

# Diatom Zonation in Southern Oregon Tidal Marshes Relative to Vascular Plants, Foraminifera, and Sea Level

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## ABSTRACT

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Diatom assemblages from four surface transects across estuarine marshes in southern Oregon show a three-part vertical ecologic zonation of the intertidal zone similar to zonations of foraminiferal and vascular plant assemblages. Gradual changes in the compositions of all three types of assemblages reflect gradational zone boundaries, 5-40 m wide. Discriminant function analysis indicates that modern mudflat, low marsh, and high marsh zones can be distinguished from one another with diatom assemblage data at three silty marshes in the middle parts of two river-dominated estuaries. However, low marsh and high marsh assemblages are less distinct from each other than are mudflat and low marsh assemblages. The compositions of vascular plant and diatom assemblages on a transect at a sandy site near the mouth of a third estuary differ from those of the silty transects. A particularly distinct diatom subzone—the marsh border subzone—is marked by a dominance of fresh-to-brackish-water diatoms in a few samples from the upper part of the high marsh and lowest part of the upland zone on all four transects. But the vertical range of the marsh border subzone is large (about 0.7 m) and its range may vary from site to site depending on the amount of freshwater seepage and runoff into marshes. The zonation of modern diatom assemblages suggests that fossil diatom assemblages, particularly those of the high marsh and marsh border subzone, will be useful in paleosea-level reconstructions.

**ADDITIONAL INDEX WORDS:** *Holocene sea-level changes, salt-marsh microfossils, U.S. Pacific Northwest, intertidal zonation, littoral paleoenvironments, coastal paleoseismology.*

## INTRODUCTION

Assessment of the consequences of coastal erosion, recent sea-level rise, and other potentially hazardous coastal processes requires an understanding of the history of Holocene sea-level change (CARTER and DEVOY, 1987; PILKEY *et al.*, 1989; WARRICK and WIGLEY, 1991). Analysis of diatom assemblages in intertidal sediment is a primary means of reconstructing past sea-level changes (*e.g.*, IRELAND, 1987; WILLIAMS, 1990; FUJIMOTO, 1990) and these methods have also been used in assessing other hazards in coastal environments, such as water pollution (MCINTIRE and MOORE, 1977). In this paper, we lay some of the groundwork for a new application of diatom analysis in coastal hazard assessment in the Pacific Northwest of the United States. Study of diatom assemblages in the tidal-wetland sediments of this region may help show whether great (magnitude >8) subduction earthquakes have occurred in the past few thousand years.

Late Holocene tidal-wetland stratigraphy in the Pacific Northwest is consistent with the suggestion of HEATON and HARTZELL (1987) that great earthquakes as large as magnitude 9 occur on the subduction-zone boundary between the North America and Juan de Fuca plates (Figure 1). Along the coasts of Washington (ATWATER and YAMAGUCHI, 1991; ATWATER, 1992), Oregon (DARIENZO and PETERSON, 1990; DARIENZO, 1991; PETERSON and DARIENZO, *in press*; NELSON, *in press*), and northern California (CLARKE and CARVER, 1992; VALENTINE, 1992) peaty, tidal-wetland soils are interbedded with mud in estuarine stratigraphic sequences. The submergence (relative rise of sea level) of at least two of these soils in northern Oregon and Washington seems too widespread (>100 km), too large (>1 m), and too sudden (<10 yr) to be attributed to any process except coastal subsidence during an earthquake. Coseismic subsidence may be caused by regional deformation of the upper (North America) plate during slip on the boundary between it and the subducting (Juan de Fuca) plate (*e.g.*, PLAFKER, 1972),

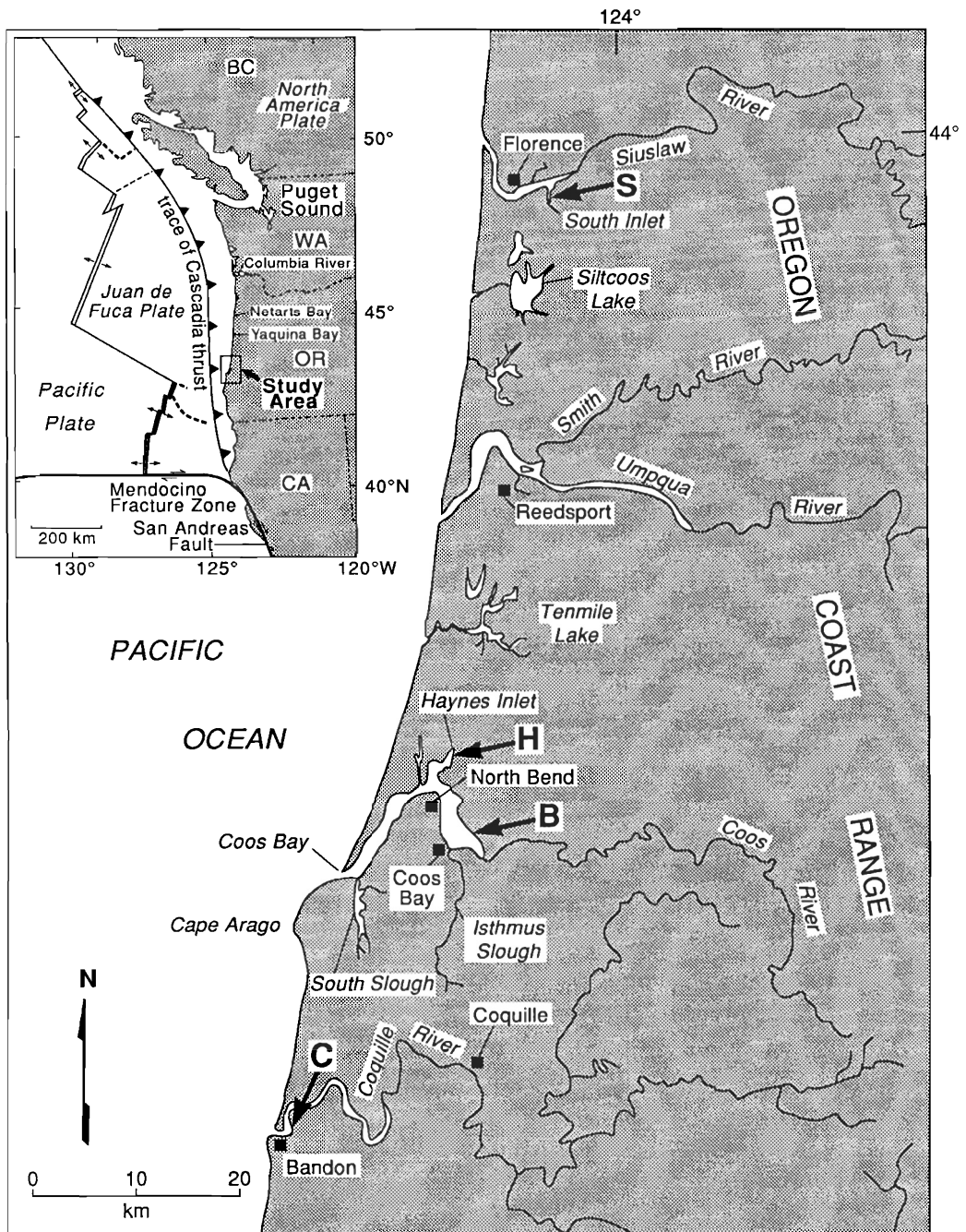


Figure 1. Location of four transects through modern tidal marshes in southern Oregon. The Haynes Inlet (transect H) and Bull Island (transect B) marshes fringe the Coos Bay estuary. The South Inlet marsh (transect S) is in a small arm of the Siuslaw River estuary. The Coquille River marsh (transect C) is across the river from an active field of sand dunes along the outer coast. In the inset figure the trace of the Cascadia thrust fault (barbed line, barbs point down-dip), where the Juan de Fuca plate is being subducted beneath the North America plate, is placed at the bathymetric boundary between the continental slope and abyssal plain; double lines are spreading ridges, solid lines are strike-slip faults, and dashed lines are other faults.

or by localized deformation from much shallower folding or faulting in the upper plate (NELSON, 1992; NELSON and PERSONIUS, in press).

Other tidal-wetland soils in the Pacific Northwest may have been submerged and buried by nontectonic processes during the gradual rise of late Holocene sea level. Peaty soils are commonly interbedded with mud in the intertidal sequences of mid-latitude passive continental margins (*e.g.*, TOOLEY, 1978; SHENNAN, 1986; STREIF, 1987; VAN DE PLASSCHE, 1991). Examples of nontectonic processes that can produce such sequences include rapid changes in the rate of regional sea-level rise combined with changing sedimentation rates, or changes in the configuration of bars and channels in tidal inlets that led to local changes in tidal range (HAGGART, 1988). Tidal-wetland soils can be shown to have been submerged by coseismic subsidence only where the abrupt upper contact of a widely-mapped, peaty soil shows convincing evidence of a sudden, substantial change (>0.5 m) in water depth (NELSON, in press).

If large parts of the outer coast of the Pacific Northwest have suddenly subsided more than 0.5 m during the late Holocene, diatom assemblages in intertidal stratigraphic sequences should reflect these sudden submergence events. In concert with stratigraphic, lithologic, and other paleoecologic analyses (*e.g.*, HEMPHILL-HALEY, 1989; JENNINGS and NELSON, 1992; MANHART, 1992), diatom assemblage studies should help estimate the amount of sudden submergence represented by the abrupt transgressive contacts commonly found at the tops of buried soils in tidal-marsh sequences throughout the region. Such studies at many sites may help distinguish stratigraphic evidence of regional or localized paleoearthquakes from evidence for more gradual relative sea-level changes produced by nontectonic processes (NELSON, in press).

The relations of diatom assemblages from different habitats to environmental variables, such as exposure, salinity, or substrate lithology in Oregon estuaries have been studied extensively (MCINTIRE and MOORE, 1977; WHITING and MCINTIRE, 1985). But no work has focused on the vertical zonation of benthic assemblages within the intertidal zone—a prerequisite for using fossil diatom assemblages to estimate past sea-level changes. Here we (1) describe modern diatom assemblages along four intertidal transects at three estuaries in southern Oregon, (2) compare the elevational distribution of these assemblages with

the distribution of vascular plants and foraminifera, and (3) show how down-core changes in fossil diatom assemblages might be used to estimate the size of past sudden submergence events.

#### VERTICAL ECOLOGICAL ZONATION IN OREGON TIDAL MARSHES

Like tidal marshes of other mid-latitude coasts, Oregon tidal marshes display a vertical ecologic zonation that reflects the different tolerances of organisms to environmental gradients across salt marshes (JEFFERSON, 1975; FRENKEL *et al.*, 1981; JENNINGS and NELSON, 1992). Many highly interrelated factors influence the composition, homogeneity, and extent of marsh plant and animal communities, but the most important of these factors are directly related to elevation relative to tide levels (*e.g.*, SCOTT and MEDIOLI, 1980a; MCKEE and PATRICK, 1988; ADAM, 1990). Tidal marshes generally form in the upper half of the intertidal zone, and most can be divided into two major zones: low marsh and high marsh. Further subdivision of tidal marshes is commonly based on specific plant or animal assemblages found on different types of substrate, on different landforms, or on salinity or tidal differences in different parts of an estuary. Although the major zone boundaries in some marshes are distinct, many investigators emphasize the overlapping distributions of many individual species (SULLIVAN, 1975; EILERS, 1975; FREY and BASAN, 1985; ADAM, 1990; JENNINGS and NELSON, 1992).

#### Vascular Plants and Foraminifera

Despite the floristic diversity and complex zonation of Oregon tidal marshes, we follow FRENKEL *et al.* (1978) in recognizing only four major floral zones in the four marshes that we sampled for diatoms: mudflat, low marsh, high marsh, and upland (Figure 4, Table 1). In the first detailed study of the zonation of intertidal foraminiferal faunas in the Pacific Northwest, JENNINGS and NELSON (1992) showed that assemblages from three of the four transects discussed in this paper reflect the same vertical zones mapped using the distribution of vascular plants (Table 1). This simple zonation allows us to map the same zones in most marshes, even in those whose plant assemblages differ from each other. These major zones are also more directly related to tide levels than are zones based on different substrates or stages of marsh succession. The plant and animal assemblages in the four major zones can be easily

Table 1. Vascular plant, foraminiferal, and diatom species characteristic of the ecological zones of four tidal marshes in southern Oregon.<sup>1</sup>

Zone	Plants <sup>2</sup>			Foraminifera <sup>3</sup>			Diatoms		
	Silty Marshes	Sandy Marsh	Silty Marshes	Silty Marshes	Silty Marshes	Silty Marshes	Silty Marshes	Silty Marshes	Sandy Marsh
Mudflat	<i>Zostera nana</i> <i>Zostera marina</i>	<i>Zostera nana</i> <i>Zostera marina</i>	<i>Miliammina fusca</i> <i>Reophax nana</i> <i>Ammotium salsum</i>	<i>Achnanthes hauckiana</i> <i>Nitzschia inconspicua</i> <i>Navicula cryptocephala</i> <i>Paralia sulcata</i> <i>Cocconeis scutellum</i> <i>Navicula perminuta</i> <i>Cocconeis placentula</i>	<i>Achnanthes hauckiana</i> <i>Nitzschia inconspicua</i> <i>Paralia sulcata</i> <i>Navicula cryptocephala</i> <i>Cocconeis placentula</i>	<i>Achnanthes hauckiana</i> <i>Nitzschia inconspicua</i> <i>Paralia sulcata</i> <i>Navicula cryptocephala</i> <i>Cocconeis placentula</i>			
Low marsh	<i>Carex lynbyei</i> <i>Triglochin maritimum</i> <i>Salicornia virginica</i> <i>Distichlis spicata</i> <i>Deschampsia caespitosa</i> <i>Lilaeopsis occidentalis</i>	<i>Carex lynbyei</i> <i>Scirpus americanus</i> <i>Scirpus cernuus</i> <i>Ruppia maritima</i> <i>Eleocharis palustris</i> <i>Lilaeopsis occidentalis</i> <i>Distichlis spicata</i> <i>Triglochin maritimum</i>	<i>Miliammina fusca</i> <i>Trachammina macrescens</i> <i>forma macrescens</i> <i>Trachammina inflata</i> <i>Haplophragmoides</i> sp. <i>Ammotium salsum</i>	<i>Achnanthes inconspicua</i> <i>Achnanthes hauckiana</i> <i>Nitzschia tryblionella</i> <i>Navicula mutica</i> <i>Navicula cryptocephala</i> <i>Navicula perminuta</i> <i>Cocconeis scutellum</i> <i>Rhopalodia gibberula</i> <i>Paralia sulcata</i>	<i>Achnanthes hauckiana</i> <i>Nitzschia inconspicua</i> <i>Paralia sulcata</i> <i>Navicula cryptocephala</i> <i>Cocconeis placentula</i>				
High marsh	<i>Deschampsia caespitosa</i> <i>Carex lynbyei</i> <i>Distichlis spicata</i> <i>Triglochin maritimum</i> <i>Salicornia virginica</i> <i>Agrostis alba</i> <i>Potentilla pacifica</i>	<i>Scirpus cernuus</i> <i>Carex lynbyei</i> <i>Jaumea carnosa</i> <i>Potentilla pacifica</i> <i>Deschampsia caespitosa</i> <i>Agrostis alba</i> <i>Triglochin maritimum</i> <i>Distichlis spicata</i> <i>Glaux maritima</i>	<i>Trochammina macrescens</i> <i>forma macrescens</i> <i>Miliammina fusca</i> <i>Trachammina inflata</i> <i>Haplophragmoides</i> sp.	<i>Achnanthes hauckiana</i> <i>Nitzschia inconspicua</i> <i>Nitzschia tryblionella</i> <i>Navicula cryptocephala</i> <i>Navicula mutica</i> <i>Navicula pusilla</i> <i>Diploneis pseudovalis</i> <i>Rhopalodia gibberula</i> <i>Achnanthes lanceolata</i>	<i>Achnanthes hauckiana</i> <i>Rhopalodia gibberula</i> <i>Paralia sulcata</i> <i>Nitzschia inconspicua</i> <i>Navicula cryptocephala</i> <i>Navicula tryblionella</i> <i>Opephora martyii</i> <i>Diploneis pseudovalis</i>				

Table 1. Continued.

Zone	Plants <sup>1</sup>			Foraminifera <sup>2</sup>		Diatoms	
	Silty Marshes	Sandy Marsh	Silty Marshes	Silty Marshes	Silty Marshes	Sandy Marsh	
Marsh border subzone	<i>Agrostis alba</i> <i>Potentilla pacifica</i> <i>Carex lynbyei</i> <i>Deschampsia caespitosa</i> <i>Distichis spicata</i> <i>Atriplex patula</i>	<i>Potentilla pacifica</i> <i>Deschampsia caespitosa</i> <i>Agrostis alba</i> <i>Aster subspicatus</i> <i>Juncus effusus</i> <i>Oenante sarmentosa</i>	<i>Trochammina macrescens</i> <i>forma macrescens</i> <i>Trochammina inflata</i> <i>Haplophragmoides</i> sp.	<i>Navicula mutica</i> <i>Navicula pusilla</i> <i>Pinnularia borealis</i> <i>Nitzschia inconspicua</i> <i>Navicula cryptocephala</i> <i>Nitzschia tryblionella</i> <i>Achnanthes hauckiana</i> <i>Navicula cincta</i> <i>Diploneis ovalis</i> <i>Fragilaria pinnata</i>	<i>Achnanthes hauckiana</i> <i>Navicula mutica</i> <i>Navicula cryptocephala</i> <i>Nitzschia tryblionella</i> <i>Nitzschia inconspicua</i> <i>Cocconeis placentula</i> <i>Navicula pusilla</i> <i>Pinnularia borealis</i>		
Upland	<i>Picea sitchensis</i> <i>Alnus rubra</i> Many other plants and shrubs	<i>Picea sitchensis</i> <i>Alnus rubra</i> <i>Lysichitum americanum</i> <i>Oenante sarmentosa</i> <i>Rumex</i> sp. Many other plants and shrubs	No foraminifera	Very low concentration of diatoms ( <i>Navicula pusilla</i> <i>Navicula mutica</i> <i>Pinnularia borealis</i> )	Very low concentration of diatoms		

<sup>1</sup>Silty marshes are in South Inlet (Siuslaw River), Haynes Inlet (Coos Bay), and Bull Island (Coos River). Sandy marsh is near the mouth of the Coquille River. Most common or dominant species listed first

<sup>2</sup>Data for silty marshes partly from sources listed in Table 2 in JENNINGS and NELSON (1992)

<sup>3</sup>From JENNINGS and NELSON (1992)

compared with those in similar zones regionally and on other coasts. Note, however, that zone boundaries are more gradational than suggested by the vertical lines on Figure 4.

### Diatoms

Despite the wide use of diatom analysis in sea-level reconstructions (e.g., SATO *et al.*, 1983; KRZYWINSKI and STABELL, 1984; ERONEN *et al.*, 1987; PIENITZ *et al.*, 1991), the ecology of relatively few intertidal species is well understood. Studies of modern intertidal diatom floras have focused on their complex ecology rather than on the vertical zonation of assemblages within the intertidal zone (e.g., HENDEY, 1964; SULLIVAN, 1978; BAILLIE, 1987). Distinguishing allochthonous (transported) from autochthonous (living in place) diatom frustules remains a difficult problem in interpreting assemblages from intertidal environments. Most studies have assumed salinity to be the dominant control on assemblage composition in many coastal settings (PALMER and ABBOTT, 1986), and for this reason, many species have been classified, based on their apparent salinity preference, into marine (polyhalobian), brackish-water (mesohalobian), and freshwater (oligohalobian) groups (e.g., PATRICK and REIMER, 1966–1975; MCINTIRE and MOORE, 1977, Figure 11.2; IRELAND, 1987). More recent studies emphasize the primary importance of life form (planktonic, benthic, or epiphytic (attached to plants)) and substrate preference, as well as salinity preference, in the interpretation of diatom assemblages (e.g., WHITING and MCINTIRE, 1985; VOS and DE WOLF, 1988; KOSUGI, 1988). Temperature, illumination, nutrient supply, density and type (although not necessarily species) of macrophytes, adaptive strategy, substrate stability, and the duration and frequency of intertidal exposure are other important ecological factors.

Many of the factors that affect the distribution of diatom species in the intertidal zone are directly related to elevation, but because diatom assemblages result from complex ecological interactions among factors determining the role of any single factor in controlling the composition of an assemblage is difficult (MCINTIRE and MOORE, 1977). The duration of supratidal exposure strongly influences factors such as salinity, sediment temperature, illumination, and macrophyte communities in the intertidal zone. Thus, for example, the salt-tolerant, epiphyte *Cocconeis scutellum*, may help identify a specific elevational

range within the intertidal zone because the eelgrass it commonly lives on grows within this range. Substrate lithology is less directly influenced by elevation, but in many tidal inlets the percentage of sand increases in the lower intertidal zone where flow velocities next to tidal channels are greater than in the silty substrate of the marsh. Because many species have particular adaptive strategies that depend on both sediment lithology and stability (WHITING and MCINTIRE, 1985), where sediment lithology and tidal current strength vary with elevation, changes in assemblage compositions will be related to tide levels.

In the Pacific Northwest, detailed studies of modern diatom floras in the Yaquina estuary (Figure 1; MCINTIRE and OVERTON, 1971; RIZNYK, 1973; MCINTIRE, 1973; MAIN and MCINTIRE, 1974; AMSPOKER and MCINTIRE, 1978) and Netarts Bay (WHITING and MCINTIRE, 1985), and cursory study of samples from eight other estuaries in Oregon (unpublished observations cited in AMSPOKER and MCINTIRE, 1986, p. 397), indicate relatively well-defined and broadly distributed marine, brackish-water, and freshwater benthic diatom assemblages. The wide latitudinal distribution of the same common species suggests that assemblages should be good indicators of estuarine environments (WHITING and MCINTIRE, 1985). Preliminary studies of intertidal transects in southwest Washington by HEMPHILL-HALEY (1989) suggest that distinct diatom assemblages reflect several subenvironments within the intertidal zone.

The few studies of the vertical zonation of intertidal diatoms in Oregon have focused on epiphytic or epilithic (attached to rocks) species (e.g., CASTENHOLZ, 1963; MCINTIRE and OVERTON, 1971; MCINTIRE, 1973; MAIN and MCINTIRE, 1974; MOORE and MCINTIRE, 1977). The vertical zonation of epipelagic (unattached forms on silty sediment), endopelagic (unattached forms in silty sediment), and epipsammic (forms attached to sand grains) species is less well understood, partly because of the difficulties of separating individuals in samples of assemblages into these life form groups. Substrate lithology and stability have a stronger influence on assemblage composition than elevation at Netarts Bay (WHITING and MCINTIRE, 1985), but only four elevations were sampled at any one site. In the Yaquina estuary, MCINTIRE and OVERTON (1971) and MCINTIRE (1973) did not find strong patterns in the distribution of epipsammic and epipelagic diatoms along horizontal salinity and temperature gradients and

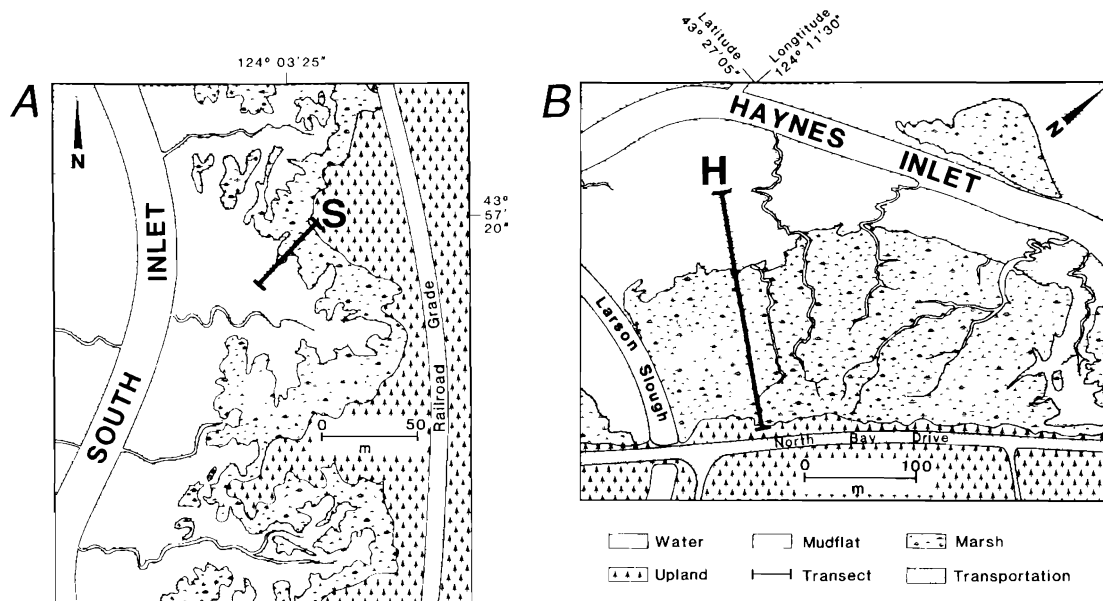


Figure 2. Detailed location maps for transects S (map A) and H (map B) showing areas of mudflat, marsh, and forested upland at low tide. Location of detailed maps in the Siuslaw River and Coos Bay estuaries is shown in Figure 1.

along vertical desiccation and isolation gradients. They concluded that the effects of such gradients on these types of floras were greatly modified by the chemical and physical properties of the sediment (McINTIRE and MOORE, 1977, p. 350). AMSPOKER and McINTIRE (1978) also demonstrated that the composition of sediment-associated assemblages was more closely related to sediment properties and a strong salinity gradient than to light, temperature, or the period of exposure.

## METHODS

### Sample Collection

A single transect from mudflat to forested upland was sampled for microfossils in each of four typical marshes in three estuaries in southern Oregon (Figures 1, 2, and 3). Foraminiferal and reconnaissance vascular plant studies of three of the four transects are described by JENNINGS and NELSON (1992). Samples containing 10–15 cm<sup>3</sup> of sediment were collected from the upper 10–15 mm of the marsh surface using a small, serrated corer. Subsamples of about 2 cm<sup>3</sup> were taken from each sample and about half of each subsample was prepared for diatom analysis.

Sample elevations on transects S, H, and B

(Figure 4A–C; JENNINGS and NELSON, 1992, their Table 1) were estimated by measuring the positions of three high tides; no leveling to distant benchmarks was attempted. Relative elevations between sample locations, measured with an alidade and rod, were reproducible within 2–3 cm and cumulative error along transects was probably <15 cm. Tide levels were estimated by averaging the height of high tide on each transect on three days of good weather and then using tide tables and nearby tidal datum data (NATIONAL OCEAN SERVICE, 1986; *written communication*, 1989) to estimate the positions of MTL (mean tide level), MHW (mean high water), and MHHW (mean higher high water) on each transect.

Tide levels on the Coquille River transect (C, Figure 4D) were estimated by reoccupying a transect originally surveyed by the NATIONAL OCEAN SURVEY (1978, their transect 1A). During this earlier study, a local tide gauge was installed near the transect to determine local MHW; other tide levels were estimated through third-order leveling to the tidal datum at Bandon, 2 km to the south. The NATIONAL OCEAN SURVEY (1978) estimated their standard error on the elevation of MHW on this transect at  $\pm 2$  cm. At our reference tidal datums in all three estuaries, MTL is 3–10 cm

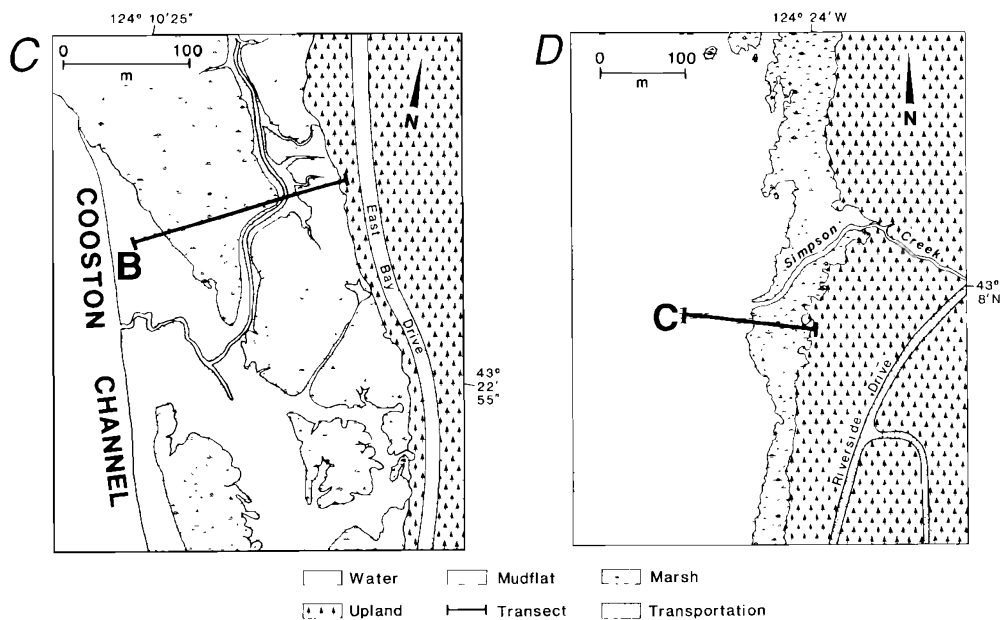


Figure 3. Detailed location maps for transects B (map C) and C (map D) showing areas of mudflat, marsh, and forested upland at low tide. Location of detailed maps in the Coos Bay and Coquille River estuaries is shown in Figure 1.

above the National Geodetic Vertical Datum of 1929. Distance between samples along all transects was measured by pacing (precision  $\pm 0.5$  m).

#### Diatom Analyses

Diatom samples were prepared (method in KASHIMA, 1986) by boiling 1–2 g of sediment in 15% hydrogen peroxide for 10 minutes to remove organic matter. Following washing in a centrifuge, a known volume of suspended sample solution was mounted on a slide with Pleulax.

One hundred individuals were identified in most prepared samples (upland samples contained <100 diatoms; Figure 4) with reference to HUSTEDT (1927–1930, 1931–1937, 1959, 1961–1964), CLEVE-EULER (1951–1955), HENDEY (1964), PATRICK and REIMER (1966–1975), and KRAMER and LANGE-BERTALOT (1986, 1988). A total of 62 species and 5 additional genera were identified in the 6,771 valves counted (Table 2). About 15% of the valves were only identified to genus level. Fragments consisting of more than half of a valve were included in the count. Concentration of diatom valves (valves/mg) was estimated by counting the number of valves in a known area of each slide. Species diversity was calculated using the

Shannon-Weaver index following GIBSON and BUZAN (1973). This index is not biased by rare or abundant species and, therefore, is particularly useful in describing intertidal assemblages that are dominated by a few species (e.g., KOIVO, 1976).

#### Interpretation of Diatom Assemblages

We follow ecologic studies such as MCINTIRE and MOORE (1977), KOSUGI (1987, 1988), and VOS and DE WOLF (1988), in our attempt to explain the distribution of diatom species in the mudflat, low marsh, high marsh, and upland zones of our Oregon transects. Salinity preference, substrate preference, pH preference, and life form (as tabulated in the above studies and VAN DER WERFF, 1960; PATRICK and REIMER, 1966–1975; MÖLDER and TYNNI, 1967–1973; TYNNI, 1979–1980; LORTIE, 1983; PALMER and ABBOTT, 1986; CULLINGFORD *et al.*, 1989; and PIENITZ *et al.*, 1991) are used to infer which species may be allochthonous and which are probably components of ecologic groups that accurately reflect environmental conditions along our transects. Very low-percentage species (<1% of sample) are likely to be allochthonous and are not used for interpretation. Many of the more common species in our assem-



Table 2. Diatom genera and species identified along four intertidal transects in southern Oregon.<sup>1</sup>

<i>Achnanthes brevipes</i>	<i>Gomphonema parvulum</i>	<i>Opephora martyii</i>
<b><i>Achnanthes hauckiana</i>*</b>	<i>Gomphonema</i> spp.	<b><i>Paralia sulcata</i>*</b>
<b><i>Achnanthes lanceolata</i>*</b>	<b><i>Gyrosigma</i> spp.</b>	<i>Pinnularia borealis</i> *
<i>Achnanthes linearis</i>	<i>Hantzschia amphioxys</i>	<i>Pinnularia mictostauron</i>
<b><i>Achnanthes minutissima</i></b>	<i>Mastogloia</i> spp.	<i>Pinnularia viridis</i>
<i>Achnanthes</i> spp.	<i>Melosira granulata</i>	<i>Pinnularia</i> spp.
<i>Amphora angusta</i> v.	<b><i>Melosira</i> spp.</b>	<i>Pleurosigma</i> spp.
<i>Amphora ovalis</i> v.	<i>Navicula cincta</i> *	<i>Rhaphoneis amphicerus</i>
<b><i>Amphora</i> spp.</b>	<i>Navicula contenta</i>	<i>Rhaphoneis surirella</i>
<i>Bacillaria paradoxa</i>	<b><i>Navicula cryptocephala</i>*</b>	<i>Rhoicosphenia curvata</i>
<i>Bidduluphia aurita</i>	<i>Navicula elginensis</i>	<b><i>Rhopalodia gibberula</i>*</b>
<i>Caloneis brevis</i>	<b><i>Navicula mutica</i>*</b>	<i>Stauroenlis phoenicentron</i>
<i>Caloneis</i> spp.	<i>Navicula peregrina</i>	<i>Surirella</i> spp.
<b><i>Cocconeis placentula</i>*</b>	<b><i>Navicula perminuta</i>*</b>	<i>Synedra pulchella</i>
<b><i>Cocconeis scutellum</i>*</b>	<b><i>Navicula pusilla</i>*</b>	<i>Synedra rumpens</i>
<i>Cocconeis</i> spp.	<i>Navicula pygmaea</i>	<b><i>Synedra tabulata</i>*</b>
<i>Cyclotella caspia</i>	<i>Navicula radiosia</i>	<i>Synedra ulna</i>
<i>Cyclotella styrolum</i>	<i>Navicula radiosia</i> v.	<i>Thalassionema nitzschioides</i>
<i>Cymbella cistula</i>	<i>Navicula salinarum</i>	<i>Thalassiosira bramapgrae</i>
<i>Cymbella minuta</i>	<b><i>Navicula</i> spp.</b>	<b><i>Thalassiosira</i> spp.</b>
<i>Diploneis ovalis</i>	<i>Nitzschia acuminatum</i> *	<i>Trachyneis aspera</i>
<i>Diploneis pseudovalis</i>	<i>Nitzschia granulata</i>	
<i>Diploneis smithii</i>	<b><i>Nitzschia inconspicua</i>*</b>	
<i>Diploneis</i> spp.	<i>Nitzschia littoralis</i>	
<i>Epithemia zebra</i>	<i>Nitzschia palea</i>	
<i>Eunotia</i> spp.	<i>Nitzschia parvula</i>	
<i>Fragilaria construens</i>	<i>Nitzschia punctata</i>	
<b><i>Fragilaria pinnata</i>*</b>	<b><i>Nitzschia tryblionella</i>*</b>	
<i>Frustulia rhomboides</i>	<b><i>Nitzschia</i> spp.</b>	

<sup>1</sup>Genera and species in bold make up 99% of the total identified valves in all samples. About 15% of all valves were only identified to genus level. Seventeen species make up 99% of the total 5,749 valves identified to species level (marked by asterisks). Only 15 of these 17 species were used in the discriminant analysis (Table 3). Except for low concentration samples, 100 valves were counted in each sample

blages are brackish-water species and most of these are thought to be relatively indifferent to salinity changes. Marine species include those typical of salinities of about 25–30‰, brackish-water species about 0.5–25‰, and freshwater species <0.5‰ (e.g., IRELAND, 1987, his Table 2.2).

Even allochthonous species, however, may be useful in paleoenvironmental interpretation because total fossil diatom assemblages should reflect conditions over a period of years (PALMER and ABBOTT, 1986). Significant percentages of planktonic or epiphytic species may characterize part of the intertidal zone even if the frustules of those species have been transported (e.g., HAGGART, 1988). Total (living + dead) foraminiferal assemblages in tidal marshes are more comparable to fossil assemblages and are less variable than living assemblages (SCOTT and MEDIOLI, 1980b); these arguments probably apply to an even greater extent to diatom assemblages where seasonal diatom blooms and other short-term factors (e.g., SULLIVAN, 1975) can markedly influence assemblages.

Post-depositional changes in diatom assemblages create other interpretive problems. The degree and depth of mixing by bioturbation of older and younger assemblages limit the resolution with which rapid changes in diatom assemblages in vertical sediment sequences can be identified. Although live diatoms have been found at depths of 10 cm in sandy sediment, epipelagic diatoms exhibit a vertical migration range of only a few millimeters (MCINTIRE and MOORE, 1977). Our samples of the total diatom assemblage from 0–1.5 cm depth are representative of the long-term (estimated at about 3–50 years) surface and shallow infaunal populations along our modern transects. However, selective fragmentation and dissolution of less resistant species, even in very young fossil samples, may hamper paleoecologic interpretation (SHERROD *et al.*, 1989).

#### RELATION OF DIATOM ASSEMBLAGES TO FLORAL ZONES

In this section, we summarize the characteristics of the four transect sites and then discuss

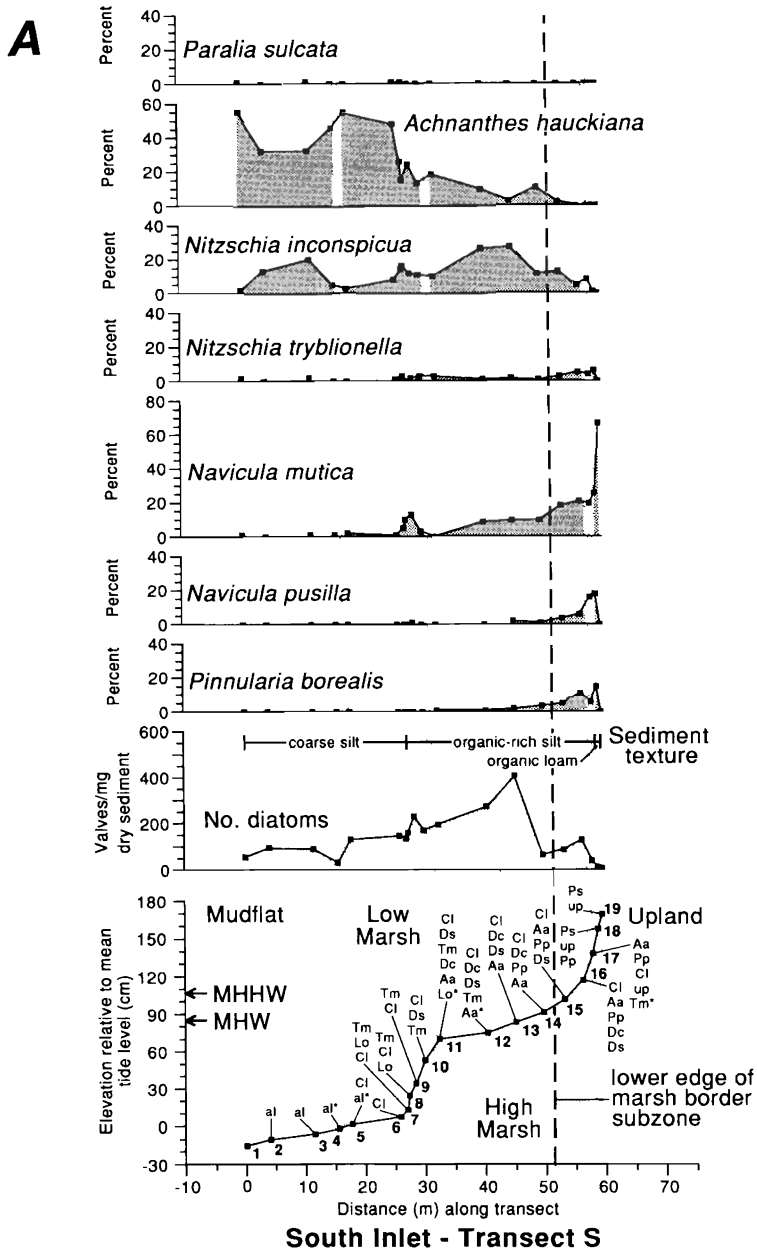
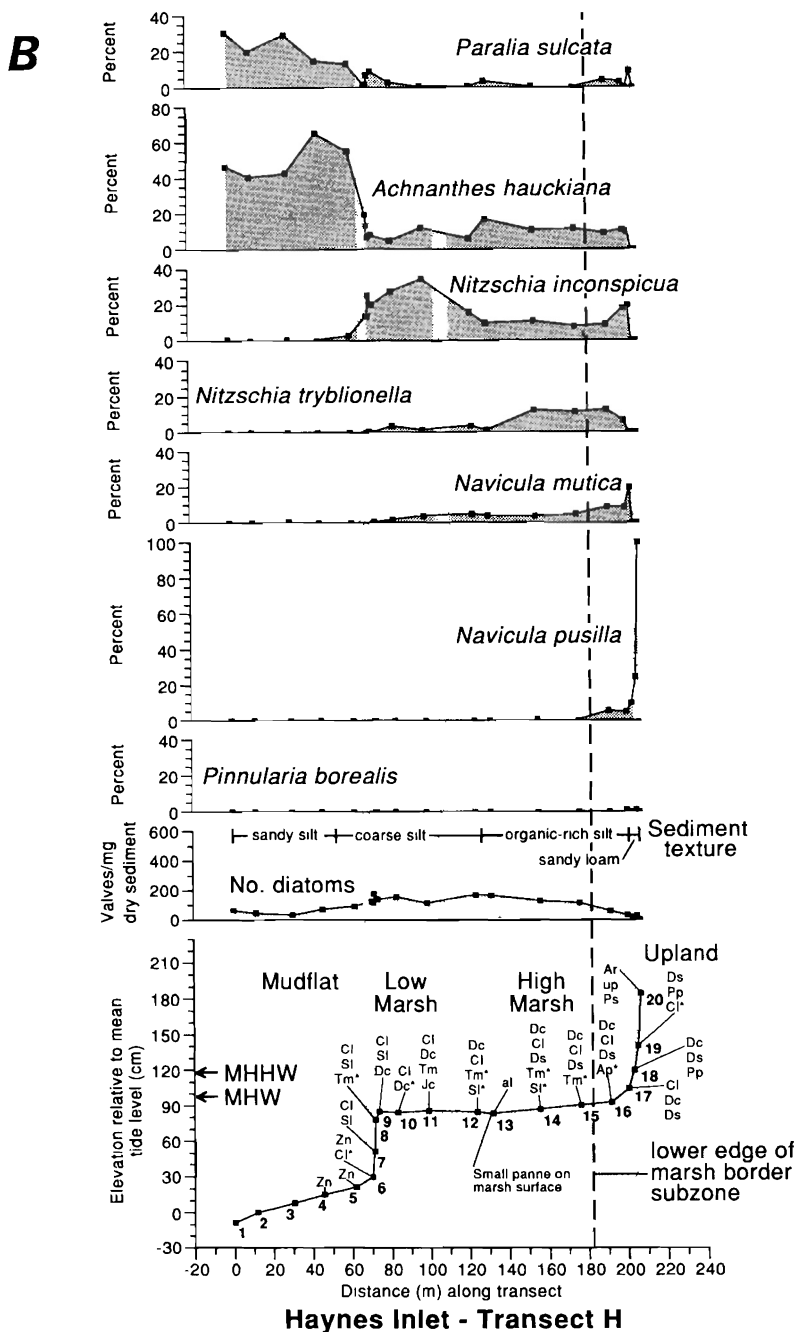
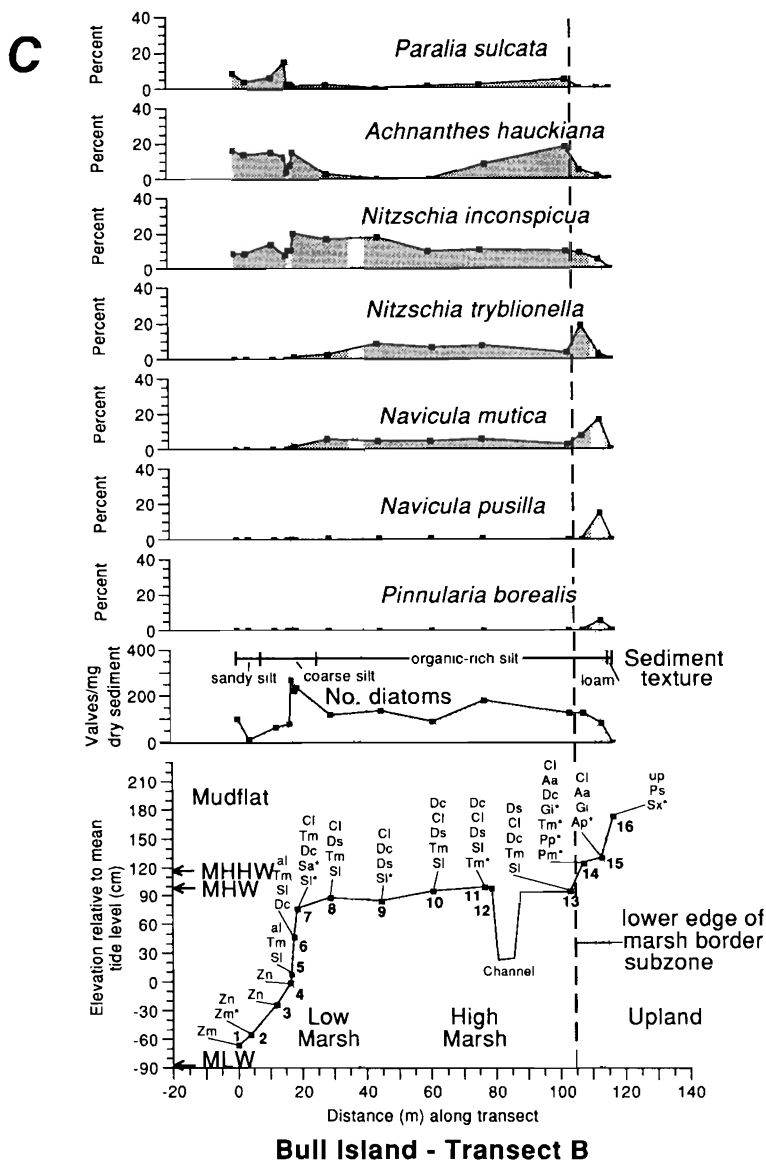


Figure 4. Elevation relative to estimated MTL, dominant vascular plant species at sample sites, total number of diatom valves/mg of dry sediment, and percentages of selected common diatom species for samples from transect S (A), transect H (B), transect B (C), and transect C (D). Sample numbers are in bold numerals. Relative areal cover (plant species covering the largest area at the top of the column) of common tidal marsh plant species shown by columns of letters as follows. Aa = *Agrostis alba*, Ap = *Atriplex patula*, Ar = *Alnus* sp., As = *Aster subspicatus*, Cl = *Carex lynbyei*, Dc = *Distichlis caespitosa*, Ds = *Distichlis spicata*, Gi = *Grindelia integrifolia*, Jb = *Juncus balticus*, Jc = *Jaumea carnosa*, La = *Lysichiton americanum*, Lo = *Lulaeopsis*



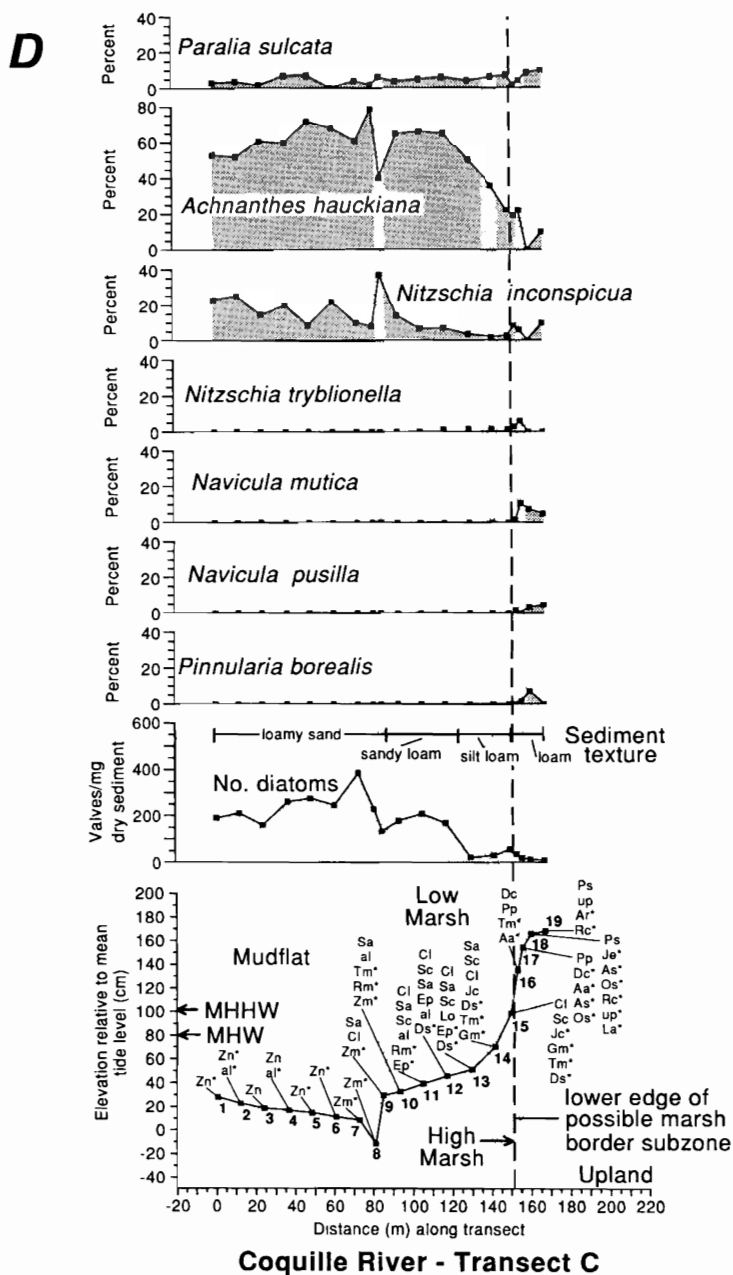
*occidentalis*, Pm = *Plantago maritima*, Pp = *Potentilla pacifica*, Ps = *Picea sitchensis*, Rm = *Ruppia maritima*, Sa = *Scirpus americanus*, Sc = *Scirpus cernuus*, Sl = *Salicornia virginica*, Sx = *Salix* sp., Tm = *Triglochin maritimum*, Zm = *Zostera marina*, Zn = *Zostera nana*, al = unidentified algae, up = unidentified upland plants.\* = < 10% cover. Sample 12 from transect B may not be representative of the high marsh (see text) and so diatom data for this sample are not shown on Figure 4C (complete diatom data available from the authors). Diatom concentrations in the 1–3 highest samples on each transect were low and only a few valves



were counted in some of these samples. Therefore, percentage data for these samples may be misleading. Elevations of tide levels on each transect estimated from the measured level of three high tides and nearby tidal datum data (see text). The approximate positions of gradational boundaries between floral zones (textured vertical lines) are estimated from the distribution of tidal marsh plants, following JEFFERSON (1975), EILERS (1975), and FRENKEL *et al.* (1978). Gradational boundaries between zones based on foraminiferal assemblages are similar to the plant-based boundaries (JENNINGS and NELSON, 1992). Changes in diatom assemblages

diatom species composition, diversity, and concentration (number of diatom valves/mg of dry sediment) in the three major vertical zones along each transect (Figure 4A–D; Table 1). We discuss

the diatom floras of the three silty-substrate transects (S, H, and B) together because the site characteristics and assemblages from these three transects are similar. The characteristics and



do not reflect a distinct boundary between the low and high marsh zones, but freshwater-tolerant species dominate the marsh border subzone near the upper border of the high marsh. The thin, dashed, vertical line shows the approximate lower boundary of the marsh border subzone. The high marsh on transect C is very narrow and a marsh border subzone is not well defined; the dashed line on Figure 4D separates samples that were assumed to be from a marsh border subzone in the discriminant function analysis from other high marsh samples.

assemblages of the Coquille River transect (C) differ from those of the other transects, and so we discuss this transect separately.

### Silty Marsh Transects

#### South Inlet-Siuslaw River (S), Haynes Inlet-Coos Bay (H), and Bull Island-Coos Bay (B)

**Setting.** The marshes of transects S, H, and B fringe steep, heavily forested slopes (Figures 1, 2, and 3; JENNINGS and NELSON, 1992). Transect S crosses a narrow marsh in a 200-m-wide inlet 9 km up the Siuslaw River from the ocean. Transects H and B cross wide, flat marshes bordering bays in the middle reaches of the Coos Bay estuary. Vertical scarps, 0.1–0.8 m high within or bordering the low marsh, are prominent features of these three transects. The transect B marsh (Figures 3 and 4C) differs from those of transects S and H in that the marsh borders a large channel of a major river, Coos River, with a drainage basin of 1,075 km<sup>2</sup>. Old maps (U.S. COAST SURVEY, 1863; U.S. COAST AND GEODETIC SURVEY, 1892; U.S. GEOLOGICAL SURVEY, 1900) show that the transect B marsh was about the same size 100–130 years ago, but that the transect H marsh has probably widened significantly through aggradation in the past 90 years.

Most of the 2 m of annual rain in the region falls between October and May. Thus, the ratio of river flow to tidal flow at the transect sites varies by more than two orders of magnitude from rainy to dry seasons (in the Siuslaw estuary by a factor of 500; UTT, 1974). Salinities near the transects rise during the summer, when the estuaries become well-mixed, then fall during periods of high runoff, when they become partially mixed or stratified (PERCY *et al.*, 1974). The measurements of UTT (1974) in the main channel of the Siuslaw River indicate that salinities near transect S are much lower than 30‰ for most of the year. At transects H and B, average salinities are closer to 30‰, probably similar to those in the middle reaches of Coos Bay.

Extreme storm tides and river floods also markedly alter salinities at the transect sites. Major floods that raise water levels several meters above normal spring water levels on the rivers in the region occur every 10–30 years (BEAULIEU and HUGHES, 1975). Large storms, such as those in 1977 and 1981, can also raise tide levels 1–2 meters above MHW. During such infrequent events, di-

atoms may be transported to elevations well above their normal intertidal ranges.

**Mudflat Zone.** Less than half of the 35–53 diatom species identified along each of the three silty transects were found in the mudflat zones of these transects. Species diversity on the mudflat of transect H was lower (1.3–1.9) than for the mudflat zones of transects S (2.0–2.5) and B (2.4–2.6). Diatom abundances are low on the mudflats of all three transects (<100 valves/mg, Figure 4A–C).

The most common diatom species (4–50% in most samples) on the mudflat are *Paralia sulcata*, *Achnanthes hauckiana*, and several benthic species, particularly *Nitzschia inconspicua*, *Navicula perminuta*, and *Navicula crytocephala* (Figure 4A). These are species typical of shallow brackish-marine and brackish estuarine environments. For example, *Navicula crytocephala* is a principal species of an ecologic group of diatoms characteristic of intertidal mudflats in The Netherlands (VOS and DE WOLF, 1988). However, both this species and *Nitzschia inconspicua* are particularly tolerant species also found in fresh-brackish water. *Achnanthes hauckiana* may have an affinity for sandy sediment in brackish water (*e.g.*, WHITING and MCINTIRE, 1985). *Paralia sulcata* is an equivocal indicator of marine water because it may be either epiphytic or planktonic, the latter especially in autumn (HAGGART, 1988; CULLINGFORD *et al.*, 1989). For this reason, this species may be an allochthonous component of our assemblages; however, the percentage of this species is highest at the most marine site with the least fluvial influence (H) and lowest at the most river-dominated site (S; Figure 4A and B). Mudflat samples of transect B (Figure 4C) differ chiefly from the mudflat samples of other silty-substrate transects in having lower percentages of *Achnanthes hauckiana*. A few percent of species typical of fresh-brackish environments, such as *Bacillaria paradoxa* and *Fragilaria pinnata*, suggest either some freshwater influence on the mudflat of transect S or that these species are allochthonous.

Other significant (>2%) diatoms of the mudflat assemblages include two epiphytic species of the genus *Cocconeis*: *C. placentula*, a fresh-brackish species with a very broad salinity tolerance, and *C. scutellum*, which is commonly found on eelgrass (*Zostera marina*) in the lower intertidal zone. The occurrence of these species with small percentages of *Synedra tabulata* (especially on tran-

sect B), another epiphyte characteristic of intertidal brackish lagoons, suggests *C. scutellum* and *C. placentula* are characteristic species of the intertidal mudflat environment and are not allochthonous.

Many other low-percentage species on the mudflat may be allochthonous. On transect B, *Thalassiosira* spp. (marine planktonic, 2–7%) are not brackish-water, intertidal species; they must have been transported.

**Low Marsh Zone.** In the low marsh, the percentages of *Paralia sulcata*, *Achnanthes hauckiana*, *Cocconeis scutellum* and some other salt-tolerant, brackish-water species decrease relative to their percentages on the mudflat, whereas the percentages of *Navicula perminuta* and *Navicula crytocephala* increase. *Nitzschia tryblionella*, *Navicula mutica*, *Rhopalodia giberula*, *Gyrosigma* spp., and *Surirella* spp. also make their first significant appearances in the low marsh zone (Figure 4A–C). *Navicula mutica* is an aerophilous (supratidal) species typical of salt marshes and wet soils, whereas *Nitzschia tryblionella* lives on the clayey sediment of intertidal or lower supratidal mudflats or in brackish lagoons (Vos and DE WOLF, 1988). Diatom concentrations are a bit higher in the low marsh zone (120–270 valves/mg) than on the mudflat, about the same as concentrations across most of the high marsh zone on transects H and B. Species diversity is similar to or slightly higher than in the mudflat zone (1.8–2.8). Thus, low marsh assemblages reflect a gradual change from the marine-influenced, brackish environment of the mudflat to a less brackish marsh environment more strongly influenced by fresh water through seepage from the adjacent upland and periods of high river and stream levels. However, especially along transects H and B, our limited number of low marsh samples and the abrupt scarp at the lower edge of the low marsh make it difficult to determine the degree to which our assemblages are representative of the low marsh zone.

**High Marsh Zone.** Assemblage changes in the upper parts of the high marsh zones of transects S, H, and B suggest that a narrow subzone (the marsh border subzone) can be distinguished in the upper part of the high marsh (Figure 4A–C). This subzone may extend into the lowest part of the upland floral zone. Across most of the high marsh, however, assemblages along the three transects are very similar to those of the low marsh zone.

In the lower and middle parts of the high marsh, most brackish-water species (e.g., *Achnanthes hauckiana*, *Cocconeis scutellum*, *Nitzschia inconspicua*) either do not change relative to percentages in the low marsh or they decrease (e.g., *Navicula perminuta*, *Navicula crytocephala*). The abundance of species tolerant of fresh water either increases (e.g., *Achnanthes lanceolata*, *Navicula mutica*) or stays the same (e.g., *Bacillaria paradoxa*, *Fragilaria pinnata*, *Rhopalodia giberula*). Two samples in the lower part of the high marsh on transect B have significant percentages (7–18%) of *Diploneis pseudovalis*, a species typically found in fresh-brackish intertidal environments. Except for a peak in the concentration of diatoms (400 valves/mg) in the middle of the high marsh on transect S, concentrations are similar throughout the high marsh (60–275 valves/mg). Species diversity values do not differ significantly either from those of the low marsh zone—20 of 21 samples have values between 2.4–2.9. Although the relative increase in freshwater-tolerant species (40–80%) is gradual across the high marsh, assemblages in the lower half of the high marsh are more like those in the low marsh than like those in the marsh border subzone. The similarity in diatom floras in the low marsh and lower and middle parts of the high marsh zone may be due to the fact that the higher half of the low marsh samples on transects H and B are at about the same elevation as samples from the high marsh zone and, therefore, would be expected to have a similar (high-marsh) flora (JENNINGS and NELSON, 1992).

Sample B-12, from the edge of a steep-walled channel 1.5-m-deep, has a high percentage of *Achnanthes hauckiana*, low percentages of *Nitzschia tryblionella* and *Navicula mutica*, and a concentration of only 50 valves/mg. Either the channel edge was eroded by tidal currents, or species characteristic of the muddy floor of the channel may have been deposited at this sample locality. Foraminiferal assemblages also suggest that sample B-12 may not be representative of the high marsh zone (JENNINGS and NELSON, 1992), and so we exclude this sample from our later quantitative analyses.

We use significant percentages of species that have low salinity tolerances to identify our marsh border subzone. This subzone encompasses much of the same elevational range as the transitional zone between the high marsh and the upland floral zones mapped by FRENKEL *et al.* (1978, 1981).

*Navicula mutica* is a major component of assemblages from this subzone, and *Navicula pusilla* and *Pinnularia borealis* are a significant part of the flora—percentages of the latter peak near the upper boundary of the subzone in the lowest part of the upland zone. Like *Navicula mutica*, *Navicula pusilla* and *Pinnularia borealis* are epipelagic, aerophilous species commonly found in wet soils, flood basins, and tidal marshes (*Hantzschia amphioxys* ecologic group of VOS and DE WOLF, 1988). Significant percentages of other species (e.g., *Frustulia rhomboides*, *Fragilaria pinnata*, *Nitzschia parvula*, and *Pinnularia mictostauron*) also suggest that freshwater dominates the environment of the marsh border subzone, but species very tolerant of a wide range in salinity, such as *Nitzschia inconspicua*, *Navicula cryptocephala*, *Diploneis ovalis*, *Navicula radiosa*, and *Navicula cincta*, are also common. The strong freshwater influence apparent in the marsh border subzone may be at least partly due to runoff and seepage from the steep, heavily forested hillsides at the upper ends of the three transects. Interestingly, *Paralia sulcata* and *Nitzschia tryblionella* also increase in abundance in the upper part of transect B, perhaps due to transport of frustules from lower intertidal or subtidal areas during spring or storm tides (e.g., CULLINGFORD *et al.*, 1989).

Diatom concentrations fall to low values (8–136) in the marsh border subzone and some of these samples (H-18 and H-19) have such low concentrations (8–10 valves/mg) that percentage data are not significant. Species diversity is similar to values in the high marsh, except for these low concentration samples.

**Upland Zone.** Diatom abundances fall dramatically in the upland zone (<10 valves/mg) and interpretations based on such small numbers of valves are questionable. However, because of the small number of samples in the marsh border subzone, we include one of these samples (S-18) in this subzone (Figures 4A and 6). The flora is dominated by species tolerant of freshwater: *Navicula mutica*, *Navicula pusilla*, and *Pinnularia borealis*. The few valves of brackish-water species were probably deposited during storm tides.

#### Sandy Marsh Transect

##### Bandon Marsh–Coquille River (C)

The transect C marsh (Figure 4D) differs from those of the other transects in several important ways. The marsh borders the Coquille River (Fig-

ures 1 and 3) only 2.2 km upriver from the sea. JEFFERSON (1975) classified this marsh as a low sand marsh with a fringe of mature high marsh bordering the upland. Our transect C is within 5 m of transect 1A of FRENKEL *et al.* (1978, p. 56; Figures 3 and 4A). The substrate of the mudflat and marsh is much sandier than along the other transects because coastal sand dunes form the west bank of the river opposite of and upwind of the marsh. Transect C also lacks a continuous scarp within the low marsh; the transect slopes gradually except where it steps up into a thick deposit of driftwood on the edge of a gently sloping forested upland. A small, 25-cm-deep channel intersects the transect at the west edge of the low marsh, but this marsh lacks the steep-walled channels developed in the other, silty-substrate marshes. At least the mudflat zone of this marsh appears to be prograding rapidly westward (JOHANNESSEN, 1961).

The proximity of the Coquille marsh to the sea suggests that the influence of marine water may be stronger during parts of the year than in the marshes of the other transects. However, the size of the Coquille River drainage basin (2,740 km<sup>2</sup>) relative to the cross-sectional area of the river mouth (625 m<sup>2</sup>) may indicate that lower salinities, more similar to those at transect S, are typical of most of the year. A small creek flows onto the tidal flat just north of our transect. FRENKEL *et al.* (1978) noted that extensive areas with the marsh plants *Scirpus americanus*, *Lilaeopsis occidentalis*, and *Scirpus cernuus* indicated much freshwater seepage into this marsh.

**Mudflat Zone.** Half the 41 species from this transect were found in the mudflat zone. In contrast to the silty-substrate transects, diatom concentration is higher on the mudflat (about 160–390 valves/mg) than along the rest of the transect (Figure 4D). Diversity ranged from 0.9 to 1.6. As in the other transects, the mudflat zone is dominated by *Achnanthes hauckiana*; *Nitzschia inconspicua* is the other major component of the flora. Low but uniform numbers of *Paralia sulcata* along the entire transect may reflect the proximity of the transect to the open ocean, or as discussed above, this species may be allochthonous. The benthic species *Navicula cryptocephala* and the epiphyte *Cocconeis placentula*, both typical of intertidal mudflats, also occur along this part of the transect; they are the only other species represented by more than a few valves in each sample.



**Low Marsh Zone.** The low marsh assemblages of transect C are notable in being indistinguishable from the mudflat assemblages. Not only are percentages of species similar in both zones, but percentages from sample to sample within both the mudflat and low marsh are less variable than along the other transects. Only in the uppermost part of the low marsh, where the substrate becomes less sandy and diatom concentrations drop, do the percentages of *Achnanthes hauckiana* and *Nitzschia inconspicua* decrease slightly. Species diversity in the low marsh is lower than in the equivalent zones on the silty transects (1.3–1.5), except for the highest sample (2.1). The environment along most of this transect seems uniform; the gradational mudflat-low marsh boundary based on plant distribution is not reflected in the distribution of diatoms.

**High Marsh Zone.** The high marsh zone of this transect is narrow (18 m wide), and the four samples from this zone span a large elevational range (0.84 m). Because sample concentrations are very low, about 20–60 valves/mg, it is difficult to characterize high marsh assemblages at this site. These samples appear similar to the high marsh samples from the other transects in that the abundance of *Achnanthes hauckiana* is low relative to abundances in the low marsh, the percentage of *Nitzschia inconspicua* is about the same as in the low marsh, and the freshwater-tolerant species *Nitzschia tryblionella*, *Navicula mutica*, *Rhopalodia gibberula*, and *Navicula cryptocephala* increase slightly in abundance across the high marsh. Some of the common freshwater-tolerant species on the other transects are missing, but a strong freshwater influence is indicated by the shallow-water epiphyte, *Opephora martyii*. If a marsh border subzone is present in this high marsh, its lower boundary probably falls between samples C-15 and C-16 (Figure 4D). Species diversity in the high marsh (2.5–2.8) is similar to values for high marshes on the other transects.

**Upland Zone.** The two upland samples have extremely low concentrations (about 10 valves/mg) consisting of mostly freshwater-tolerant species (e.g., *Navicula mutica*, *Pinnularia borealis*, *Navicula pusilla*, *Navicula radiosa*, *Navicula contenta*, *Eunotia* spp., and *Cocconeis placentula*), some of which were not found along the other transects (e.g., *Hantzschia amphioxys*). However, a few percent of brackish-water forms, such as three species of *Achnanthes*, *Cycotella caspia*, *Nitzschia acuminatum*, and significant percent-

ages of *Paralia sulcata* (the highest percentages on this transect) suggest that these upland samples may be comparable to the marsh-border zone samples on some of the other transects.

#### QUANTITATIVE ANALYSIS OF ASSEMBLAGE ZONES

Figure 4A–D shows that assemblages of selected diatom species distinguish the marsh (high and low zones) from the mudflat and upland zones, except on transect C where the low marsh and mudflat assemblages are very similar. The presence of separate low marsh and high marsh zones (generally identifiable from plant and foraminiferal distributions) and the presence of a marsh border subzone (indicated by the dominance of freshwater-tolerant diatoms) are less clear. We used two methods to quantitatively confirm the presence of the assemblage zones: gradient analysis using a similarity index and discriminant function analysis.

The SIMI similarity index proposed by STANDER (1970) and described by MCINTIRE and MOORE (1977, p. 358) helped us determine if diatom percentage data could be used to group the samples into distinct vertical zones that generally correspond to the main floral zones along the transects. In Oregon, the index has been used to study the relations between diatom assemblages and intertidal variables (exposure and salinity) by MCINTIRE and OVERTON (1971) and MAIN and MCINTIRE (1974). We did not include a number of identified taxa in most of our quantitative analyses because many are represented by only a few valves in any one sample (Table 2). Although *Paralia sulcata* and *Cocconeis scutellum* may be allochthonous, we included these species in our analyses because they are characteristic species of specific intertidal zones. We calculated the index for each sample along each of the four transects using (1) percentage data for the entire identified assemblages, and (2) percentage data for the 17 most abundant species (Table 2). With both of the two data sets, the largest changes in the value of the index along the transects usually occurred near (at or within 1 sample of) the floral zone boundaries. However, in most cases all changes in the index were small indicating that the zone boundaries along most transects are gradational. We found larger index changes along most transects with the entire data set than with the 17-species set. Perhaps counts of 200–300 valves/sample, which would allow including more

Table 3. Results of discriminant function analysis of diatom assemblages in intertidal ecologic zones.<sup>1</sup>

Analysis No.	No. of Transects Analyzed	Total No. (and no. of misclassified) Samples in Each Zone <sup>2</sup>				
		Mudflat	Low marsh	High marsh	Marsh border	Upland
1	4	21 (3)	21 (7)	26 (2)	hm	6 (1)
2 <sup>3</sup>	4	21 (2)	21 (5)	24 (2)	hm	na
3	3	13 (0)	16 (0)	20 (2)	hm	na
4 <sup>4</sup>	4	na	na	16 (1)	12 (0)	na
5	3	na	na	13 (0)	9 (0)	na

<sup>1</sup>Variables in all discriminant function analyses (method of SYSTAT, INC., 1989) included all but two of the 17 most common species (Table 2) and the number of valves/mg of sediment. Percentage data for *Cocconeis placentula* and *Synedra tabulata* did not appear to be normally distributed and so these two species were not used in the analyses (discriminant analysis requires normally distributed variables). Group (zone) classification in all samples along the four transects is based on plant distributions as shown in Figure 4A-D

<sup>2</sup>Number of samples misclassified into adjacent zones shown in parentheses. hm, samples in this subzone grouped with other high marsh samples for this analysis; na, samples in this zone not included in analysis

<sup>3</sup>Samples with <20 valves/mg (S-19, H-18, H-19, H-20, B-2, B-16, C-18, C-19) not included in analysis

<sup>4</sup>Samples with significant percentages of freshwater-tolerant species from near the upper edge of the marsh (S-15, S-16, S-17, S-18, H-17, H-18, H-19, B-14, B-15, C-18, C-19) are grouped into the marsh border subzone

species in the analysis, would result in larger changes in index values along the transects. The low marsh-high marsh boundary was the least distinct boundary: in two transects the 17-species analysis showed a more distinct boundary within the high marsh than on its lower edge, suggesting a separate subzone in the upper part of the high marsh. Thus, the diatom similarity indices generally show a three-fold zonation (mudflat, marsh, upland), but they do not support a major zone boundary within the marsh.

Discriminant function analysis allowed us to explore the extent to which the assemblages in low marsh samples are distinct from assemblages in mudflat and high marsh samples, and whether a marsh border subzone could be recognized at the upper edge of the high marsh. This procedure produces linear combinations of independent variables that best classify samples into previously determined groups (McINTIRE and MOORE, 1977; DAVIS, 1983).

We did five separate discriminant analyses using the SYSTAT statistical package (Table 3). In the first analysis, discrimination among the four zones on all four transects was not distinct; the best results were obtained with the high marsh samples where only two of 26 samples were classified into the wrong zone. Discrimination of the low marsh samples from mudflat and high marsh samples improved when low concentration samples were not included (analysis 2, Table 3), but 5 of 21 low marsh samples were grouped in the mudflat zone and two mudflat samples were grouped in the low marsh zone.

The vascular plant and diatom floras of the Coquille River marsh (transect C) differ significantly from those of the silty marshes, and so, in the third analysis we analyzed only samples from transects S, H, and B. Discrimination of the three zones markedly improved in this analysis. Two high marsh samples were grouped in the low marsh, but all other samples were correctly classified (Table 3; Figure 5). The close proximity of the three sample clusters on Figure 5 indicates gradational zone boundaries in these three marshes.

Both the fourth and fifth analyses indicate that diatom assemblages in samples from the marsh border subzone are distinct from samples in the lower parts of the high marsh. In the fourth analysis (all transects), only one high marsh sample was misclassified. In the fifth analysis (transects S, H, and B), no samples were misclassified.

Thus, the results of our discriminant function analysis confirm both our qualitative assessment of the percentage diagrams of selected species (Figure 4) and the results of the gradient analysis using the similarity index.

#### COMPARISON OF MARSH ZONATION USING PLANT, FORAMINIFERA, AND DIATOM ASSEMBLAGES

Assemblages of three different types of organisms (vascular plants, foraminifera, and diatoms) suggest a similar three- or four-part vertical ecologic zonation along four intertidal transects in southern Oregon (Figure 4A-D). Gradual changes in the compositions of all three types of assemblages show that zone boundaries are very gra-

dational and not necessarily coincident among each of the three types of assemblages. Discriminant analysis indicates that the mudflat, low marsh, and high marsh zones can be objectively distinguished with either foraminiferal (JENNINGS and NELSON, 1992) or diatom assemblage data, where salinity and substrate characteristics are similar (the three silty transects). Even in similar settings, however, low marsh diatom floras are not always distinguishable from those of the lower and middle part of the high marsh. JENNINGS and NELSON (1992) suggested that foraminiferal assemblages might be used to divide the low marsh into two subzones, but the small number of low marsh samples and the steep scarp in the low marsh of the three silty transects obscures the relations between both types of microfossil assemblages and elevation.

Differences between the composition of vascular plant and diatom assemblages on the Coquille River transect (Figure 4D) and those on the silty transects suggest that differences between the Coquille site and the other sites in substrate lithology and other factors are at least as important as tide levels in determining the character of plant and diatom assemblages. The Coquille transect is located at a less protected site with a much sandier, probably less stable substrate than the sites of the silty transects. The Coquille site is also much closer to the sea than the other transect sites, but no measurements are available to determine whether salinities are higher at this site during most of the year than at the other sites.

Vascular plant communities along the Coquille transect show a mudflat, low marsh, high marsh, upland zonation, but the diatom assemblages do not differ between mudflat and low marsh zones. The four high marsh sample assemblages from the Coquille transect are similar to those from the high marsh zones on the other transects, but some dominant and characteristic species on the other transects are not found. High marsh diatom assemblages in fossil samples from sites similar to the Coquille site, especially those deposited near the upper edge of the high marsh, could probably be distinguished from mudflat samples, but no more than a two-part diatom zonation of the intertidal zone (mudflat, marsh) can be justified at this site.

On the three silty transects in the middle parts of the Siuslaw and Coos Bay estuaries, low- and high-marsh vascular plant, foraminiferal, and diatom assemblages are less distinct from each other

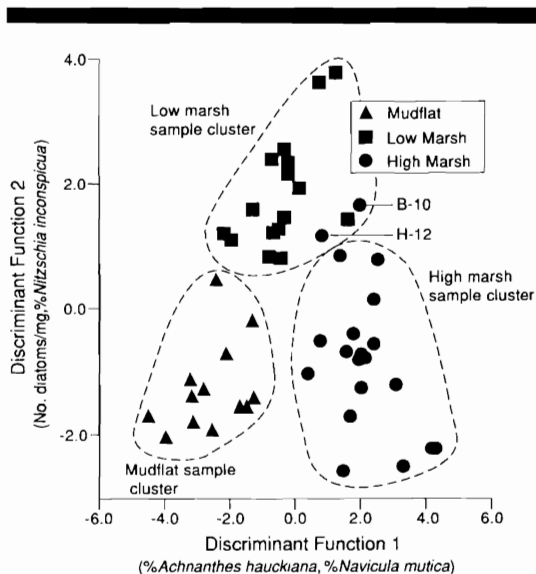


Figure 5. Plot of first and second discriminant function scores in the third discriminant function analysis of 49 transect samples from mudflat, low marsh, and high marsh zones in the three transects (S, H, and B) across silty, brackish-water marshes (Table 3). Variables listed on each discriminant function axis are those variables that most strongly correlate with that function. Hand-drawn dashed lines enclose clusters of samples classified by the analysis into mudflat, low marsh, and high marsh groups. The samples in the low marsh cluster are separated from samples in the high marsh and mudflat clusters by discriminant function 2, whereas discriminant function 1 distinguishes high marsh from mudflat samples. Only two high marsh samples near the boundary between the low marsh and high marsh sample clusters (H-12 and B-10) were misclassified in this analysis, but the proximity of the three sample clusters shows that boundaries between assemblage zones are gradual.

er than from adjacent upland and mudflat assemblages. Diatom assemblages, in particular, may be less useful than foraminiferal or plant assemblages in distinguishing low marsh samples from high marsh samples, at least in the middle reaches of southern Oregon estuaries. Regional studies of tidal marsh plant distribution (JEFFERSON, 1975; FRENKEL *et al.*, 1978) and our discriminant function analyses generally support the division of Oregon tidal marshes into low and high marsh ecologic zones. However, other more detailed zonations based on local site factors (*e.g.*, substrate lithology, wave exposure, position relative to tidal and stream channels or driftwood accumulations) may be equally valid at many sites.

Limited data (12 samples on 4 transects, 5 with low concentrations) from the upper parts of our

four transects suggest that diatom assemblages in the upper part of the high marsh and lowest part of the upland (the marsh border subzone) are more distinct from assemblages in lower samples from the high marsh than are either vascular plant or foraminiferal assemblages. Discriminant function analysis shows that the marsh border subzone is particularly distinct on the three silty transects (Table 3). Because the lower boundary of the marsh border subzone is between MHW and MHHW, this subzone may correspond with some mature high-marsh floral zones in other areas (e.g., FREY and BASAN, 1985). FRENKEL *et al.* (1978, 1981) used the presence of tidal marsh plant species such as *Potentilla pacifica* and *Aster subspicatus*, decreases in the abundance of *Juncus balticus*, *Deschampsia caespitosa*, and *Agrostis alba*, and increases in upland plant species to define a transitional ecotone between the high marsh and the upland zones in southern Oregon. Our marsh border subzone encompasses more of the high marsh and less of the upland than the transitional zone of these authors. The rather marked change in diatom assemblages at the lower edge of our subzone, however, may have more to do with seepage and runoff from the steep hillsides at the upper ends of our transects than to changes in environmental factors directly related to tide levels. Regardless of its origin, identification of the marsh border diatom subzone may be valuable in paleosea-level studies (at least in southern Oregon) because its lower boundary seems more sharply defined than other zone boundaries and is close to MHW (discussed below).

#### DIATOM ASSEMBLAGE ZONES AS INDICATORS OF SEA-LEVEL CHANGES

Although intertidal diatom floras show potential for the precise reconstruction of small-scale sea-level changes (PALMER and ABBOTT, 1986), few studies have successfully used diatom assemblages to divide the intertidal zone into more than two vertical ecologic zones (marsh and tidal flat). Studies such as KOSUGI (1988) and VOS and DE WOLF (1988) relate some ecologic groups of diatoms to, for example, salt marsh, lower intertidal, or supratidal environments, but the relation of the subenvironments preferred by specific ecologic groups to tide levels is not a focus of these studies.

In contrast, students of foraminiferal assemblages in the intertidal zones of many coasts have

sought to identify narrow assemblage zones with a defined elevational relation to sea level (MTL in this study) to use in the interpretation of fossil assemblages from cores and outcrops (SCOTT and MEDIOLI, 1986; SCOTT and LECKIE, 1990; THOMAS and VAREKAMP, 1991; JENNINGS and NELSON, 1992). Where vertical range can be determined for each assemblage zone, limits can be set on the size of changes in paleosea levels that can be identified from fossil assemblage changes in the subsurface. In such studies, the precision of estimating the size of sea-level changes is limited chiefly by the vertical range of locally determined assemblage zones (JENNINGS and NELSON, 1992). For this reason, studies of fossil foraminiferal faunas in Maritime Canada and New England are especially valuable in sea-level studies because the vertical ranges of the high-marsh assemblage zones are small (10–30 cm; e.g., SCOTT and LECKIE, 1990).

The large vertical ranges of the ecologic zones defined by floral, foraminiferal, and diatom assemblage data in our southern Oregon transects (>0.6 m, Figure 6) limit the precision with which the amount of submergence can be estimated from fossil assemblage data. JENNINGS and NELSON (1992) found that the vertical ranges of foraminiferal zones in Oregon and British Columbia are larger than equivalent zones in Maritime Canada and New England. On our southern Oregon transects, low and high marsh diatom assemblages are not distinct; the vertical range of the combined (low and high) marsh zone is about 1.1–1.5 m. Diatom assemblages of the marsh border subzone are distinct from those of the marsh and mudflat zones on the silty transects, but the vertical range of the marsh border zone is also large (about 0.7 m) and its range may vary considerably at different sites depending on the amount of freshwater seepage and runoff into the marsh. Unfortunately, our few samples do not clearly define the upper boundary of this subzone.

Only minimum changes in relative sea level can be estimated from changes to or from upland or mudflat sediments in stratigraphic sequences because the elevations of the upper boundary of the upland zone and lower boundary of the mudflat zone are undefined. Because of the large ranges of the combined marsh zone and marsh border subzone on our four transects (Figure 6), an upward stratigraphic change from a marsh border assemblage to a low or middle marsh assemblage in a core or outcrop could indicate as much as 1.7 m of submergence or as little as 0.7 m. Few sudden

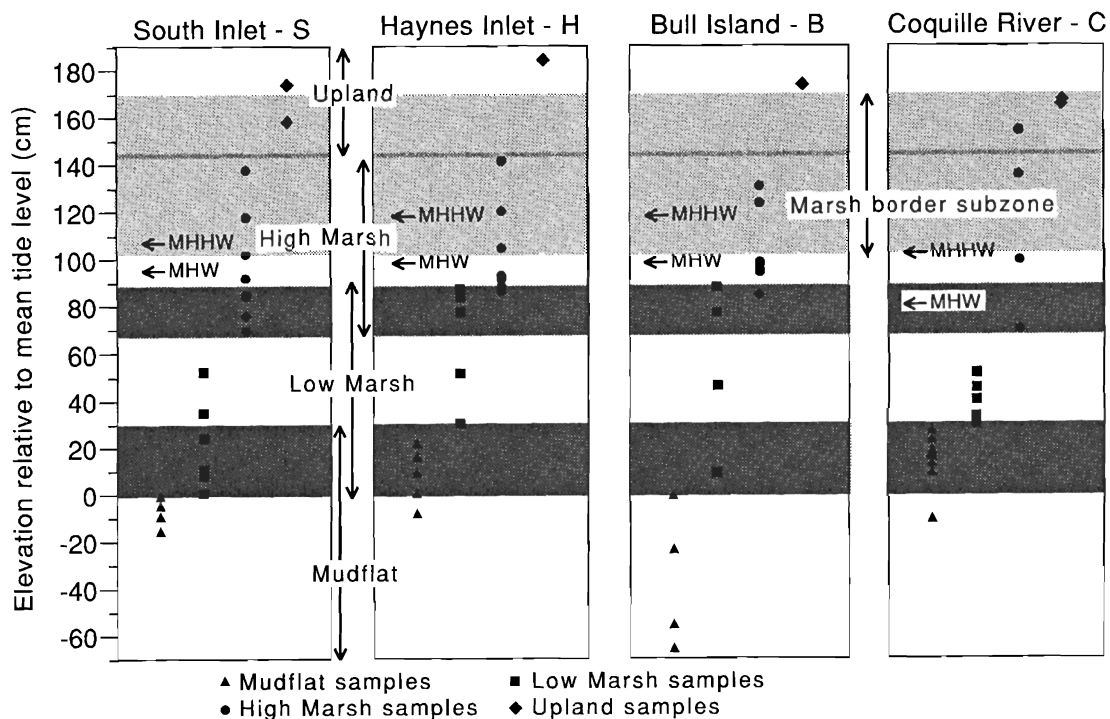


Figure 6. Elevation of transect samples in each floral zone. MTL at each transect estimated from the measured level of at least three high tides, nearby (1–4 km) tidal datum data (NATIONAL OCEAN SERVICE, *written communication*, 1989), and tide tables (NATIONAL OCEAN SERVICE, 1986). MHW on transect C was measured with a portable tide gauge. MHHW and MHW at each site are marked on the left side of each column (Figure 4A–D). Dark shaded bands show the vertical range of the boundaries between zones on the four transects. Ranges are large where samples from adjacent zones overlap. However, the ranges shown are minimum values because the elevation of zone boundaries in different marshes within and among Oregon estuaries varies depending on how many environmental factors affect marsh development. There is no overlap between the upland and high marsh zones, but our marsh border diatom subzone (light shaded band) encompasses samples from the upper part of the high marsh and lowest part of the upland zones.

submergence events resulting from coseismic tectonic subsidence have exceeded 2 m (*e.g.*, PLAFKER, 1972) and, therefore, this value is probably an upper limit for sudden submergence events along the southern Oregon coast.

A further limitation in using foraminiferal or diatom assemblage zones to reconstruct sea-level changes is that the vertical range of assemblage zones and the relations of their boundaries to tide levels differ from site to site depending on many marsh development and ecologic factors (*e.g.*, SCOTT and MEDIOLI, 1980a; FRENKEL *et al.*, 1981; SCOTT and LECKIE, 1990). Even our limited number of samples shows that the vertical ranges and elevations of our zone boundaries differ by 0.2–0.3 m from one transect to another (Figure 6).

However, the elevational ranges of high marsh vegetation zones in estuaries along the Oregon coast probably differ from these values by at least a few decimeters; some zone boundary elevations (relative to MSL) in different marshes may differ by 0.50–0.7 m (*e.g.*, FRENKEL *et al.*, 1981). Some of the differences in boundary elevations on our transects may also result from errors in estimating the position of MTL without the benefit of locally installed tide gauges.

Our reconnaissance study of four intertidal transects suggests there may be less potential for using diatom assemblages to identify the sediments of former low and high marsh environments than with foraminiferal assemblages. Diagenesis, however, may limit the use of both

foraminiferal and diatom assemblages in the paleoecologic interpretation of sediments >1,000 years old (SHERROD *et al.*, 1989; MANHART, 1992). However, the lower boundary of the marsh-border diatom subzone may be a good indicator of MHW in the marsh stratigraphic sequences in the middle reaches of Oregon estuaries. This boundary is about 0.1 m above MHW on transects S and B, and about 0.06 m below MHW on transect H; it may therefore be a more precise sea-level indicator (perhaps indicating MHW to within  $\pm 0.2$  m) than the more gradational boundaries of the foraminiferal and other diatom zones. Other subzones within the high or low marsh, equivalent to those identified on the east coast of North America, are not well defined in Oregon. More extensive intertidal microfossil studies in the Pacific Northwest are needed to better define the vertical extent of the marsh border subzone and to show whether other subzones with narrower vertical ranges can be widely recognized.

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