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EPISODIC TECTONIC SUBSIDENCE OF LATE HOLOCENE SALT MARSHES, NORTHERN OREGON CENTRAL CASCADIA MARGIN

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Abstract. Salt marsh subsurface deposits (0-4 m depth) in Netarts Bay, a small coastal lagoon of northern Oregon, record six events of marsh burial in the last several thousand years. Five of the buried marsh surfaces show sharp, nonerosional upper contacts with either anomalous sand layers (tsunami deposits) or tidal flat mud deposits. These sequences indicate episodic, abrupt subsidence of the marsh surfaces to low intertidal levels. In contrast, lower marsh contacts with underlying intertidal muds are gradational, indicating gradual uplift and development of the marsh. Three independent measures of deposit elevation relative to mean tidal level (percent organics, diatom assemblages, and percent eolian sand) have been used to estimate vertical displacements of marsh surfaces. Abrupt subsidence displacements of 1-1.5 m alternate with gradual uplift displacements of the order of 0.5-1.0 m. The vertical tectonic movements are interpreted to reflect coseismic strain release (abrupt subsidence) following interseismic strain accumulation (gradual uplift), associated with interplate coupling between the Juan de Fuca Plate and the North American plate in the Cascadia subduction zone. Recurrence intervals between subsidence events range from possibly less than 300 years to at least 1000 years, with the last dated event likely occurring 300-400 radiocarbon years before present (RCYBP). Significant ^{14}C age overlaps of at least four subsidence events recorded at Netarts and reported for southern Washington and other northern Oregon bays (at 300-500, 1000-1300, 1400-1800, and 3000-3300 RCYBP) suggest the potential for event synchroneity over at least 200 km of the central part of the Cascadia subduction zone. Additional work is needed to test the synchroneity of these episodic events of coseismic subsidence.

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INTRODUCTION

The Oregon continental margin extends along 450 km of the central part of the Cascadia subduction zone. However, this segment, along with the Northern California, Washington, and British Columbia segments, has not experienced a substantial subduction zone earthquake in historical time (Figure 1). The absence of large thrust earthquakes has been attributed to terminated subduction or to aseismic subduction associated with a shallow angle of subduction, excessive sediment lubrication or malleability of the young, subducting Juan de Fuca plate [Ando and Balazs, 1979; Acharya, 1981]. However, the historical record (<200 years) might be too short to rule out coseismic subduction processes [Heaton and Kanamori, 1984; Heaton and Hartzell, 1986]. Studies of relative plate motion and of recent oceanic plate seismicity indicate an oblique subduction and north-south compression of the southern Juan de Fuca plate, in accord with the northward migration of the Mendocino triple junction [Riddihough, 1984; Kelsey and Carver, 1988; Spence, 1989]. Yet Pliocene-Pleistocene imbricate thrusts and shelf fold and fault belts that dominantly trend north-south off the Oregon coast demonstrate a significant component of east-west convergent strain [Kulm and Fowler, 1974; Clarke et al., 1985]. Recent studies of deep, small-scale seismicity along the northern Cascadia

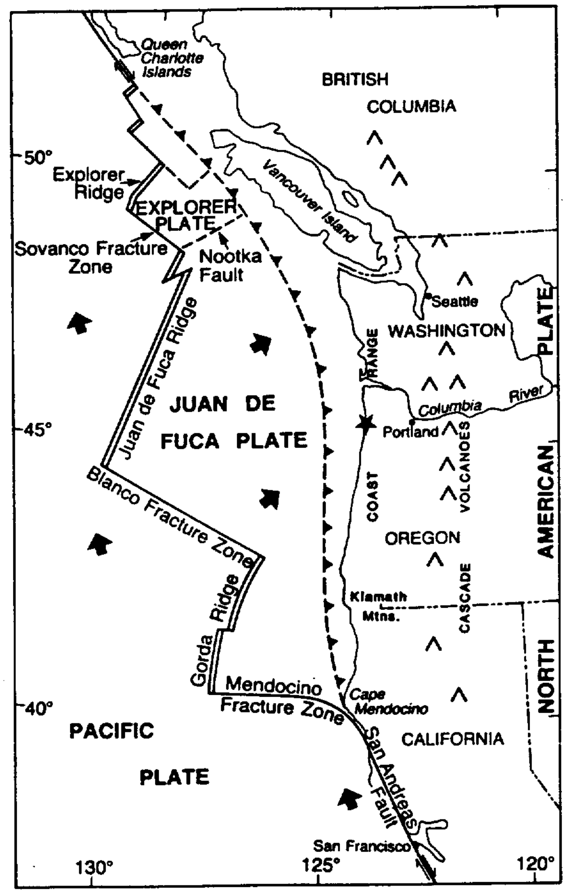


Fig. 1. Tectonic map of the Cascadia Margin. Star marks the study site. The approximate location of the trench axis, marking the boundary between the North American plate and the subducting Juan de Fuca Plate, is shown by a thrust boundary (dashed line).

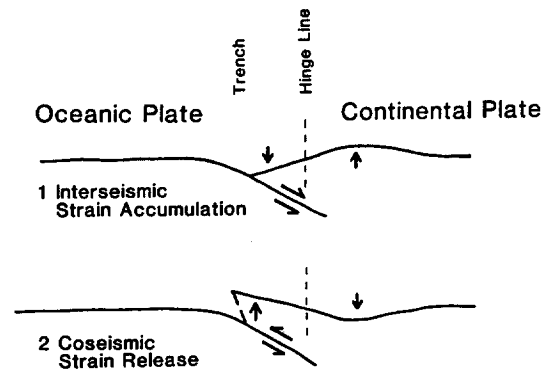


Fig. 2. Diagram of vertical coastal tectonics associated with (1) coupled strain accumulation and (2) coseismic shear dislocation between a subducting oceanic plate and an overriding continental plate [after Ando and Balazs, 1979].

margin, north of 46° latitude, indicate tensional forces associated with trench normal subduction of the northern Juan de Fuca plate [Taber and Smith, 1985; Weaver and Baker, 1988].

One test of active subduction tectonics in the Cascadia margin would be the evidence of cyclic uplift and abrupt subsidence of coastal areas. Such vertical tectonics are forced by the alternation of interseismic coupling (strain accumulation) and coseismic shear dislocation (strain release) of the subducting oceanic plate and overlying continental plate [Fitch and Scholtz, 1971]. When the subducting plate and overlying continental plate are coupled, the leading edge of the continental plate is dragged downward, producing an associated uplift on the opposite (landward) side of a flexure hinge line (Figure 2). When interseismic stresses overcome the frictional coupling, the coseismic strain release results in abrupt tectonic uplift (seaward of the hinge line) and corresponding abrupt subsidence (landward of the hinge line). Significantly, such abrupt vertical displacements of the sea floor produce large tsunamis [Heaton and Hartzell, 1986]. The alternation of coastal uplift and abrupt coastal subsidence together with tsunami deposition provides a potentially unique record of interplate paleoseismicity in strongly coupled subduction zones.

Such events of abrupt coastal subsidence (1-3 m) on the landward side of trench parallel hinge lines were observed in association with the 1946 Nankaido earthquake [Fitch and Scholz, 1971], the 1960 Chile earthquake [Plafker and Savage, 1970] and the 1964 Alaska earthquake [Savage and Hastie, 1966; Plafker, 1972; Ovenshine et al., 1976]. Multiple events of abrupt submergence of late Holocene wetland surfaces have also recently been reported for the coast of southwest Washington [Atwater, 1987] and for northwestern Oregon (W. Grant, personal communication, 1988). These records of relative sea level change are interpreted as positive evidence for active subduction tectonics (including coseismic subsidence) along the central Cascadia margin. Similar field evidence of abrupt changes in relative sea level have been reported for Netarts Bay in northern Oregon [Peterson et al., 1988].

In this paper we describe in detail the stratigraphy and tectonic implications of buried marsh deposits from Netarts Bay, a coastal lagoon in northern Oregon (Figure 3). The small marsh of Netarts Bay was chosen for a detailed study of late Holocene records of relative sea level change on the basis of its protection from ocean storm waves and its negligible fluvial influence. These conditions are important to insure as complete and uncomplicated a record of relative sea level change as possible. In addition, its central position in the Cascadia margin (45°N) allows for the comparison of neotectonic processes in northwestern Oregon with reported marsh burial events in larger estuaries of southwestern Washington

[Atwater, 1987]. The stratigraphic evidence and sedimentological evidence for episodic, abrupt marsh burial are discussed. In addition, the approximate radiocarbon ages and vertical displacements of six subsidence events that occurred during the last several thousand years are presented. Our study results argue for abrupt tectonic subsidence associated with coseismic strain release events in this historically aseismic subduction zone.

BACKGROUND

To interpret vertical tectonics from salt marsh stratigraphies it is important to understand the relationship between relative sea level and the dynamics of marsh development. Salt marshes occupy a narrow elevation zone (with respect to mean sea level) between estuarine tidal flats (lower intertidal) and upland (supratidal). For this reason they have been used as indicators of tidal level positions to document changes in relative sea level [Kraft, 1971]. Salt marshes develop initially by encroaching on a relatively barren tidal flat. The marsh gradually builds upward (by trapping sediment and accumulating peat) to a point where (1) tidal influence diminishes, (2) sediment supply decreases, and (3) marsh elevation stabilizes. Salt marsh development is affected by many factors, including but not limited to tidal range, sediment supply, sediment resuspension (erosion), and basin salinity, as well as changes in relative sea level [Redfield, 1972; Niering and Warren, 1980]. The influence of these different factors can be discriminated by observing marsh stratigraphies from different marsh settings, both within a tidal basin and between different tidal basins. Only relative sea level changes will force system wide responses of marsh progradation or burial in the different marsh systems.

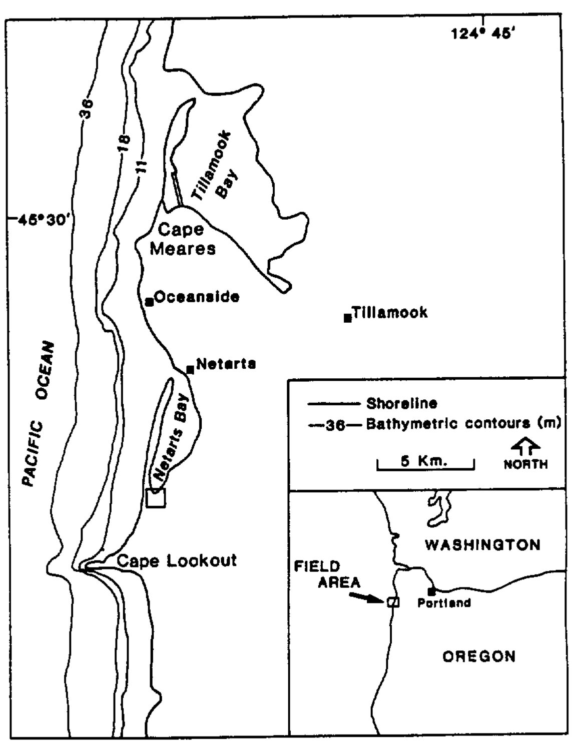


Fig. 3. Location of study site on the northern Oregon coast (box). Netarts Bay, approximately 55 km west of Portland, Oregon (inset), is located between two headlands, Cape Lookout and Cape Meares. The bay is protected from the ocean by a barrier spit that extends nearly to the northern end of the small coastal lagoon.

A critical assumption in the use of relative sea level records to investigate vertical tectonic motions is that the rates of tectonic displacement and of eustatic (global) sea level change are sufficiently different to discriminate between the two. Relative sea level records from several margins [Oldale and O'Hara, 1980] indicate that low rates of net eustatic sea level rise (possibly less than 1 mm yr^{-1}) occurred during late Holocene time (0-3000 years B.P.). Observed rates of relative sea level change that significantly deviate from this average rate of eustatic sea level rise are usually ascribed to local tectonic processes. While spikes in eustatic sea level change during the late Holocene have been reported [Fairbridge, 1961], but not globally confirmed, it is unlikely that eustatic sea level changes and tectonic displacements would produce the same asymmetry in the rates of sea level rise and fall. Finally, evidence of extremely rapid (catastrophic) sedimentation directly above submerged marsh horizons would clearly argue for abrupt vertical tectonic displacements and not eustatic sea level changes.

METHODS

To describe, analyze, and interpret buried peats in Netarts Bay, a total of 13 cores were taken to depths of 4-6 m in two orthogonal transects across the small salt marsh (0.5 km^2 in area) between 1985 and 1987 (Figure 4). Subsurface coring to depths of 4-6 m represents the limit of hand coring methods used in Netarts Bay. Continuous cores were taken with 3 m and 6 m lengths of plastic pipe, 5 cm and 7.5 cm in diameter, respectively. The core was used for peat ^{14}C dating, x-radiography of sedimentary structures, and sediment composition analyses. A gouge corer (2.5 cm diameter) was also used to collect cores at successive 1 m intervals to depths of 4-6 m. These cores were used for stratigraphic and depth control owing to sediment compaction (average 10% of core length) associated with the continuous coring method. All cores were stored in a refrigerated core facility at Oregon State University. All core sites and representative modern marsh and tidal flat surfaces (total of 13 locations) were surveyed into local mean tidal level (MTL). The local mean tidal level was

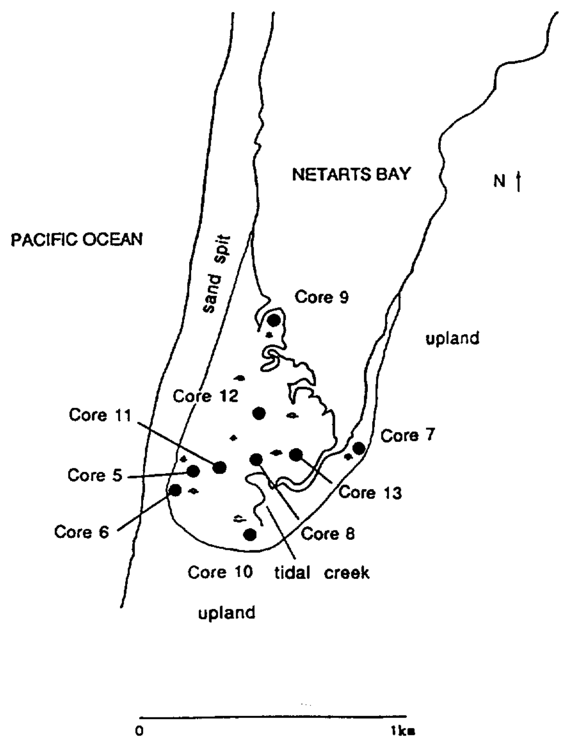


Fig. 4. Core site locations in the southern marsh of Netarts Bay. Core sites were chosen to cross the full length and width of the marsh system. The transects are oriented normal to the two major sediment sources, for example, the barrier dunes and the tidal basin. Only one tidal creek completely crosses this relatively undissected marsh.

established from one month of continuous tide gauge data recorded in a tidal creek between core sites 7 and 13 [Darienzo, 1987].

The split cores were examined in the lab and logged relative to a 1 cm reference scale. Upper marsh contacts and sediment capping layers were measured at 1 mm scales. Selected horizons were subsampled for measures of (1) sediment bulk density, after drying at 60°C for 24 hours [Gardner, 1965], (2) relative abundance of organic material, that is, weight loss on ignition at 380°C for at least 10 hours [Andrejko et al, 1983], (3) relative abundances of sand (diameter > 0.062 mm sieve diameter) and of silt and clay in the inorganic fraction, after oxidation by H_2O_2 [Folk, 1980], and (4) sand source mineralogy by petrographic analysis of pyroxenes in heavy mineral separates [Peterson et al., 1984]. Subsamples were examined for microfossil assemblages (diatoms) which are diagnostic of salinity and elevation relative to MTL [Whiting and McIntire, 1985; Patrick and Reimer, 1986]. Examination of peat samples (bulk samples and thin sections) for identifiable plant fragments that are diagnostic of high marsh elevations were generally unsuccessful, because of the degradation of plant fossils in marsh horizons sampled in the Netarts marsh cores. The top 5-10 cm of eight buried peats were hand picked to remove potential contaminants such as modern descending roots, then rinsed and oven dried for radiocarbon dating of representative marsh horizons. X ray radiographs of selected core sections were taken to confirm in situ marsh development, that is, vertical root growth, and to identify sedimentary structures diagnostic of sediment transport regimes.

RESULTS

In an effort to estimate vertical tectonic displacements from the late Holocene marsh stratigraphies in Netarts Bay, several independent measures of paleomarsh surface elevation, relative to late Holocene mean tidal level, were established. These independent variables, include (1) reversing tidal flat and marsh horizon development (general stratigraphy) and (2) quantitative analysis of sediment composition. Both methods of reconstructing changes in paleomarsh elevation rely on detailed information about the modern marsh horizons and corresponding elevations relative to tidal range.

Tidal Range and Modern Marsh Elevations

The modern marsh surface elevations at nine core sites, located along two transects (Figure 4), were found to range from 1.1 m to 1.5 m above MTL (Table 1). An elevation of 1.5 m MTL probably represents the upper range of salt marsh development in southern Netarts Bay, as established by freshwater shrubs colonizing the marsh surface at site 10 (1.5 m MTL). Although a 0.5-1.0 m vertical erosional scarp currently fronts the northern margin of the Netarts marsh, varying stages of low marsh development (0.2-0.8 m MTL) and transitional low-high marsh development (0.8-1.1 m MTL) are observed in protected bay sites (Table 1). Finally, only barren mud flats or algae- and Zostera -covered mud flats are found at or below low intertidal elevations of 0.2 m MTL. The total vertical range of the modern salt marsh in the study site is 0.2-1.5 m MTL. However, the elevation range of the modern high marsh surface is much narrower, 1.1-1.5 m MTL.

Vertical Marsh Sequences

Detailed core logs of the Netarts marsh cores (sites 5-13; Figure 5) indicate a series of alternating peats and very low organic muds to sandy muds (burial unit) extending to a depth of at least 4.5 m below the present marsh surface. The very low organic (VLO) muds contain only minor amounts of detrital organics and some descending rootlets. The maximum number of burial units (6-7) are found in core sites (5, 7, 10, and 11) near the west, east, and

TABLE 1. Tidal Level, Core Site Elevation, and Key Plant Assemblages in the Netarts Marsh

Tide	Elevation, m	
MHHW	+1.0	
MHW	+0.8	
MTL	+0.0	
MLW	-0.7	
MLLW	-1.0	
Core Site	**Elevation, m MTL**	
5	1.2 HM	
6	1.4 HM	
7	1.4 HM	
8	1.4 HM	
9	1.1 TM	
10	1.5 HM	
11	1.4 HM	
12	1.3 HM	
13	1.3 HM	
Type	**Elevation Range, m MTL**	**Plant Assemblage**
High marsh	1.1-1.5	Deschampsia caespitosa Potentilla pacifica Grindelia integrifolia Juncus balticus
Low marsh	0.2-0.8	Distichlis spicata Scirpus americanus Salicornia virginica
Tidal flat	<0.2	barren, algae or Zostera covered

HM, high marsh; TM, transitional (low-high) marsh.

south margins of the salt marsh. The contacts between the peats and underlying VLO muds are generally characterized by gradual transitions from finely laminated muds (5-150 cm in thickness) to overlying peaty sand or peaty mud horizons (5-125 cm thickness). The peaty horizons are abruptly overlain by distinct, sediment-capping layers (SCL) that range from 1 cm to 25 cm in thickness. The SCL horizons are generally composed of a basal sand or muddy sand layers which grade upward into sandy mud or laminated sand and mud. The SCL horizons are overlain by very finely laminated muds (millimeter to submilliter thick laminations). Grain size analyses of the SCL layers [Darienzo, 1987] indicate frequency distribution modes in either the fine sand or very fine sand size fractions [Folk, 1980]. The burial unit is thus characterized by three distinct layers above a sharp contact with a peaty surface, (1) an anomalous sediment capping layer, (2) a finely laminated clay and silt layer, and (3) a peaty mud or peaty sand layer (Figure 5). The complete burial unit containing all three layers is found in four out of the six burial events recorded at Netarts Bay.

Stratigraphic Correlation

Individual stratigraphic horizons of peats and VLO muds are correlated throughout the Netarts marsh system (Figure 5) on the basis of depth (relative to the MTL reference datum) and on the relative position of distinct stratigraphic layers, discussed below. The lateral continuity of specific horizons across the marsh indicates (1) a system wide (southern basin) response to the episodic burial of existing marsh horizons, (2) high preservation of buried peat horizons, and (3) a minimal differential settling or compaction between marsh sites. Substantial settling or compaction between core sites would make correlation between buried peat layers more difficult. However, the stratigraphic correlation of marsh horizons can be tested independently of measured elevation, as shown below.

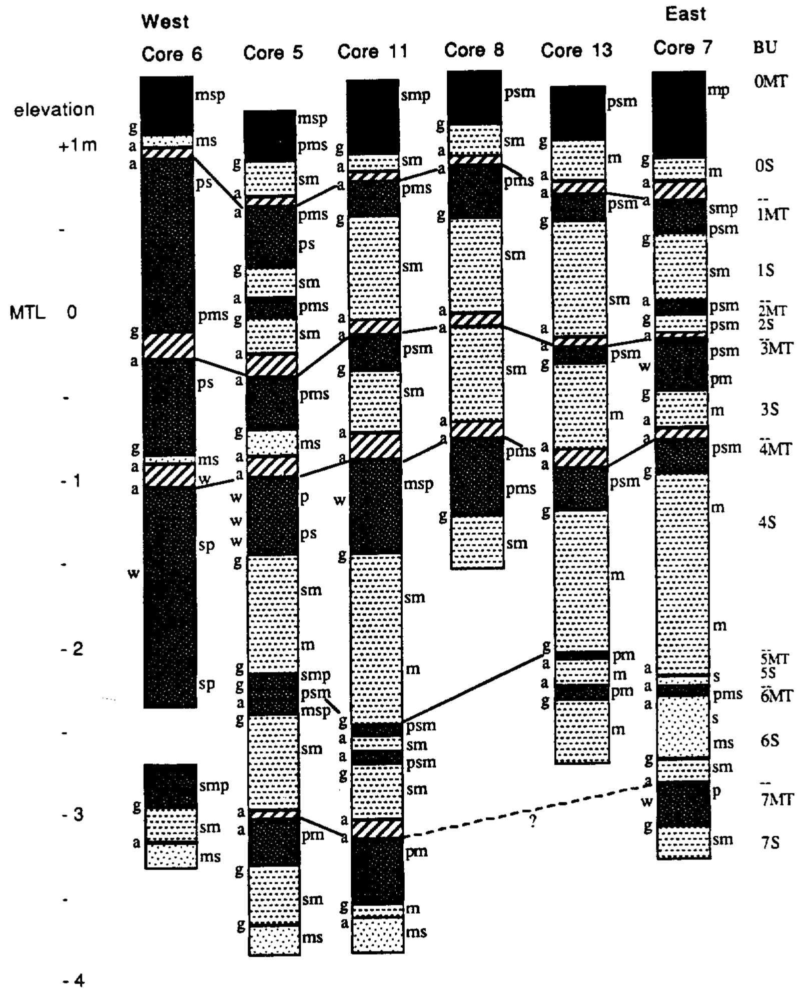


Fig. 5. Marsh core logs of Netarts Bay. Stratigraphic correlations of buried marsh horizons (lines) are based on (1) depth, (2) distinct burial units, and (3) the number of burial events downcore.

Significantly, only parts of the burial unit are found in some core intervals. For example, there are no SCL horizons associated with the second buried peaty horizon near zero MTL at sites 5, 7, and 10, and this peaty horizon is completely absent from the remaining core sites (Figure 5). Although the third buried peaty horizon is also missing from site 8, a conspicuous SCL horizon is present, and it denotes the continuity of this stratigraphic "event" horizon across the central marsh area. In contrast to the absence of peat development after some burial events at core sites toward the center of the marsh, the peat development at site 6 is nearly continuous, being interrupted only by the thin SCL horizons. This probably reflects (1) a greater sediment deposition rate there due to its proximity to the sand spit (a source of eolian sand supply), (2) a higher deposit elevation at site 6 prior to the burial events and (3) maximum protection from basin wind waves produced by onshore winds. Finally, the fifth and sixth peat horizons, observed at sites 5, 10, 11, and 13, are anomalous in several respects. For example, none of these peat horizons are associated with SCL horizons, and the intervening mud layers between the peat horizons are very thin (5-15 cm thick). In summary, three specific burial events (the second, fifth, and sixth buried peats) can be clearly discriminated and correlated on the basis of distinct horizons (stratigraphic fingerprints).

The system wide variability in sequence stratigraphy for successive burial horizons demonstrates that burial events likely differed in the rate and/or magnitude of relative sea level change. On the other hand, the variability between core sites shows that the perimeter and interior marsh sites record somewhat different responses to corresponding burial events. For example, at core site 8, a marsh apparently never developed after burial

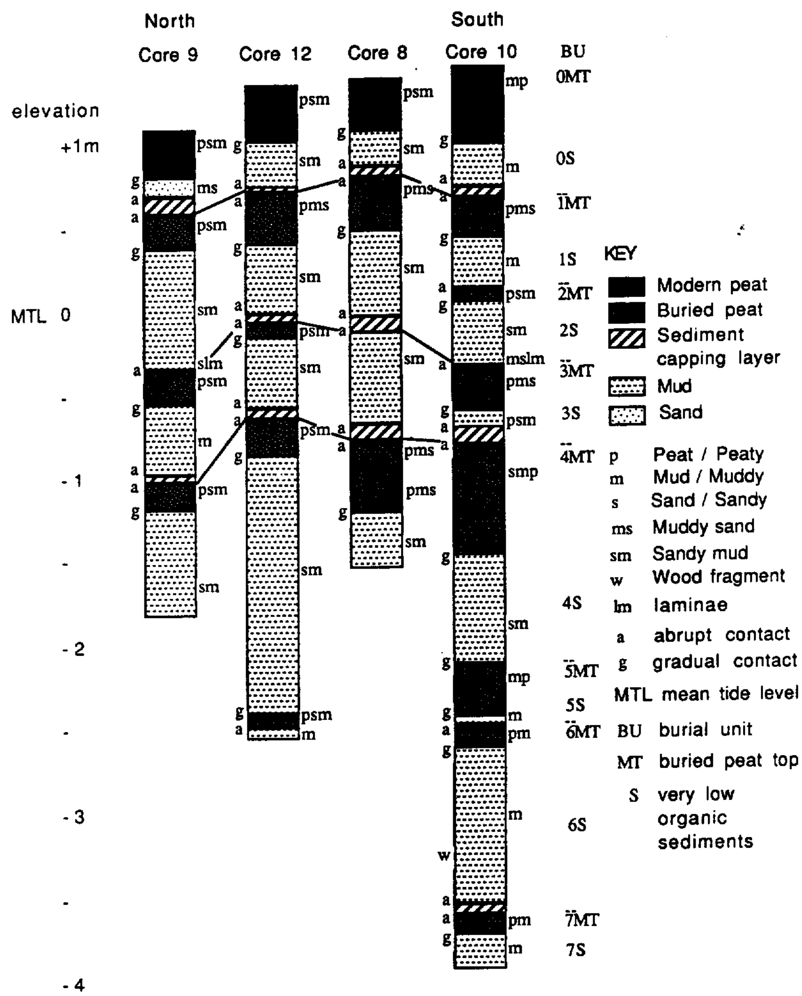


Fig. 5 (continued)

event four (Figure 5). Similarly, after burial event four there was less marsh development in the interior sites 11, 12, and 13 than in the perimeter marsh sites. This is consistent with observed modern marsh development in Netarts Bay, in which peat thicknesses decrease from the perimeter of the bay to the interior bay sites (Figure 5). This trend in marsh development is also reported from modern marsh systems of passive margins [Redfield, 1972].

Sediment Composition Indicators of Marsh Elevation

Quantitative sediment analyses were performed on buried peat tops and VLO sediment horizons in selected cores (sites 5-10) to establish the mechanisms of marsh burial and marsh redevelopment after burial in Netarts Bay (Table 2). Potential indicators of marsh surface elevation relative to MTL, such as percent organics (peat development), diatom assemblages (fresh or brackish), and sediment source (tidal or eolian), should change with the alternation between VLO horizons (tidal flat muds) and dense peat horizons (high marsh surfaces). These sediment properties do show similar downcore trends in core 5 (Figure 6). The three variables show maximum values in the peat horizons and minimum values in the intervening mud horizons. A comparison of the relative abundances of organics, freshwater diatoms, and sand in the remaining core sites shows a positive correlation of these variables, again with maximum values in peat horizons (Table 2). In subsequent sections each of these variables will be discussed in detail, explaining how its vertical and lateral changes in the cores can be used to interpret the response of the Netarts marsh system to changes in relative sea level.

As noted earlier, the second and third buried peat horizons are missing from several of the interior marsh sites, and the VLO sediment horizons are generally missing from site 6. In these cases,

TABLE 2. Sediment Composition Data From Netarts Marsh

Horizons	Elevation (m)MTL	Sand Percent	Silt/Clay Percent	Density Dry (g/cc)	Organics Percent	Diatoms*
Core site 5						
Surface	1.20					
0MT	1.06	66.6	33.4	0.32	18.6	0
0S	0.78	40.9	59.1	0.59	6.9	0
1MT	0.50	84.6	15.4	0.28	15.0	20
1S	0.11	29.0	71.0	0.61	5.8	0
2MT	0.03	89.3	10.7	0.30	13.7	0
2S	-0.15	27.6	72.4	0.60	5.5	0
3MT	-0.52	76.9	23.1	0.94	8.0	0
3S	-0.80	52.5	47.5	0.73	4.6	0
4MT	-1.10	91.7	8.3	0.18	52.1	20
4S	-1.87	21.9	78.1	0.75	5.1	0
5MT	-2.18	45.1	54.9	0.32	27.0	20
5S	-2.28	30.1	69.9	0.50	15.0	20
6MT	-2.34	86.6	13.4	0.40	29.0	20
6S	-2.56	13.0	87.0	0.72	7.3	0
7MT	-3.12	7.6	92.4	0.43	17.3	0
7S	-3.47	16.1	83.9	0.77	6.2	0
Core site 6						
Surface	1.40					
0MT	1.24	75.0	25.0		44.1	0
0S	1.05	56.0	44.0	0.70	5.1	0
1MT	0.73	98.0	2.0		21.7	20
1S	0.25	97.0	3.0		8.1	0
2MT†	0.18	95.0	5.0		8.0	0
2S	-0.13	55.0	45.0		8.3	0
3MT	-0.50	98.4	1.6	0.85	10.8	20
3S	-0.87	52.0	48.0		3.8	0
4MT	-1.40	98.4	1.6	0.56	27.2	20
4S†	-2.33	98.8	1.2		27.9	20
Core site 7						
Surface	1.40					
0MT	1.24	2.0	98.0	0.34	32.8	0
0S	0.82	1.7	98.3		9.7	0
1MT	0.60	29.2	70.8		26.8	0
1S	0.28	14.6	85.4	0.72	9.1	0
2MT	0.00	26.9	73.1		13.7	0
2S	-0.12	19.7	80.3		3.8	0
3MT	-0.28	39.1	60.9		21.9	0
3S	-0.59	7.6	92.4	0.74	5.3	0
4MT	-0.87	12.3	87.7		21.9	0
4S	-1.15	4.6	95.4	0.57	5.3	0

TABLE 2. (continued)

Horizons	Elevation (m)MTL	Sand Percent	Silt/Clay Percent	Density Dry (g/cc)	Organics Percent	Diatoms*
Core site 8						
Surface	1.40					
0MT	1.24	20.9	79.1		19.0	0
0S	0.89	14.8	85.2	0.46	8.0	0
1MT	0.71	73.2	26.8		20.4	0
1S	0.34	19.3	80.7	0.73	5.0	0
2MT†	0.12	13.0	87.0		5.0	0
2S	0.06	11.0	89.0		5.0	0
3MT†	-0.19	15.0	85.0		5.0	0
3S	-0.32	11.6	88.4	1.11	4.5	0
4MT	-0.93	89.1	10.9	0.40	20.3	0
4S	-1.34	22.9	77.1	0.98	4.4	0
Core site 9						
Surface	1.10					
0MT	0.94	34.8	65.2		11.3	0
0S	0.76	55.1	44.9	0.59	7.7	0
1MT	0.54	47.4	52.6		19.6	0
1S	0.16	45.4	54.6	0.70	4.0	0
2MT†	0.06	35.0	65.0		4.0	0
2S	-0.28	32.5	67.5		4.0	0
3MT	-0.39	37.5	62.5	0.39	15.5	0
3S	-0.84	4.2	95.8	0.76	4.8	0
4MT	-1.06	28.5	71.5		10.0	0
4S	-1.57	19.1	80.9	0.71	4.7	0
Core site10						
Surface	1.40					
0MT	1.30	1.3	98.7	0.34	27.6	10
0S	0.93	3.8	96.2		6.5	0
1MT	0.66	71.4	28.6	0.67	13.0	20
1S	0.31	3.8	96.2	0.83	6.2	0
2MT	0.08	44.7	55.3		11.5	0
2S	-0.10	10.2	89.8		4.9	0
3MT	-0.35	85.7	14.3	0.40	14.0	0
3S	-0.62	10.7	89.3		12.0	0
4MT	-0.95	13.9	86.1	0.30	25.0	20
4S	-1.70	20.5	79.5		3.8	0

MT, buried peat top; S, very low organic sediments.
*Diatom assemblages: brackish-marine, 0; mixed, 10; fresh, 20.
† Estimated horizon interval.

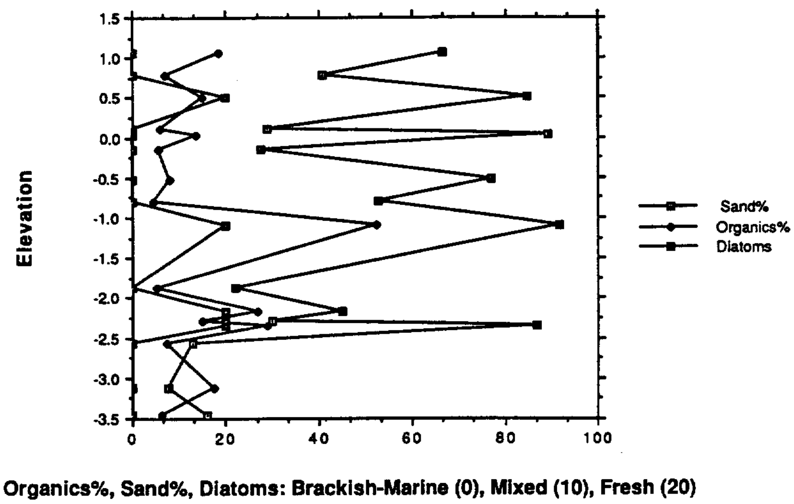


Fig. 6. Plots of percent organics, brackish/marine and freshwater diatom abundances, and percent fine sand as a function of elevation relative to MTL at core site 5 (see Figure 5 for general stratigraphy). All three variables show maximum values in marsh horizons and minimum values in intervening tidal flat deposits.

sediment samples were analyzed from representative depths in the cores, as determined from known horizon depths at adjacent sites (Table 2).

Percent Organics

The percent weight of organic material some 5-15 cm from the modern marsh surface ranges from 11% to 44% at sites 5-10 (Figure 7). The highest values of organic material (32-44%) are found at sites 6,7, and 10 adjacent to the west, east, and south perimeters of the marsh. These sites are characterized by high marsh plant assemblages and the highest elevations of the modern marsh surface (Table 1). The percent organic material at these sites decreases with depth from the modern marsh surface 0MT to minimum values (5-10%) in the underlying, VLO muds of the uppermost sediment layer 0S (Figure 7). These trends confirm field observations of marsh cut banks which showed that dense peat development in the modern marsh is generally restricted to elevations above 1 m MTL. This elevation apparently reflects the upper limit of abundant sediment supply by tidal currents (1 m MTL is modern Mean High High Water or MHHW) in the Netarts Marsh. Above this elevation, organics accumulate more rapidly than do fine-grained inorganic sediments, which are largely supplied by tidal circulation.

Although the percent organic material in corresponding peaty horizons varies between the different core sites, at least one core site displays an organic content in excess of 20% for each of the horizons 1MT, 3MT, and 4MT. By comparison, maximum organic contents under 14% in the poorly developed 2MT horizon at sites 5, 7, and 10 indicate that either this marsh surface did not reach a high marsh elevation or that postburial oxidation of the peat reduced the preburial organic content. Since postburial oxidation should only reduce the organic contents of peaty horizons, the presence of abundant organics (> 20%) in horizons 1MT, 3MT, 4MT, 5MT, and 6MT must reflect relatively dense peat development in a high marsh setting (> 1m MTL) prior to marsh burial (Figures 6 and 7).

Interestingly, the minimal organic content and lack of any peat development in the uppermost sediment layer 0S (0.7-1.1 m MTL) is inconsistent with the elevations of modern low marsh development (0.2 to 0.8 m MTL), well below the level of this VLO sediment horizon. This sediment horizon must have been deposited at a significantly lower MTL elevation than the elevation at which it now exists, thus arguing for a substantial drop in relative sea level after its deposition. The apparent vertical displacement of this youngest VLO mud layer relative to the MTL is more fully discussed in later sections of this report.

Diatom Assemblages

The relative abundances of freshwater and marine-brackish water diatoms in buried peat horizons provides a second measure of deposit elevation relative to MTL. Since Netarts Bay lacks any significant fluvial input, the presence of freshwater diatoms (Table 3a) reflects either freshwater ponding on a supratidal marsh surface during rainy periods or perhaps a forested wetland surface (also supratidal). Buried peat tops that are dominated by freshwater diatoms were only found in the perimeter marsh cores 5, 6 and 10 (Table 2). The horizons 1MT, 3MT,

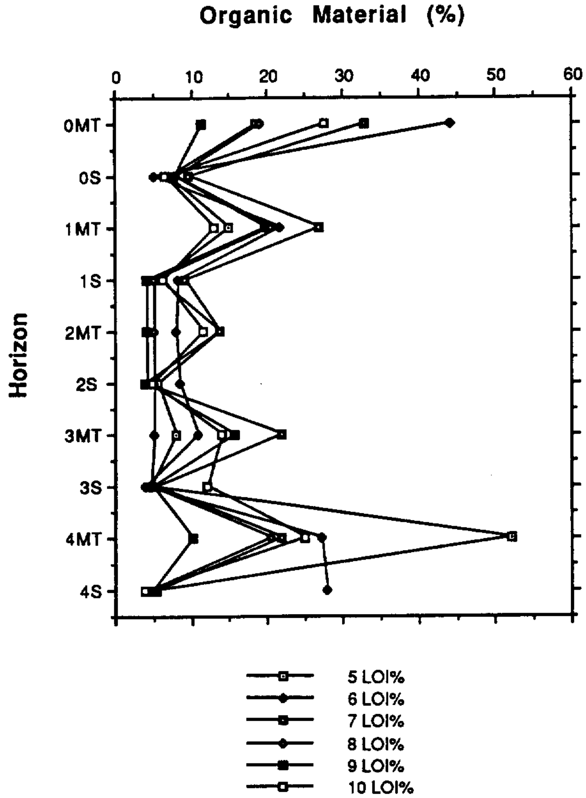


Fig. 7. Plots of percent organics (weight % loss on ignition) as a function of position in burial unit (0-4) at 6 core sites (5-10). MT, marsh top; S, tidal flat sediments. The percent of organics reaches maximum values in buried marsh horizons and reflects peat development relative to inorganic sediment supply rate (see Figure 5 for general stratigraphy).

4MT, 5MT, and 6MT contained diatom assemblages dominated by freshwater genera from one or more core sites (Figures 6 and 8). Significantly, the modern marsh horizon (0MT), ranging from 1.1 to 1.5 m MTL, is dominated by marine and brackish water diatoms at all of the core sites, except site 10 which had a mixed assemblage at 1.5 m MTL. Most of the modern marsh sites analyzed have apparently not reached a sufficiently high elevation relative to MTL to support either mixed or dominantly freshwater assemblages of diatoms. This would imply that the buried marsh horizons that are dominated by freshwater diatoms must have existed at elevations of at least 1.5 m MTL prior to burial by bay muds.

With one exception (horizon 5S), the overlying laminated muds (VLO horizons) are dominated by marine and brackish water diatoms (Figures 6 and 8). Freshwater diatoms were either rare or absent from these sediment horizons. Selected horizon contacts were analyzed for the interval of transition between freshwater diatoms (peat top) and overlying

TABLE 3a. Diatom Assemblages Diagnostic of Salinity in Netarts Bay

Brackish-Marine[a]	Freshwater[b]
Paralia sulcata	Pinnularia sp.
Biddulphia aurita	Cymbella sp.
Grammatophora sp.	Melosira sp.
Coscinodiscus sp.	Eunotia sp.
Actinoptychus sp.	Epithemian sp.
Plagiogramma sp.	Tabularia sp.
Rhabdonema sp.	Gomphonema sp.
Camplyodiscus sp.	

[a] Whiting and McIntire [1985].
[b] Patrick and Reimer [1986].

marine-brackish water diatoms (very low organic sediments), as shown in Table 3b. It is apparent that vertical transitions of diatom assemblages across the contacts, for example, between the peat tops and either the sediment capping layers or the laminated muds, are extremely small (less than 1 cm). An exception to these abrupt diatom transitions occurs at the contact between 5MT and the overlying laminated muds 4S. The gradual transition of fresh to marine-brackish water diatoms over this 40 cm interval (Table 3b) substantiates the interpretations of gradual subsidence implied by (1) color change (from dark brown to gray) and (2) decrease in percent organics observed across this unique contact at sites 5, 10, 11, and 13. However, abrupt transitions from fresh diatoms (peat tops) to brackish diatoms (SCL or VLO layers) in the majority of the burial units imply an asymmetry in the apparent rate of sea level change. That is to say, a fast relative sea level rise (submergence) is followed by a gradual relative sea level fall (emergence), assuming (1) similar sediment supply rates and (2) no postdepositional erosion of SCL layers.

Sand Supply

Increases of sand abundance (10-70%) from laminated mud horizons to overlying peaty deposits is observed at most sites in the Netarts marsh (Table 2). The relative abundances of sand in corresponding horizons also varies greatly (0-90%) between core sites. For example, the general abundance of sand in both peat and very low organic sediment horizons clearly decreases from west to east with increasing distance from the spit (Figure 9a). By comparison, no such decrease is found from north to south with increasing distance from the bayward marsh margin (Figure 9b). The origin of the sand in selected peats and VLO layers, including 0MT, 3MT, 7MT (site 5), 1S, 3MT (site 7), and 1S (sites 8 and 9; Figure 5), has been established on the basis of grain rounding and mineralogy of the nonopaque heavy mineral

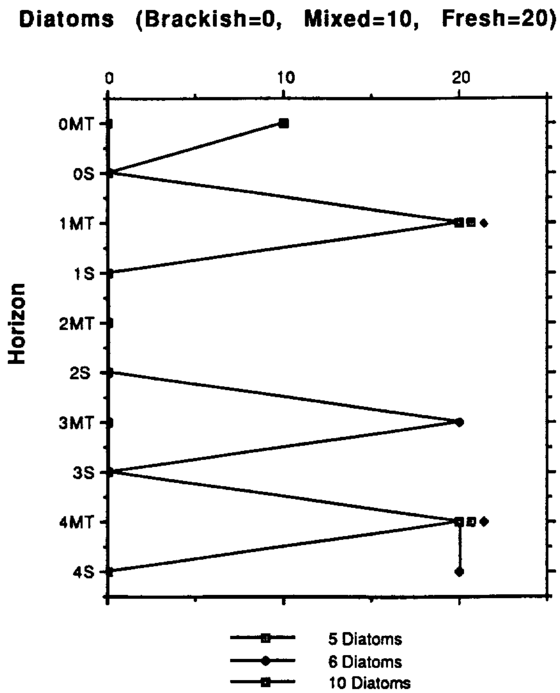


Fig. 8. Plots of diatom assemblages, including dominantly brackish/marine, mixed, and dominantly freshwater, as a function of position in burial units (0-4) at six core sites 5-10, (see Figure 5 for general stratigraphy). Changes in diatom assemblages denote changes in deposit elevation relative to MTL, for example, brackish water (intertidal) and freshwater (supratidal).

fraction. The well-rounded, orthopyroxene-rich sand of the modern and buried peats (hypersthene:augite > 0.18) is derived from the littoral zone, as shown by similarities of beach sand pyroxene ratios (hypersthene:augite ratio > 0.18). It contrasts sharply with the angular, orthopyroxene-poor sand of the bay creeks (hypersthene:augite ratio = 0), as well as with the extensively weathered sand of the eroding bay terraces [Darienzo, 1987]. Finally, grain size analyses of the peat top sands indicate grain size modes (maximum abundance) only in the fine sand size fraction, for example, a dune sand source. A littoral origin and eolian transport of the sand in peat tops is consistent with the observed increase of peat sand abundance toward the bay spit (Figure 9a).

The vertical cycles of silt plus clay to sand dominance in the marsh system are clearly related to episodic changes in the elevation of the depositional environment relative to MTL. A lowering of the marsh horizons relative to MTL results in burial by intertidal mud flats. As the low intertidal muds accumulate and/or are uplifted to upper intertidal marsh settings, the supply of silt and clay from tidal and storm currents are reduced relative to the ongoing supply of fine sand by eolian transport. In the modern high marsh setting, 1.1-1.5 m MTL, the eolian sand is the major component (> 50%) of the inorganic fraction at only the two sites 5 and 6 (closest to the spit). By comparison, eolian sand is the dominant inorganic sediment in 1MT from five sites and in 4MT from 4 sites (Figures 9a and 9b). This trend is consistent with the distribution of freshwater diatoms which are rare in the modern high marsh but which are dominant in the very high marsh settings reached in 1MT and 4MT.

Sediment Capping Layers

The small-scale stratigraphies of the sediment capping layers (SCL) were examined in detail to identify their trends in basal sandy layer thickness and their patterns of sand and mud deposition, which are used to constrain their possible mechanism(s) of

TABLE 3b. Diatom Transitions Across Selected Horizon Contacts At Sites 5 and 10

Site	Horizon	Depth, m MTL	Organics, wt. % (Loss on Ignition)	DiatomAssemblages
5	0SCL	+0.62	6	brackish
	1MT	+0.63	15	fresh
10	3SCL	-0.78	5	brackish
	4MT	-0.79	25	fresh
5	4SCL	-1.34	5	brackish
		-1.70	7	brackish
		-1.94	8	brackish = fresh
		-2.07	12	fresh > brackish
		-2.10	24	fresh
	5MT	-2.14	28	fresh

SCL, sediment capping layer; MT, buried peat top.

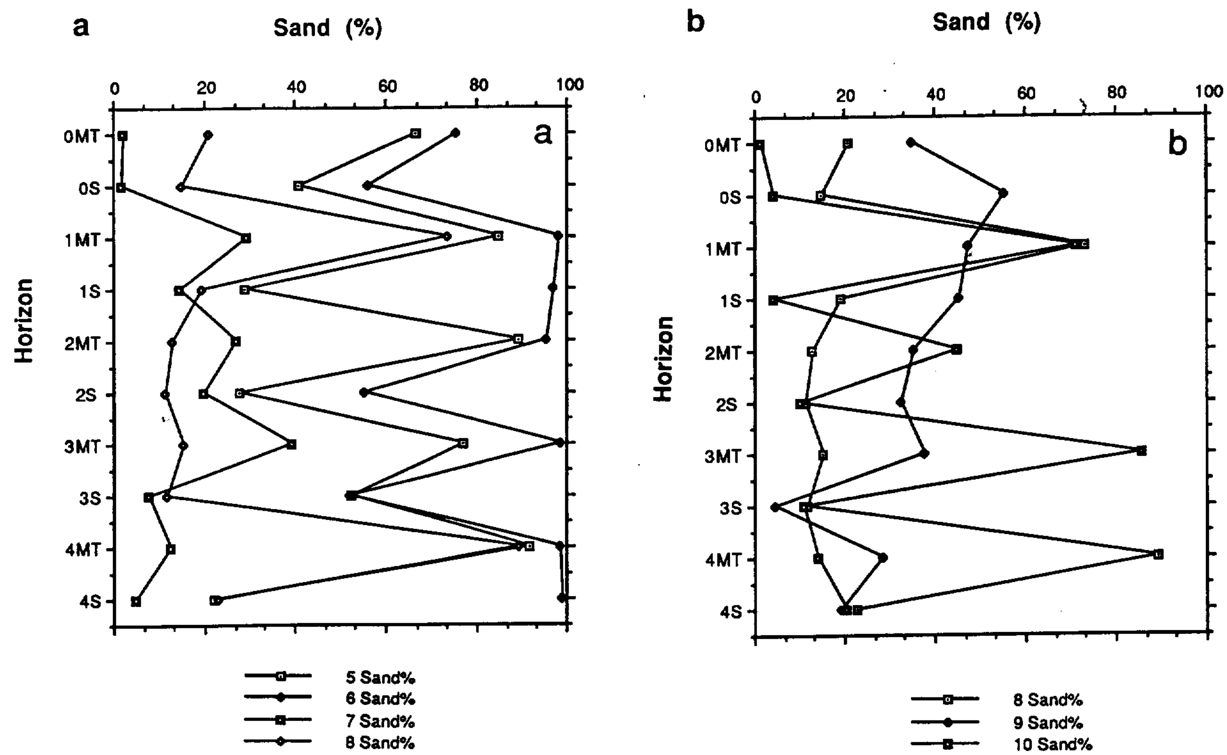


Fig. 9. (a) Plots of percent sand (> 0.062 mm diameter size) as a function of position in burial units (0-4) at four west-east core sites (5,6,7,8). The fine sand has a littoral origin, and it is largely supplied to the marsh system by eolian transport from the barrier dunes to the west (see Figure 5 for general stratigraphy). (b) Same as above, but for three north-south core sites (8,9,10).

formation (Figure 10). Of primary interest are the layers of sand or sandy mud that comprise either the base or the entire thickness of the SCL horizons. Spatial trends in the thickness of the basal sandy layer might establish directions of sand transport. Significantly, there is no consistent change in the basal sandy layer thicknesses from west to east in the SCL horizons above the tops of buried marsh layers 1 and 3 (Figure 10), thereby ruling out the spit or ocean beaches as the immediate source of the anomalous sand supply. By comparison, the basal sandy layers in several SCL horizons (above 1MT,3MT, and 4MT) do show dramatic thickening and thinning from north to south in the observed core sites. For example, minimum sand thicknesses are generally found at site 9 (northern marsh/bay margin) and/or at site 10 (southern marsh/upland margin) in observed SCL horizons in the north-south transect. Scouring at site 9 and diminishing sand supply at site 10 could explain these sand dispersal patterns, indicating a north to south direction of sand transport. While local variation in SCL thickness is evident, the extensive lateral continuities (> 1 km) of the very thin SCL horizons (generally < 20 cm) can only have formed as a result of episodic catastrophic events, each covering the entire southern Netarts basin.

Alternating sand and mud deposition observed in the SCL horizons could indicate the temporal variability of transport and depositional energy associated with the SCL formation. The SCL horizons above 1MT, 4MT, and 7MT are characterized by relatively homogeneous layers of sand or muddy sand which contain few if any intervening mud laminae (Figure 10). When present, the mud laminae generally occur toward the top of the SCL horizons. In contrast, the SCL horizon above 3MT at sites 5, 6, 11, and 12 is distinctly layered (Figure 10). Alternating sand and mud layers, ranging from 1 mm to several centimeters in thickness, are observed in this SCL horizon at these western core sites. None of the SCL horizons show any indication of cross bedding or bioturbation in the basal sand-rich layers, as established by X-radiographs of these layers from the Netarts core sites (Figures 11a,11b, and 11c). The alternating sediment layers and the lack of cross bedding in the muddy sands demonstrate sediment deposition out of a turbulent suspension. Alternations between sand

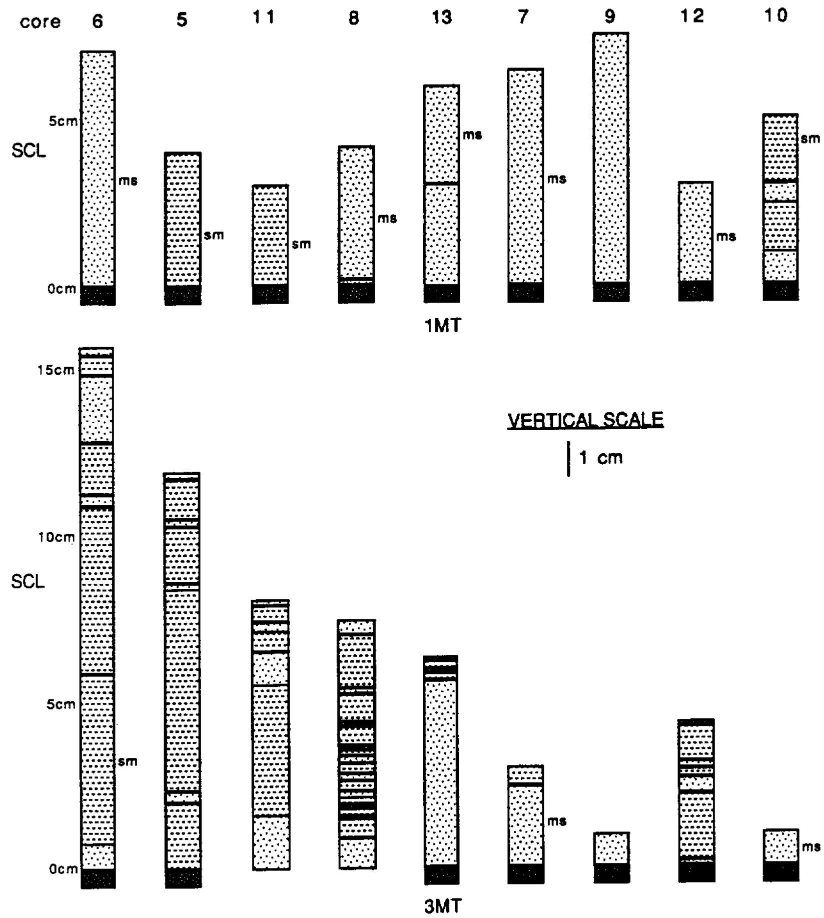


Fig. 10. Detailed stratigraphy of the sediment capping layer (SCL), showing variabilties of basal sand thickness and of sand and silt layering between different burial sequences above buried marsh horizons 7, 4, 3, and 1 (see general stratigraphy in Figure 5).

and clay/silt deposition within a single SCL horizon indicate time-varying conditions (pulses) of sediment entrainment, transport, and deposition. Decreasing grain size and generally decreasing laminae thickness upward in the SCL horizons imply a waning energy of deposition during the final period(s) of SCL formation. The lack of any bioturbation within the SCL layers implies that the time intervals for the development of the SCL horizons were very short.

Radiocarbon Ages

The modern and buried marsh (peat) horizons were radiocarbon dated to establish the recurrence interval of burial events and duration of marsh redevelopment after each event in Netarts Bay (Figure 12). Typically, the upper 5-10 cm of buried peat were used to estimate the age of the buried marsh horizons. However, the age of the upper peat horizon is considered a maximum age for the marsh burial event because the event occurred after high marsh development. Longer sections (15-20 cm in length) of the extreme bottoms of four marsh horizons (MM, BM1, BM3, and BM4) were used to date the initial development of the marsh horizon and to constrain the age estimate of the previous marsh burial event. The radiocarbon ages of the buried peat horizons range from about 400 years (BM1) to about 3300 years (BM7), as measured in radiocarbon years before present (RCYBP). Additional upper peat horizons have ages (RCYBP) of approximately 1220 (BM2), 1600 (BM3), 1700 (BM4), and 3000 (BM5 and BM6). The longest recurrence interval between burial events is of the order of 1000 years (BM5 to BM4), while the shortest recurrence intervals are possibly less than 300 years (BM7 to BM6 and BM4 to BM3).

The youngest buried marsh horizon (BM1) was dated at the bottom (1240+/-80 RCYBP) lower middle (690+/-110 RCYBP) and top (370+/-60 RCYBP) to constrain the rate of marsh redevelopment after burial. The wide range in ages of the marsh horizon demonstrates a long duration of marsh recovery, for example, 500-900 years of marsh

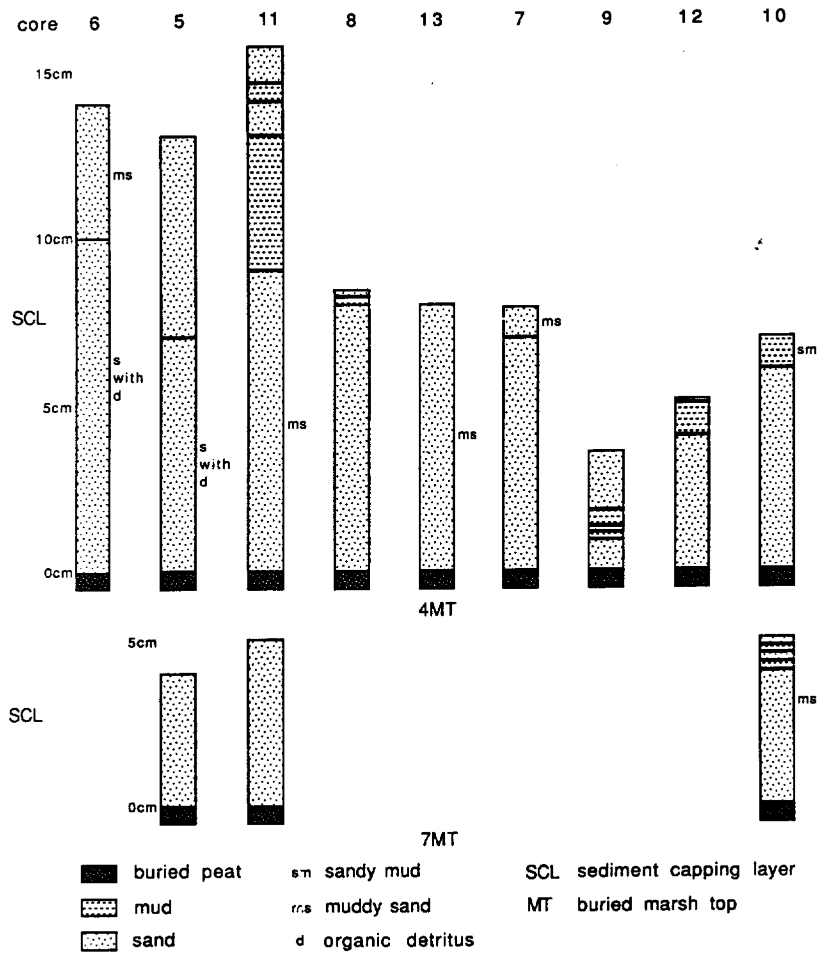


Fig. 10 (continued)

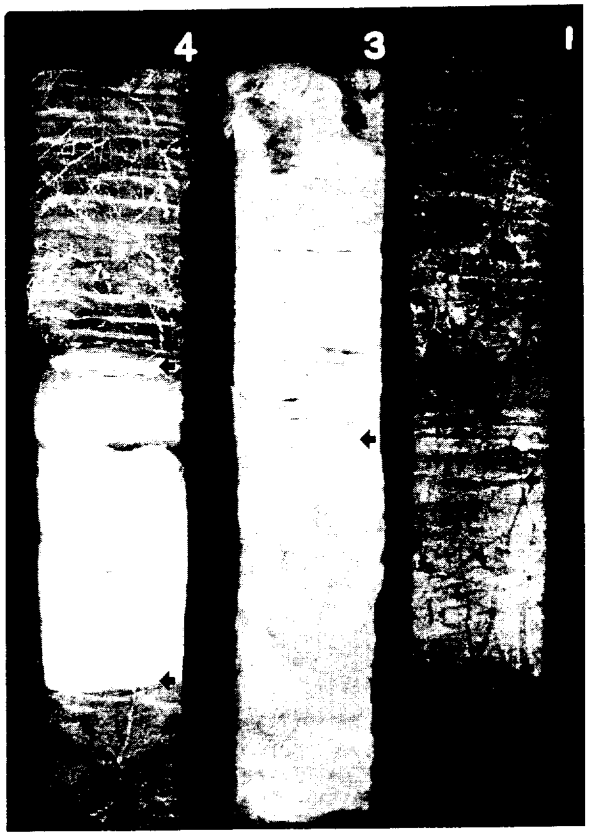
development. As a result, the dating of marsh burial events with composite (thick) peat samples introduces potentially significant errors in estimating event timing. Counting-statistic errors and radiocarbon calibrations further increase the actual age uncertainties of the peat horizons [Stuiver and Reimer, 1986]. The radiocarbon age of the peats give only approximate true ages of the marsh horizons, and they overestimate the age of the burial event. However, three of the most recent burial events are temporaly distinct events based on calibrated radiocarbon ages at the 95 percent confidence interval (Figure 12).

DISCUSSION

Tectonic Subsidence

The episodic burial of the marsh horizons in Netarts Bay is the result of cyclic tectonic subsidence and uplift which is superimposed on a condition of net rise of relative sea level during the last several thousand years. The net relative rise in sea level at Netarts Bay is 4.0-4.4 m (TMM-TBM7; Figure 12) for a period of 3.3-3.8 x 10^3 years, yielding a net relative rise rate of 1.1-1.3 mm yr^{-1}. During this time at least six separate cycles of marsh development and subsequent marsh burial occurred, each reflecting a tectonic cycle of interseismic uplift and coseismic subsidence. Very sharp contacts exist between well-developed marsh surfaces and overlying sediment capping layers or laminated bay muds in five out of the six burial cycles. There is no evidence of buried marsh surface erosion, so the sharp contacts are assumed to represent very rapid changes in deposit elevation relative to MTL. Rapid changes in deposit elevation are substantiated by the lack of mixed diatom assemblages across all but one (5MT) of the high-marsh to VLO mud contacts (Table 3b). The subsidence of the 5MT horizon was clearly not abrupt, as shown by a very gradational upward transition of percent organics and of fresh to brackish/marine diatoms over a 40 cm interval between the 5MT and 4S horizons (Figure 5 and Table 3b).

a



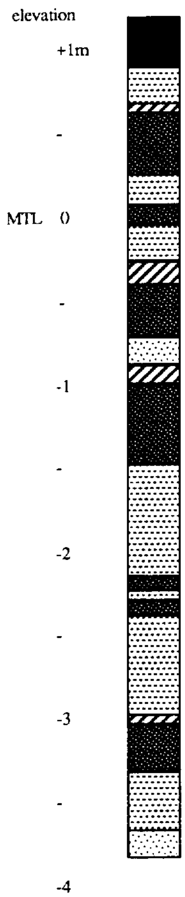
b

c

Fig. 11a. X ray radiographs of selected sediment capping layers (1, 3, and 4) in core site 9 (northern edge of marsh system). Light layers denote SCL basal sands (maximium x ray absorption) above dark peaty horizons (minimum x ray absorption). Arrows denote the approximate lower and upper boundaries of the basal sandy layers of the SCL horizons. Significantly, these layers lack any internal cross bedding.

Fig. 11b. X ray radiographs of selected sediment capping layers (1, 3, and 4) in core site 8 (central area of marsh system). See Figure 11a for general description of features. Significantly, the third sediment capping layer (SCL 3) overlies tidal flat muds at this core site. This SCL horizon is also distinctive at the western core sites (5, 6, and 11) due to its alternating laminations of sand and mud (see detailed stratigraphy in Figure 10).

Fig. 11c. X ray radiographs of selected sediment capping layers (1, 3, and 4) in core site 10 (northern edge of marsh system). See Figure 11a for general description of features. A thin layer of muddy sand occurs within the basal sandy layer of the first SCL horizon. Very faint laminations (silt and/or organic detritus) are also apparent toward the top of the basal sandy layer in the third SCL horizon.



elevation (m)	beta #	age (RCYBP)	age (C13 adj)	age (cal. yr BP)	location
+1.19	19096	125.2+/-0.9%	-	-	T-MM
+0.89	24932	450+/-80	440+/-80	310-626	B-MM
+0.63	24933	370+/-60	350+/-60	290-520	T-BM1
+0.24	25208 (19094)	690+/-110 (1240+/-80)	700+/-110 -	520-908 -	B-BM1
+0.05	24934	1270+/-60	1220+/-60	970-1290	T-BM2
-0.41	24520	1670+/-80	1640+/-80	1354-1769	T-BM3
-0.71	24935	1430+/-80	1450+/-80	1189-1520	B-BM3
-1.03	24521	1840+/-60	1760+/-60	1540-1869	T-BM4
-1.49	24936	2090+/-70	2040+/-70	1870-2298	B-BM4
-3.21	24522	3220+/-90	3170+/-90	3145-3636	T-BM5
-3.37	25030	2850+/-70	2820+/-70	2779-3191	T-BM6
-4.01	24523	3300+/-100	3290+/-100	3274-3827	T-BM7

KEY

MM modern marsh
BM buried marsh
T top
B base

Fig. 12. Core log and radiocarbon ages from core sites 5 and 11. Buried marsh horizons range in radiocarbon age before present (RCYBP) from about 400 to 3300 RCYBP. Radiocarbon dating was performed by Beta Analytic Incorporated (beta #), and standard pretreatment leaches to remove potential contaminants were used. Peat ages were adjusted by $^{12}C/^{13}C$ ratios and all ages were calibrated by ^{14}C reservoir fluctuations. Calibrated ages are based on sample two-sigma deviations about ^{14}C calibration curves established from tree ring dating [Stuiver and Reimer, 1986].

Tsunami Deposits

Further evidence of abrupt burial of four horizons (1MT, 3MT, 4MT, and 7MT) is shown by the presence of sediment capping layers (SCL), which lack the regular fine laminations of either the overlying VLO muds or the basal peaty horizons (Figures 10 and 11). The SCL horizons are thought to represent locally generated tsunami deposits [Peterson et al, 1988], as has been reported for the origin of similar deposits along the southwest Washington coast [Atwater, 1987]. The SCL sands in the Netarts marsh sequences cannot have been derived from river flooding or local runoff, because there are no rivers in the Netarts coastal lagoon, and the sand mineralogy of the SCL horizons reflects the bay-marine sand sources. A subaerial (direct eolian) origin of the sediment capping layers is ruled out by (1) the deposition of clay and silt with sand in the SCL basal intervals, (2) the intervening mud layers, and (3) the widespread presence of the marine-brackish diatoms in the SCL horizons (Table 3b). In addition, some SCL horizons contain grain size modes in the very fine sand fraction, a sediment size fraction that is known to be abundant in southern tidal flats of the Netarts Bay [Glanzman et. al., 1971]. The tsunami from the 1964 Alaskan earthquake reached Netarts Bay and locally scoured the southern bay tidal flats to several centimeters depth (B. Wick, personal communication, 1987), but was not large enough to deposit sand over the modern high marsh. The absence of cross-bedding structures in the SCL horizons (Figure 11) indicates that the SCL sands were transported and deposited out of turbulent suspension rather than from small-scale oscillatory currents or subcritical traction currents that produce ripples and dunes on the bay bottom.

Elevations of peat surfaces capped by tsunami deposits from stratigraphically correlated burial sequences in adjacent core sites generally differ by less than 15 cm (Figure 5). These elevation ranges of buried peat surfaces are not significantly different from the surface irregularities of the modern marsh (Table 1). The small vertical offsets of buried peat surfaces argue against substantial erosion of subsided marshes by the invading tsunami waves. Large plant fragments, peat clumps, and/or mud rip-up clasts are rare or absent from the sediment capping layers. For example, abundant peaty detritus is not apparent in the x-radiographs of either the capping tsunami sands or in the silts toward the top of the SCL horizons from the majority of the core sites (Figures 10 and 11a, 11b, and 11c). However, abundant organic detritus is present in the basal sands of one SCL horizon (above 4MT) at the two sites nearest the spit, that is, sites 5 and 6 (Figures 10 and 11). Tsunami run up along the bayward side of the spit adjacent to these sites might have eroded and entrained vegetation growing in the loose dune sands near the spit/bay margin. Although the tsunami surges were capable of transporting fine sand over the lengths and widths of the subsided marshes, for example, distances greater than 0.75 km, the bottom shear stresses were insufficient to dismember the densely rooted marsh tops.

Magnitude of Tectonic Subsidence

As mentioned previously, the Netarts salt marsh grows within a restricted range of tidal level due to a variety of factors. A high marsh surface (>1.1 m MTL) and a very high marsh surface (>1.5 m MTL) in Netarts Bay can be established on the basis of three independent sediment properties: percent organics, diatom assemblages, and percent sand. At least two of the buried marsh surfaces, 1MT and 4MT, appear to have been very high marsh surfaces (>1.5 m MTL) that subsided by at least 1.3-1.5 m to low intertidal elevations (<0.2 m MTL). These low intertidal mud flats could not support low marsh development. By comparison, buried marsh horizons 3MT, 5MT, and 7MT were probably high marsh surfaces (>1.1 m MTL) which must have subsided by at least 0.9-1.1 m to have been covered by VLO muds. Significantly, these estimates of subsidence (approximately 1.0-1.5 m) are within the range of measured vertical displacements (1-3 m) produced by coseismic coastal subsidences associated with the southern Chile (1960) and Gulf of Alaska (1964) subduction zone earthquakes [Heaton and Hartzell, 1986].

A very thin muddy layer (5S; Table 2), containing fresh water diatoms at sites 5, 10, 11 and 13, is laterally present between two marsh surfaces 6MT and 5MT (Figure 5). Although a system wide marsh burial is recorded at this interval, there is no evidence of a significant and/or persistent subsidence event separating the 5MT and 6MT marsh horizons. The unusual separation and gradual subsidence of the 5MT horizon makes this stratigraphic interval particularly unique among the subsidence events recorded in the Netarts marsh. The mechanism(s) responsible for the origin of the thin marsh couplet and the gradual subsidence of the upper marsh surface (5MT) are presently unknown.

Tectonic Cycles of Uplift and Subsidence

In addition to the episodic subsidence of the Netarts marsh there is evidence of cyclic tectonic uplift. For example, the four youngest subsidence events (1MT-4MT) should total 4-5 m in vertical displacement, as outlined above. However, the measured distance between 0MT and 4MT (approximately 2.3 m) accounts for only one half of the expected displacement from abrupt subsidence events. Using the known presubsidence marsh elevations (1.1-1.5 m MTL) and the postsubsidence tidal mud elevations (less than 0.2 m MTL), it is possible to estimate the tectonic motions (minimum displacements) for the last four tectonic cycles (Figure 13). For example, the estimated elevation of the buried marsh surface 1MT at core site 5 is 1.5 m MTL, based on the freshwater diatoms at the top of the buried marsh. To reach an estimated tidal flat elevation of 0.1 m MTL immediately above the buried marsh surface, the surface must drop at least 1.4 m. However, the modern marsh surface has a measured elevation of 1.2 m MTL. Thus to reestablish the marsh (modern horizon) there would need to be 1.1 m of tidal flat and marsh deposition. Yet, the distance between the buried marsh surface and the modern marsh surface is approximately 0.6 m, about 0.5 m less than what should be expected to accumulate from deposition after subsidence. This is the same magnitude of shortening (0.5 m) as observed for the average of four tectonic cycles (1MT-4MT) when the total section shortening (2-2.5 m) is divided by the total number of cycles (4).

Much of this section shortening (of the order of at least 0.5 m per event) must be taken up by tectonic uplift between successive subsidence events. Any section shortening due to sediment compaction must be small, and it must occur shortly after deposition. For example, there is no evidence of greatly increasing sediment bulk density in successively deeper horizons to account for the estimated section shortening of nearly 50% (Table 2). We have reconstructed the successive development of the existing stratigraphic section (core site 5) on the basis of (1) measured lengths of burial intervals and (2) estimated subsidence displacements (Figure 14). For example, the top of BM4 (developed at 1.5 m MTL)

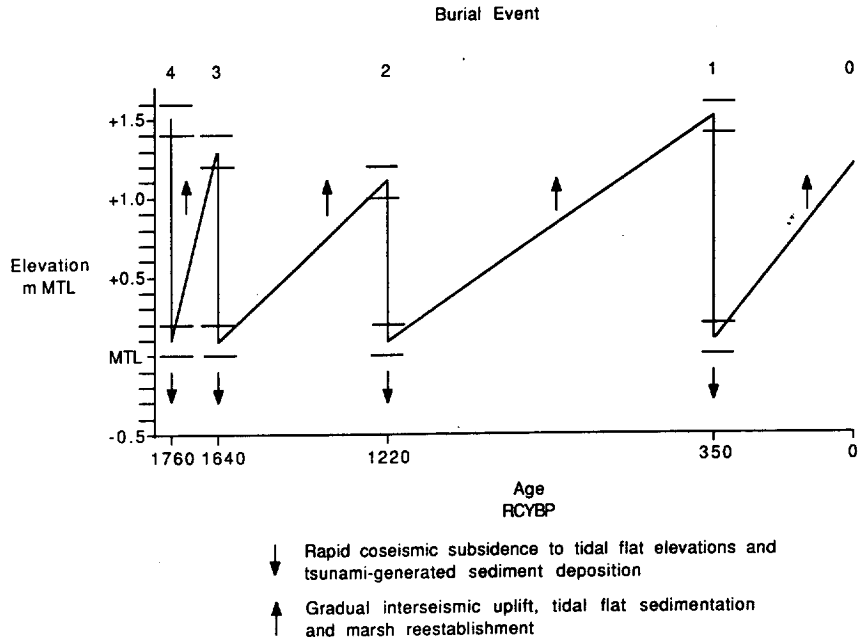


Fig. 13. Estimates of buried marsh surface elevations and tidal flat elevations relative to MTL, showing the amount of coseismic subsidence and gradual interseismic uplift plus sedimentation (net emergence) as a function of burial event ages (RCYBP) for buried peats 1-4. Preburial and postburial elevation estimates are based on diatom assemblages, percent sand, and percent organics (Table 2) measured from core site 5 horizons. Event ages are taken from Figure 12. Linear elevation increases between successive burial events are diagrammatic. The variability in rate of elevation change (emergence) during the interseismic periods are not presently known for the Netarts system.

is subsided to 0.1 m MTL (see Figure 13). Vertical accretion (measured section from site 5 in Figure 5) is subtracted from the estimated marsh top elevation of BM3 (1.3 m MTL from Figure 13) to derive the magnitude of tectonic uplift. This process is repeated for successive subsidence and accretion/uplift cycles to reconstruct the stacking of marsh burial sequences 1-4 (Figure 14).

Finally, the relative uplift (0.5-1.0 m) of the first VLO sediment layer 0S (0.7-1.1 m MTL) above the level of modern low marsh development (starting at 0.2 m MTL; Figure 5, Table 1) supports the longer-term evidence of tectonic uplift between successive subsidence events. A minimum uplift rate of 1.4 mm yr^{-1} is calculated for this most recent interseismic period using (1) the estimated elevation at the base of 0S, (2) the surveyed elevation of the lowest low marsh development, and (3) the radiocarbon age (350 years B.P.) of the buried marsh surface. As previously noted, the bayward edge of the marsh is an erosional feature, rather than one of progradation, suggesting that the interseismic uplift that produced the modern marsh surface has either greatly diminished or is terminated. Therefore the calculated uplift rate of 1.4 mm yr^{-1} for the most recent interseismic period is assumed to be conservative.

<u>Recurrence Intervals of Tectonic Subsidence</u>

Calibrated ages for five out of the upper six marsh top horizons do not overlap at the two sigma level, for example, modern (T-MM), 290-520 years B.P. (T-BM1), 970-1290 years B.P. (T-BM2), 1354-1769 years B.P. (T-BM3), and 3145-3636 years B.P. (T-BM5), as shown in Figure 12. These dates confirm stratigraphic interpretations of discrete marsh burial events separated by significant periods of intervening laminated tidal flat deposition, followed by marsh horizon development. Although an average recurrence interval of 600 years for 6 subsidence events in roughly 3600 years can be calculated, it is clearly not representative of the range in actual recurrence intervals (possibly <300 to 1000 years) measured in the Netarts marsh.

It is possible that minor subsidence events of too little displacement or of too frequent recurrence might not be recorded as distinct buried peats. For example, the stratigraphic record might not record a peat to mud transition from a minor displacement

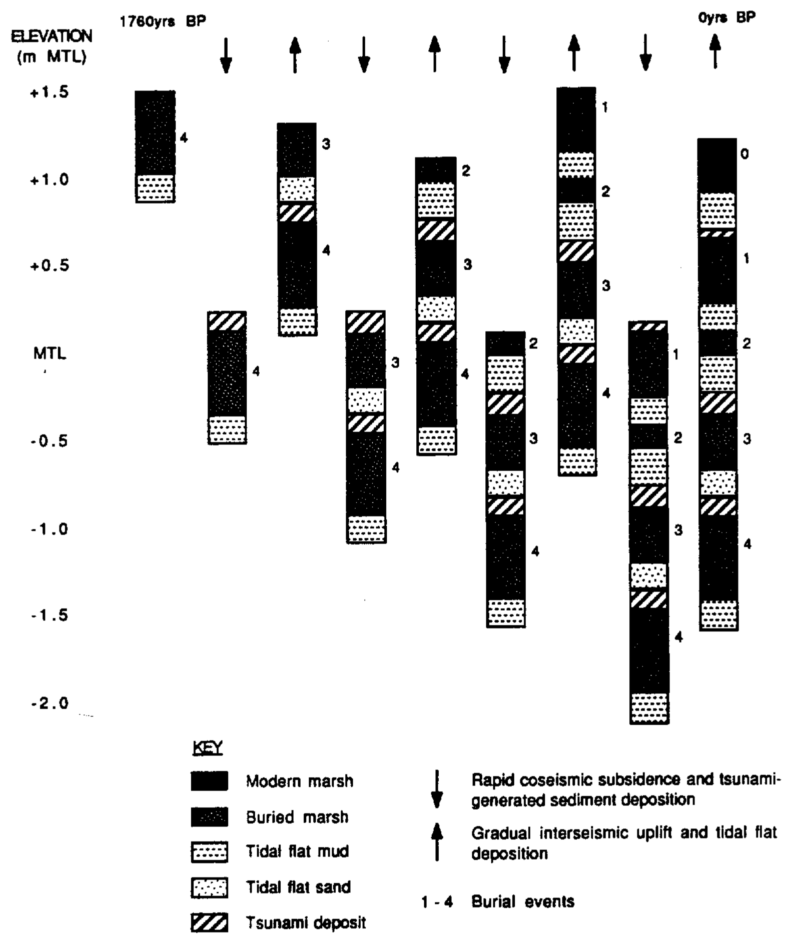


Fig. 14. Stratigraphic stacking model of rapid subsidence and gradual sedimentation plus tectonic uplift events that would produce the upper 2.5 m of the stratigraphic section at core site 5 (see Figure 5). The buried marsh surface elevations are taken from midpoints of the elevation ranges shown in Figure 13. The differences between subsidence (total vertical displacement) and section length (sediment accretion due to relative sea level rise) are attibuted to tectonic uplift, assuming little or no significant compaction of sediments after initial burial.

event (<0.5 m) but instead would show only continuous peat development. Alternatively, a marsh burial cycle might not be recorded if a subsidence event occurred prior to the recovery of the marsh from a previous burial event. However, there is no evidence of sediment capping layers in the core sequences other than those closely associated with buried marsh surfaces. For example, either (1) the SCL horizons are directly overlying buried marsh surfaces or (2) the SCL horizons above tidal flat muds correspond to adjacent SCL horizons that are in contact with marsh tops (Figure 5). This argues against the common occurrence of coseismic subsidence (tsunami-producing events) that went unrecorded due to a lack of prior marsh development.

Alternatively, one abrupt burial event (burial unit 2 in cores 5, 7, and 10) did occur in the Netarts basin without deposition of a sediment capping layer (Figure 5). The lack of a sediment capping layer (tsunami deposit) above this abruptly buried peat top, containing a sharp uneroded upper contact with tidal flat muds, is presently unexplained.

General Model of Marsh Response to Tectonic Forcing

The late Holocene marsh sequences in Netarts Bay record multiple episodes of marsh burial in response to tectonic subsidence. Marsh burial by floods or storm surges is precluded by negligible fluvial input into this coastal lagoon and by the high degree of marsh protection from ocean storm conditions by the sand spit to the west (Figure 3). Furthermore, the persistent changes in deposit elevation, following abrupt burial events, rule out marsh burial by (1) interannual changes in tidal inlet geometries, (2) short-term fluctuations in ocean circulation and sea level, or (3) distantly generated tsunamis (not associated with Cascadia subduction zone seismicity). Finally, while the consistently strong asymmetry in relative sea level changes (abrupt submergence and gradual emergence) is predicted for subduction zone tectonics, it is highly unlikely to be produced by minor oscillations of eustatic (global) sea level.

Interestingly, the interior marsh sites record both fewer subsidence events and less marsh development (thinner peats) than the perimeter marsh sites (Figure 5). Apparently, the rates of marsh reestablishment in the central marsh areas, particularly sites 8, 9, and 12, lag behind those of the more protected perimeter sites. For example, a lack of marsh recovery at site 8 after the subsidence of 4MT (Figure 5) precluded evidence of the two subsequent events of marsh burial (3MT and 2MT). In contrast, at least one burial event (2MT) is not recorded at site 6, adjacent to the barrier spit, due to the nearly continuous vertical growth of marsh flora at this site. It is clear that not all marsh sites in the coastal lagoon record the same information about past tectonic events.

The events of tectonic strain release recorded at Netarts Bay are unlikely to be the product of local folding and faulting in the upper plate. Limited exposures of late Pleistocene terraces along the eastern edge of Netarts Bay do not show evidence of substantial recent deformation [Peterson et al., 1988]. More convincingly, similar late Holocene events of abrupt marsh burial are observed in adjacent bays, Nehalem 45.7°N and Salmon 45.0°N, a few tens of kilometers to the north and south of Netarts Bay, respectively (W. Grant, personal communication, 1988). Significantly, the observed marsh burial sequences from both of the bays adjacent to Netarts Bay show the same asymmetry of coseismic subsidence followed by interseismic deposition and/or uplift that we have documented in Netarts Bay.

Finally, significant ^{14}C age overlaps are observed for at least four burial horizons (300-500, 1000-1300, 1500-1800, and 3000-3300 RCYBP) which are dated at Netarts Bay and reported for southwest Washington [Atwater, 1988]. The similarity of burial sequences (similar number of events and event age ranges) observed over at least a 200 km coastline argues for potentially synchronous events of coseismic strain release forced by subduction zone tectonics. However, much additional work is needed to constrain the sequence and timing of specific burial events to more rigorously test the potential for event synchroneity along this margin.

CONCLUSIONS

1. Episodic burials of six high marsh horizons by sediment capping layers and/or low intertidal mud flats in Netarts Bay represent system wide responses to alternating cycles of tectonic subsidence and uplift in late Holocene time.

2. Five of the burial events recorded in the Netarts marsh show very abrupt (catastrophic) marsh burial by tsunami deposits, which are consistent with coseismic subsidence associated with tectonic strain release along the central Cascadia subduction zone off northern Oregon.

3. The recurrence intervals between subsidence events range from a few hundred years to at least one thousand years, with the greatest duration between subsidence events occurring after a gradual (aseismic) subsidence interval.

4. The marsh record of abrupt tectonic subsidence in this coastal lagoon is spatially variable because of local environmental control of marsh recovery following tectonic subsidence events.

5. Several events of coseismic coastal subsidence observed at Netarts Bay have significant age overlaps with subsidence events reported for other bays in northern Oregon and in southwest Washington, suggesting the potential for event synchroneity over regional distances of at least 200 km.

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