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Stratigraphy, pollen history and geochronology of tidal marshes in a Gulf of Maine estuarine system: Climatic and relative sea level impacts

Larry G. Ward [a,*], Brent J. Zaprowski [b,1], Kevin D. Trainer [b,2], P. Thompson Davis [c]

[a] Department of Earth Sciences, Center for Coastal and Ocean Mapping, and Jackson Estuarine Laboratory, University of New Hampshire, 24 Covolos Road, Durham, New Hampshire, 03824, United States

[b] Department of Earth Sciences, University of New Hampshire, Durham, New Hampshire, 03824, United States

[c] Department of Natural and Applied Sciences, Bentley College, Waltham, Massachusetts, 02452, United States

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ABSTRACT

Sedimentologic and stratigraphic characteristics of five tidal marshes in Great Bay Estuary, New Hampshire, which is located on the western boundary of the Gulf of Maine, were assessed from 20 vibracores, detailed descriptions of surficial environments, pollen analyses, and radiocarbon dating. Modern marsh sequences in Great Bay Estuary initiated with a time-transgressive basal peat that formed at the upland-brackish marsh boundary. The oldest basal peat deposit sampled during this study was dated at ~4560 cal yr B.P. (based on an age of 4060±40 ^{14}C yr B.P.). The original tidal marshes that formed in Great Bay Estuary apparently were unable to accrete at a high enough rate to allow seaward expansion, resulting in a transgressive sequence of low marsh or mudflat sediments overlying the basal peat. The transgressive tidal marsh sequence is capped by high marsh sediments that corresponded to a slowing of relative sea-level (RSL) rise in the region and regressive seaward expansion of the tidal marshes. However, significant variations from these transgressive-regressive sequences occur in the Great Bay tidal marshes as a result of more recent marsh expansion and tidal channel migrations.

Detailed pollen analyses of a vibracore taken in a tidal marsh along Squamscott River with a sedimentary record spanning the last ~3900 cal yr B.P. exhibit five well-documented marker horizons including: 1) an increase of *Tsuga* (hemlock); 2) the appearance of *Picea* (spruce); 3) *Tsuga* and *Fagus* (beech) declines; 4) an increase in *Ambrosia* (ragweed) coupled with a sudden decrease in *Quercus* (oak); and 5) the *Castanea* (chestnut) decline. Using published ages for these pollen horizons and a calibrated ^{14}C age obtained during this study for a basal peat, accretion rates for this marsh system over five time intervals were calculated: 1) 0.4 to 0.5 mm yr^{-1} from ~3900 to 2850 cal yr B.P.; 2) 0.6 mm yr^{-1} from ~2850 to ~1960 cal yr B.P.; 3) 0.8 mm yr^{-1} from ~1960 to ~580 cal yr B.P.; 4) 0.7 to 0.8 mm yr^{-1} from ~580 to ~210 cal yr B.P.; and 5) 0.8 to 0.9 mm yr^{-1} over the last 210 years. The long-term accretion rate for the entire sequence based on the calibrated ^{14}C age of the basal peat was 0.6 to 0.7 mm yr^{-1}. This result agrees with accretion rates determined from calibrated ^{14}C ages from two other tidal marsh systems in Great Bay Estuary with accretion rates between ~0.6 to ~0.8 mm yr^{-1}. Higher accretion rates were obtained at a nearby tidal marsh with 1.2 mm yr^{-1} for just the marsh and 1.3 mm yr^{-1} for the marsh and underlying subtidal sediment.

The results of this study indicate that the sedimentology and stratigraphy of moderate-size tidal marshes in rocky, glaciated coasts are highly variable and are strongly influenced by complex interactions among RSL, climatic variations, and anthropogenic influences. For instance, the early development of many of the marshes in the Great Bay Estuary area were likely driven by changes in rates of RSL resulting in transgressive onlap boundaries, subsequently overlain by regressive intertidal marsh sequences. However, more recent changes in tidal marsh sediment composition deposited during a relatively slow, steady RSL rise likely result from other forcings, such as changes in minerogenic and orogenic sediment inputs due to anthropogenic effects, tidal channel migrations, major storms causing erosion of the marsh, or climatic changes causing shifts in sediment delivery or vegetation.

* Corresponding author. Tel.: +1 603 862 2337; fax: +1 603 862 0839.
E-mail addresses: Larry.Ward@unh.edu (L.G. Ward), bjzaprowski@salisbury.edu (B.J. Zaprowski), kdtrainer@geoinc.com (K.D. Trainer), pdavis@bentley.edu (P.T. Davis).

[1] Present address: Department of Geography and Geosciences, Salisbury University, Salisbury, Maryland, 21801, United States.

[2] Present address: GeoInsight, Inc., Westford, Massachusetts, 01886, United States.

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1. Introduction

During the last several decades, systematic studies of tidal marsh systems have led to major advances in our understanding of marsh origin, development, and maintenance (for reviews see Frey and Basan, 1985; Fletcher et al., 1993; Cahoon and Reed, 1995; Jennings et al., 1995; and Ward et al., 1998). However, accompanying these advances in our understanding has been the realization that tidal marsh systems are inherently complex and are influenced by interactions among physical, biological, and chemical processes (Torres et al., 2006). In addition, these processes tend to vary, sometimes dramatically, with shifts in climatic settings, local or relative sea-level (RSL) fluctuations, and tidal regimes.

Fletcher et al. (1993) found strong evidence that fluctuations in the rates of RSL rise shifted the balance between marine and terrestrial influences in a tidal marsh system along the mid-Atlantic seaboard of the United States, resulting in identifiable transgressive onlap boundaries and regressive sequences. However, Kelley et al. (1995) found no evidence over the last several millennia of changes in the rate of RSL rise driving shifts between emergent and submergent sequences in a tidal marsh system in the western Gulf of Maine. Rather, Kelley et al. (1995) attributed changes in composition of the salt marsh sediment column to tidal channel migration and salt panne deposits. Furthermore, Kelley et al. (2001) pointed out that shifts from high to low marsh plant zonations could be caused by a number of factors other than sea level including tidal channel migration, salt panne formation and filling, storm deposition or erosion, and ice-rafting.

Orson and Howes (1992) found that shifts in vegetation in New England salt marshes were strongly influenced by changes in the geomorphic setting, as well as RSL. Warren and Niering (1993) and Donnelly and Bertress (2001) documented changes in vegetation in tidal marsh systems driven by an acceleration in the rate of RSL rise over the last several decades. Donnelly and Bertress (2001) demonstrated a shift from high marsh to low marsh vegetation and a decrease in the organic content of the sediment in a salt marsh system in Narragansett Bay, Rhode Island (located just south of the Gulf of Maine), starting in the late 19th century and attributed this shift to an acceleration in local RSL rise increasing tidal inundations. Warren and Niering (1993) presented a model that implied that an imbalance between marsh accretion and RSL rise resulted in longer hydroperiods, increasing sediment water content (and anoxic conditions), salinity, and sulfide levels, while lowering redox potential, resulting in a change in the plant community.

Based on studies conducted further north in Nova Scotia, Jennings et al. (1995) argued that tidal marsh sediments appearing to be emergent and submergent sequences could have developed during steady RSL rise due to episodic storm events. Jennings et al. (1993) showed evidence that storm inputs could shift the balance between minerogenic and organogenic sedimentation. Stumpf (1983), Cahoon et al. (1995), and Goodbreed et al. (1998) verified the importance of storm deposition to salt marshes on the mid-Atlantic and Gulf coasts of the United States. More recently, Donnelly et al. (2001) demonstrated that major storm events such as hurricanes are recorded in tidal marsh deposits in northeastern United States. Van de Plassche et al. (2006) argued that major storms can erode marshes creating accommodation space, ultimately resulting in higher accretion rates and regressive sequences. Furthermore, storm activity could cause a shift in the balance of minerogenic versus organic driven accretion in tidal marshes.

It is clear from these studies, and others, that tidal marsh morphology, sedimentology, and stratigraphy vary considerably due to a suite of factors. Therefore, detailed studies assessing basic tidal marsh properties and processes, such as controls of minerogenic or organogenic sediment composition (Allen 1990, 1995), accretion rates and processes over varying temporal and spatial scales (Kearney and Ward, 1986; Cahoon and Reed, 1995; Ward et al., 1998; Churma et al., 2001; Churma and Hung, 2004; Leonard and Croft, 2006; Nyman et al., 2006; van Proosdij et al., 2006; Turner et al., 2006; Wood and Hine, 2007), and marsh geochronology (Fletcher et al., 1993) are needed. In addition, a range of environmental settings must be studied to evaluate regional variations in depositional environments (Torres et al., 2006). Ultimately, the integration of these studies will lead to the development of new and more refined predictive numeric models of basic processes such as tidal marsh formation and composition, tidal channel evolution, marsh hydrology, or marsh surface elevation change (Allen, 1990, 1995; Callaway et al., 1996; Rybczyk and Cahoon, 2002; D'Alpaos et al., 2006; Gardner and Wilson, 2006; Marani et al., 2006).

In this paper we synthesize the results of our studies conducted in estuarine salt marshes in Great Bay Estuary, New Hampshire, United States (Fig. 1). Depositional environments, stratigraphic relationships, pollen assemblages, and late Holocene accretion rates were examined in order to further our understanding of marsh development and the influence of external forcings such as RSL or climate change over the last several thousand years. Our results provide insights into the composition, geologic history, and controlling processes of temperate tidal marshes where biological, geochemical, and sedimentological processes tend to vary seasonally between cold harsh winters when ice impacts can be important and the summers when rapid plant growth and larger freshwater inputs can dominate. With new efforts to understand and model tidal marsh systems (Torres et al., 2006), as well as manage these valuable resources, these studies are particularly timely.

2. Site description

2.1. Relative sea level (RSL)

The late Quaternary sea-level history for the western Gulf of Maine is complex as a result of major eustatic changes and large isostatic adjustments of the crust from the Laurentide ice sheet (Belknap et al., 1987; Belknap et al., 1989a,b; Birch, 1990; Kelley et al., 1992; Gehrels and Belknap, 1993; Barnhardt et al., 1995; Kelley et al., 1995; Gehrels et al., 1996; Belknap et al., 2002). During the late Pleistocene, the Laurentide ice sheet extended across southern Maine and New Hampshire into the Gulf of Maine (Schnitker et al., 2001; Kelley et al., 1992; Belknap et al., 2002). Although limited in scope, the general deglacial history for coastal New Hampshire area was summarized in Moore (1978), largely based on a number of earlier studies conducted in Maine. According to Moore (1978), ice thickness in the Great Bay Estuary area during the maximum glacial extent was on the order of 1500 m. During deglaciation, the ice retreated northwesterly through the Great Bay region. As was described for southern Maine (Belknap et al., 1987; Hunter and Smith, 2001; Retelle and Weddle, 2001; Schnitker et al., 2001), ice retreat was probably in contact with the ocean, resulting in a marine incursion landward of the present coast and deposition of glaciomarine sediments to the marine limit in New Hampshire (Moore, 1978; Birch, 1989). Following the removal of the ice sheet, isostatic uplift of the crust led to a marine regression. The magnitude of the RSL lowstand has been debated, but extensive studies conducted in Maine argue convincingly for a RSL at ~55 to ~60 m below present (Belknap, 1987; Shipp et al., 1989; Kelley et al., 1992; Belknap et al., 2002). Following the lowstand between ~11,000 and ~10,800 yr B.P., RSL transgressed rapidly until between ~10,000 and ~9000 yr B.P., then very slowly until ~7000 yr B.P., then continued to rise, but not as rapidly as in the early Holocene, until ~5000 to ~4000 yr B.P. (Barnhardt et al., 1995; Belknap et al., 2002). A well-constrained RSL curve for the last 4000 years has been developed based on studies conducted in the backbarrier salt marshes at Wells, Maine, located ~45 km to the north of Great Bay Estuary, and is most applicable to this study (Gehrels, 1994; Kelley et al., 1995; Gehrels et al., 1996; Gehrels et al., 2002). Kelley et al. (1995) reported RSL rise at Wells

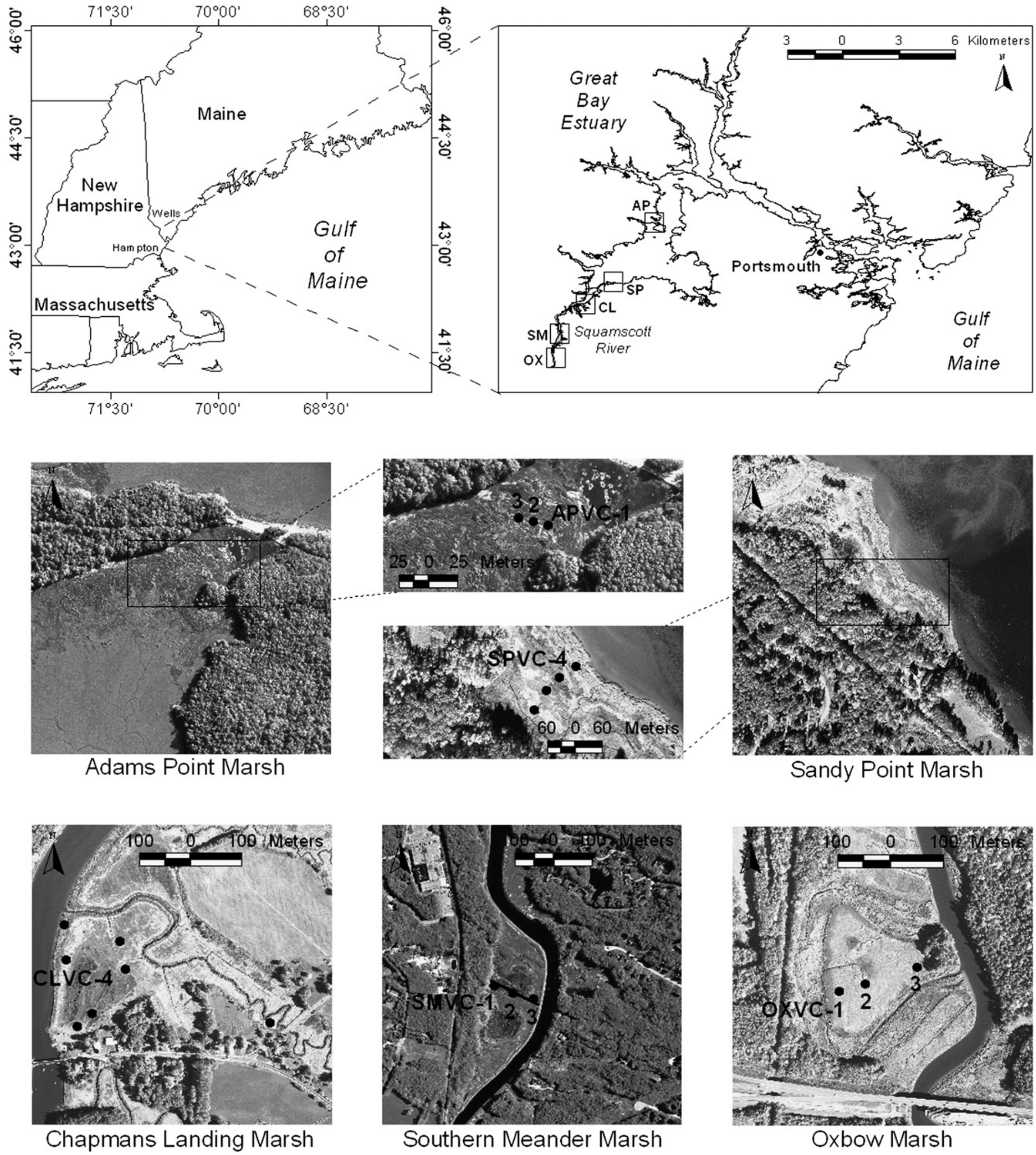

Fig. 1. Location map of the study sites in Great Bay Estuary, New Hampshire. Five estuarine tidal marshes were cored during this study including Adams Point Marsh (AP), Sandy Point Marsh (SP), Chapmans Landing Marsh (CL), Southern Meander Marsh (SM), and Oxbow Marsh (OX). The locations of each of these sites are shown in the upper right figure. Vertical aerial photographs of the marshes show the locations of the vibracores discussed in the text. The solid line in the image of Southern Meander Marsh marks the location of the surface transect sampled to describe modern marsh environments.

was about 0.8 mm yr^{-1} at 4000 yr B.P., 0.4 mm yr^{-1} at 2000 yr B.P., and 0.2 mm yr^{-1} at 1000 yr B.P. Gehrels et al. (2002) showed that the rate of RSL rise at Wells, and other locations in Maine, has accelerated over the last several centuries and has risen ~30 cm since ~1800 A.D.

The displacement of the New Hampshire coastline as a result of the RSL changes described above was summarized in Ward and Adams (2001). Due to the magnitude of the changes in RSL in the Gulf of Maine, the position of the New Hampshire shoreline shifted over 40 km. During the maximum transgression with ice retreat, the ocean flooded inland approximately 25 km. During the maximum regression, the coastline was ~15 km seaward of its present position.

2.2. Great Bay Estuary

Great Bay Estuary is located at the boundary between Maine and New Hampshire on the western margin of the Gulf of Maine (Fig. 1). The estuarine system is strongly influenced by outcropping bedrock and antecedent topography, as well as the character of the overlying

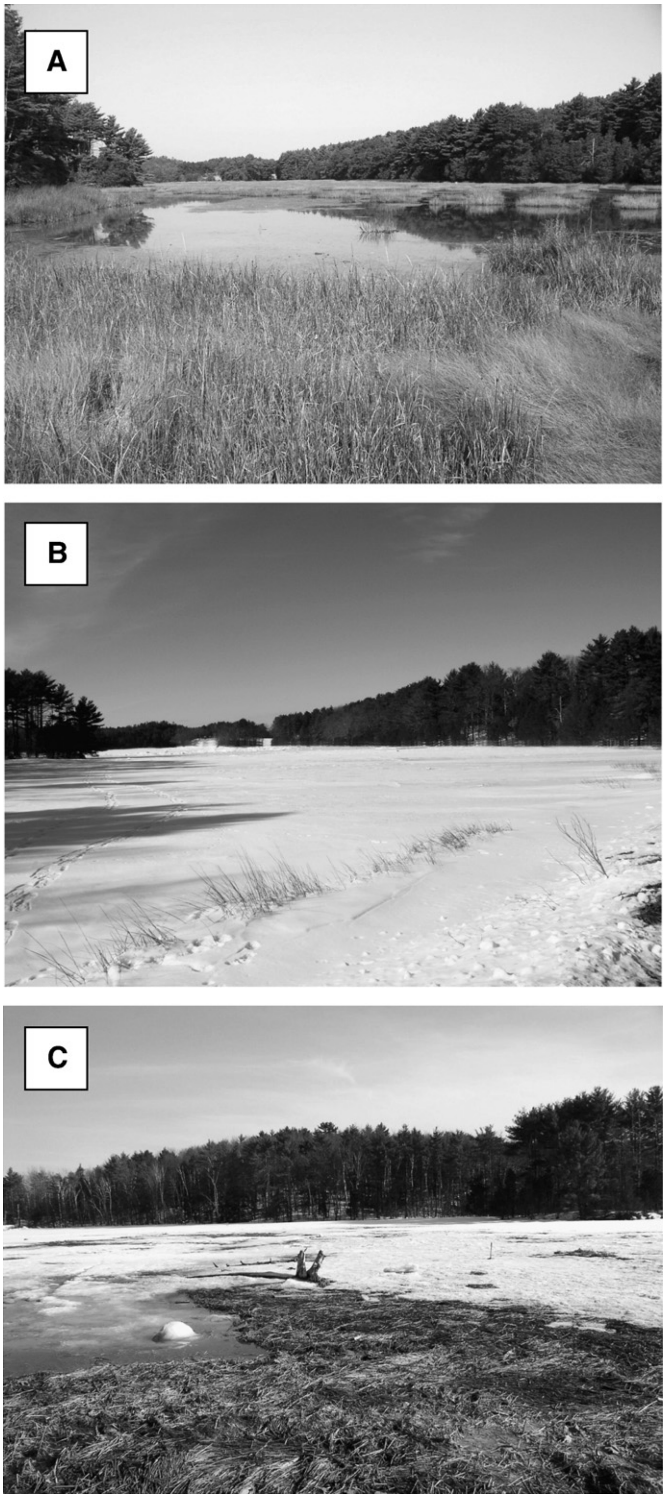

Fig. 2. Ground photographs of Adams Point Marsh (labeled as AP in Fig. 1) in August 2006 (A) and in March 2005 (B) and (C). Note the large salt panne shown in A. The image in B shows the extent of ice cover during some winter periods. The ice tends to clip or remove aboveground biomass and erodes, transports, and deposits sediment as shown in C.

Quaternary deposits (Birch, 1989; Ward, 1992; Ward and Bub, 2005). Bedrock typically underlies glacial till, sandy drumlins, stratified sand and gravel of ice-marginal deposits, or glaciomarine sediments (Birch, 1989; Koteff, 1989). Estuarine sediments cap the sequence. The glaciomarine deposits, which are commonly exposed in low-lying areas (Birch, 1990), are largely composed of silt and clays with intermittent fine sands and are equivalent to the Presumpscot Formation found in coastal Maine (Bloom, 1963). Because of the influence of bedrock on Great Bay Estuary, relatively steep nearshore gradients are common.

The largest expanses of salt marshes in Great Bay Estuary are found in the Great Bay area, especially along the Squamscott River (Fig. 1), one of three rivers that empty into the upper estuary (Ward et al., 1993). The salt marshes are defined as New England-type (Frey and Basan, 1985), which formed when river valleys were flooded by the Holocene marine transgression (McIntire and Morgan, 1964; Trainer, 1997). The tidal marshes in Great Bay Estuary are an important component of the estuarine environment, as elsewhere in the Gulf of Maine, serving as nurseries for many types of juvenile fish (Dionne et al., 1999; Eberhardt, 2004), filtering nutrients and sediments from the incoming rivers, and acting as a buffer against flooding (Burdick et al., 1997; Short et al., 2000; Morgan and Short, 2002).

Tidal marshes in Great Bay Estuary typically are composed of *Spartina alterniflora* in the low marshes and dominantly *Spartina patens* with *Distichlis spicata, Juncus gerardii,* and *Salicornia europaea* in the high marshes (Short, 1992). However, depending on the range of salinity, more complex admixtures of plants can occur in the high marsh including *Amaranthus cannabinus, Aster spp., Atriplex patula, Impatiens capensi, Iva frutescens, Limonium nashii, Lythrum salicaria, Phragmites australis, Scirpus robustus, Solildago sempervirens, Spartina pectinata, Triglochin maritimum*, and *Typha augustifolia* (Josselyn and Mathieson, 1980; Ward et al., 1993). The high marsh environment largely dominates the estuarine marshes, with salt pannes being common (Fig. 2). Many of the marsh systems are dissected by large tidal channels, as well as by some human-made drainage ditches. Forest cover adjacent to the tidal marshes is common. However, following the European settlement of the area in the early 1600s, much of the watershed in Great Bay Estuary was stripped of its forests for lumber and farming (Bampton, 1999). Subsequently, the area was farmed heavily until the mid-1800s, when agriculture shifted westward and the present forests grew back (Fitts, 1912; Hart, 1994). Today, the nearby upland areas also include combinations of open water, freshwater wetlands, fields, and urban areas in addition to forests.

The tidal range in Great Bay Estuary varies from 2.6 m (3.0 m for spring tides) at the mouth to 2.1 m (2.4 m for spring tides) at the entrance to Squamscott River in the upper estuary (NOAA, 2005). The

Table 1
Location, elevation, and recovery data for vibracores taken in Great Bay Estuary tidal marshes

Core no.	Latitude	Longitude	Elevation NAVD88 (m)	Core Length (m)	Core Surface Displacement (m)	Difference (%)
SPVC-1	43.0554972	−70.8997639	1.23	5.95	−0.01	0
SPVC-2	43.0556806	−70.8999528	1.23	5.89	0.25	4
SPVC-3	43.0558250	−70.9000389	1.16	5.92	0.28	5
SPVC-4	43.0561167	−70.9000111	0.88	5.88	0.09	1
CLVC-1	43.0414917	−70.9253111	1.19	5.22	0.05	1
CLVC-2	43.0405806	−70.9243028	1.16	4.72	0.16	3
CLVC-3	43.0398056	−70.9257722	1.30	3.87	0.23	6
CLVC-4	43.0406250	−70.9258139	1.23	7.38	0.02	0
CLVC-5	43.0399389	−70.9247139	1.21	5.37	0.17	3
CLVC-6	43.0372806	−70.9221611	1.16	3.41	0.18	5
CLVC-7	43.0396167	−70.9266139	1.30	3.18	0.09	3
SMVC-1	43.0191556	−70.9357528	1.24	2.83	0.05	2
SMVC-2	43.0188167	−70.9345917	1.24	5.90	0.38	6
SMVC-3	43.0187611	−70.9337139	1.14	3.17	0.05	1
OXVC-1	43.0025528	−70.9417278	1.03	3.78	0.21	6
OXVC-2	43.0027611	−70.9407389	1.11	5.85	0.24	4
OXVC-3	43.0030056	−70.9394083	1.12	3.00	0.24	8
APVC-1	43.0953139	−70.8698333	1.23	3.04	unknown	unknown
APVC-2	43.0953667	−70.8700389	1.12	4.46	unknown	unknown
APVC-3	43.0954278	−70.8702694	1.04	4.31	0.66	15

See Fig. 1 for locations. The core surface displacement is the difference between the elevation of the marsh surface adjacent to the core barrel versus inside the barrel at the end of the coring process. This difference was used to compute a depth correction factor for samples taken for radiocarbon dating (Table 2) and for pollen horizons (Table 3).

Table 2
Supporting information for location, type of material analyzed, radiocarbon ages, and computed accretion rates for samples taken in Great Bay Estuary tidal marshes

Location (core number)	Sample depth (cm)	Sample depth adjusted (cm)	NOSAMS lab and accession no.	Type of material dated	$\delta^{13}C$ (‰) PDB	Age (^{14}C yr B.P.)	Age (mean cal yr B.P.)	Age (2 σ min cal yr B.P.)	Age (2 σ max cal yr B.P.)	Minimum accretion rate (mm yr^{-1})	Maximum accretion rate (mm yr^{-1})
Adams Point Marsh (APVC-3)	274	323	16812 OS-11525	Basal Peat (*S. alterniflora* roots and stems)	−14.60	4060±40	4560	4540	4654	0.6	0.7
Southern Meander (SMVC-2)	251	268	16668 OS-11527	Basal Peat (*unknown*)	−25.00	3590±35	3900	3838	3959	0.6	0.7
Oxbow Marsh (OXVC-2)	134	140	16667 OS-11526	Base of High Marsh (*S. alterniflora* stems)	−12.66	1810±25	1750	1695	1775	0.8	0.8
Oxbow Marsh (OXVC-2)	550	574	16665 OS-11192	Channel Floor (tree bark)	−26.23	7590±40	8400	8317	8451	0.7	0.7
Chapmans Landing (CLVC-4)	101	same	16670 OS-11180	Base of Marsh (*S. alterniflora* stems)	−14.77	955±55	860	826	909	1.2	1.2
Chapmans Landing (CLVC-4)	730	same	16669 OS-11193	Tidal Flat (tree bark)	−28.54	4900±55	5640	5554	5686	1.3	1.3

See Fig. 1 for vibracore locations. Minimum accretion rates calculated from sample depth and mean calibrated age with no adjustment for possible compaction. Maximum accretion rates determined from adjusted sample depth (computed depth accounting for possible compaction in core). ^{14}C ages converted to calibrated years using Calib 5.0.2 (Stuiver and Reimer, 1993; Stuiver et al., 2005).

freshwater discharge into Great Bay Estuary averages ~3.1 $m^3 s^{-1}$, with strong seasonal patterns (Short, 1992). Highest average discharges occur in the late winter to early spring and commonly are associated with snow melt, while the lowest average discharges occur in summer and fall (Ward and Bub, 2005). New Hampshire has a temperate climate with distinctive seasons. The mean annual temperature for coastal New Hampshire (measured near Great Bay) is 8.9 °C (48.0 °F) for 1971–2000, with monthly averages ranging from −4.1 °C (24.7 °F) in January to 21.5 °C (70.7 °F) in July. The tidal marshes and estuarine tributaries are frequently ice covered in winter, which has major impacts on biological, chemical, and sedimentological processes (Fig. 2) (Meese et al., 1987; Argrow and FitzGerald, 2006). The mean annual precipitation is 1222.5 mm (48.13 in.), with a nearly uniform monthly pattern (NOAA, 2002). The rate of RSL rise in Great Bay Estuary measured at Portsmouth from 1926 to 1986 is 1.75 mm yr^{-1} (NOAA Tides and Currents, 2008; WWW).

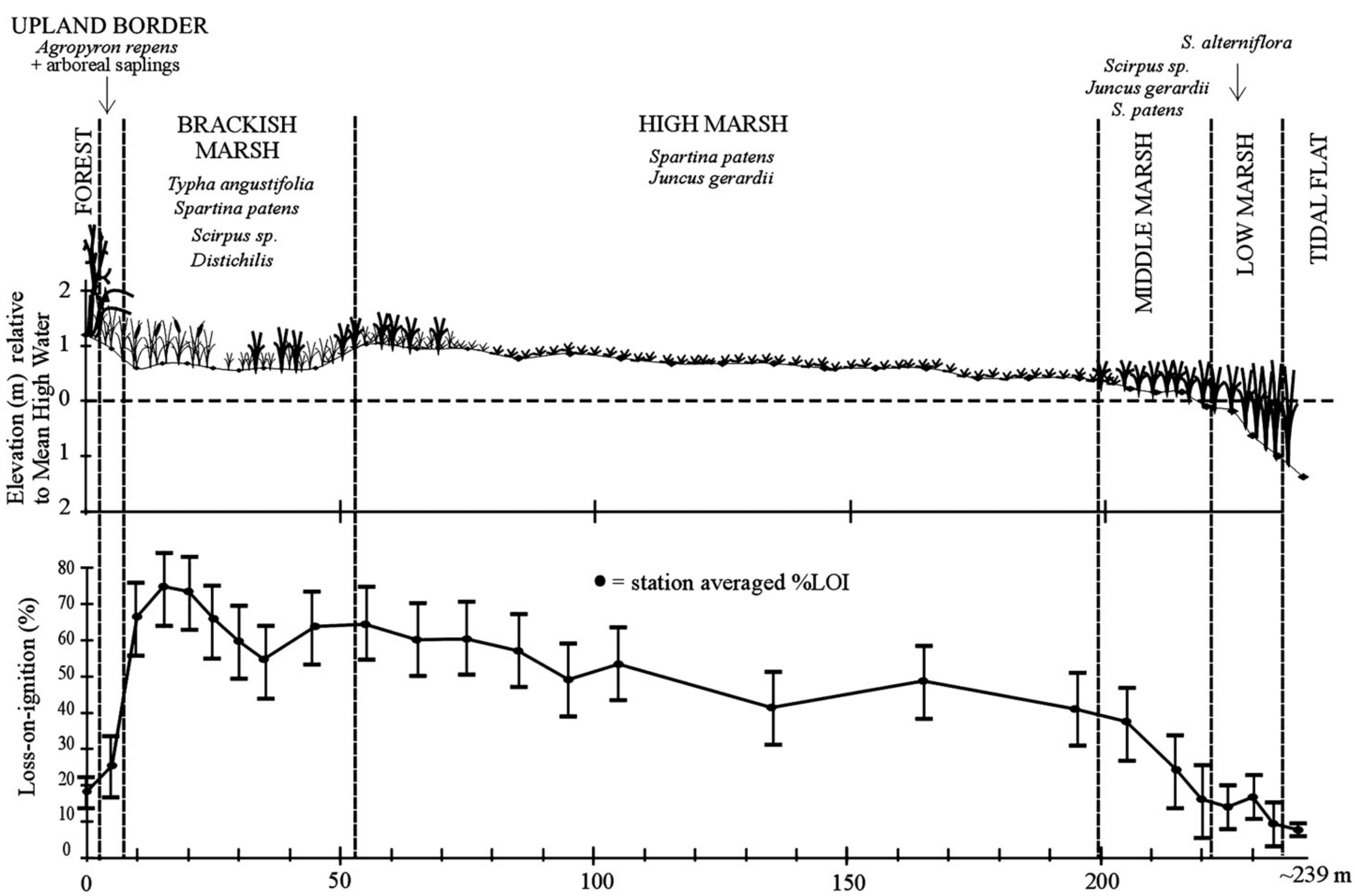

Fig. 3. Transect across Southern Meander Marsh (see Fig. 1). The transect extends from the upland border to the channel edge. The particulate organic content of the surficial marsh sediment determined from loss on ignition for each station along the transect is shown on the lower figure.

2.3. General Holocene stratigraphy

Holocene stratigraphic sequences for estuarine and tidal marsh deposits in New Hampshire were described by Haug (1976) and Keene (1970, 1971), respectively. Haug (1976) focused on the late Quaternary stratigraphy in the main tidal channel in Great Bay (Fig. 1) and found that the pre-Holocene sediments (glacial tills, outwash, marine sediments) typically underlie (often unconformably) an organic-rich layer that was dated about 9290 cal yr B.P. (8340±200 ^{14}C yr B.P.). Haug (1976) identified the organic layer as indicative of the initial Holocene transgression into upper Great Bay Estuary. In a more detailed study of the tidal marshes in Hampton–Seabrook Estuary, Keene (1970) described the Holocene sediments in the salt marshes and noted the presence of an organic-rich layer composed of the remains of twigs, leaves, and plants debris in a silty or sandy matrix directly overlying pre-Holocene sediments. The plant debris was predominantly salt marsh, but contained some fresh to brackish marsh plants. The oldest age obtained for this peat layer was about 7710 cal yr B.P. (6850±155 ^{14}C yr B.P.). Keene (1970) argued that the peat layer was likely deposited at the marine limit as the marsh transgressed over the uplands. Keene (1970) also noted that the organic-rich, time transgressive peat deposit graded upward into tidal flat or subtidal estuarine sediments, but was capped by the typical marsh building sequence of low marsh grading upward into high or brackish marsh sediments.

3. Methods

Representative modern marsh environments were sampled in summer 1997 along a 229-m transect using standard techniques. The transect, which was located on the Southern Meander Marsh study site (Fig. 1), extended from the fringing forest just above the upland boundary seaward to the adjacent tidal channel. The transect intersected vibracore site SMVC-1 ~60 m from the upland border (between stations 11 and 12). Relative elevations of the marsh surface along the transect were estimated relative to SMVC-1, which had an elevation of 1.24 m (NAVD88; Table 1), using a Brunton compass, rod, and a tape (after Compton, 1985). Cores, ranging in length from 12 to 26 cm, were collected at 31 stations along this transect and analyzed for root size and density, as well as organic content by loss on ignition (LOI). Each LOI analysis consisted of three replicas taken from near the surface of the core.

Stratigraphic relationships and subsurface sediment characteristics of five tidal marshes were determined from 20 vibracores collected in summer and fall, 1996 (Fig. 1). The vibracores, which were 7.6 cm in diameter and ranged in length from 2.83 to 7.38 m (Table 1), were collected using methods described by Lanesky et al. (1979). Each vibracore was surveyed with a total station with reference to bench-marks at Adams Point or near the mouth of the Squamscott River. Care was taken in the field and during transport of the cores not to cause compaction and to minimize any loss of the sediment column. Examination of the cores after opening revealed no evidence of compaction or disturbances (i.e., distortion of bedding planes). However, differences (typically <6%) in the elevation of the sediment surface outside the core barrel versus inside the barrel at the completion of the coring processes were observed at most of the sampling sites (Table 1). This difference between elevations was most likely due to “rodding,” where friction between the core barrel and the sediment inside the barrel essentially prohibits new material from entering the nose of the core barrel. At this point the core barrel and the sediment act as a solid

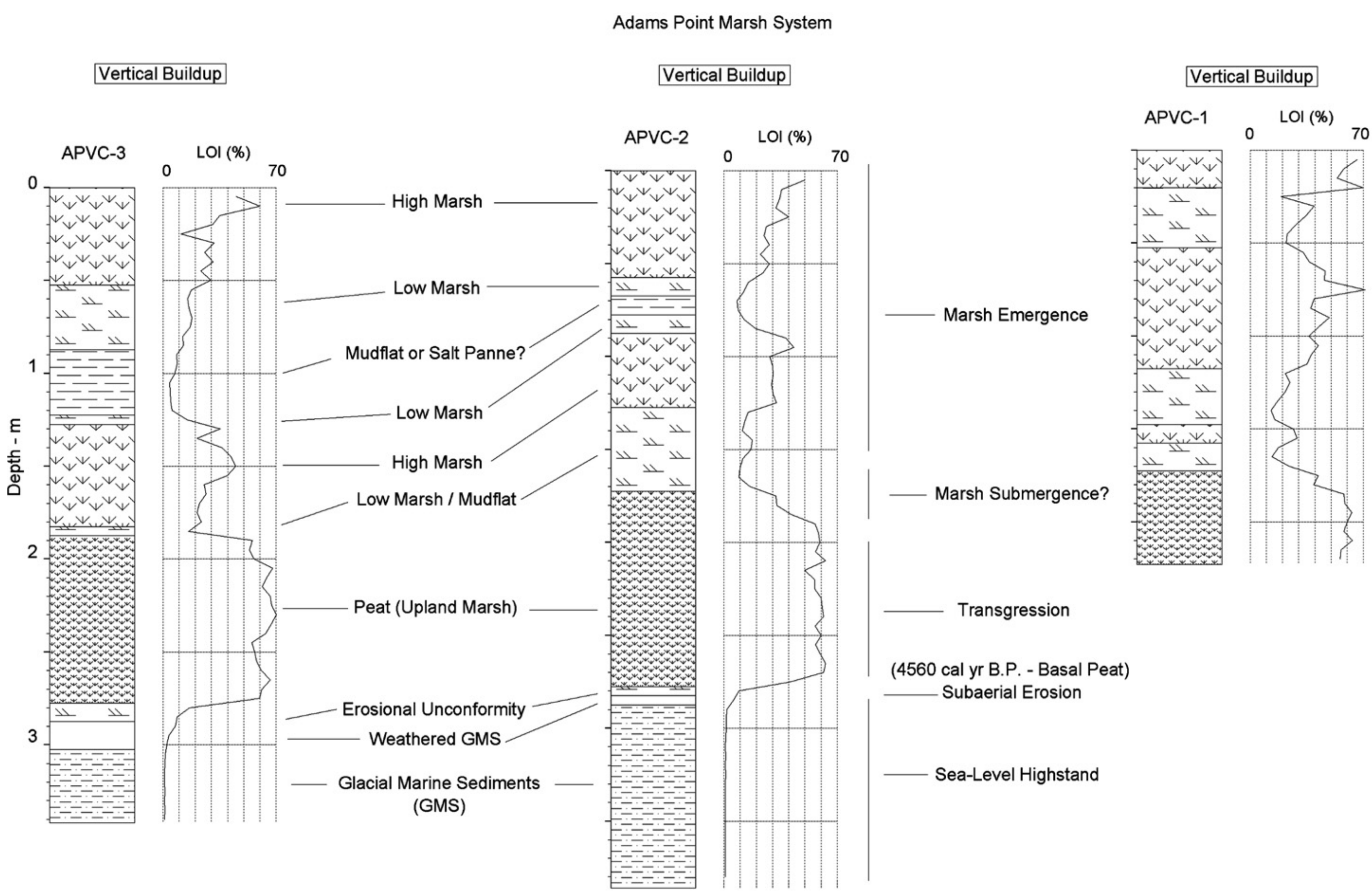

Fig. 4. Core logs, interpreted depositional environments, and major process influencing the marsh at the time of deposition for Adams Point Marsh (Fig. 1). The total distance from APVC-1 to APVC-3 is ~30 m. The depth scale is the same for all three cores. Relative elevations among the cores indicated by the vertical position in the figure. All three vibracores display stratigraphic sequences that reflect the vertical building of the marsh.

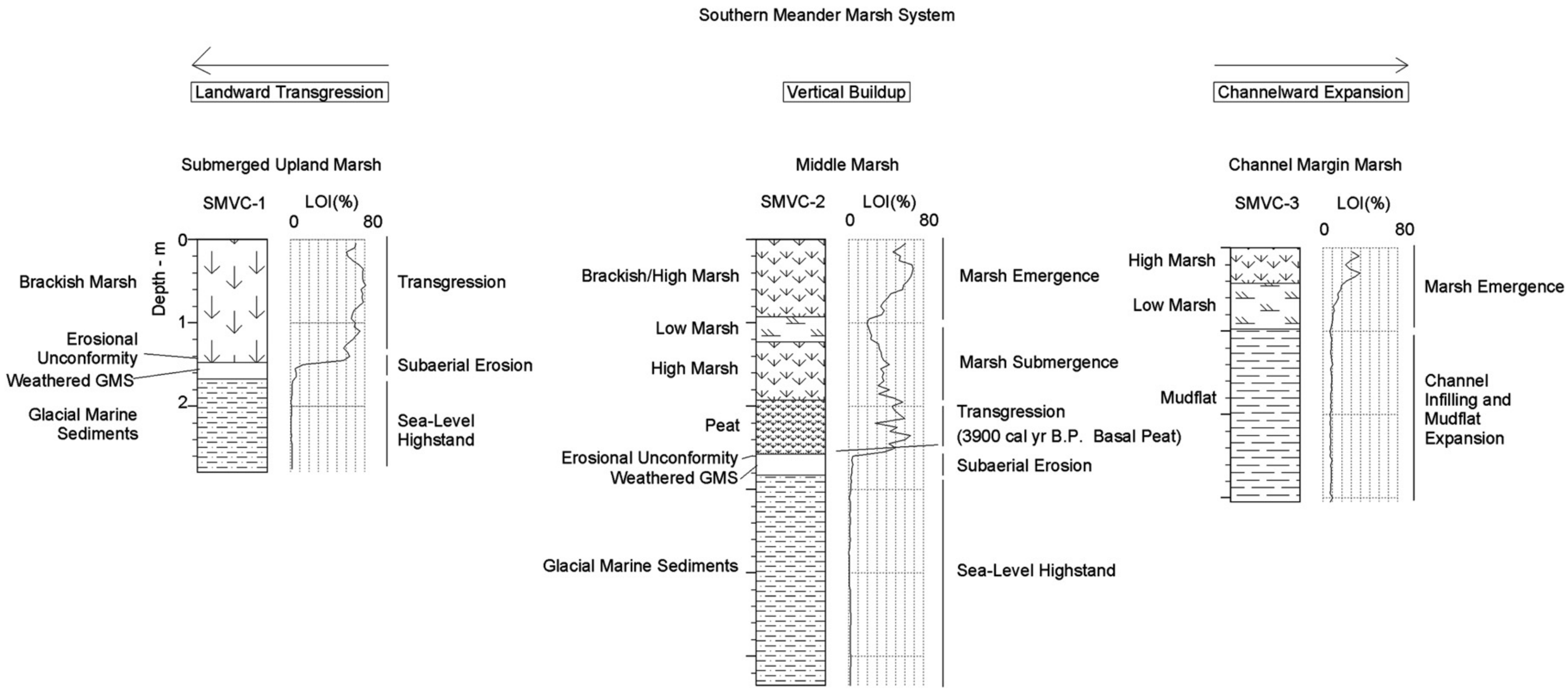

Fig. 5. Core logs, interpreted depositional environments, and major processes influencing the marsh at the time of deposition for Southern Meander Marsh (Fig. 1). The total distance from SMVC-1 to SMVC-3 is ~175 m. The depth scale is the same for all three cores. Relative elevations among the cores indicated by the vertical position in the figure. The vibracores display three stratigraphic sequences that reflect the relatively recent transgression over the upland boundary (SMVC-1), vertical buildup of the marsh (SMVC-2), and channelward expansion of the marsh (SMVC-3).

rod and continued coring simply pushes the entire unit through the sediment. Nevertheless, since it could not be discounted that compaction of the core may have occurred, all sample depths used for ^{14}C or pollen analyses and subsequently calculation of accretion rates were recomputed and adjusted so that the recovered core was the same length as the amount of penetration into the marsh (Table 1). The stratigraphic profiles and core logs were not adjusted as the small changes in almost all instances had no effect on the interpretations.

All vibracores were analyzed for sediment and root characteristics, LOI, and bulk density. Selected cores were analyzed for grain size. Six organic samples for ^{14}C dating were extracted from four of the cores. Either small bits of what appeared to be tree bark or individual *Spartina alterniflora* plant fragments were used for the ^{14}C analyses (Table 2). However, in one case (SMVC-2) the material was not identifiable (Table 2), but the stratigraphic position (basal peat), color (blackish), and $\delta^{13}C$ value (−25.00) indicated it was from the upland marsh border (Belknap et al., 1989b; Churma et al., 1987; Gehrels et al., 1996; Lamb et al., 2006). Grain size was determined on sediment samples using standard sieving and pipetting techniques described in Folk (1980). Sediment organic content was estimated by determining LOI after Ball (1964); the samples were dried in an oven at 55 °C for 24 h, and then ignited at 450 °C for 4 h. Bulk density was determined by removing a ~1–3 cc sample from the cores with a scalpel or syringe, determining volume by displacement in water (if removed by a scalpel), and weighing. Organic matter samples were ^{14}C dated with accelerator mass spectrometry (AMS) at the National Ocean Sciences Accelerator Mass Spectrometry (NOSAMS) facility at Woods Hole Oceanographic Institute, Woods Hole, Massachusetts. Radiocarbon ages were calibrated using CALIB 5.0.2 (Stuiver and Reimer, 1993; Stuiver et al., 2005). Pollen analyses were done using methods outlined in Faegri and Iverson (1989), with *Lycopodium* grains added as a tracer. At least 300 terrestrial pollen grains were counted for each sample and identified to the genus level, if possible (cf. Kapp, 1969; Richard, 1970; McAndrews et al., 1973; Faegri and Iverson, 1989; Moore et al., 1991). Species of *Poaceae* (grasses), *Quercus* (oak), *Betula* (birch), *Acer* (maple), *Picea* (spruce), and *Ostrya-Carpinus* (hornbeam) were grouped together under the genus heading, while *Pinus* grains were identified to the species level and then grouped into two categories: *Pinus strobus* (white pine) and “Other pine”. Rare grains of non-arboreal (NAP) or arboreal (AP) pollen (i.e. only seen once or twice in 35 samples) were grouped under the categories “Other NAP” and “Other AP.” Grains that could not be identified were counted but noted as “Indeterminate.”

4. Results

4.1. Modern marsh environments

Tidal marsh systems found in the Great Bay Estuary typically display distinct zonations with characteristics plants, organic content, and soil characteristics that have been frequently described for salt marshes along the eastern seaboard of the United States (Redfield, 1967, 1972; Harrison and Bloom, 1977; Niering and Warren, 1980; Frey and Basan, 1985; Kennish, 1990; Fletcher et al., 1993; Kelley et al., 1995). Although some of the smaller fringing marshes in Great Bay Estuary are primarily composed of low marshes, the more mature

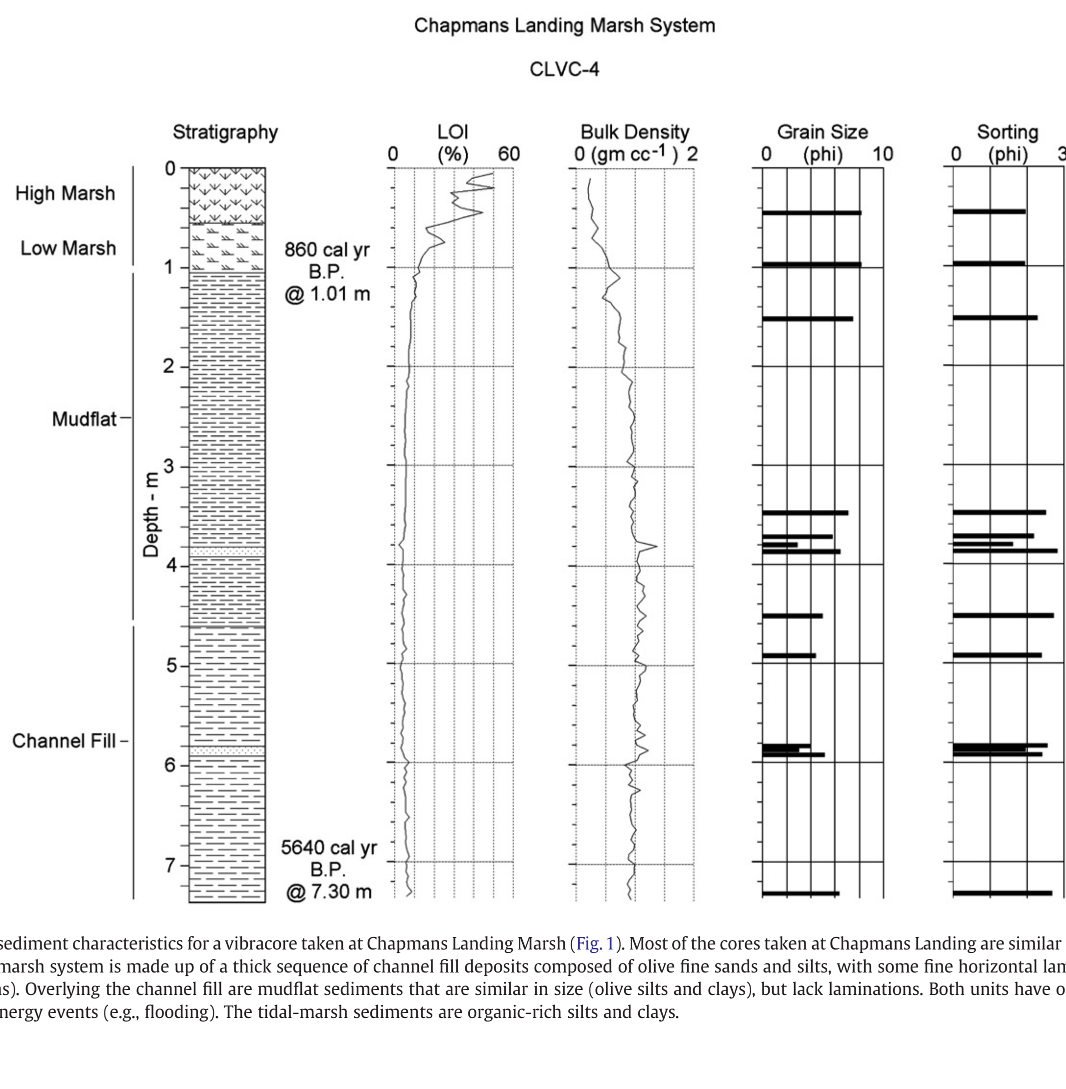

Fig. 6. Core log and sediment characteristics for a vibracore taken at Chapmans Landing Marsh (Fig. 1). Most of the cores taken at Chapmans Landing are similar to CLVC-4 and are not included here. The marsh system is made up of a thick sequence of channel fill deposits composed of olive fine sands and silts, with some fine horizontal laminations and organic debris (sticks, acorns). Overlying the channel fill are mudflat sediments that are similar in size (olive silts and clays), but lack laminations. Both units have occasional sand lenses indicative of high-energy events (e.g., flooding). The tidal-marsh sediments are organic-rich silts and clays.

systems, such as those sites sampled during this study, contain a full range of environments from terrestrial/palustrine to marine intertidal. For example, the sediments at the upland border adjacent to the forest in the Southern Meander Marsh (Fig. 1) tend to be blackish in color with moderate organic content (mean LOI = 26 ± 8.5%, see Fig. 3). *Agropyron repens* and *Myrica gale* are the major vegetation types. Just seaward of the upland border, the brackish marsh subenvironment is composed largely of *Typha angustfolia*, *Scirpus* sp., *Distichilis* sp., and *Spartina patens*, which form organic-rich (mean LOI = 66 ± 10%), black-brown muds. Standing water is common in this area. The brackish marsh transitions abruptly into the high marsh environment, the largest subenvironment in the tidal marshes in Great Bay Estuary (Ward et al., 1993). Vegetation consists of *Juncas gerardii* common closest to the brackish marsh boundary and predominantly *S. patens* with some *Distichilis sp*. The sediments are organic-rich (mean LOI = 53 ± 10%) and brown to dark brown in color. Within this subenvironment are several large salt pannes that frequently contain standing water. Between the high and low marsh, a transitional or middle marsh occurs that has vegetation types similar to the high marsh environment (*S. patens*, *Juncus gerardii*, *Scirpus* sp.), but dark brown soils with lower organic content (mean LOI = 27 ± 10%). The low marsh environment is dominated by *S. alterniflora* and has gray-brown muddy soils with low organic content (mean LOI = 15 ± 6%). The surface elevation of the marsh quickly declines through the low marsh, grading into the tidal flats. The tidal flats are composed predominately of gray sediments with very low organic content (mean LOI = 9 ± 1%) and no vegetation.

4.2. Stratigraphic relationships

4.2.1. Holocene marsh stratigraphy

Two vibracores taken at Adams Point Marsh (APVC-2 and APVC-3; Fig. 4) and one vibracore from the middle of the Southern Meander marsh (SMVC-2; Fig. 5) are representative of the marsh building processes where it appears that tidal channel migrations or channel-ward or upland expansions have not occurred. Hence, these sites likely depict tidal marsh development from the initial marine transgression through the modern marsh building process. Underlying the marsh stratigraphic sequence are glaciomarine sediments composed of cohesive, blue-grey silts and clays with some silty sands. The glaciomarine sediments, which tend to underlie many of the Holocene deposits found in Great Bay Estuary, were deposited during the late Quaternary marine incursion that occurred during the deglaciation of the Gulf of Maine. Subsequent subaerial exposure caused by crustal rebound created an erosional unconformity on the surface of the glaciomarine sediments. As a result, the uppermost portion of the

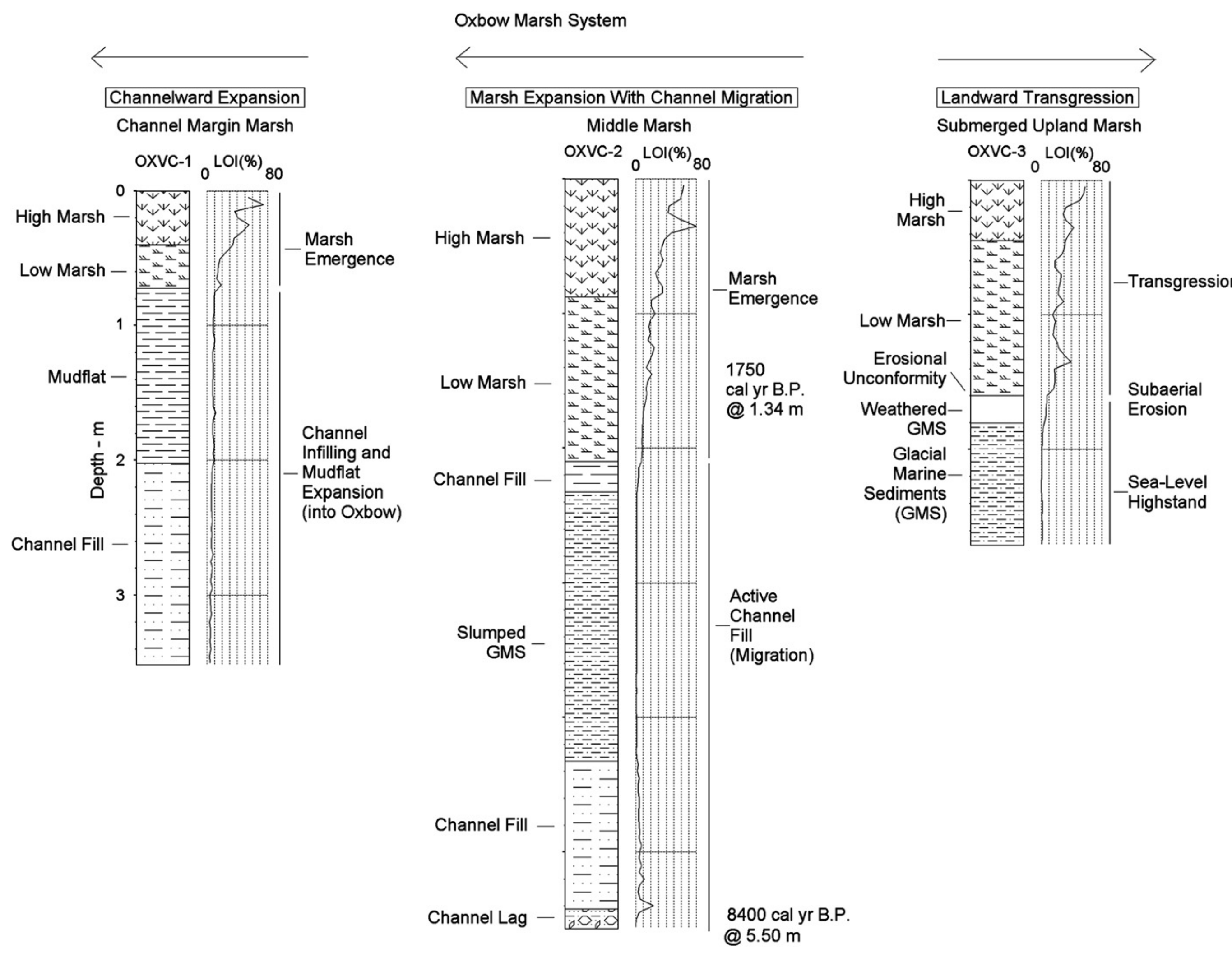

Fig. 7. Core logs, interpreted depositional environments, and major processes influencing the marsh system at the time of deposition for Oxbow Marsh (Fig. 1). The total distance between OXVC-1 and OXVC-3 is ~180 m. The depth scale is the same for all three cores. Relative elevations among the cores indicated by the vertical position in the figure. The vibracores display three stratigraphic sequences that reflect the recent transgression over the upland boundary (OXVC-3), meandering of the main estuarine tributary tidal channel (OXVC-2), and the tidal channel being cutoff with an oxbow forming (OXVC-1).

glaciomarine sediments has a rusty-orange weathered zone indicating subaerial exposure. At the Southern Meander Marsh site, the glaciomarine sediments contain medium to coarse sand lenses up to 50 cm thick that may represent subaqueous outwash deposition.

Above the weathered glaciomarine unit, the sediments rapidly change into organic-rich material with flakes of mica and plant macrofossils (e.g., twigs, sparse pine needles). This organic-rich layer, also called the basal or transgressive peat, overlies the glaciomarine sediments and marks the boundary of the initial marine transgression at that location. Based on comparison to the characteristics of the surface transect, the basal peat is interpreted as the forest and upland border subenvironments (Figs. 3–5). Radiocarbon dating of the basal peat at Adams Point Marsh and Southern Meander Marsh yielded ages of 4560 cal yr B.P. (4060 ± 40 ^{14}C yr B.P.) and 3900 cal yr B.P. (3590 ± 35 ^{14}C yr B.P.), respectively (Table 2).

Directly above (e.g., 240–190 cm in SMVC-2) the forest/upland border section, LOI increases to ~50–70% and the sediments have a dark brown to black color, high root density, and a texture similar to "coffee-grounds." The high LOI values and stratigraphic position indicate that this unit is likely the brackish or upper high marsh environment. This entire sequence, including the forest/upland border and brackish and upper high marsh, is analogous to the time-transgressive peat deposited during the latest marine transgression that has been previously described in the region (McIntire and Morgan, 1964; McCormick, 1968; Keene, 1970, 1971; Haug, 1976; Kelley et al., 1995; Trainer, 1997).

The organic content of the sediment column directly above the transgressive peat gradually decreases, indicating a shift towards low marsh environments. In SMVC-2 (Fig. 5), the LOI decreases from nearly 60% at 190 cm to 18% at 97 cm and the sediment becomes grayish in color and has low root density. However, the sediment column is capped at both locations by the typical marsh building sequence of low marsh transitioning back into high marsh. For instance, the organic content in core SMVC-2 gradually increases from 18% at 97 cm to nearly 70% at 26 cm, indicating a shift back towards high marsh environments. However, from 26 cm to the surface, the organic content of the sediments fluctuates. Here, the marsh sediments are brownish silts and clays with generally lower organic content.

4.2.2. Effect of marsh expansion and channel migrations

The Holocene tidal marsh sequence described in the previous Section 4.2.1 was not found at all sites sampled during this study. Furthermore, within a single marsh system, the stratigraphic sections also varied depending on the location. For example, while the core taken in the middle of the marsh system at Southern Meander (SMVC-2) appears to record the initial marine transgression and the marsh building process, the most landward core (SMVC-1) is typical of submerged upland marshes (Fig. 5). Here, brackish marsh deposits overlie weathered glaciomarine sediments reflecting the more recent marine transgression of the landward edge of the marsh over the upland (Stevenson et al., 1986; Ward et al., 1998). Similarly, core SMVC-3 taken at the channel margin has a thin marsh sequence over channel fill and/or mudflat deposits formed as the marsh expanded channelward (Ward et al., 1998). Keene (1970) found similar patterns in the backbarrier marshes at Hampton-Seabrook Estuary, located ~15 km to the southeast along the coast of New Hampshire.

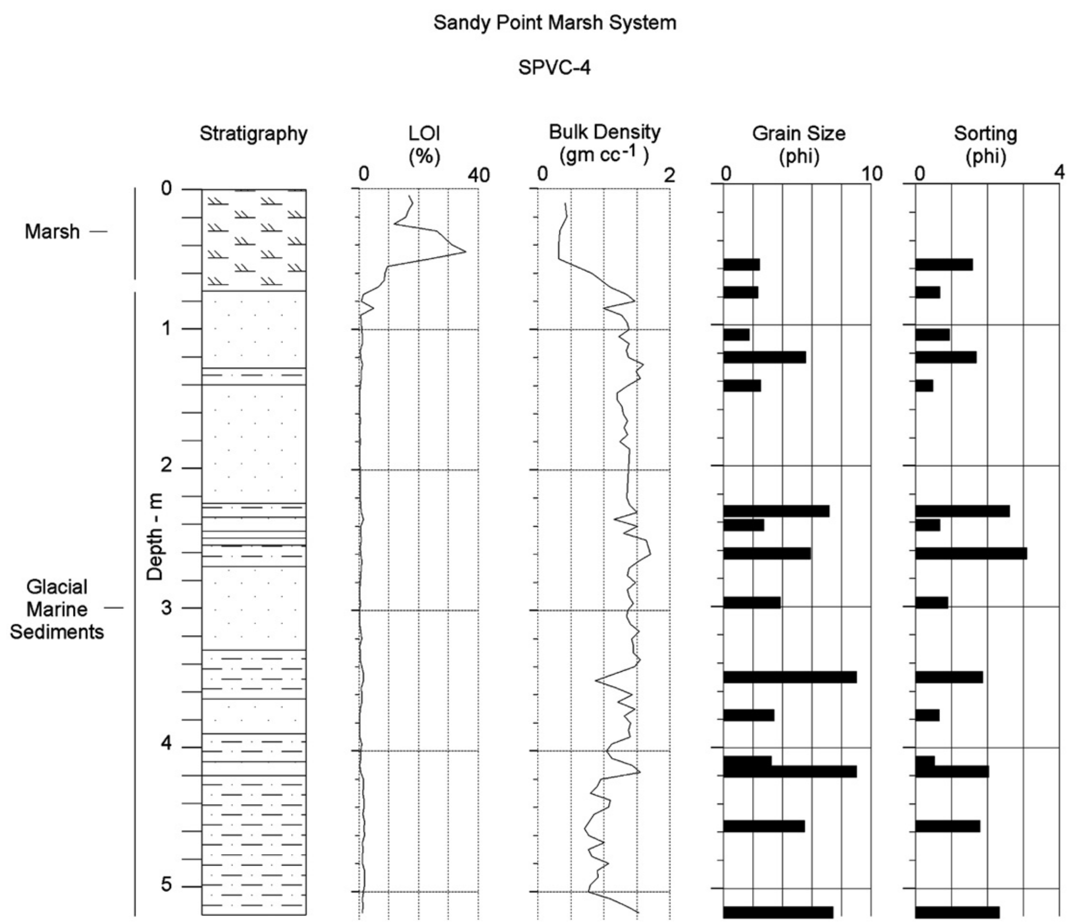

Fig. 8. Core log and sediment characteristics for a vibracore taken at Sandy Point Marsh (Fig. 1). The tidal marsh at Sandy Point overlies glaciomarine sediments consisting of sand lenses (dotted pattern), likely deposited by submarine glacial discharge, interbedded with muddy marine sediments of the Presumpscot Formation (dashed lines). The sand lenses tend to be buff to gold, fine to medium sands near the marsh deposits, becoming gray, fine sands at depth. The glaciomarine sediments are gray silts and clays. The marsh sequence capping the core consists of brownish silts and clays, along with fine to medium sands deposited during storm events.

Whereas the variability in tidal marsh stratigraphy over relatively short distances is demonstrated at the Southern Meander Marsh system as a result of changes in depositional environments (recent transgression over uplands or channelward expansion), the stratigraphic sections found at Chapmans Landing (Fig. 6) and Oxbow Marsh sites (Fig. 7) display the impacts of channel migration and abandonment. At these sites, the sediments are dominated by tidal channel deposits or subtidal estuarine deposits that transition upward into low, then high marsh sediments. For example, the marsh section cored at OXVC-2, located near the middle of Oxbow Marsh (Figs. 1 and 7), clearly shows an active channel fill sequence with a channel lag deposit and a large slump block of the glaciomarine sediments (blue-grey muds with some fine sand) that was likely eroded from the channel bank as meandering occurred. The channel lag deposits are composed of olive silts grading downward into laminated sands with wood debris. The marsh sediments capping the sequence are brown silts and clays with increasing organic content towards the surface. In contrast, the marsh site cored at OXVC-1 was a low-energy environment at the margin of an abandoned channel and is primarily composed of fine-grained silts and clays with increasing organic content upward. This sequence is similar to sequence found at SMVC-3, a channel margin location at the Southern Meander Marsh (Fig. 5).

Other variations also occur in the tidal marsh sequences in Great Bay Estuary. For instance, at Sandy Point the tidal marshes have developed directly over glaciomarine sands (likely deposited subtidally) that interfinger with fine-grained sediments of the Presumpscot Formation (Fig. 8). In addition, the seaward edge of the Sandy Point marsh has coarse-grained sediments within the modern marsh, likely eroded from the sandier subtidal sediments that lie seaward of Sandy Point and deposited on the adjacent marsh surface during storm events. Ward et al. (1998) described similar deposits in a tidal marsh in Chesapeake Bay that was located adjacent to an open bay where significant wave energy could develop, creating small coarser-grained deposits during storms.

4.3. Pollen distribution

Core SMVC-2 was chosen for the description of pollen assemblages because the stratigraphic analyses showed no erosional unconformities or other evidence of a hiatus in the Holocene sediments. Therefore, the sediment column likely contains an uninterrupted sequence for the last ~3900 cal yr B.P. (3590 ^{14}C yr B.P.) (Table 2). Results of the pollen analyses reveal distinctive changes from the basal peat to the surface that are consistent with pollen studies conducted elsewhere in New England, largely lakes and bogs (Davis, 1969, 1983; Davis et al., 1975, 1980; Webb et al., 1983; Davis and Jacobson, 1985; Gaudreau and Webb, 1985). Consequently, the pollen stratigraphy sheds light on events occurring within the Squamscott River watershed and provides a general geochronology for the sediment column.

The chief arboreal pollen types found at 250 cm depth directly above the unconformity in the glaciomarine sediments, which signifies the base of the Holocene sedimentary package, are *Pinus strobus* (white pine), *Quercus* (oak), *Castanea dentata* (chestnut), and *Betula* (birch) (Fig. 9). There are also minor amounts of *Acer* (maple),

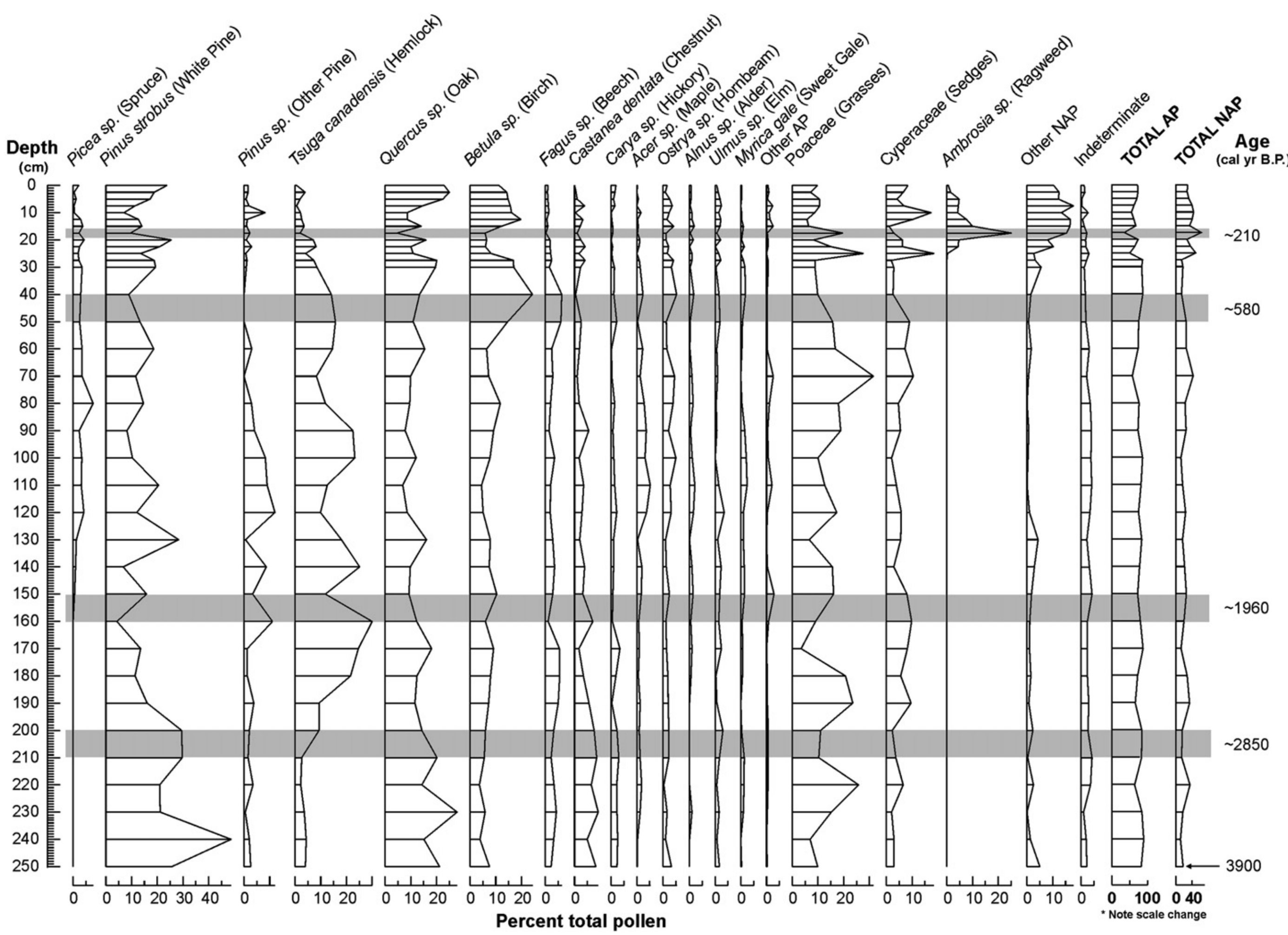

Fig. 9. Pollen assemblages found in the Holocene sediments in vibracore SMVC-2 in the middle of the Southern Meander Marsh. The stratigraphy below the marsh consisted of glaciomarine sediments with little pollen. See Fig. 1 for location and Fig. 5 for the stratigraphy of SMVC-2.

Fagus (beech), *Tsuga* (hemlock), *Ostrya* (hornbeam), *Ulmus* (elm), and *Carya* (hickory). The non-arboreal pollen components at 250 cm depth consist chiefly of *Cyperaceae* (sedges) and *Poaceae* (grasses). From 250 to 190 cm depth the amounts of *Quercus*, *Pinus strobus*, *Carya*, and *Castanea dentata* generally decrease from the base upward. *Tsuga* percentages started out low at the bottom of the Holocene sediments (250 cm depth), but rapidly increase at 200-210 cm depth to become one of the dominant forest species. With the exception of *Tsuga*, it appears from the pollen assemblages in the core that the forest composition of the area was fairly consistent from 200 to 50 cm depth, although all species fluctuate independently. From 200 to 50 cm depth *Quercus*, *Pinus strobus*, *Tsuga*, *Castanea dentata*, and *Betula* are the dominant species with minor amounts of *Fagus*, *Acer*, *Picea* (spruce), *Ulmus*, and *Alnus* (alder). *Picea* first appears at 150–160 cm depth. At 40–50 cm depth, changes take place among several species, as *Tsuga* begins to go into a decline that continues to the surface, *Pinus strobus* declines slightly, and *Quercus, Betula,* and *Ostrya* increase. At 30–40 cm depth, *Fagus* begins to decrease. Overall, arboreal species compose over 80% of the pollen at the 40–50 cm depth. However, at 25 cm depth, a sharp decline occurs in almost every arboreal species. At the same time, percentages of all non-arboreal species begin to increase. Exotic non-arboreal species such as *Ambrosia* (ragweed) also begin to appear. This trend reverses around the 10 cm depth as *Pinus strobus*, *Betula*, *Quercus*, *Picea* and *Carya* increase and non-arboreal species decrease. *Castanea dentata* begins to decline at the 5 cm depth and disappears from the record at the top of the core.

5. Discussion

5.1. Holocene accretion rates and marsh geochronology

5.1.1. Based on radiocarbon dating

Accretion rates of four of the marshes studied in the Great Bay Estuary were estimated from six ^{14}C ages (Table 2). The average accretion rate for the core from Southern Meander Marsh (SMVC-2), based on an age of ~3900 cal yr B.P. (3590±35 ^{14}C yr B.P.) for an unidentified plant fragment taken from a basal peat at a depth of 251 cm (268 cm if adjusted for compaction), is 0.6 mm yr^{-1} (0.7 mm yr^{-1} adjusted) (Fig. 5, Table 2). This accretion rate agrees with the long-term accretion rate (~0.6 to ~0.7 mm yr^{-1}) determined from a ^{14}C age on a basal peat (a *Spartina alterniflora* fragment) from Adams Point Marsh (APVC-2, Fig. 4). The plant fragments used for the ^{14}C analyses from the Southern Meander Marsh and from Adams Point Marsh were from the basal peat that represents the initial Holocene transgression at that location.

Accretion rates determined from *Spartina alterniflora* fragments from nearer the surface of marsh deposits at the Oxbow Marsh (OXVC-2) and Chapman Landings (CLVC-4) were higher than those determined for the basal peat. For instance, the ^{14}C age from a *Spartina alterniflora* fragment taken from 134 cm depth (140 cm if adjusted for compaction) from the Oxbow Marsh (OXVC-2) had an age of ~1750 cal yr B.P. (1810±25 ^{14}C yr B.P.) giving an accretion rate of 0.8 mm yr^{-1} (Fig. 7; Table 2). The ^{14}C age for a *Spartina alterniflora* fragment from 101 cm depth from Chapmans Landing (CLVC-4) was ~860 cal yr B.P. (955±55 ^{14}C yr B.P.), indicating an accretion rate of ~1.2 mm yr^{-1} (Fig. 6; Table 2). The increase in the accretion rate as the marshes become younger is not unexpected and partially reflects the relatively high proportion of the sediments that are low marsh, increased sediment input since European colonization (Ward et al., 1998), the high rate of RSL rise that has occurred over the last two centuries (Donnelly, 2006a), and minimal autocompaction.

The long-term accretion rate for the entire core from Chapmans Landing Marsh based on the ^{14}C age (~5640 cal yr B.P.) of a tree bark fragment collected at 730 cm depth was high as well (1.3 mm yr^{-1}), indicating relatively rapid deposition in a channel fill-tidal flat sequence capped by a thin marsh (CLVC-4, Fig. 6). In contrast, the accretion rate determined from a ^{14}C age (~8400 cal yr B.P.)on tree bark from channel lag deposit at 550 cm depth (574 cm if adjusted for compaction) in the Oxbow Marsh (OXVC-2) was relatively low at 0.7 mm yr^{-1} (Fig. 7; Table 2). The low accretion rate may not be representative of the channel fill sequence since the tree bark found in the channel lag deposit used to date the core could have been eroded from an older deposit.

5.1.2. Based on pollen geochronology

Five major dated horizons (Fig. 9) were identified in core SMVC-2 from Southern Meander Marsh based on well-documented local and regional shifts in pollen assemblages and include the following.

1. An increase in *Tsuga* initiates at 200–210 cm below the marsh surface. This increase corresponds to a recovery of *Tsuga* that occurred between ~2850 cal yr B.P. (Davis, 1969; Winkler, 1982; Allison et al., 1986) and ~3500 cal yr B.P. (Fuller, 1998) from a parasitic disease that decimated the species at ~5500 cal yr B.P. For this study, the 2850 cal yr B.P. age has been assigned for the horizon because of the proximity of the study area (within New Hampshire) used by Allison et al. (1986). Furthermore, 2850 cal yr B.P. is a more reasonable age for the horizon location in the stratigraphic column and yields a more consistent accretion rate for the time period.
2. *Picea* appears at 150–160 cm depth, corresponding to an increase observed at many locations in the New England area at ~1960 cal yr B.P. (Deevey, 1951; Davis, 1969, 1983; Davis et al., 1975, 1980; Webb et al., 1983; Gaudreau and Webb, 1985; Gajewski, 1988).
3. *Tsuga* begins to decrease at 40–50 cm depth corresponding to a major decline at ~580 cal yr B.P. over a wide region of northeastern United States (Davis et al., 1980; Spear et al., 1993; Campbell and McAndrews, 1994). *Pinus strobus* also declined during this time (Davis et al., 1980).
4. *Ambrosia* concentrations peak and *Quercus* declines at 15–20 cm depth. Brush and DeFries (1981), Brush et al. (1982), Brush (1984), Clark and Patterson (1984, 1985), Kearney and Ward (1986), and Kearney et al. (1994) have demonstrated that shifts in arboreal and non-arboreal pollen species in tidal marshes reflect the impact of European settlers in the surrounding watersheds. Gehrels et al. (2002) documented an increase in *Ambrosia* in salt marshes in Maine and assigned a date of ~1760 A.D. due to rapid population growth. Historical data from southeastern New Hampshire place the beginning of the European settlement in this region at ~1631 A.D. (Fitts, 1912; Nelson, 1965). The *Ambrosia* peak, along with the decrease in *Quercus,* represents the height of land clearing and agricultural activities and is assigned a date of ~1785 A.D. for this study (Webb, 1973; Davis, 1976; Brugam, 1978; Winkler, 1985; Hart, 1994; Bampton, 1999).
5. *Castanea* (chestnut) begins to decrease at 5 cm depth, which agrees with the well-known pathogen-caused chestnut decline starting in ~1915 A.D. (Anderson, 1974; Allison et al., 1986).

Using the unadjusted mid-points of the depth intervals over which the pollen horizons occurred, the published ages of correlated pollen horizons, and the ^{14}C age from the basal peat in SMVC-2, the geochronology and the accretion rates for five time intervals over the last ~3900 cal yr (~3590 ^{14}C yr B.P.) were estimated for core SMVC-2: 1) ~0.4 mm yr^{-1} from ~3900 to ~2850 cal yr B.P.; 2) ~0.6 mm yr^{-1} from ~2850 to ~1960 cal yr B.P.; 3) ~0.8 mm yr^{-1} from ~1960 to ~580 cal yr B.P.; 4) ~0.7 mm yr^{-1} from ~580 to ~210 cal yr B.P.; and 5) 0.8 mm yr^{-1} over the last 210 years (Fig. 10, Table 3). The accretion rates were also computed using the adjusted mid-point of the depth interval for the pollen horizons, which makes little difference in the results (Table 3).

In general, the estimated accretion rates using the pollen horizons agree reasonably well with accretion rates determined from the ^{14}C ages from this study and with other reported observations for salt marshes in the region (Keene, 1971; Orson and Howes, 1992). In addition, these accretion rates are well within the range expected considering published RSL rise estimates over similar periods (Kelley

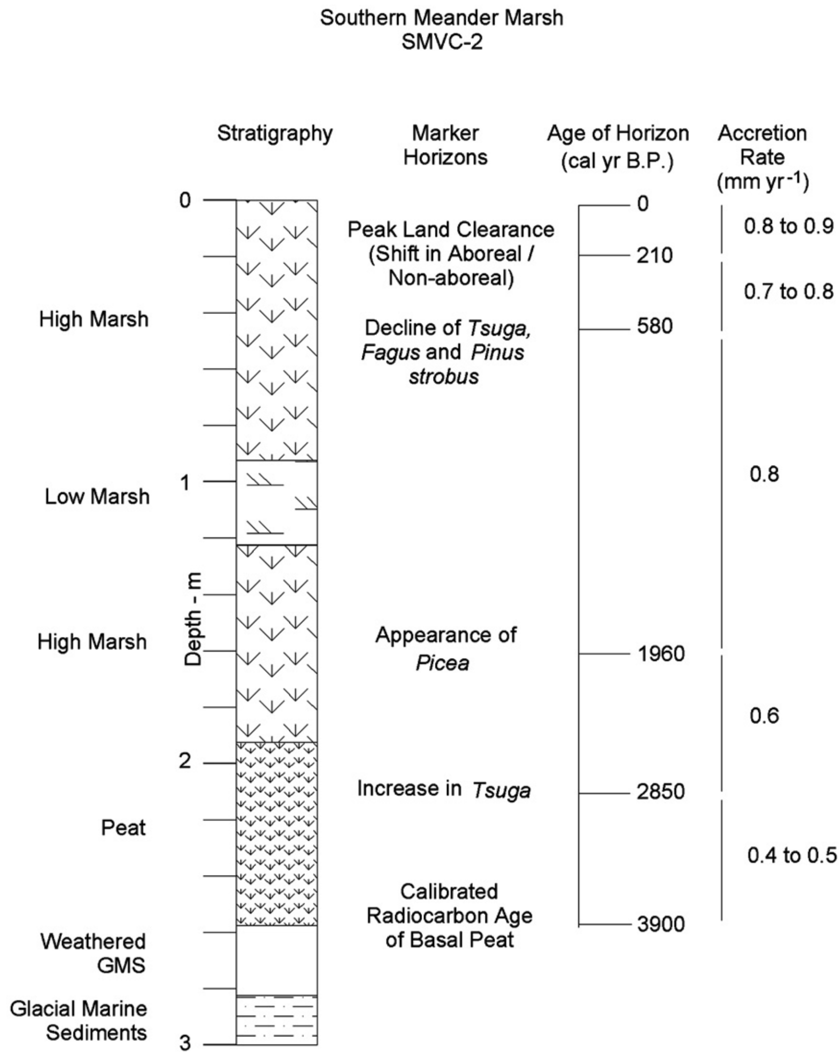

Fig. 10. Pollen marker horizons, sediment column geochronology, and accretion rates for core SMVC-2.

et al., 1995; Gehrels et al., 1996; Gehrels, 1999; Donnelly et al., 2004; Donnelly, 2006a). Furthermore, the increase in accretion rates as the salt marsh becomes younger is not unexpected. Undoubtedly, the highest accretion rate occurring over the most recent interval (last ~210 years) is caused or enhanced by the two- to three-fold increase in RSL rise over the last century (Donnelly et al., 2004; Donnelly, 2006a) and the increase in inorganic sediment supply (Kearney and Ward, 1986). In contrast, the trend of decreasing accretion rates as the marsh sediments become older at Southern Meander Marsh is most likely caused in part by autocompaction of the sediment column with time (Gehrels et al., 1996, 2002; Gehrels, 1999).

5.1.3. Recent accretion rates

Although the accretion rate at Southern Meander Marsh for the last ~210 years was the highest measured during this study based on pollen horizons for predominantly high marsh sediments, it likely underestimates more recent accretion rates significantly. For example, accretion rates based on ^{210}Pb and ^{137}Cs profiles (Ward, 1994) for two high marsh sites in Great Bay Estuary (Adams Point and Chapmans Landing) were close to or exceeded the recent local RSL rise of ~1.75 mm yr^{-1} measured by a tide gage in Portsmouth Harbor (NOAA Tides and Currents, 2008; WWW). In addition, recent accretion rates based on measuring changes in the elevation of the marsh surface at several sites in Great Bay Estuary over the last decade (Boumans et al., 2002) are also similar to or exceed recent rates of RSL rise. This increase in accretion rates over the recent past (last century) is a well-documented phenomenon that has been recorded at many sites along the eastern seaboard of North America (Kearney and Ward, 1986; Orson and Howes, 1992; Orson et al., 1998; Fletcher et al., 1993; Roman et al., 1997; Varekamp and Thomas, 1998; Ward et al., 1998; Gehrels, 1999; Van de Plassche, 2000; Churma et al., 2001; Donnelly and Bertress, 2001; Kearney, 2001) and in England (Long et al., 1999; Plater et al., 1999). For instance, Goodman et al. (2007) reported accretion rates for marshes along the coast of Maine over a 17-year period from 1986 to 2003 between 1.4 and 4.2 mm yr^{-1}, averaging 2.8 mm yr^{-1}.

5.2. Relative sea level, climatic, and anthropogenic effects on salt marsh stratigraphy and composition

5.2.1. Effect of late Holocene relative sea-level rise

The development of the general stratigraphic sequences found in the tidal marshes of Great Bay Estuary was strongly influenced by RSL fluctuations starting with a marine regression with a lowstand between ~11,000 and ~10,800 yr B.P. (Belknap et al., 2002) in the western Gulf of Maine that resulted in the erosion of the surface of the pre-Holocene glaciomarine sediments. The lowstand was followed by a transgression and deposition of organic-rich upland and high marsh sediments that initiated a transgressive onlap boundary. Two of the salt marshes cored during this study, Adams Point Marsh (APVC-2; Fig. 4) and Southern Meander Marsh (APVC-2; Fig. 5), clearly reveal

Table 3
Marsh accretion rates based on pollen horizons (dated from the literature) and a calibrated ^{14}C age for a vibracore taken in Southern Meander Marsh (SMVC-2)

Sample depth (cm)	Adjusted sample depth (cm)	Pollen horizon or radiocarbon age	Age of horizon (^{14}C yr B.P.)	Age of horizon (cal yr B.P.)	Accretion rate surface to horizon (mm yr^{-1})	Accretion rate surface to adjusted horizon (mm yr^{-1})	Time period (cal yr B.P.)	Minimum accretion rate for Interval (mm yr^{-1})	Maximum accretion rate for interval (mm yr^{-1})
2.5	2.5	Decline in *Castanea*	–	~100	–	–	–	–	–
17.5	18	Peak land clearance (shift in aboreal/ non-aboreal species)	–	~210	0.8 (0–17.5 cm)	0.9 (0–18 cm)	Present to ~210	0.8 (0–17.5 cm)	0.9 (0–19 cm)
45	47	Decline of *Tsuga, Fagus,* and *Pinus strobus*	~550	~580	0.8 (0–45 cm)	0.8 (0–47 cm)	~210 to ~580	0.7 (17.5–45 cm)	0.8 (19–47 cm)
155	162	Appearance of *Picea*	~2000	~1960	0.8 (0–155 cm)	0.8 (0–162 cm)	~580 to ~1960	0.8 (45–155 cm)	0.8 (47–162 cm)
205	214	Rebound in *Tsuga*	~2750	~2850	0.7 (0–205 cm)	0.8 (0–214 cm)	~1960 to ~2850	0.6 (155–205 cm)	0.6 (162–214 cm)
251	262	Radiocarbon age of basal peat	~3590	~3900	0.6 (0–251 cm)	0.7 (0–262 cm)	~2850 to ~3900	0.4 (205–251 cm)	0.5 (214–262 cm)

See Fig. 1 for core location and Fig. 5 for stratigraphy. Sample depth is the mid-point of the depth interval identified for the pollen horizon. The adjusted depth is the mid-point of the depth interval allowing for possible compaction. The accretion rate (surface to horizon) shows the average accretion rate for the sediment column from the surface to the dated horizon. The accretion rate (surface to adjusted horizon) is based on the adjusted sample depth. The minimum accretion rate is for the time interval between horizons based on the ages and the unadjusted sample depth. The maximum accretion rate for interval is based on the adjusted depths. The accretion rate based on the decline in *Castanea* was not computed as the sampling interval does not provide great enough resolution to determine accurately the horizon.

the transgressive onlap boundary above the erosional unconformity in the glaciomarine sediments. Overlying the erosional unconformity are forest/upland to low marsh sediments. The transgressive onlap boundary initiated at ~4560 and ~3900 cal yr B.P. at Adams Point Marsh and at Southern Meander Marsh, respectively.

Although there are several processes observed in tidal marshes that can cause a shift from upland or high marsh to low marsh environments with an accompanying decrease in organic content, including storm erosion and salt panne formation (Kelley et al., 2001), the initial changes in marsh composition (organic content) demonstrated in cores APVC-2 and SMVC-2 are attributed at least in part to RSL rise from ~4000 to ~3000 cal yr B.P. Despite the slowing of RSL rise in the region from earlier Holocene rates (Belknap et al., 1989a), RSL appears to have still outpaced accretion and created an accretionary deficit. Evidence of RSL rise outpacing sediment deposition during the early marine incursion can be found in the accretion rates estimated from the pollen horizons identified in core SMVC-2 from Southern Meander Marsh (Table 3) and from the RSL curve for nearby Wells, Maine (~40 km to the northeast). For instance, the accretion rate in core SMVC-2 from ~3900 to ~2850 cal yr B.P. in the lower portion of the marsh sequence is on the order of 0.4 to 0.5 mm yr^{-1} (Table 3), whereas the rate of RSL determined at nearby Wells, Maine at ~4000 yr B.P. is 0.8 mm yr^{-1} (Kelley et al., 1995). Although other factors are clearly involved, such as underestimating the rate of sediment accretion due to autocompaction or differences in RSL in Great Bay Estuary as compared to Wells, Maine, it appears an accretionary deficit may have occurred during this interval that caused or contributed to a transgressive sequence or a reduction in the organic content of the marsh sediments. Ultimately, an accretionary deficit can lead to increased flooding of the marsh surface (Stevenson et al., 1986) and longer hydroperiods (Cahoon and Reed, 1995), resulting in a shift towards more salt tolerant or low-marsh plant species, and higher rates of inorganic sedimentation (Warren and Niering, 1993; Ward et al., 1998). This shift has been seen at several other locations in the region (Keene, 1971; Haug, 1976), increasing the probability that it is related to an accretionary deficit.

Above the apparent transgressive sequence in the marshes at Adams Point (APVC-1 and APVC-2) and Southern Meander Marsh (SMVC-2), a progression from low marsh to high marsh occurs indicating a marsh building or regressive sequence. This marsh building sequence is seen in SMVC-2 from ~100 to ~30 cm depth. Part of the reason for the likely expansion of the marsh and the increase in organic content of the marsh sediments is the continued slowing of RSL and relatively high sediment accretion rates. For instance, the rate of marsh accretion in SMVC-2 from ~1960 to ~580 cal yr B.P. was on the order of 0.8 mm yr^{-1} (Table 3). However, the rate of RSL rise at ~2000 cal yr B.P. at Wells, Maine, had slowed to ~0.4 mm yr^{-1} and by ~1000 yr cal yr B.P. RSL had slowed to 0.2 mm yr^{-1} (Kelley et al., 1995). Again, other factors are undoubtedly involved, but marsh accretion rates substantially exceeding local RSL would push towards a positive accretionary balance. Ultimately, the positive accretionary balance would lead to expansion of high-marsh (less salt tolerant) plant species and a shift from minerogenic to more organogenic sedimentation. The shift towards the higher organic content (LOI) of the sediments from ~100 to ~30 cm of core SMVC-2 may reflect this trend.

5.2.2. Climatic effects

Organogenic input to salt marshes and consequently organic content of the sediments is strongly influenced by primary productivity and preservation of organic matter, which, in turn, is linked to the salinity of the substrate (Niering and Warren, 1980). Salinity of an estuarine marsh is not only controlled by tidal fluctuations, but also by variables such as height of the groundwater table, river discharge, and the amount of precipitation that falls onto the marsh surface and in the watershed (de Rijk and Troelstra, 1997; Hughes et al., 1998; Cronin et al., 2000). Regional climate change, particularly precipitation, or lack thereof, influences all of these variables. A number of recent studies have shown that the precipitation patterns have changed significantly over the Holocene (Cronin et al., 2000; Newby et al., 2000; Shuman et al., 2001; Shuman and Donnelly, 2005). Although it is not possible with the data at hand from this study to relate specific climate variations to shifts in marsh vegetation (e.g., low or high marsh species) or changes in the organic content of the sediment column, it is reasonable to assume that climatic fluctuations causing changes in fluvial discharge and salinity have had an impact on the composition of the tidal marshes in Great Bay Estuary.

Along with shifts in temperature and precipitation, it has been well documented in recent studies in northeastern United States that the frequency and intensity of storms has varied over the Holocene (Noren et al., 2002; Donnelly, 2006b). The impact of storm activity eroding marshes and ultimately forcing longer periods of inundation and higher inorganic sedimentation rates cannot be discounted (Stumpf, 1983; Jennings et al., 1993, 1995; Cahoon and Reed 1995; Cahoon et al., 1995; Roman et al., 1997; Goodbreed et al., 1998; Donnelly et al., 2001; Van de Plassche et al., 2006). Ultimately, these effects could cause a shift in the balance of minerogenic versus organic driven accretion in tidal marshes.

At two of our study sites (Adams Point Marsh and Southern Meander Marsh; Figs. 4 and 5, respectively), the low marsh sediments overlying the high marsh environment, as indicated by a decrease in organic content, may be the result of other forcings such as shifts in climatic patterns or storm erosion in the tidal marshes, rather than an accretionary deficit as discussed above. This explanation is especially true for Adams Point Marsh, which is located within Great Bay and more exposed to potentially erosive forces. In contrast, the changes in marsh composition seen at the Southern Meander Marsh, located along the Squamscott River, may reflect changes in river discharge and precipitation in the watershed.

Clearly, the concept that climatically-controlled changes in salt-marsh processes needs to be given consideration in the study of salt-marsh development and composition over time (cf. Varekamp et al., 1992; Fletcher et al., 1993; Nydick et al., 1995; Van de Plassche et al., 1998; Varekamp and Thomas, 1998; Van de Plassche, 2000). Thus, the fluctuations in the composition of the marsh in the sediment column from cores APVC-1 and APVC-2 at Adams Point Marsh and from core SMVC-2 at Southern Meander Marsh may have been forced, at least in part, by changes in precipitation, cooler weather, or increases in storm activity.

5.2.3. Anthropogenic effects

Previous studies have shown that changes in inorganic sediment inputs related to land clearing over the last two centuries certainly had an impact on accretion rates and marsh composition (Brush et al., 1982; Kearney and Ward, 1986; Stevenson et al., 1988; Ward et al., 1998; Gehrels et al., 2002). Kearney and Ward (1986) demonstrated that accretion rates in marshes along the Nanticoke River in Chesapeake Bay (United States) nearly doubled in a number of areas over the last century compared to the early 19th century, most likely due to increases in inorganic sediment supply related to clearing of the watersheds (Meade and Trimble, 1974; Meade, 1982) and the increase in the rate of RSL rise. Furthermore, the impacts of an increase in RSL rise, inorganic sediment loading, or changes in salinity may be enhanced by ditching in the salt marshes (Orson and Howes, 1992; Warren and Niering, 1993). Since the forests in the watershed around Great Bay Estuary were cleared, largely for ship building, the decreases in LOI content near the surface seen in most of the vibracores taken during this study (Zaprowski, 1998) and the higher accretion rate over the last two centuries in core SMVC-2, are likely related at least in part to higher inorganic sediment runoff.

6. Conclusions

The stratigraphic characteristics, sediment column geochronology, long-term accretion rates, and pollen history of mesotidal, temperate estuarine salt marshes in Great Bay Estuary were assessed from the mapping of modern depositional environments, vibracores, radiocarbon dating, and pollen analysis. Collectively, this dataset provides insights into the controls of marsh development and composition for Gulf of Maine tidal marshes in estuarine settings. Based on the results of this study, the following conclusions are made.

1. Basal peat from two tidal marshes in upper Great Bay Estuary found at depths of 2.51 m and 2.74 m below the surface during this study were identified as transgressive marsh deposits and dated at ~3900 cal yr B.P. (3590±35 ^{14}C yr B.P.) and ~4560 cal yr B.P. (4070±40 ^{14}C yr B.P.), respectively.
2. Determination of pollen assemblages in marsh sediments identified five marker horizons previously described and dated in the literature including the following: the rebound of *Tsuga* (assigned an age of ~2850 cal yr B.P. for this study); the appearance of *Picea* (~1960 cal yr B.P.); the decline of *Tsuga*, *Fagus*, and *Pinus strobus* (~580 cal yr B.P.); an increase of non-arboreal species, especially *Ambrosia* coupled with a sudden decrease of arboreal species, especially *Quercus*, (~210 cal yr B.P.); and a dramatic decrease in *Castanea* (~1915 A.D.).
3. ^{14}C ages (~4560 and ~3900 cal yr B.P.) of basal peat indicate that the long-term accretion rates for the marsh sequences in Great Bay Estuary were ~0.6 to 0.7 mm yr^{-1}. However, more recent accretion rates based on ^{14}C ages of marsh deposits over the last ~1750 and ~860 cal yr B.P. were 0.8 and 1.2 mm yr^{-1}, respectively. Determination of accretion rates over varying time intervals based on pollen horizons from a sediment core indicate a gradual increase over the last ~3900 cal yr B.P. from 0.4 to 0.5 mm yr^{-1} at the base of the marsh sediments (−3900 cal yr B.P.) to 0.8 to 0.9 mm yr^{-1} over the last 210 years. More recent accretion rates (within the last century) are likely significantly higher.
4. Changes in depositional environments and resulting tidal marsh composition and stratigraphic sequences are largely driven by changes in RSL when viewed over the last several millennia. However, local changes in marsh stratigraphy results from internal processes such as marsh expansion and tidal channel migrations. Also, shifts in the organic content of the marsh sediment column over the last several centuries likely also reflect the influence of climate fluctuations and anthropogenic influences.

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