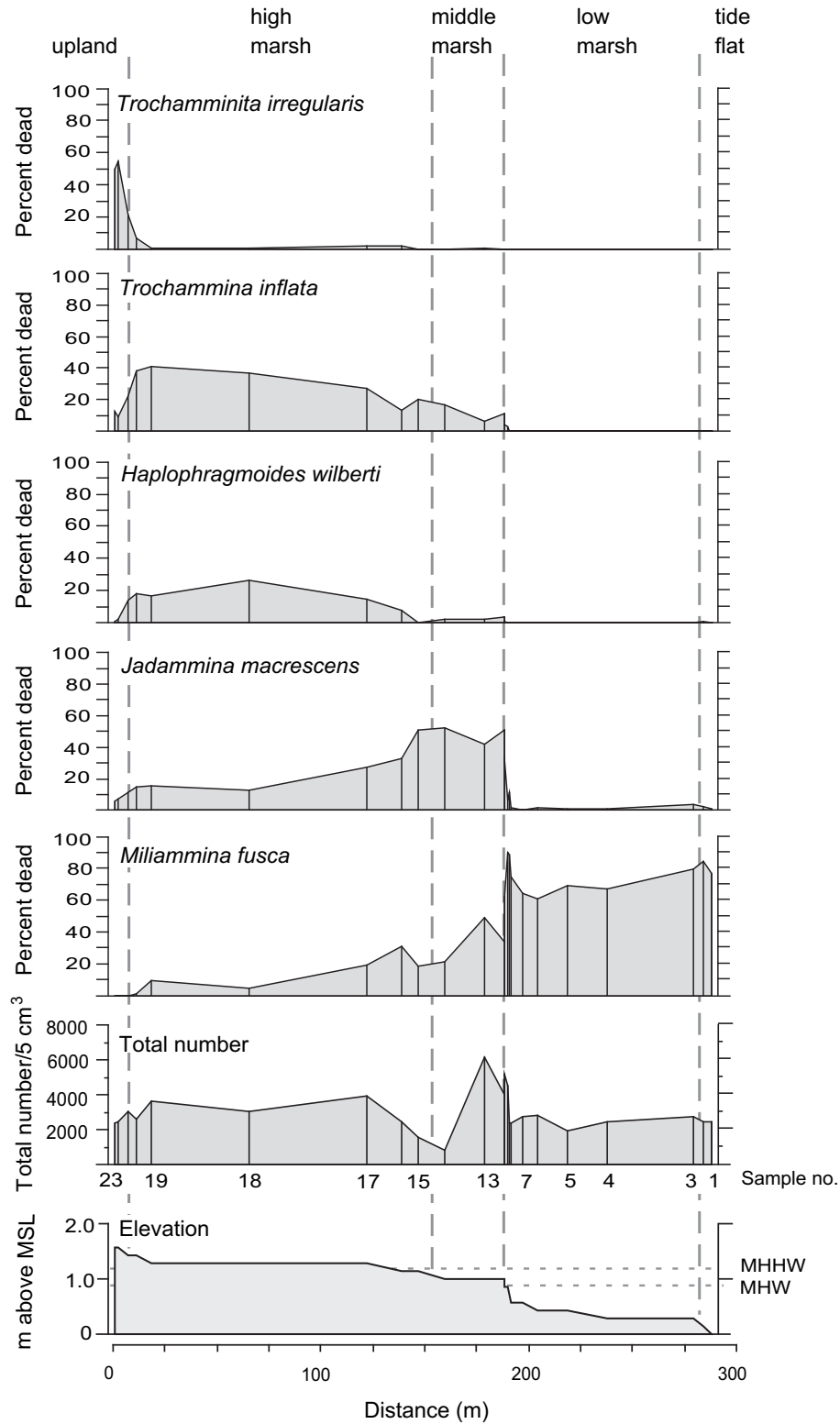
Fig. 5. Percent of the five most dominant species in death assemblages from the Siuslaw River transect (43° 58′ 26″N, 124° 04′ 13″W). Concentration of foraminifers (per 5 cm³), elevation, tidal levels, and floral zones are shown.

range between 18% and 11% within the high and middle marsh. At the middle marsh-low marsh boundary LOI decreases from 12% to 2% in the mudflat. The substrate of the upland, high and middle marsh is largely clay and silt (53–85%). At the boundary between middle and low marsh, the clay-silt fraction decreases to 20% to be

replaced by coarser size fractions and is at its lowest (11%) in the tidal flat. Throughout the entire transect the pH is below 6.3, suggesting acidic conditions, with a minimum of 3.9 in the low marsh. Across the transect salinity is variable. It increases rapidly from 5 to 12 from the upland to high marsh. In the high and middle marsh,

Fig. 6. Percent of the five most dominant species in death assemblages from the South Sough transect (43° 17′ 32″N, 124° 19′ 26″W). Concentration of foraminifers (per 5 cm³), elevation, tidal levels, and floral zones are shown.

salinity ranges between 12 and 16 and decreases rapidly from 17 at the landward edge of the low marsh to 9 at the seaward edge and increases to 11 in the tidal flat. Vegetation cover is >85% in the upland, high and middle marsh and decreases rapidly to 10% at the seaward edge of the middle marsh. The low marsh is sparsely vegetated (5–10%).

CCA and partial CCA on environmental data from the Nehalem River transect were used to evaluate which environmental variables control the species distribution (Table 2; Fig. 9). The length of the arrows on Fig. 9 approximates the importance of each environmental variable in explaining the variance in the foraminiferal data. The orientations of the arrows show their estimated
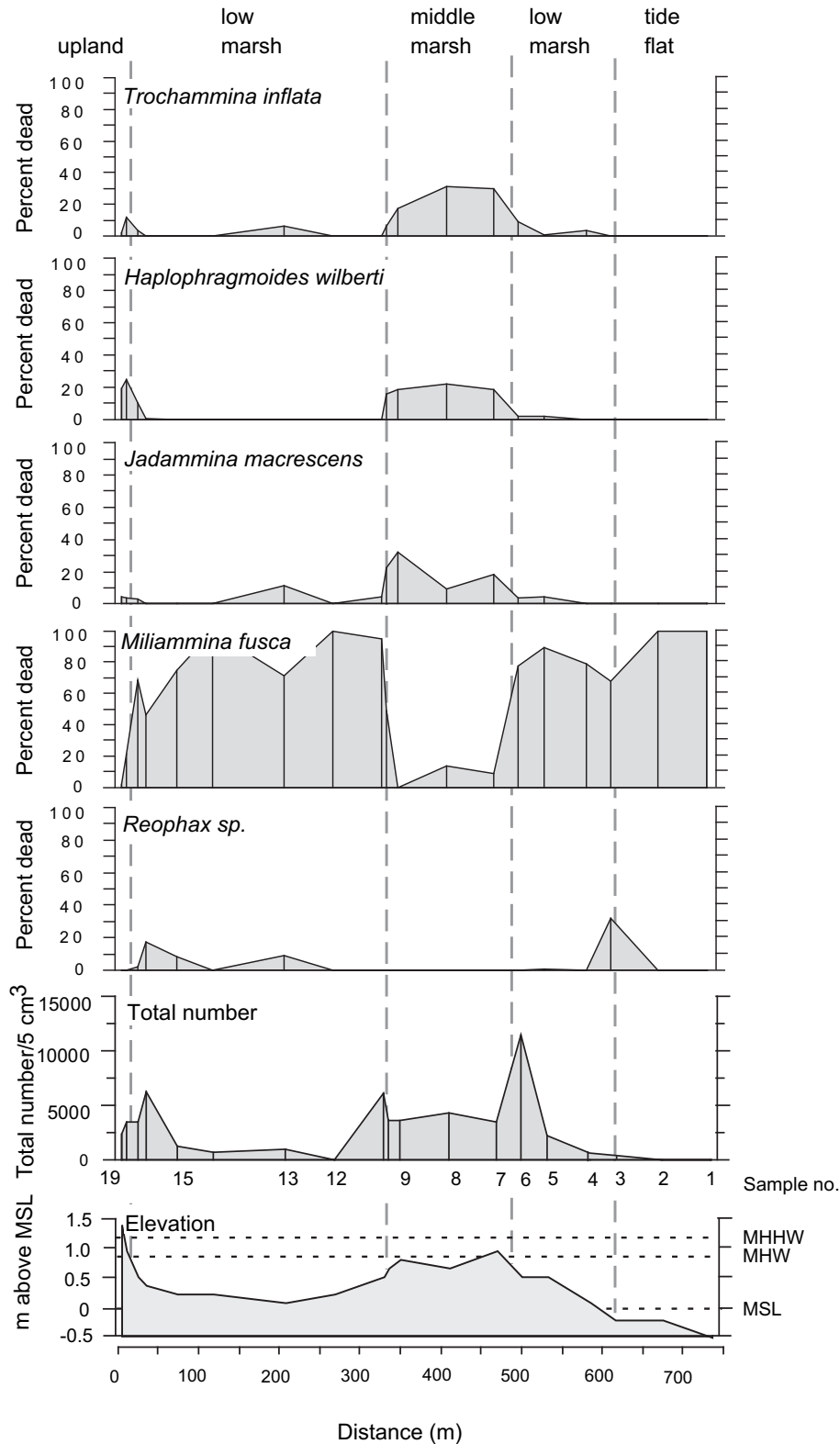
Fig. 7. Percent of the five most dominant species in death assemblages from the Coquille River transect (43° 4′ 48″N, 124° 14′ 47″W). Concentration of foraminifers (per 5 cm³), elevation, tidal levels, and floral zones are shown.

correlation to ordination axes and other environmental variables. CCA Axis One (eigenvalue = 0.67) and Axis Two (eigenvalue = 0.20) explain 62% of the total variance in the foraminiferal data (Fig. 10a). Inter-correlation among the variables with Axes One and Two illustrates that elevation, vegetation cover and clay-silt fraction are

highly correlated with Axis One, and that salinity and pH are correlated with Axis Two, whereas LOI shows a joint correlation between the axes (Fig. 9a). Thus, Axis One reflects the major transition from upland and high marsh plotted on the left to low marsh and tidal flat plotted on the right. On the species-environment
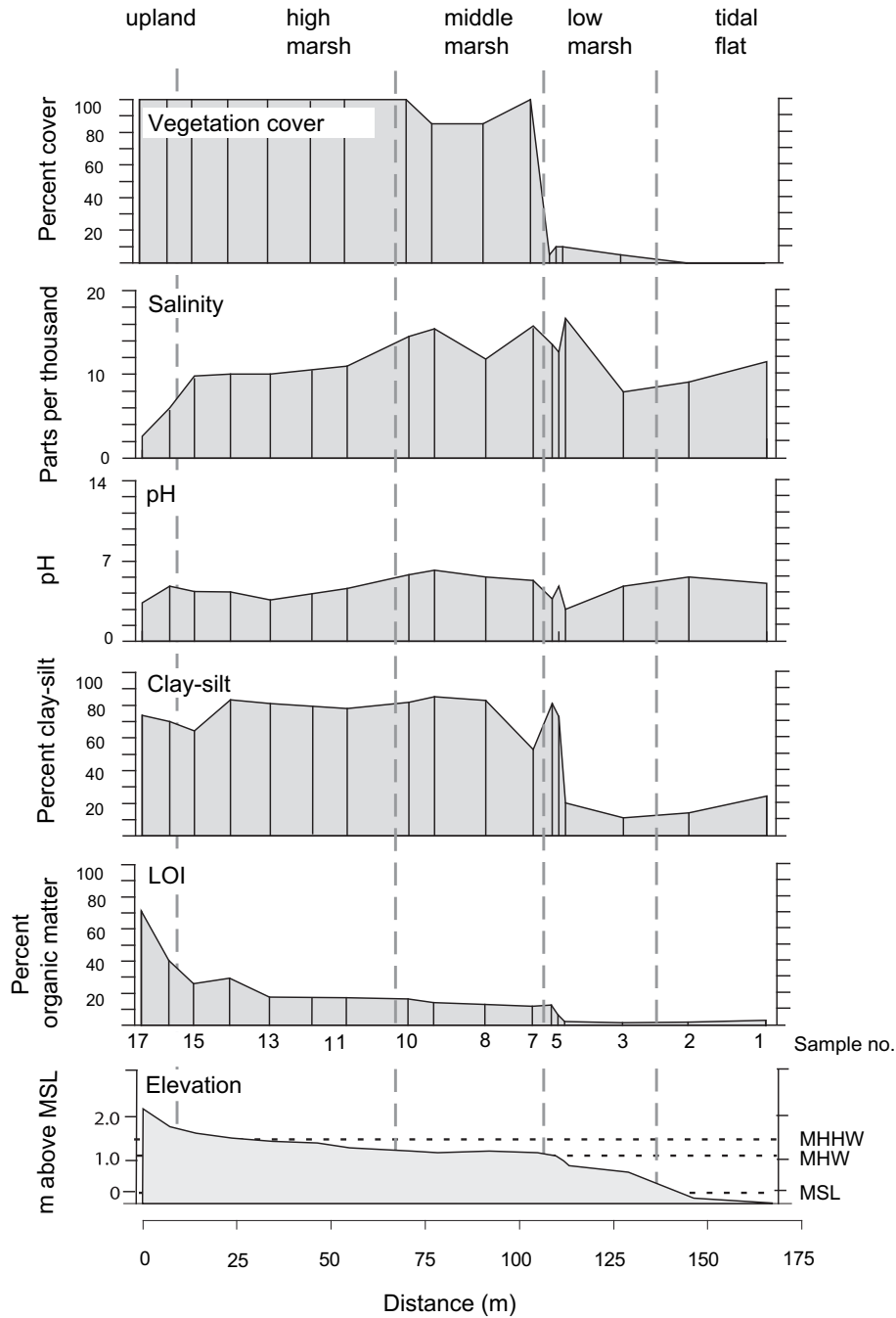
Fig. 8. The distribution of environmental variables elevation, salinity, pH, clay-silt fraction, loss on ignition and vegetation cover from the Nehalem River transect. Tidal levels and floral zones are shown.

biplot (Fig. 9b) the position of each species projected perpendicularly onto the environmental variable arrows approximates their weighted average optima along each variable. The upland and high marsh species *B. pseudomacrescens*, *T. inflata* and thecamoebians found to the left, correspond to high values of elevation, vegetation cover, percent clay-silt fraction and LOI while the low marsh and tidal flat species of *M. fusca*, *Ammobaculites* sp. and organic linings fall to the right.

Partial CCAs show that 78% of the variance can be explained by the environmental variables (Fig. 9c) and that the total explained variance is composed of 39% elevation, 12% clay-silt fraction, 8% LOI, 5% pH, 4% vegetation cover, 3% salinity and 29% inter-correlation between these variables (Fig. 9d). The associated Monte Carlo

Table 2
Summary of CCA and partial CCA results from dead foraminiferal assemblages at Nehalem River.

Axes	1	2	3	4	Total inertia
Eigenvalues:	0.671	0.204	0.108	0.072	1.406
Species-environment correlations:	0.969	0.915	0.91	0.847	
Cumulative percentage variance					
of species data:	47.7	62.2	69.9	75	
of species-environment relation:	61.2	79.8	89.7	96.3	
Sum of all eigenvalues					1.406
Sum of all canonical eigenvalues					1.096
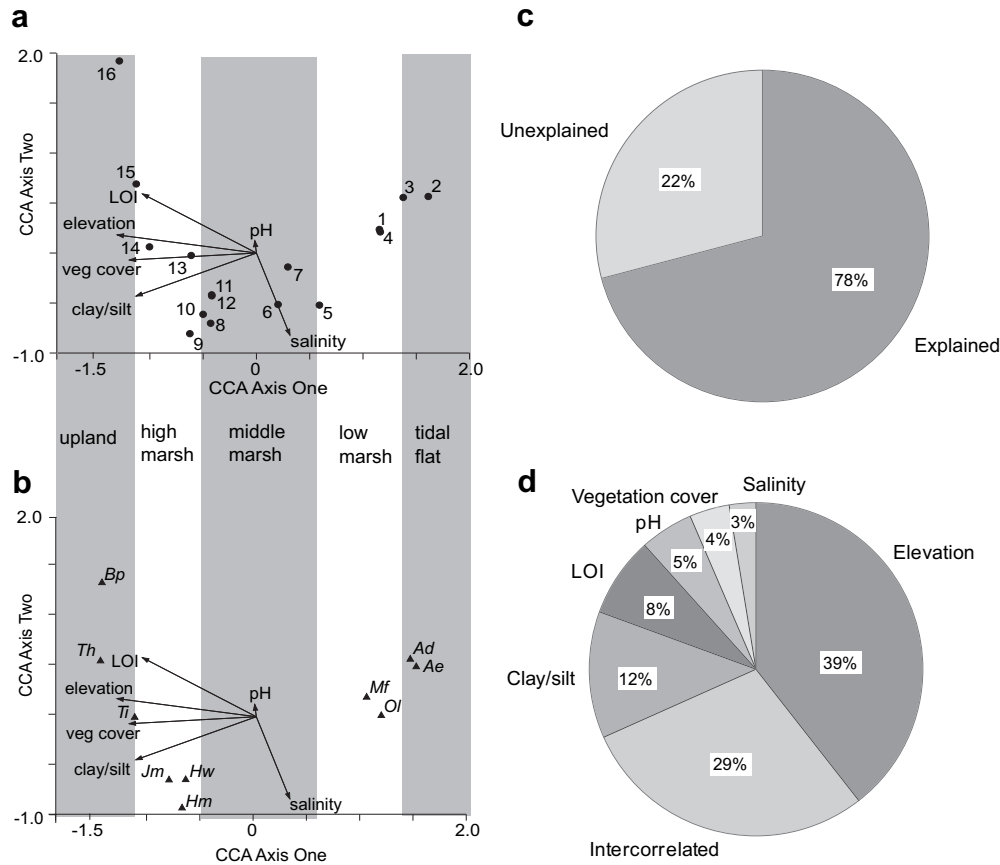
Fig. 9. Canonical Correspondence Analysis ordination axes biplots of (a) samples relative to environmental variables and (b) species relative to environmental variables from Nehalem River. Pie charts show the total variation of the contemporary assemblages from Nehalem River in: (c) explained and unexplained portions; and (d) components representing the unique contributions of elevation, salinity, LOI, clay-silt fraction, vegetation cover, pH and inter-correlations among gradients. Species abbreviations: Ad = *Ammobaculites dilatus*; Ae = *Ammobaculites exiguous*; Bp = *Balticammina pseudomacrescens*; Hm = *Haplophragmoides manilaensis*; Hw = *Haplophragmoides wilberti*; Jm = *Jadammina macrescens*; Mf = *Miliammina fusca*; Ol = *Organic linings*; Th = *Thecamoebians*; and Ti = *Trochammina inflata*. Environmental abbreviations: LOI = loss on ignition, veg cover = vegetation cover. Only samples with counts greater than 40 individuals and species that contribute 5% of the dead assemblage are included in the CCA analysis. Shading reflects approximate floral zones along Axis One (elevation gradient).

permutation tests illustrate that elevation, clay-silt fraction, and LOI are statistically significant ($p = 0.0020$–0.0320, 499 permutations) under the reduced model which tests whether the *p*-value is significant.

5. Discussion

### 5.1. Elevation-dependent faunal zones

Unconstrained cluster analysis and DCA was used to classify the contemporary samples from the five transects into elevation-dependent faunal zones. The Siuslaw River and Coquille River assemblages are placed into faunal Zones I and II, whereas at Nehalem River, Salmon River and South Slough Zone I is subdivided into faunal Zones Ia and Ib (Fig. 10).

Faunal Zone I at the Siuslaw and Coquille Rivers (SI-I and CQ-I, Fig. 10) is composed of *T. inflata*, *H. wilberti*, *B. pseudomacrescens* and includes *T. irregularis* at the Coquille River. This faunal zone spans the upland, high and middle marsh floral zones from above mean higher high water (MHHW) to below mean high water (MHW; Fig. 10). Other studies in the Pacific Northwest (Jennings and Nelson, 1992; Nelson and Kashima, 1993; Guilbault et al., 1995, 1996; Scott et al., 1996; Patterson et al., 1999; Sabean, 2004; Hawkes et al., 2005; Nelson et al., 2008) and elsewhere (Scott and Medioli, 1978; Murray, 1991; Boomer, 1998; Haslett, 2001; Horton and Edwards, 2006) found *T. inflata* to be a dominant species of the

high and middle marsh. Similarly, *B. pseudomacrescens* has been found in the high marsh in Maine (Gehrels and van de Plassche, 1999), Norway (Murray and Alve, 1999), British Columbia (Patterson et al., 1999; Riveiros et al., 2007) and the United Kingdom (Horton and Edwards, 2006). *H. wilberti* (although not commonly differentiated from *Haplophragmoides* sp.) commonly occupies the high and middle marsh (Jennings and Nelson, 1992; Guilbault et al., 1996; Scott et al., 1996; Gehrels and van de Plassche, 1999; Patterson et al., 1999; Horton and Edwards, 2006).

Faunal Zone Ia, above MHHW, comprises the upland and high marsh floral zones at Nehalem River, Salmon River and South Slough (Fig. 10). At Nehalem River, Zone Ia is composed of *T. inflata* and *B. pseudomacrescens*. At Salmon River Zone Ia is dominated by *T. irregularis*, which was also found in British Columbia by Guilbault et al. (1995, 1996). Zone Ia at South Slough includes the three above mentioned species.

Faunal Zone Ib is found in the middle marsh floral zone below MHW at Nehalem River and South Slough and above MHW at Salmon River (Fig. 10). At Salmon River, Zone Ib is composed of *H. wilberti* and *T. inflata*. At Nehalem River, Zone Ib is composed of *H. manilaensis* and *J. macrescens*. At South Slough, Zone Ib is dominated by *J. macrescens* and *M. fusca*. Similar middle marsh faunal assemblages have been described from elsewhere in the Pacific Northwest with the exception of *J. macrescens* (Scott and Medioli, 1978; Guilbault et al., 1995, 1996; Scott et al., 1996; Sabean, 2004; Hawkes et al., 2005; Nelson et al., 2008). High percentages of

Detrended Correspondence Analysis

Elevation-Dependent Faunal Zonea
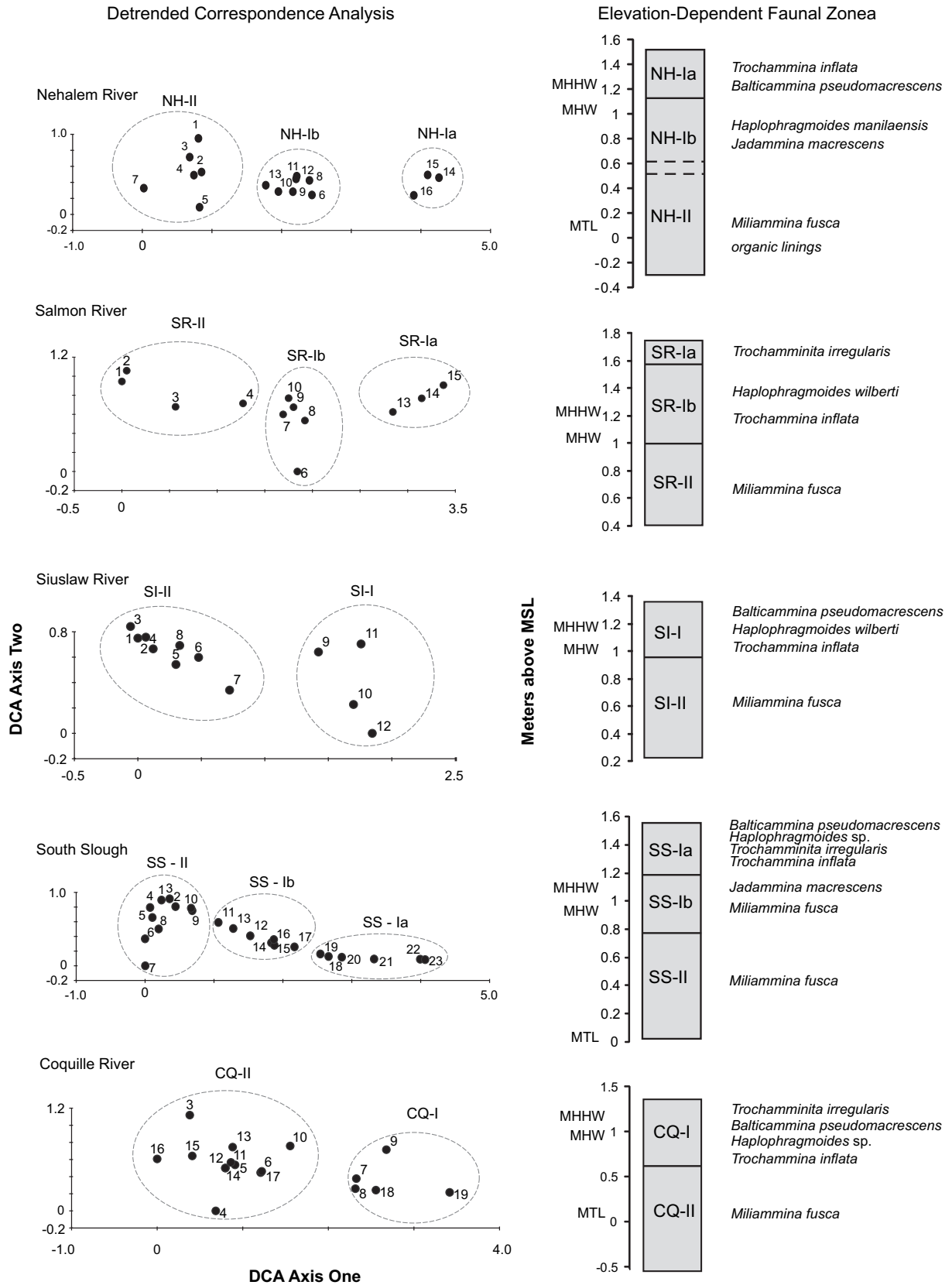
Fig. 10. Summary foraminiferal assemblages and faunal zones (shown on right) determined by unconstrained cluster analysis based on unweighted Euclidean distance (Figs. A1–A4) and detrended correspondence analysis (DCA, shown on left) for the five study areas. DCA Axis One most closely reflects the elevational gradient. Siuslaw and Coquille Rivers have two faunal zones whereas Nehalem River, Salmon River and South Slough have three faunal zones. Dashed lines refer to overlapping boundaries between zones. Elevation (m MSL) and tidal levels are shown. Only samples with counts greater than 100 individuals per 5 cm³ and species that contribute 5% of the dead assemblage are included in DCA plots.

Table 3
Statistical summary of the performance of weighted averaging partial least squares (WA-PLS) for the screened set of contemporary foraminiferal data.

Estimated errors		
component	RMSE	r^2
1	7.83	0.82
2	7.07	0.85
3	6.66	0.87
Prediction errors		
component	RMSEP	r^2
1	8.26	0.80
2	7.74	0.82
3	9.42	0.77

J. macrescens are more commonly found in high marsh floral zones; near monospecific assemblages have been recorded at the marsh-to-upland transition, close to MHHW (Scott and Medioli, 1978; Scott and Medioli, 1980; Gehrels, 1994; Horton and Culver, 2008). Edwards et al. (2004) concluded that monospecific assemblages are site-specific. Assemblages near the upper limit of tides in general are increasingly difficult to find because most marsh areas have been ditched and are backed by embankments, roads, and other structures. Likewise, Murray and Alve (1999) and Southall et al. (2006) found *J. macrescens* to dominant the middle and low marsh.

Faunal Zone II is distinct at all five intertidal environments due to percentages of *M. fusca* >35% in all samples. Zone II extends from below MHW to MTL in the low marsh and tidal flat floral zones (Fig. 10). Low marsh and tidal flat assemblages studied by Jennings and Nelson (1992), Guilbault et al. (1995), Scott et al. (1996), Patterson et al. (1999), Sabean (2004), Hawkes et al. (2005) and Nelson et al. (2008) in the Pacific Northwest and elsewhere (Murray, 1971, 1973; de Rijk and Troelstra, 1997, 1999; Horton et al., 1999; Edwards and Horton, 2000; Horton and Edwards, 2006) are also dominated by *M. fusca*.

Unlike assemblages on the coasts of eastern North America and the United Kingdom, where the low marsh and tidal flat environments have a high concentration and diversity of calcareous species (e.g., Phleger, 1970; Murray, 1991; Gehrels et al., 2001; Buzas et al., 2002; Culver and Horton, 2005; Horton and Edwards, 2006), only low percentages of calcareous species at the seaward edge of the Salmon River transect (2.3%) were found. Jennings and Nelson (1992) found similarly low percentages of calcareous foraminifera in mud flat samples from Haynes Inlet and Bull Island, Coos Bay (<3% and <10%, respectively) and at South Inlet in Siuslaw River

(<4% with the exception of one sample with 46% *Haynesina orbiculare*). However, Hunger (1966) found abundant *Ammonia beccarii* and *Elphidium* sp. in samples from the lower and considerably more saline tidal flat of Netarts Bay.

The absence of calcareous foraminifera may be attributable to the low pH of the intertidal environment. This inference is supported by measurements of pH across the Nehalem River marsh which varies between 3.8 and 6.3. A low pH affects both the cell protoplasm and the calcareous test of foraminifera (Bradshaw, 1968; Green et al., 1993). To survive, the cell must remain between relatively narrow pH limits; experiments have shown that *A. beccarii* cannot survive for more than 75 min at a pH of 2 (Bradshaw, 1968). Low pH stresses calcareous foraminifera because they must spend considerable energy recalcifying their tests (Boltovskoy and Wright, 1976). Phelger (1970) found a high correlation between low pH and low foraminiferal abundance and diversity. Boltovskoy and Wright (1976) found evidence of dissolution (etching) of the calcium carbonate tests where the pH of the environment was below 7.8. Alve and Nagy (1986) reported dissolution of tests under a pH range of 6.5–7.2. Recently, Berkeley et al. (2007) concluded that for pH conditions below typical seawater (∼7.2), changes in the concentration of carbonic acid or bicarbonate and/or increases in hydrogen sulphide production (driven by the rate at which organic matter is supplied) favors the dissolution of calcium carbonate in the tests of calcareous foraminifera (Berkeley et al., 2007). Abundant organic test linings (<40%) were found in the surface samples from the low marsh and tidal flat at Nehalem River. Edwards and Horton (2000) suggested that the presence of test linings represents dissolution of calcareous species due to taphonomic and laboratory processes (e.g., decay of tests in unrefrigerated samples).

5.2. Environmental variables and species distribution

The two environmental variables thought to be responsible for the distribution of foraminifera in the intertidal environment are elevation, which controls the duration and frequency of tidal exposure (e.g., Scott and Medioli, 1980; Horton, 1999; Horton and Edwards, 2006), and salinity (e.g., Jonasson and Patterson, 1992; de Rijk, 1995, 1997; Goldstein and Watkins, 1998). Although the two are commonly interdependent (e.g., Phleger, 1970; Murray 1971; Horton and Edwards, 2006), de Rijk (1995a, b, 1997) and de Rijk and Troelstra (1997) concluded that the distribution of foraminifers on
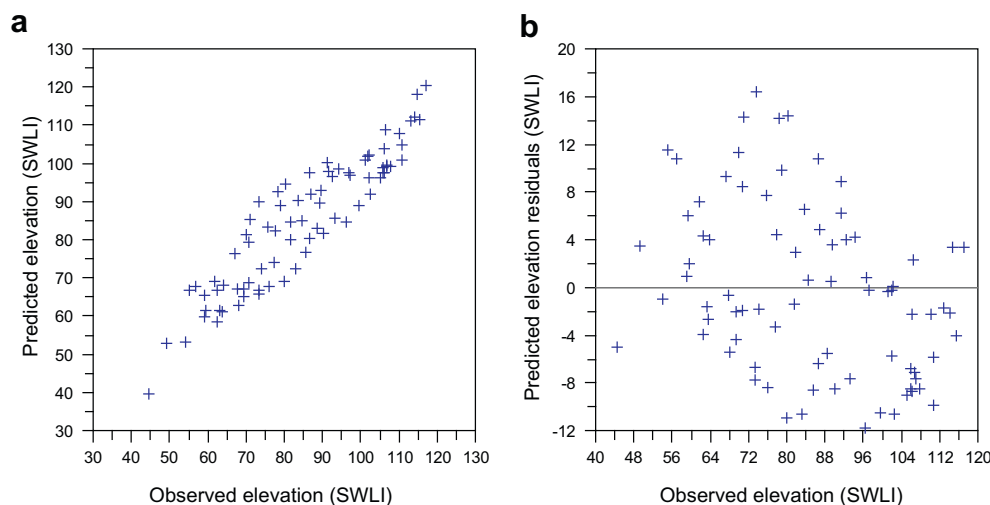
Fig. 11. (a) Plot of WA-PLS predicted SWLI versus observed SWLI for contemporary foraminifera samples in the regional dataset. (b) Plot of WA-PLS residual SWLI versus observed SWLI for the same surface foraminifera samples. Residual SWLI are equal to the predicted SWLI minus observed SWLI. RMSEP = 7.74 and $r^2_{jack} = 0.82$.
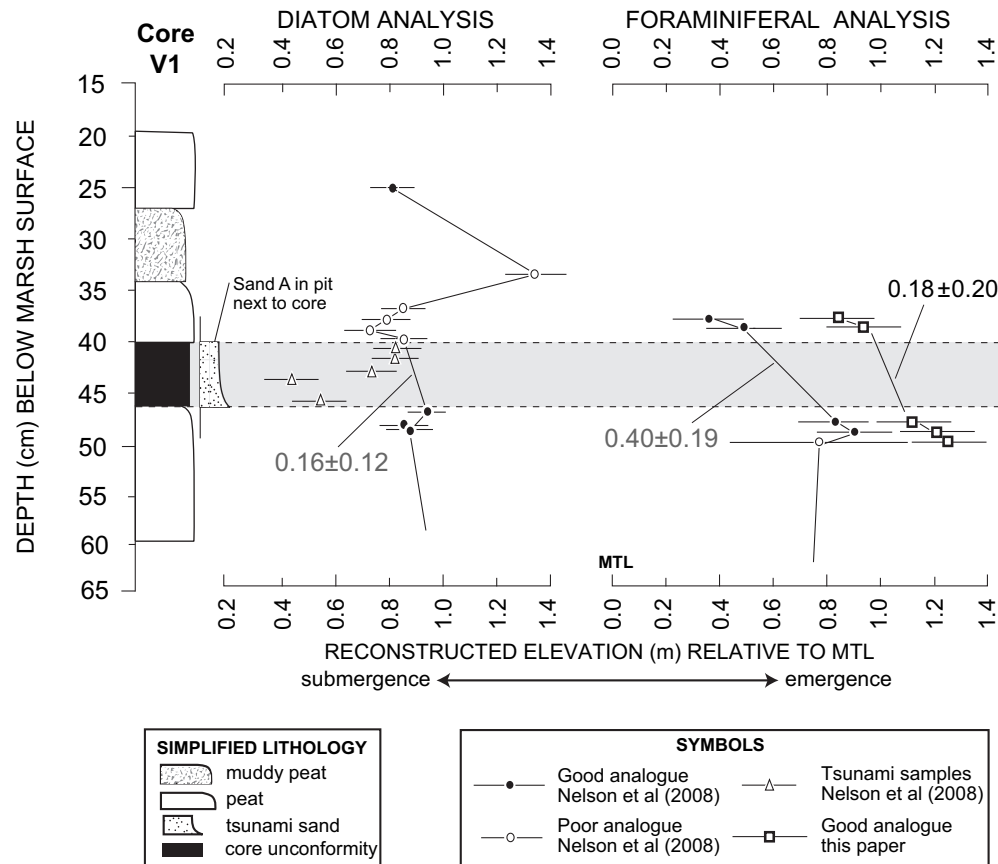
Fig. 12. Stratigraphy and WA-PLS reconstructions of the sediment sequence bisecting the AD 1700 earthquake at Alsea Bay. Reconstructed elevation estimates made from fossil foraminifera assemblages in core V1 from Nelson et al. (2008) using diatoms and foraminifera (light gray estimates) and using modified foraminifera taxonomy (black estimate) in this paper. Good analogue samples are shown as black circles and poor analogue samples as open circles for the Nelson et al. (2008) data. Open squares show the revised reconstruction in this paper. Samples from tsunami-deposited sand beds (gray shading) where reconstructions were not made are shown as open triangles.

the Great Marshes of eastern Massachusetts are controlled by local spatial and temporal changes in a number of environmental variables (notably salinity) and not primarily by elevation. The gradients of the extensive tidal surfaces of the Great Marshes are extremely low, and the surfaces have a variable microtopography. In contrast, the Coquille River transect shows an elevation-dependent faunal zonation despite large irregularities in marsh surface topography created by river meander scars.

The results from CCA and partial CCAs of the foraminiferal and environmental data from Nehalem River further support the hypothesis that foraminiferal assemblages are strongly correlated with elevation, which explains 39% of the total variance. Horton and Edwards (2006) similarly found that approximately 42% of the contemporary foraminiferal distribution is controlled by elevation in intertidal environments of the UK. Due to inter-correlation between environmental variables at Nehalem River (29% of the explained variance), elevation cannot be inferred to be independent of other variables. This result might be anticipated because other variables are also dependent on the frequency and duration of tidal exposure as controlled by elevation. Similar inter-correlations among variables and intertidal foraminifera have been observed (Horton et al., 2003; Horton and Edwards, 2005; Woodroffe, 2006).

5.3. Example of reconstructing coastal subsidence during a great Cascadia earthquake

A succession of statistical methods has been applied to tidal marsh foraminiferal datasets for reconstructing relative sea-level, with results from transfer function analysis being the most objective

(e.g., Guilbault, et al., 1996; Horton et al., 1999; Gehrels et al., 2001; Horton and Edwards, 2006; Kemp et al., 2009). Nelson et al. (2008) used both foraminiferal and diatom transfer functions on a core at Alsea Bay, on the central Oregon coast, to calculate the amount of subsidence during the giant Cascadia earthquake of AD1700. Diatom- and foraminiferal-based amounts of subsidence were inconsistent (0.40 ± 0.19 m for foraminifera; 0.16 ± 0.12 m for diatoms), perhaps because the fossil diatom samples used for calculations had no good analogs in the contemporary dataset used to develop the transfer function. Nelson et al. (2008) emphasized the need to acquire large modern datasets that sample a full range of tidal environments to avoid the problem of no-analog fossil samples.

To address the above, a transfer function was developed and used to estimate the amount of coseismic subsidence during the AD1700 earthquake from the data of Nelson et al. (2008) at Alsea Bay (Fig. 1). The transfer function was applied to foraminiferal assemblage data above and below the upper contact of a buried marsh OA horizon at 0.46 m depth in the core studied by Nelson et al. (2008; Fig. 12). The horizon is sharply overlain by medium gray tsunami-deposited sand (Nelson et al., 2008). *B. pseudomacrescens*, *T. inflata* and *J. macrescens* dominate the assemblage in the buried marsh horizon indicating a middle to high marsh environment. The tsunami sand was not sampled for foraminifera. The increase in abundance of *M. fusca* with no decrease in *T. inflata* in the overlying muddy peat indicates a low-middle marsh environment.

The WA-PLS (weighted averaging partial least squares) unimodal-based technique was used, following ter Braak and Juggins (1993) and Birks (1995), based on the 91 samples and 18 species from the five study sites. Performance of the transfer functions was

assessed in terms of the root-mean square of the error of prediction (RMSEP) and the squared correlation (r^2) of observed versus predicted values. The RMSEP indicates systematic differences in prediction errors, whereas the r^2 measures the strength of the relationship of observed versus predicted values. These statistics were calculated as 'apparent' measures in which the whole training set was used to generate the transfer functions and assess their predictive ability. The data were also jack-knifed (also known as 'leave-one-out' measures) to measure the overall predictive abilities of the dataset.

The transfer function analysis yields statistics for six components. The choice of the component for the final transfer function used depends upon the prediction statistics (RMSEP and r^2) and parsimony, i.e. choosing the component with the lowest values that gives an acceptable model (Juggins, written communication). Component 2 was selected for the WA-PLS transfer function because it performs significantly better than other components when jack-knifed errors are considered ($r^2_{jack} = 0.82$): prediction errors (RMSEP) are lower and squared correlations (r^2) are higher (Table 3). Using component 2, the relationship between observed and foraminifera-predicted elevation is strong (Fig. 11). The error estimate for sample-specific former sea-level in this reconstruction (RMSEP$_{jack}$ = 0.20 m) is comparable to local and regional transfer functions from temperate marshes of Europe (e.g., Horton et al., 1999; Gehrels et al., 2001; Horton and Edwards, 2006; Leorri et al., 2008) and the Atlantic Coast of the North America (e.g. Gehrels, 2001; Kemp et al., 2009).

The transfer function was used to estimate coseismic subsidence in AD1700 as 0.18 ± 0.20 m (Fig. 12: similarly, using *T. irregularis* instead of *B. pseudomacrescens* in the fossil reconstruction the coseismic subsidence estimate is 0.22 ± 0.20 m). Reconstructed elevations for the buried marsh ranged from 1.08 ± 0.20 m MSL to 1.172 ± 0.22 m MSL, and the two samples in muddy peat above the tsunami sand gave results of 0.824 ± 0.20 m MSL and 0.898 ± 0.20 m MSL. All five fossil samples had good modern analogs in the contemporary dataset (below the maximum dissimilarity coefficient in the contemporary dataset). Interestingly, the subsidence estimate closely matches the diatom function estimate of Nelson et al. (2008), whose five overlying samples lacked good analogs, but is less than half the foraminiferal estimate of Nelson et al. (2008), which did have good analogs in their contemporary dataset. Note, however, that all estimates overlap within errors. The much larger contemporary dataset and consistent application of taxonomy facilitates more reliable reconstructions of past changes in marsh elevation related to coseismic subsidence without complications in taxonomy caused by changes in taxonomists. Furthermore, the larger sample number provides a higher likelihood of encountering all possible modern analogues in present salt marsh environments by using five estuaries along the Oregon coast. Taxonomy inconsistencies in core samples are complicated and an absence of taxonomic plates precludes any reassessment of the AD 1700 fossil samples from Nelson et al. (2008) and data used within. Re-identification and analysis of new fossil samples from the AD 1700 earthquake subsidence at Alsea Bay is likely the soundest approach to identifying the best estimate of coseismic subsidence.

6. Conclusions

Use of fossil foraminiferal assemblages in reconstructing former sea-levels requires an understanding of their contemporary distributions within the intertidal environment. Foraminifera were identified in 91 surface samples and measured environmental variables (elevation, loss on ignition, clay-silt fraction, pH, salinity and vegetation cover) along transects in intertidal environments at

five estuaries along the Oregon coast. Multivariate analyses (unconstrained cluster analyses and detrended correspondence analysis) were used to divide the 91 foraminiferal assemblages into elevation-dependent faunal zones, two at Siuslaw and Coquille Rivers, and three at Nehalem River, Salmon River and South Slough (Fig. 10). Zones Ia, Ib and I include areas with upland, high marsh and middle marsh plant communities; Zone II corresponds with low marsh and tidal flat areas. Zones I and Ia are dominated by *T. irregularis*, *B. pseudomacrescens*, *H. wilberti* and *T. inflata*. Zone Ib assemblages are composed of *T. inflata*, *H. wilberti*, and *J. macrescens* and Zone II is dominated by *M. fusca*. The faunal zonation is similar to zonations reported from other intertidal environments of central western North America and elsewhere. However Oregon intertidal environments show certain site-specific differences such as the absence of *J. macrescens* in faunal Zones I and Ia, and the near absence of calcareous species in faunal Zone II. The near absence of calcareous species is attributed to dissolution of calcareous tests due to the low pH of intertidal sediment on the Oregon coast.

Canonical correspondence analysis (CCA) and partial CCA of the contemporary foraminiferal assemblages and environmental data from the Nehalem River transect show that the faunal zonation of foraminifera is elevation-dependent. As an example of how this elevation-dependent zonation can be used to reconstruct past coseismic and interseismic sea-level changes at the Cascadia subduction zone, a regional-scale transfer function was developed using foraminiferal data from the five studied marshes. The transfer function demonstrated a strong relationship between observed and predicted elevations ($r^2_{jack} = 0.82$; RMSEP$_{jack}$ = 0.20 m). Applications of the transfer function to a core at Alsea Bay produced an estimate of subsidence during the giant Cascadia earthquake of AD1700 (0.18 ± 0.20 m) comparable to the reconstruction of Nelson et al. (2008) using a diatom-based transfer function, but less than half the estimate of Nelson et al. (2008) using their foraminiferal transfer function, perhaps because of differences in taxonomy and the species relationship to elevation.

Appendix

Figs. A1 (Salmon River), A2 (Siuslaw River), A3 (South Slough), A4 (Coquille River). (a) Unconstrained cluster analysis (unweighted Euclidean distance) diagram showing groupings of samples (b) plot of samples showing detrended correspondence analysis where samples with similar assemblages plot closer together and (c) vertical zonation of foraminiferal death assemblages (%). Only samples with counts greater than 100 individuals and species that contribute 5% of the dead assemblage are included. Individual samples cannot be assigned a faunal zone.
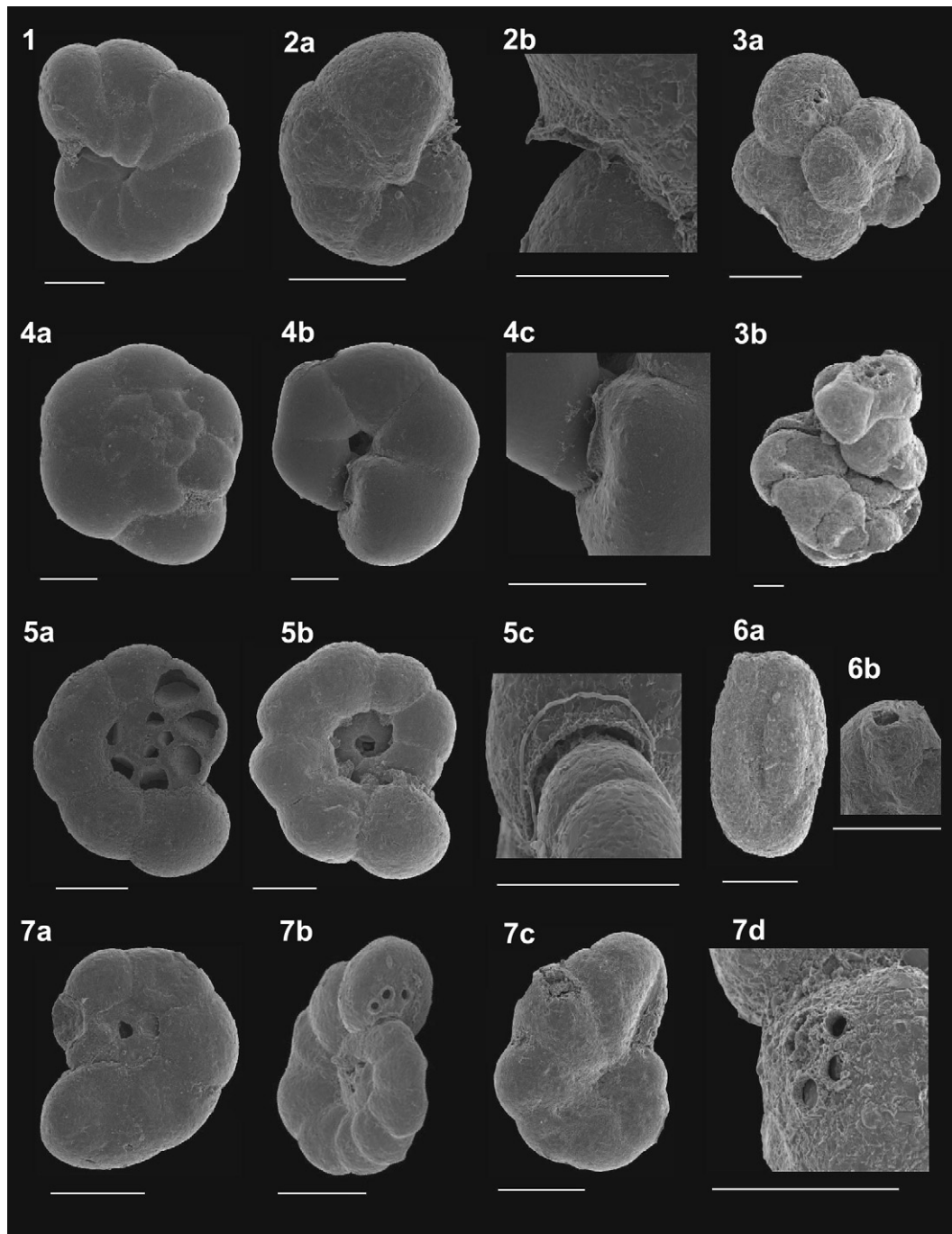
Plate I. Scale bars equal 100 μm. (1) Haplophragmoides manilaensis, side view. (2a) Haplophragmoides wilberti, side view. (2b) Haplophragmoides wilberti, aperture view. (3a) Trochamminita irregularis, side view. (3b) Trochamminita irregularis, aperture view. (4a) Trochammina inflata, dorsal view. (4b) Trochammina inflata, ventral view. (4c) Trochammina inflata, aperture view. (5a) Balticammina pseudomacrescens, dorsal view. (5b) Balticammina pseudomacrescens, ventral view. (5c) Balticammina pseudomacrescens, aperture view. (6a) Milliammina fusca, side view. (6b) Milliammina fusca, aperture view. (7a) Jadammina macrescens, dorsal view. (7b) Jadammina macrescens, dorsal and aperture view. (7c) Jadammina macrescens, ventral view. (7d) Jadammina macrescens, aperture view.
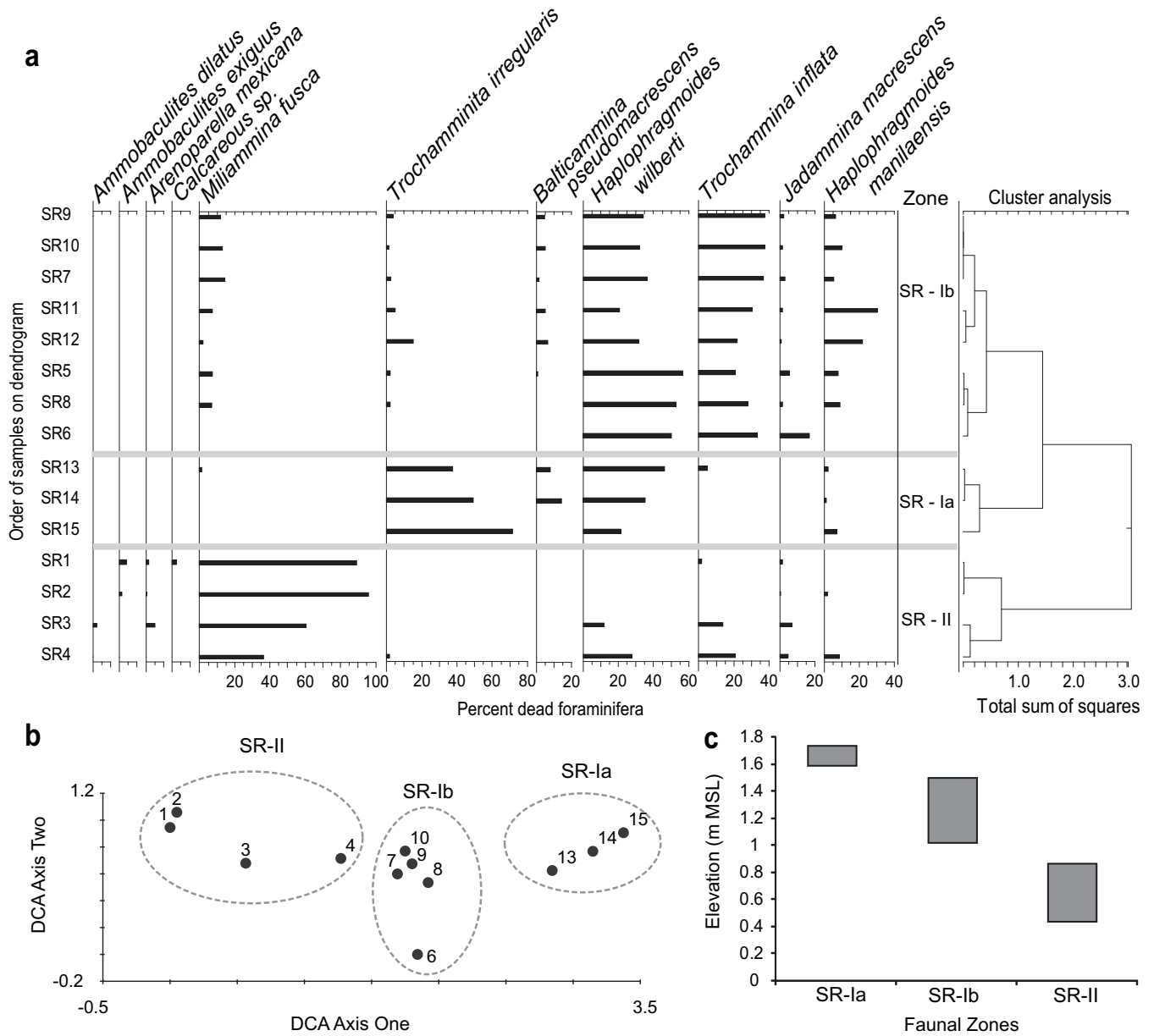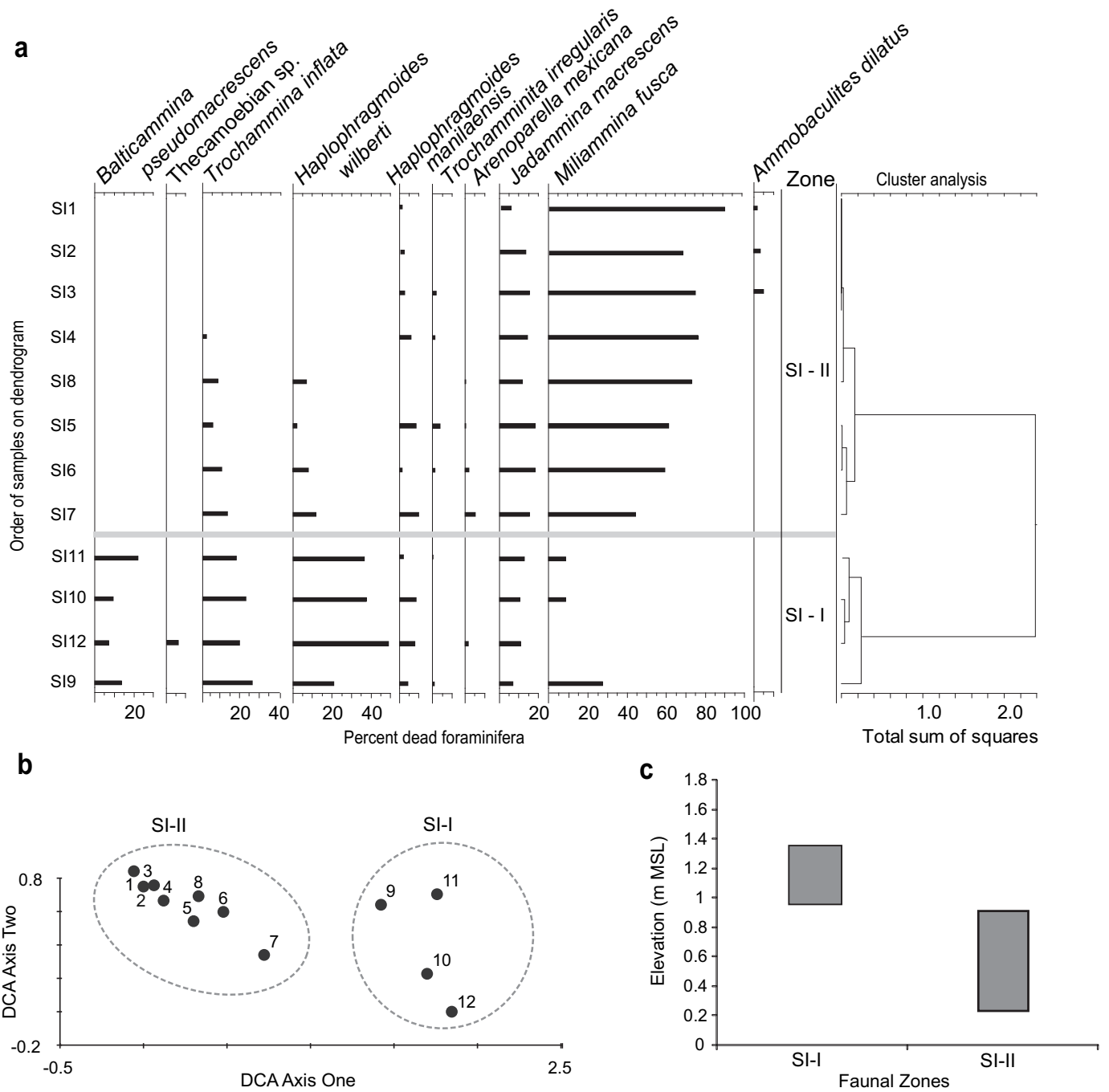
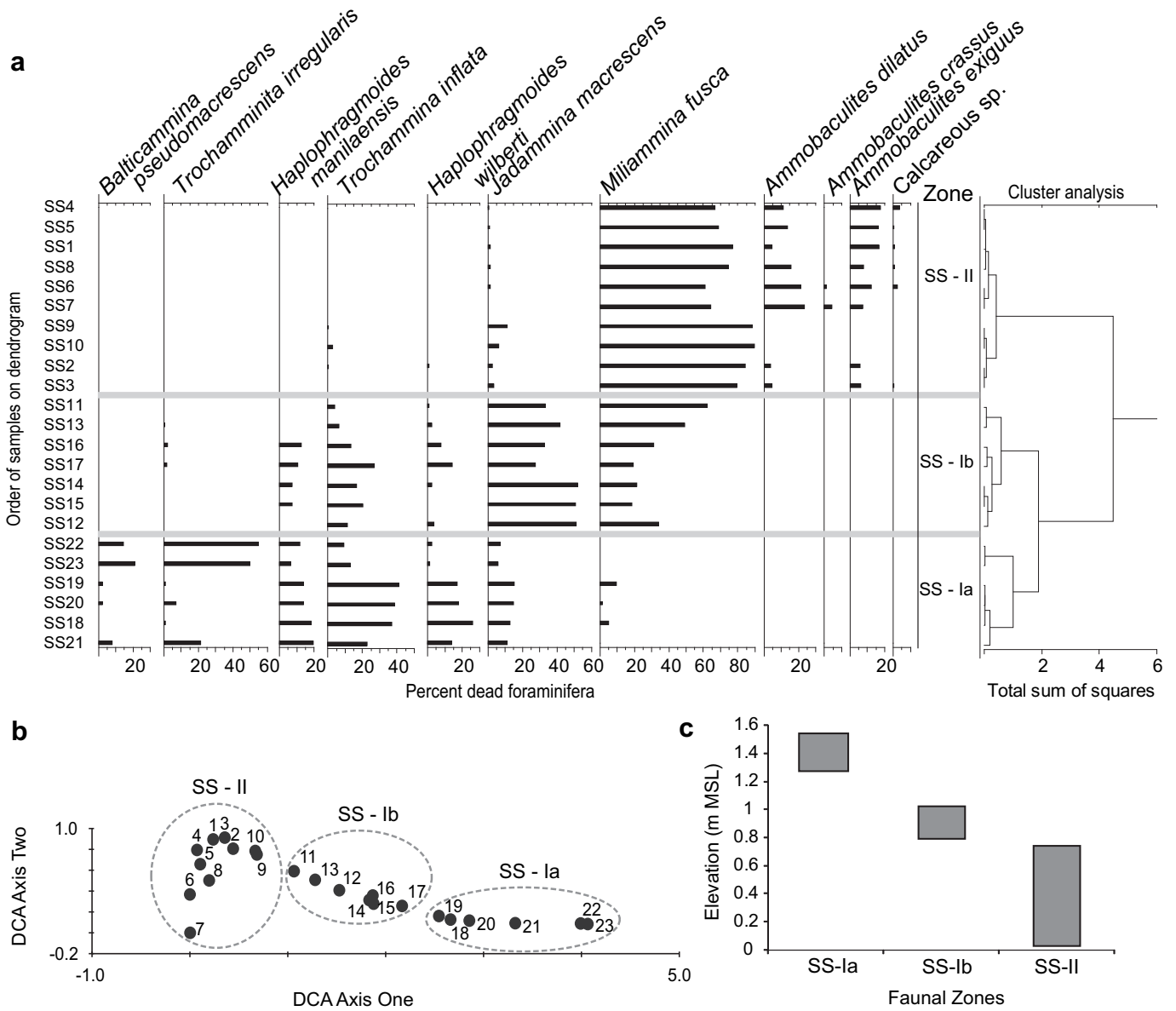Fig. A1. Salmon River.

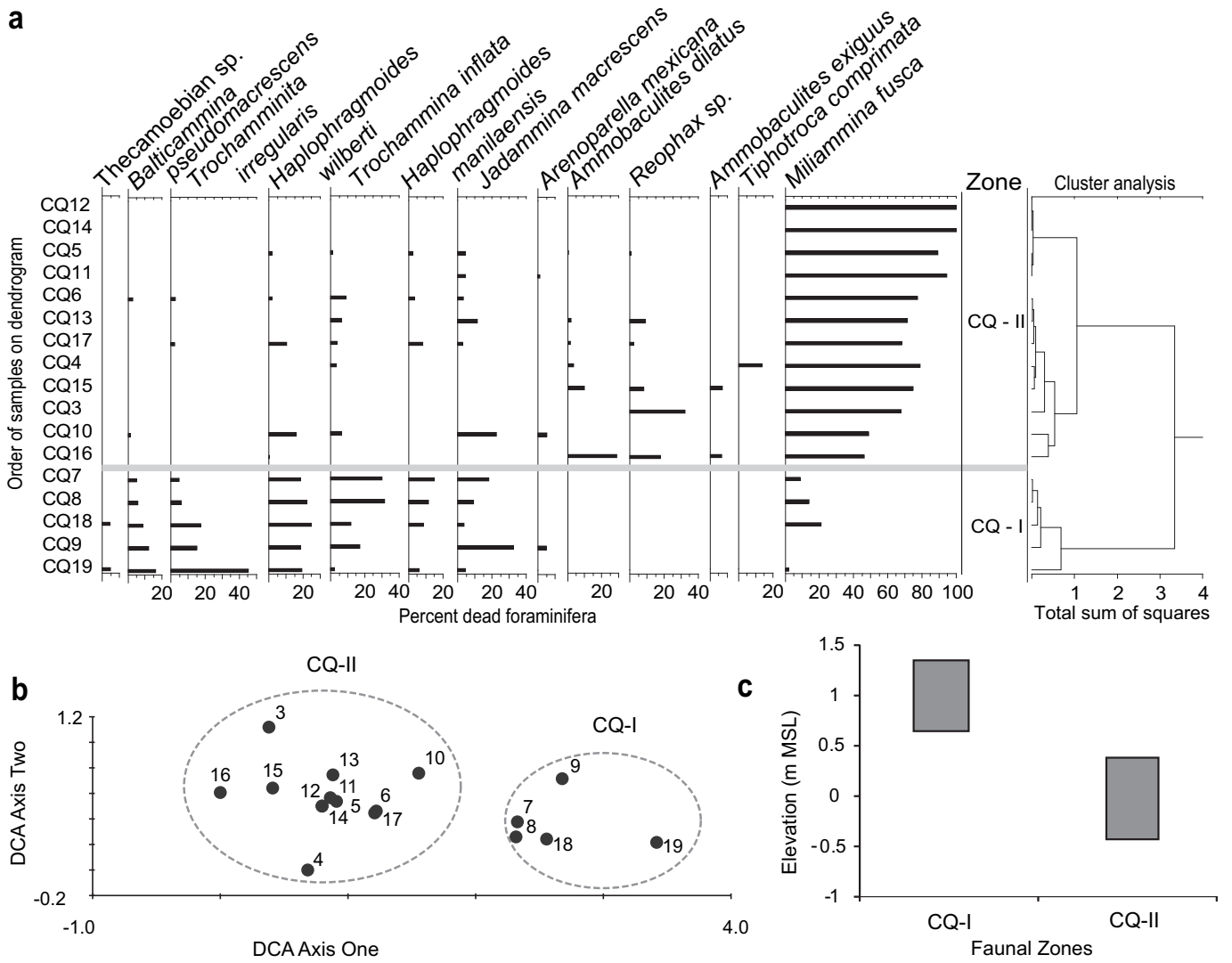Fig. A2. Sinuslaw River.

Fig. A3. South Slough.

Fig. A4. Coquille River.

A.1. Taxonomy

The dominant agglutinated foraminifera encountered in surface and subsurface sediment from the five study sites in Oregon intertidal environments are described and illustrated here. Phenotypic variation within species, together with superficially similar species has resulted in an often confusing nomenclature.

Suborder Textulariina

Balticammina pseudomacrescens
(Brönnimann, Lutze and Whittaker, 1989)
Plate I, Figs. 5a–c.
Balticammina pseudomacrescens Brönnimann, Lutzeand Whittaker, 1989, p. 169, pl. 1, Figs. 1–5, pl. 2, Figs. 1–9, pl. 3, Figs. 1–4.

Haplophragmoides manilaensis (Andersen, 1953)
Plate I, Fig. 1.
Haplophragmoides manilaensis Andersen, 1953, p. 22, pl. 4, Fig. 8,
Haplophragmoides bonplandi Todd and Brönnimann, 1957, p. 23, pl. 2
Scott and Medioli, 1980, p. 40, pl. 2, Figs. 4 and 5.

Haplophragmoides wilberti (Andersen, 1953)
Plate I, Figs. 2a–c.
Haplophragmoides wilberti Andersen, 1953, p. 21, pl. 4, Fig. 7.
Boltovskoy and Virdarte, 1977, p. 39, pl. 3, Fig. 3.
Netti et al., 1977, pl 1, Figs. 12 and 13.

Jadammina macrescens (Brady, 1870)
Plate I, Figs. 7a–d.
Trochammina inflata (Montagu) var. macrescens Brady, 1870, p. 290, pl. 11, Figs. 5a–c.
Jadammina polystoma Bartenstein and Brand, 1938, p. 381, text–Figs. 1–3.
Jadammnina macrescens (Brady); Brönnimann and Whittaker, 1984a, p. 303–309, Figs. 1–21 (lectotype)

Miliammina fusca (Brady, 1870)
Plate I, Figs. 6a,b.
Quinqueloculina fusca Brady, 1870, p. 286, pl. 11, Figs. 2a–c.
Miliammina fusca Brady. Murray, 1971, p. 21, pl. 3, Figs. 1–6.

Trochammina inflata (Montagu, 1808)
Plate I, Figs. 4a–c.
Nautilus inflatus Montagu, 1808, p. 81, pl. 18, Fig. 3.
Trochammina inflata (Montagu). Brönnimann and Whittaker, 1984b, p. 311–315, Figs. 1–11 (neotype erected).

Trochamminita irregularis (Cushman and Brönnimann)
Plate I, Figs. 3a,b.
Zaninetti et al., 1977, pl. 1., Figs. 10 and 11.

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