700 yr sedimentary record of intense hurricane landfalls in southern New England

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ABSTRACT

Five intense (category 3 or greater) hurricanes occurring in 1635, 1638, 1815, 1869, and 1938 have made landfall on the New England coast since European settlement. Historical records indicate that four of these hurricanes (1635, 1638, 1815, and 1938) and hurricane Carol, a strong category 2 storm in 1954, produced significant storm surges (>3 m) in southern Rhode Island. Storm surges of this magnitude can overtop barrier islands, removing sediments from the beach and nearshore environment and depositing overwash fans across back-barrier marshes, lakes, and lagoons. In a regime of rising sea level, accumulation of marsh, lake, or lagoon sediments on top of overwash deposits will preserve a record of overwash deposition.

We examined the record of overwash deposition at Succotash salt marsh in East Matunuck, Rhode Island, and tested the correlation with historical records of intense storms. Aerial photographs taken after hurricanes in 1954 and 1938 show overwash fans deposited at the site. Analysis of 14 sediment cores from the back-barrier marsh confirmed the presence of these fans and revealed that 4 additional large-scale overwash fans were deposited within the marsh sediments.

The four overwash fans deposited since the early seventeenth century at Succotash Marsh matches the historical record of significant hurricane-induced storm surge. These fans were most likely deposited by hurricanes in 1954, 1938, 1815, and either 1638 or 1635. Radiocarbon dating of two prehistoric overwash fans indicated that these were deposited between A.D. 1295–1407 and 1404–1446 and probably represent intense hurricane strikes. In the past 700 yr, at least 7 intense hurricanes struck the southern Rhode Island coast and produced a storm surge that overtopped the barrier at Succotash Marsh.

Keywords: barrier beaches, overwash, Rhode Island, salt marshes, storms.

INTRODUCTION

Intense category 3, 4, and 5 landfall hurricanes can result in substantial loss of life and resources. In addition, intense hurricanes also result in significant alteration of coastal sedimentary environments, and in appropriate depositional settings a geologic record of these events can be preserved (Davis et al., 1989). Potential links between human-induced climate change and the frequency and intensity of tropical cyclones (Emanuel, 1987; Henderson-Sellers et al., 1998) and the recent concentration of resources and population in areas where intense hurricanes may strike (Pielke and Landsea, 1998) necessitate examination of decadal- to millennial-scale variability in hurricane activity. Although historical records of North American hurricanes date back 370 yr, reliable records maintained by the National Oceanic and Atmospheric Administration (NOAA) only go back to the late nineteenth century (Neumann et al., 1993). To extend the observation period for intense hurricane strikes, we used sediment cores to reconstruct the overwash history of Succotash salt marsh in southern Rhode Island. We matched this record to the historic record of storms, and we established the age of prehistoric overwash deposition dating back to A.D. 1300.

Back-barrier salt marsh sediments can contain evidence of past storms (Kelley et al., 1995). These marshes typically form on relic flood tidal deltas or overwash deposits that have raised the sediment surface within back-barrier lagoons to intertidal elevations, allowing emergent halophytic vegetation to colonize (Godfrey and Godfrey, 1974). Tidal flow through inlets and washover associated with storm surge are the most common mechanisms that transport barrier sediments landward into back-barrier marshes or lagoons (Schwartz, 1975). If the rate of sea-level rise is great enough, these deposits are preserved

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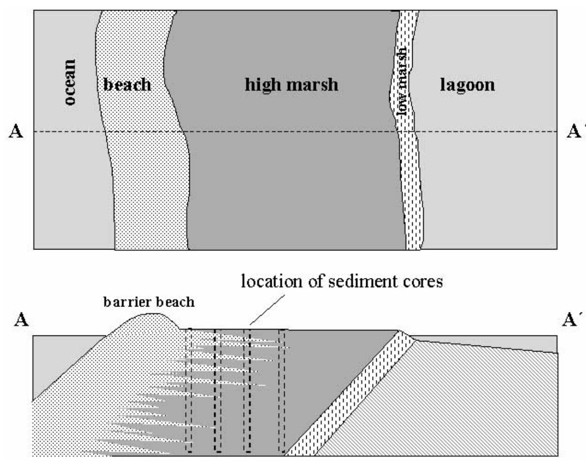

Figure 1. Map view and cross section of conceptual model of overwash deposition and the landward translocation of the barrier-marsh system in a regime of rising sea level. Overtopping of the barrier beach by storm surge results in overwash fan deposition across back-barrier marshes. Overwash fans are preserved as sea level increases and they are covered with marsh deposits. Transects of Vibracores are used to identify and map overwash deposits. Vertical exaggeration is ~100× to 500×.

as the barrier migrates over marsh or lagoon deposits. This translation of facies in space and time often results in alternating marsh and overwash deposits overlying flood-tidal delta and lagoonal mud deposits (Fig. 1). Only a storm surge of sufficient height to overtop the entire barrier would result in sheet overwash deposits across the entire back barrier (Schwartz, 1975). By using sheet overwash deposits within coastal wetland sediments as proxies for hurricane landfalls, we have extended the historic record of intense hurricane strikes in New England into the prehistoric period.

Several studies have attributed deposits in the geological record to storm-induced sedimentation. Davis et al. (1989) identified three storm-generated facies within coastal lagoons in Florida. Shinn et al. (1993) documented lime-mud deposited by turbidity currents, associated with hurricane Andrew in 1992, in incised channels on the Grand Bahama Bank. Liu and Fearn (1993) used overwash deposits recovered in sediment cores from Lake Shelby, Alabama, to develop a 3500 yr record of intense hurricane strikes on the Alabama coast. Similar methods were employed by Liu and Fearn (2000) in order to reconstruct a record of hurricane strikes for the panhandle of Florida. Boothroyd et al. (1985) identified deposits associated with storm surges in a stratigraphic study of back-barrier systems in southern Rhode Island. Orson and Howes (1992), Warren and Niering (1993), Niering and Warren (1980), Kelley et al. (1995), Bravo et al. (1997), Roman et al. (1997), and Orson et al. (1998) identified sand and silt deposits within New England marsh-peat sequences as storm deposits.

STUDY SITE

Succotash salt marsh is an unditched back-barrier coastal wetland located in East Matunuck, Rhode Island (41°22′47′′, 71°31′16′′; Fig. 2). The barrier beach (East Matunuck State Beach) is a product of east to west littoral drift; much of the sediment is supplied from the erosion of glacial deposits at Matunuck Point, less than 2 km to the west (McMaster, 1960). The barrier−marsh−salt pond complex overlies glacial till and outwash deposits south of the recessional Charlestown moraine (Kaye, 1960). Glacial till is occasionally exposed at the surface as small islands within the marsh (Fig. 2). The average tidal range on the ocean side of the barrier is ~1 m; extreme spring tidal ranges reach 1.5 m (National Oceanic and Atmospheric Administration [NOAA]/National Ocean Service [NOS]/Center for Operational Oceanographic Products and Services [CO-OPS], 2000). Two salt ponds separate the barrier-marsh system from the mainland Potter's Pond, located to the northwest, and Point Judith Pond, to the northeast. Currently, tidal exchange occurs only through the Point Judith breachway to the east of Succotash Marsh. This inlet was excavated in 1909 and three breakwaters that form the Point Judith Harbor of Refuge were completed in 1914 (U.S. Army Corps of Engineers [USACE], 1962).

In order to understand how past changes in the geomorphology have influenced the depositional regime at the site, we used maps, surveys, aerial photography, and historical accounts to reconstruct the historical changes in the back-barrier marsh. Prior to the construction of the permanent breachway, Potter's and Point Judith Ponds were connected to the ocean via the currently abandoned channel network within Succotash Marsh (Fig. 2). The great September gale of 1815 opened this old inlet, which remained active until sealed by longshore transport of sediment shortly after 1903 (U.S. House of Representatives, 1903; Lee, 1980; Fig. 2). Before the inlet opened in 1815, an active inlet existed more than 1 km to the west of the current breachway (Lee, 1980). The modern beach height is ~3 m above mean sea level, similar to the height of 2.5−3 m measured at the study site in the mid 1970s (Simpson, 1977).

HISTORIC HURRICANES IN NEW ENGLAND

New England protrudes into the western Atlantic and is often in the path of fast-moving tropical storms and hurricanes as they track north. Intense hurricanes of category 3 or greater on the Saffir-Simpson scale (maximum sustained wind speeds >178 km/hr) are rare in New England, however. Boose et al. (2001) have reconstructed damage patterns of historical New England hurricanes since European settlement. They conclude that since A.D. 1620 four intense hurricanes (greater than category 3) occurring in 1635, 1815, 1869, and 1938 have significantly affected the southern Rhode Island coast.

The first historical record of an intense hurricane striking New England is the great colonial hurricane of August 25, 1635 (Fig. 2, inset). Accounts of storm surge of more than 4 m on the southeastern New England coast and further accounts of extensive destruction of forests within the region indicate that the 1635 storm was at least a category 3 hurricane at landfall (Boose et al., 2001; Ludlum, 1963).

In addition to the four category 3 hurricanes identified by Boose et al. (2001), a ''very great tempest, or hiracano at S.W.'' on August 13, 1638, with a storm surge of nearly 4.5 m in southern Rhode Island was noted in the writings of Governor John Winthrop of the Massachusetts Bay Colony (Ludlum, 1963). Although Boose et al. (2001) estimated the intensity of this hurricane as category 2, the estimate is based on only two observations and the magnitude of the storm surge in southern Rhode Island (Fig. 3) is consistent with a category 3 storm making landfall to the west of southern Rhode Island (Fig. 2, inset).

The great September gale of 1815 struck Long Island and southern New England on the morning of September 23, 1815. Historians have frequently equated this storm to the 1938 New England hurricane (Ludlum, 1963; Minsinger, 1988; Snow, 1943). The hurricane of 1815 made landfall on Long Island, New York, $<$16 km to the east of the landfall of the 1938 hurricane (Fig. 2), and resulted in a similar damage pattern. The water level from this storm at Succotash Marsh was estimated to have reached more than 3.4 m above mean sea level (Fig. 3) (USACE, 1962). Historical accounts document the opening of an inlet within Succotash Marsh and extensive overwash fans associated with storm surge overtopping the barrier (Lee, 1980).

On September 8, 1869, a compact hurricane estimated as category 3 made landfall on southeastern New England (Boose et al., 2001; Ludlum, 1963). The storm made landfall near Stonington, Connecticut, and passed just to the west of Rhode Island (Fig. 2). The short duration of hurricane-force winds and the timing of landfall coincident with low tide combined to minimize the height of storm surge. A storm surge of 2 m above mean high water (Fig. 3) was noted in nearby Narragansett Bay (Bristol, Rhode Island).

The September 21, 1938, hurricane, the last intense hurricane to strike southern New England, made landfall on central Long Island (Fig. 2) (Brooks, 1939). The storm surge rose more than 3 m above normal spring tide levels along the open coast (Fig. 3), while focusing of the surge in Narragansett and Buzzards Bays resulted in more than 5 m of storm surge in many areas (Paulsen, 1940; Redfield and Miller, 1957). Storm surge and wave action caused significant overwash of barrier beaches, coastal modification, and erosion from Long Island, New York, to southeastern Massachusetts (Wilby et al., 1939; Nichols and Marston, 1939). Aerial photographs document that the barrier adjacent to Succotash Marsh was overtopped and an extensive overwash fan was deposited across the marsh. The visible extent of overwash deposition at Succotash Marsh from the 1938 hurricane is outlined in Figure 2. Sand and silt layers ~15 cm below the current sediment surface in salt marshes from Connecticut to Cape Cod have been attributed to the 1938 hurricane (Orson and Howes, 1992; Warren and Niering, 1993; Bravo et al., 1997).

In addition to these intense hurricanes, at least 27 category 1 and 2 hurricanes have made landfall in southern New England in the past 400 yr (Boose et al., 2001; Ludlum, 1963; Neumann et al., 1993). Storm surge heights for several category 1 and 2 hurricanes during the twentieth century (hurricanes Bob, 1991, Gloria, 1985, Donna, 1960, Carol, 1954, and the great Atlantic hurricane, 1944) are displayed in Figure 2. Storms of this intensity resulted in storm surge heights of $<$2 m. The only historical exception is Carol in 1954, a strong category 2 hurricane at landfall, which struck at a time of astronomical high tide and resulted in a storm surge height of more than 3 m above mean sea level (Fig. 3). Aerial photographs taken immediately after hurricane Carol document the deposition of an overwash fan at Succotash Marsh (Fig. 2).

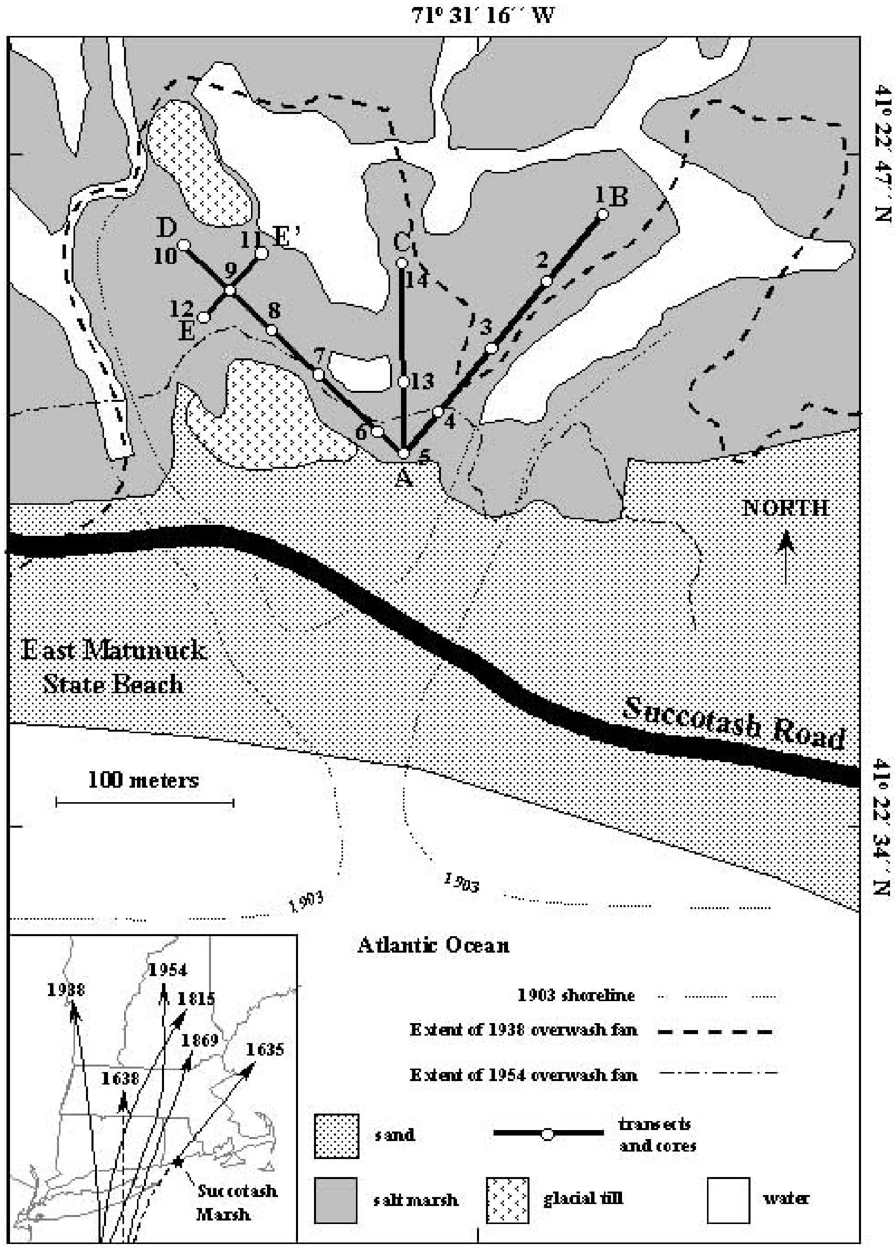

Figure 2. General study site location map of southern New England (A) with storm tracks of historic hurricanes mentioned within the text. Dashed tracks are poorly defined by historic data. Map of Succotash Marsh in East Matunuck, Rhode Island, shows core locations, noted by open circles. Dashed lines indicate the extent of overwash deposition within Succotash Marsh associated with hurricanes in 1954 and 1938 determined from historical aerial photography. The dotted line indicates the 1903 configuration of the inlet that was active during the nineteenth century A.D. (U.S. House of Representatives, 1903).

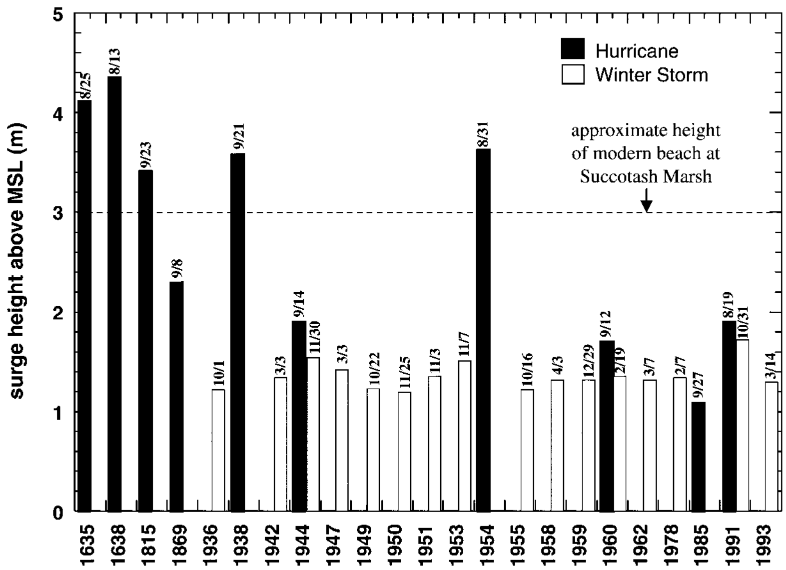

Figure 3. Storm surge heights in southern Rhode Island relative to contemporary mean sea level (MSL). The modern barrier height of ~3 m above MSL at Succotash Marsh is noted by a dashed line. The height of storm surges dating back to 1936 has been measured by nearby tide gauges at Newport, Rhode Island, and New London, Connecticut (NOAA/NOS/CO-OPS, 2000; USACE, 1962). Historical written accounts of storm surge heights were used for storms that predated the tide gauges (Ludlum, 1963).

OBJECTIVES AND HYPOTHESES

Rhode Island has been significantly affected by all five intense hurricanes striking southern New England within the historic period (1635, 1638, 1815, 1869, and 1938; Boose et al., 2001; Ludlum, 1963; Fig. 2). Copious historical accounts of these events and the presence of numerous back-barrier marshes along the southern Rhode Island coast made it an ideal location from which to obtain sedimentary records of these events. We analyzed 14 Vibracores along four transects in Succotash Marsh, East Matunuck, Rhode Island, in order to measure the magnitude, extent, and timing of overwash deposition.

To guide our study, we developed the following four primary hypotheses and tested them with field studies and laboratory analyses. (1) Overwash fans resulting from the overtopping of the barrier beach by storm surge are preserved within back-barrier marsh sediments. Coring the back-barrier marsh and mapping of continuous bodies of sand within the marsh sediments tested this hypothesis. (2) Overwash fans noted from historical aerial photographs and accounts associated with hurricanes in 1954, 1938, and 1815 can be identified within back-barrier marsh sediments. In order to test this hypothesis we dated overwash fans using a variety of isotopic and stratigraphic methods and compared the timing and extent of overwash deposition to historical information. (3) Storm surge of more than 4 m noted in southern Rhode Island during hurricanes in 1638 and 1635 resulted in the deposition of overwash fans at Succotash Marsh, which are likely preserved and can be identified and dated. We used radiocarbon and pollen stratigraphic dating to locate this interval of time within the back-barrier marsh stratigraphy and determined if evidence of significant overwash fan deposition was apparent. (4) The age of any prehistoric overwash fans preserved within Succotash Marsh can be defined with multiple accelerator mass spectrometry (AMS) radiocarbon dates. Calibrated AMS radiocarbon results from plant fragments within peat intervals at the base of any prehistoric overwash fans are compared to test this hypothesis.

METHODS

Core Collection and Description

Fourteen Vibracores (Lanesky et al., 1979) along four transects at Succotash Marsh were taken for sediment analyses and dating (Fig. 2). Cores 1−5 were taken along transect A−B oriented roughly northeast to southwest and extending 180 m from the barrier edge of the marsh. Cores 6−10 were taken along transect A−D oriented perpendicular to transect A−B, approximately northwest to southeast, extending 175 m from core 5. Cores 11 and 12 were obtained along transect E−E′, which extends perpendicular to transect A−D and is centered on core 9. Transect A−C is composed of cores 5, 13, and 14 and extends north 100 m from core 5. Elevations and locations of cores were determined relative to a local benchmark using a Leica TC800 Total Survey Station. Cores were described in the lab by sediment type, texture, grain size, character of the transitions between zones, and color (based on the Munsell Soil Color Chart). Plant macrofossils were identified and the relative abundance of each species estimated using the Niering et al. (1977) rhizome key. Cores were wrapped in plastic to prevent desiccation and refrigerated at 10 °C.

Dating and Correlation Among Cores

We obtained 11 radiocarbon dates from the base of overwash deposits in cores 2, 3, 4, 9, 11, 12, and 14. Peat samples of 0.5−1 cm^3 were removed from the base of sand layers in each of these cores. These samples were screened through a 1 mm sieve and the remaining plant fragments were submitted to Beta Analytic Inc., Miami, Florida, for AMS radiocarbon dating. Fluctuations in atmospheric concentrations of ^{14}C in time require that radiocarbon ages be calibrated to calendar years when interpreting paleoenvironmental records (Bartlein et al., 1995). The nonlinear relationship between radiocarbon time and calendar time can result in multiple calendar age ranges derived from one radiocarbon age and associated analytical uncertainty. The results have been calibrated for secular changes in ^{14}C concentrations using the Calib 4.1 program (Stuiver et al., 1998) at two standard deviations and are presented in Table 1. The calendar ages with the highest probability occur where the reported radiocarbon age intercepts the calibration curve. The mutual overlap of calibrated radiocarbon age ranges from samples of peat at the base of an overwash fan is used to provide the most likely age range of that stratigraphic unit.

In order to provide additional age control in the historic period, we used four other methods of age estimation: (1) pollen stratigraphic events, (2) lead pollution horizons, (3) estimates of marsh accretion rates linked to local rates of sea-level rise, and (4) ^{137}Cs activity. The increase of agricultural indicators ca. A.D. 1700 is well represented by pollen data and allows this event to be used as a biostratigraphic marker (Brugam, 1978; Russell et al., 1993; Clark and Patterson, 1985). Increases in the relative abundance of pollen from the native weeds *Ambrosia* (ragweed) and *Rumex* (sorrel) mark this time. The pollen of *Ambrosia*, however, is easily confused with that of *Iva frutescens* (marsh elder), a common salt marsh plant, and poor preservation in many of the samples from Succotash Marsh precluded secure differentiation of *Iva* from *Ambrosia* pollen. We therefore used increases in the abundance of *Rumex* to interpret the agricultural horizon. Sediment samples (21 from 5 cores) were screened through a 0.500 mm sieve to remove plant macrofossils and fine-grained sand. The samples were then prepared for pollen analysis using standard laboratory procedures (Faegri and Iverson, 1989). In some samples, extra treatments of hydrofluoric acid were required to remove excess sand. We counted a minimum of 200 pollen grains per sample and derived *Rumex* percentages relative to total tree pollen.

We also analyzed lead concentrations in the sediments and used the industrially caused increase in Pb concentration as a dated stratigraphic marker. Lead pollution introduced to the atmosphere beginning at the onset of the industrial revolution quickly precipitated out of the atmosphere and was rendered immobile in many anoxic marsh sediments (McCaffrey and Thomson, 1980; Bricker-Urso et al., 1989). Lead pollution in the region has been well documented and increased substantially in the middle 1800s (Nixon, 1995). Peat intervals in cores 3, 4, 5, 6, 7, 8, 9, 11, and 12 were subsampled every 2 cm and analyzed for lead concentrations using X-ray fluorescence spectrometry (Klockenkamper, 1997). The record of lead pollution preserved in marsh sediments provides estimates for the age of the peat interval when lead concentrations increase substantially over background levels.

The preservation in sediments of ^{137}Cs associated with nuclear weapons testing provides two dated stratigraphic markers in recent marsh sediments (Delaune et al., 1978). The beginning of ^{137}Cs deposition occurred in A.D. 1954 and the maximum took place in A.D. 1963. We took 7 samples from peat intervals from the top 35 cm of core 7 for ^{137}Cs analysis. The samples were dried and sent to H. Jeter of Teledyne Brown Engineering, Westwood, New Jersey, for analysis. The activity of ^{137}Cs was measured using a high-resolution gamma ray spectrascope and results are reported in picocuries per gram dry weight of sediment.

Vertical accretion in New England's coastal marshes has been closely tied to relative sea-level rise (Redfield, 1965, 1972; McCaffrey and Thomson, 1980). Regional sea-level data can therefore be used to estimate the marsh sedimentation rate and help define the age of overwash deposits. Southern New England tide gauges show that sea level rose between 2 and 2.5 mm/yr for the past 100 yr (Emery and Aubrey, 1991).

TABLE 1. RADIOCARBON DATES AND CALIBRATED CALENDAR DATES FOR SUCCOTASH MARSH, RHODE ISLAND

Index number	Laboratory number	Core	^{14}C age (A.D.)	Calibrated 2σ calendar age (intercepts)*	δ^{13}C (‰)	Sample depth (cm)
1	Beta-115171	Succ2	460 ± 40	A.D. 1407–1484 (1439)	–14.1	86.5–87.5
2	Beta-103313	Succ3	580 ± 50	A.D. 1295–1436 (1332, 1340, 1398)	–17.1	86–86.5
3	Beta-115172	Succ3	430 ± 50	A.D. 1411–1522 A.D. 1571–1627 (1445)	–13.2	66–67
4	Beta-135397	Succ4	490 ± 30	A.D. 1404–1446 (1430)	–14.1	74–75
5	Beta-135398	Succ4	280 ± 30	A.D. 1518–1596 A.D. 1621–1662 (1642)	–16.9	66–67
6	Beta-135399	Succ4	210 ± 30	A.D. 1645–1682 A.D. 1734–1806 A.D. 1931–1947 (1665, 1784, 1789)	–15.0	52–53
7	Beta-115173	Succ9	630 ± 40	A.D. 1285–1407 (1304, 1367, 1385)	–12.5	78–78.5
8	Beta-115174	Succ11	480 ± 40	A.D. 1402–1474 (1434)	–16.3	87–88
9	Beta-115176	Succ12	570 ± 40	A.D. 1300–1373 A.D. 1377–1433 (1334, 1336, 1400)	–17.7	100–101
10	Beta-115175	Succ12	270 ± 40	A.D. 1494–1500 A.D. 1515–1599 A.D. 1616–1671 A.D. 1779–1798 A.D. 1945–1945 (1645)	–14.9	75–76
11	OS-23293	Succ14	515 ± 50	A.D. 1317–1353 A.D. 1388–1451 (1418)	–11.3	79–80

*Age(s) in parenthesis are the calendar age where the reported radiocarbon age intercepts the calibration curve.

RESULTS

The 14 cores have similar stratigraphies consisting of alternating intervals of high-marsh peat and clean, poorly laminated, fine to medium sand within the upper 1 m (Figs. 4, 5, 6, 7, and 8). Peat deposits range in color from very dark, grayish-brown to black with predominantly *Distichlis spicata, Spartina patens,* and *Spartina alterniflora* remains. Sand layers consist of very fine to medium sand and range in color from dark gray to light, brownish gray. The contact between sand deposits and the underlying peat deposits is abrupt. The transition between the sand deposits and the overlying peat deposits is generally gradational, typically occurring over 2.5 cm or more. Underlying these deposits are interbedded mud and fine to coarse sand with detrital organic laminae, and occasional gravel. A complex layer of fine to medium sand interbedded with silt, organic mud, and thin (<2 cm) peat layers (19−30 cm depth in core 1; Fig. 4) is evident between 10 and 45 cm depth in cores 1–5 (Fig. 5).

Interpretation of Sediment Units

Clean, fine to medium, poorly laminated, moderately well sorted sand units are interpreted as overwash deposits. Aerial-photographic evidence of overwash fans deposited at the site in 1938 and 1954 (Fig. 2), the abrupt nature of the contacts, and the lateral continuity of these sediments suggest that these deposits are overwash fans associated with storm surge overtopping the barrier beach.

High-marsh peat units represent continuous deposition of tidally derived mud and sand as well as autogenic organic material. The accumulation of high-marsh sediments is restricted to elevations close to mean high water, where such sediments accrete vertically, generally keeping pace with moderate rates of local sea-level rise (Orson et al., 1998; McCaffrey and Thomson, 1980; Redfield, 1965, 1972). These deposits consist of mud and sand within a matrix of *D. spicata, S. patens,* and

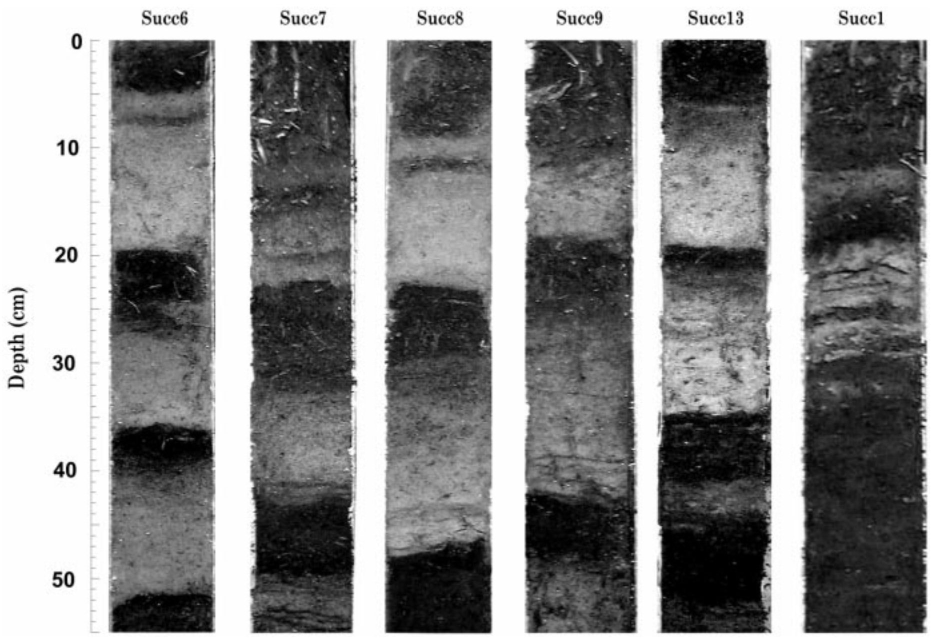

Figure 4. Photographs of the upper 55 cm of selected cores. Dark units are salt-marsh peat. Light units are very fine to medium sand. Note the abrupt nature of the upper contacts between the peat and the overlying sand. The contact between the peat and the underlying sand units tends to be more gradational. A complex unit of sand interbedded with mud and thin peat intervals interpreted as channel levee or dredged deposits is evident between 19 and 30 cm in core 1.

S. alterniflora roots and rhizomes. The abrupt upper contact of these units represents the growing surface at the time of instantaneous overwash deposition or in some cases may represent an erosional contact. The fibrous nature of the high-marsh peat likely reduces or eliminates erosion of the high-marsh surface during overwash. The lower contact of marsh units is often gradational as a result of root penetration into overwash sand below.

The complex unit of variable thickness consisting of fine to medium sand interbedded with silt and organic mud (core 1, 19−30 cm; Fig. 4) is interpreted as channel-levee deposits. These deposits are present in cores adjacent to the abandoned channels (Figs. 2 and 5). The diverse nature of the sediment suggests repeated deposition associated with numerous events of varying energies. In addition, some of these deposits may be dredged material from early attempts to maintain a navigable channel nearby in the nineteenth century (Lee, 1980).

The basal unit in all cores consists of poorly sorted, fine- to coarse-laminated sand with numerous organic interbeds, and locally numerous pebbles and small cobbles. These deposits are consistent with subtidal deposition associated with tidal flow through an inlet in the barrier system and are interpreted as flood tidal-delta deposits and associated flood channels. This unit is similar to other tidal-delta deposits described in the microtidal lagoons of southern Rhode Island (Boothroyd et al., 1985).

Overwash Fan Correlation and Dating

Overwash sand was correlated across cores by using sediment characteristics such as color, texture, stratigraphic position, and the character of the peat intervals that bound them. Radiocarbon dates, as well as pollen and lead stratigraphic markers across multiple cores, provided a means of verifying these correlations.

We identify six overwash fans within the upper 1 m of sediment of Succotash Marsh. Fan I is 1−3 cm thick and occurs between 3 and 12 cm. Fan I is absent from cores 1, 2, 9, 11, and 14 (Figs. 5, 6, 7, and 8). The ^{137}Cs activity measured on the upper 30 cm of core 7 indicates no detectable ^{137}Cs in the two samples below fan I in core 7 (Fig. 9). The ^{137}Cs is present (0.073 $\pm$ 0.066 pCi/g dry) within the sample from fan I at 11.5−13 cm and indicates that deposition of this interval occurred in A.D. 1954. The level of ^{137}Cs increases to a maximum (0.88 $\pm$ 0.15 pCi/g dry) within the sample at 9−10 cm and marks the A.D. 1963 horizon.

Fan II is 1−20 cm thick and occurs between 7 and 23 cm depth in all cores. Analysis of Pb concentrations in cores 6, 7, 8, 9, 11, and 12 reveals that concentration of Pb within the sediments increases above downcore background levels of ~20 ppm within the peat interval below fan II (Fig. 10). In cores 3, 4, and 5, Pb concentrations increase above background levels within the peat below the complex unit of fine to medium sand interbedded with silt, organic mud, and thin peat layers (interpreted as channel-levee or dredge deposits).

Fan III occurs between 35 and 57 cm depth in all cores, excluding core 14, and is bounded above by peat with high concentrations of Pb and below by peat with background concentrations of Pb (~20 ppm) (Fig. 10). Pollen analysis of sediment samples from core 4 reveals an increase in the relative abundance of *Rumex* pollen that most likely dates to between A.D. 1700 and 1750, when Europeans had sufficiently cleared the southern New England landscape (Fig. 11). *Rumex* pollen increases from <2% to >4% within the peat interval directly below fan III in core 4 (Fig. 11). Pollen analysis on samples from the peat interval directly below fan III in cores 2, 9, 11, and 12 reveals between 9% and 23% *Rumex* (Fig. 11). A radiocarbon-dated sample (6) from the base of fan III in core 4 yielded calibrated age ranges of A.D. 1645–1682, A.D. 1734–1806, and A.D. 1931–1947, the range of A.D. 1734−1806 being most compatible with the high *Rumex* values.

Fan IV occurs between 40 and 76 cm in all cores except 1, 2, 3, and 10 and is bounded above by peat containing >4% *Rumex* pollen. The peat layer below fan IV has between 0% and 3% *Rumex* pollen (Fig. 11). A radiocarbon-dated sample (5) from the peat at the base of fan IV in core 4 produced the calibrated ranges A.D. 1518–1596 and A.D. 1621–1662. A radiocarbon-dated sample (10) from the peat at the base of fan IV in core 12 yielded the calibrated-age ranges A.D. 1494–1500, A.D. 1515–1599, A.D. 1616–1671, and A.D. 1779–1798.

Fan V occurs between 52 and 100 cm in all cores except core 10. Six peat samples (1, 3, 4, 8, 9, and 11) from the base of fan V were radiocarbon dated (Table 1; Figs. 5, 6, 7, 8, and 12). These samples all yielded calibrated-age ranges in the early fifteenth century A.D., although two samples (9 and 11) also have ranges in the fourteenth century A.D. (Table 1; Fig. 12).

Fan VI occurs between 69 and 107 cm depth in all cores except cores 1, 2, 8, 10, and 14. Two radiocarbon dates from samples of

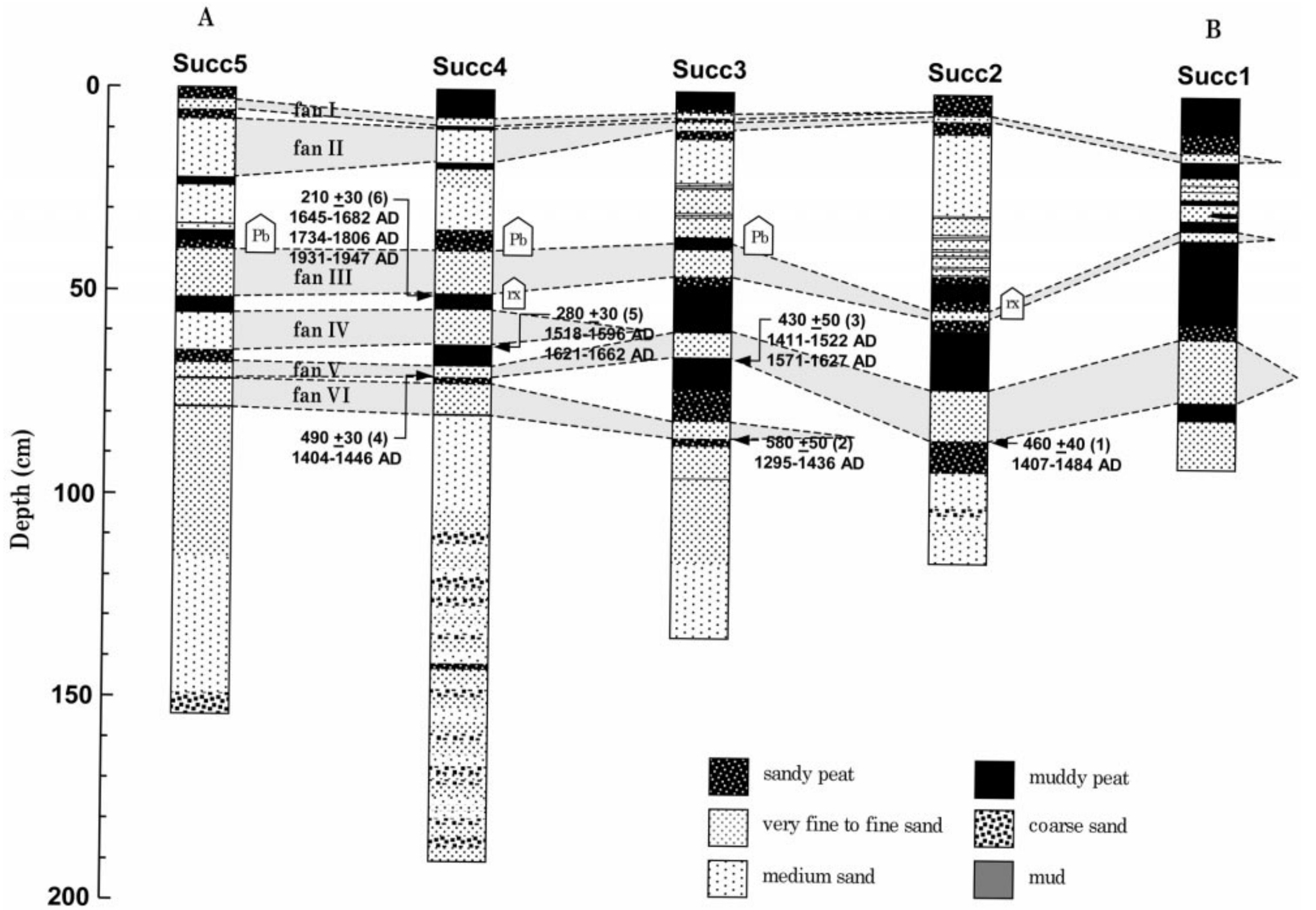

Figure 5. Logs of cores from transect A–B. Overwash fans have been correlated between cores (shaded in gray) and labeled fans I–VI. Solid arrows mark the location of radiocarbon-dated samples, the dates of which are presented with 2σ calibrated age ranges (sample numbers noted in parentheses correspond to those presented in Table 1). Large arrows labeled Pb denote the stratigraphic interval where the concentration of Pb increases over background levels associated with the industrial revolution (see Fig. 10). Arrows labeled rx denote the stratigraphic interval where *Rumex* pollen increases above 3%, indicating widespread European-style clearance of the landscape (ca. A.D. 1700) (see Fig. 11).

peat (2 and 9) from the base of fan VI in cores 3 and 9 yielded calibrated-age ranges of A.D. 1295–1436 and A.D. 1285–1407, respectively (Table 1; Fig. 12).

DISCUSSION

Succotash Marsh began to accumulate between 600 and 700 yr ago on flood tidal-delta deposits associated with a relic inlet proximal to the study site. Following the closure of this inlet, marsh vegetation (*S. alterniflora, S. patens, D. spicata*) colonized these protected sand flats, and peat accumulation commenced, roughly keeping pace with sea-level rise. As a result of the close proximity of the barrier beach, episodic storm events with significant storm surge deposited overwash fans across this region of the marsh. Following overwash deposition, marsh vegetation colonized the overwash sand and initiated peat development again. Six large-scale overwash fans have been mapped across the study site since the initiation of salt-marsh deposits at the site (Figs. 5, 6, 7, and 8).

The sensitivity of the site to overwash deposition is dependent on the height and width of the barrier beach as well as distance from the barrier. The relative rarity of overwash deposition preserved at the site (6 deposits in ~700 yr) suggests that the height of the barrier beach has not varied substantially from its modern height. The two closest long-term tide gauge records to Succotash Marsh at Newport, Rhode Island, and New London, Connecticut, have recorded storm surge heights more than 1.5 m above mean sea level at least eight times since 1930 and 1938, respectively (NOAA/NOS/CO-OPS, 2000). If the height of the barrier were significantly lower than present, given the high rate of occurrence of storms capable of overtopping a barrier height of <1.5 m above mean sea level, we expect that overwash would likely have occurred much more frequently. Conversely, if the past barrier height was considerably higher than present, overwash would be extremely unlikely to occur. Dune heights of close to 3 m measured less than two decades following hurricane Carol (1954) and less than four decades after the 1938 hurricane (Simpson, 1977), along with a large supply of sediment to the barrier, suggest that the beach recovers relatively quickly (within 10–30 yr) after being overwashed. In a regime of rising sea level, barrier beaches migrate landward primarily by overwash deposition and flood tidal-delta for-

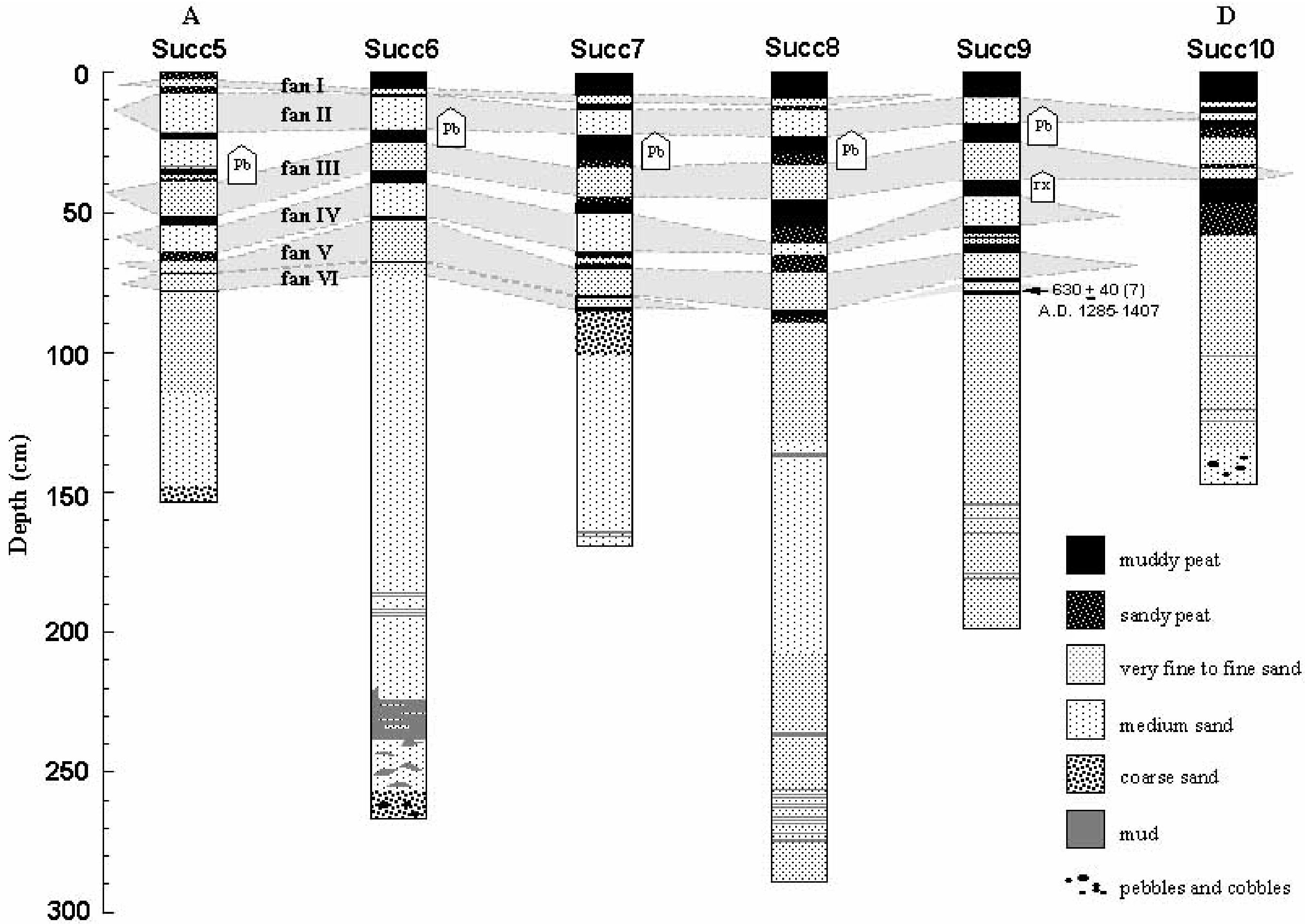

Figure 6. Logs of cores from transect A–D. Overwash fans have been correlated between cores (shaded in gray) and labeled fans I–VI. Solid arrows mark the location of radiocarbon-dated samples, the dates of which are presented with 2σ calibrated age ranges (sample numbers noted in parentheses correspond to those presented in Table 1). Large arrows labeled Pb denote the stratigraphic interval where the concentration of Pb increases over background levels associated with the industrial revolution (see Fig. 10). Arrows labeled rx denote the stratigraphic interval where *Rumex* pollen increases above 3%, indicating widespread European-style clearance of the landscape (ca. A.D. 1700) (see Fig. 11).

mation (Pierce, 1970; Dillon, 1970; Schwartz, 1975; Fig. 1). As the barrier at Succotash Marsh has transgressed landward, the distance from the area of study to the barrier has presumably decreased. This decrease has potentially resulted in the site being increasingly susceptible to overwash deposition. The likely position of the barrier farther seaward in the past may indicate that older overwash fans have been transported greater distances.

The formation and migration of inlets within the barrier-marsh system can potentially alter the sensitivity to overwash events. The presence of an active inlet nearby would expose the surrounding marsh to high-velocity currents and waves capable of depositing sand and gravel during small storm events and spring tides. This kind of depositional regime is evident at Succotash for most of the nineteenth century after an inlet was opened adjacent to the study site in the great September gale of 1815 (Lee, 1980). Following the opening of this inlet, areas of the marsh adjacent to the inlet channels received multiple pulses of sand and mud deposition with little or no vegetation development. This deposition continued until the inlet was closed by longshore transport of sediment ca. A.D. 1900. The complex sand and mud deposition throughout this interval likely represents numerous storm events of varying intensity and potentially deposition during spring tides. Once the inlet sealed, only storms with surge heights capable of overtopping the barrier resulted in the deposition of sand on the marsh.

Severe winter storms caused substantial coastal flooding in New England. The strongest winter storms in New England are termed ‘‘nor'easters'' and intensify over the relatively warm ocean waters along the East Coast of the United States, south of New England. These storms often produce strong northeast winds, hence the name nor'easter. This northeast wind can cause storm surges of magnitudes similar to those resulting from hurricanes, but typically on northeast-facing coastlines. Many severe winter storms have battered southern New England since European settlement, some of the most infamous occurring in 1723, 1888, 1944, 1953, 1962 (Ash Wednesday storm), 1978 (blizzard of 1978), 1991 (the ‘‘perfect storm'') and 1993 (‘‘storm of the century''). Historical accounts of these storms confirm that damage from their storm surges was restricted to northeast-facing coastlines (Snow, 1943; Dickson, 1978; Fitzgerald et al., 1994). In addition, records

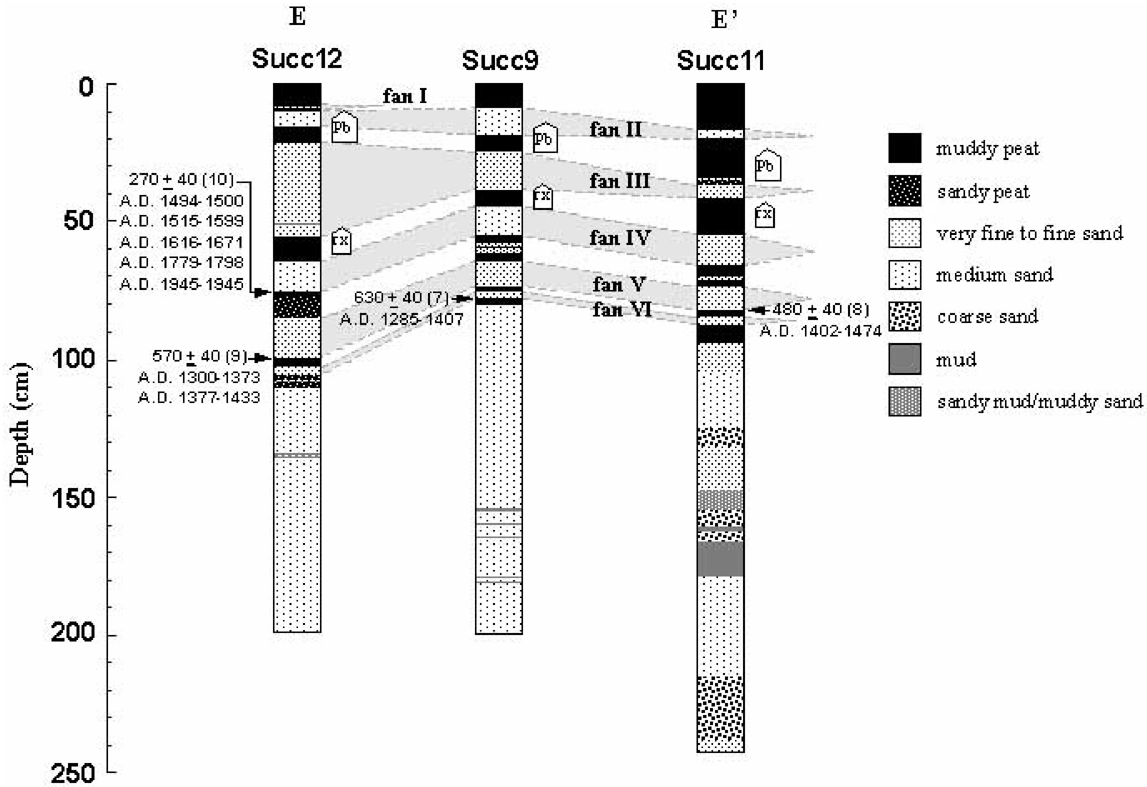

Figure 7. Logs of cores from transect E−E′. Overwash fans have been correlated between cores (shaded in gray) and labeled fans I−VI. Solid arrows mark the location of radiocarbon-dated samples, the dates of which are presented with 2σ calibrated age ranges (sample numbers noted in parentheses correspond to those presented in Table 1). Large arrows labeled Pb denote the stratigraphic interval where the concentration of Pb increases over background levels associated with the industrial revolution (see Fig. 10). Arrows labeled rx denote the stratigraphic interval where *Rumex* pollen increases above 3%, indicating widespread European-style clearance of the landscape (ca. A.D. 1700) (see Fig. 11).

from nearby tide gauges show that storm surge heights associated with severe winter storms this century never exceeded a height of 2 m above mean sea level near Succotash Marsh (Fig. 3). The south-facing orientation of the Succotash Marsh system makes this site much more susceptible to landfalling hurricanes with intense southerly winds than to oceanic winter storms, which generally have strong northeast winds. Only hurricanes in 1954, 1938, 1815, 1638, and 1635 resulted in storm surge heights exceeding the modern barrier height of Succotash Marsh during the historic interval (Fig. 3).

Overwash fans documented at Succotash Marsh with aerial photographs in 1954 and 1938 are consistent with the distribution of fans I and II. The first occurrence of ^{137}Cs within fan I delimits the age of this fan I deposit to A.D. 1954 (Fig. 9). Estimates of marsh accretion, based on regional sea-level rise rates of between 2 and 2.5 mm/yr (Emery and Aubrey, 1991), would suggest that between 9 and 12 cm of peat would be expected to accumulate on top of the 1954 overwash fan since it was deposited. Similarly, between 12 and 15 cm of peat would be expected to accrete on top of the 1938 overwash fan since it was deposited. These are likely maximum estimates, because some time is required for the overwash fan to become vegetated and for peat formation to occur. The average depths of peat above fan I and fan II are 7 cm and 11 cm, respectively. The combination of evidence from aerial photographs, ^{137}Cs activity, and the amount of peat accreted above fan I and fan II, is consistent with these deposits resulting from hurricane Carol (1954) and the 1938 hurricane.

Directly below the peat layer underneath fan II, channel-levee and/or dredge spoil deposits consisting of a complex mix of sand and mud exist in cores from transect A−B that do not appear to correlate to the other cores farther away from the channel (Fig. 5). These deposits likely result from the activation between A.D. 1815 and 1900 of the now-abandoned inlet and channel system adjacent to the study site and/or dredged material dumping (Fig. 2). This channel system became active as a result of the 1815 hurricane and was closed again by longshore transport by A.D. 1909 (Lee, 1980). Therefore, the age of these deposits is confined to between A.D. 1815 and 1909. Increases in Pb concentrations in and above this unit confirm deposition after ca. A.D. 1850 (Fig. 10).

A radiocarbon date (6) from the base of fan III in core 4 yielded calibrated ranges of A.D. 1645–1682, A.D. 1734–1806, and A.D. 1931–1947. The increase of *Rumex* pollen in this peat interval indicates deposition after ca. A.D. 1700. The A.D. 1645–1682 age range is therefore too old and can be eliminated. The A.D. 1931–1947 age range can be eliminated, because this peat interval lacks evidence of the Pb pollution in the late nineteenth and twentieth centuries. The age of this peat interval is therefore between A.D. 1734 and 1806 (Fig. 12). This calibrated-age range combined with elevated Pb levels within the sediments above fan III and evidence of Euro-

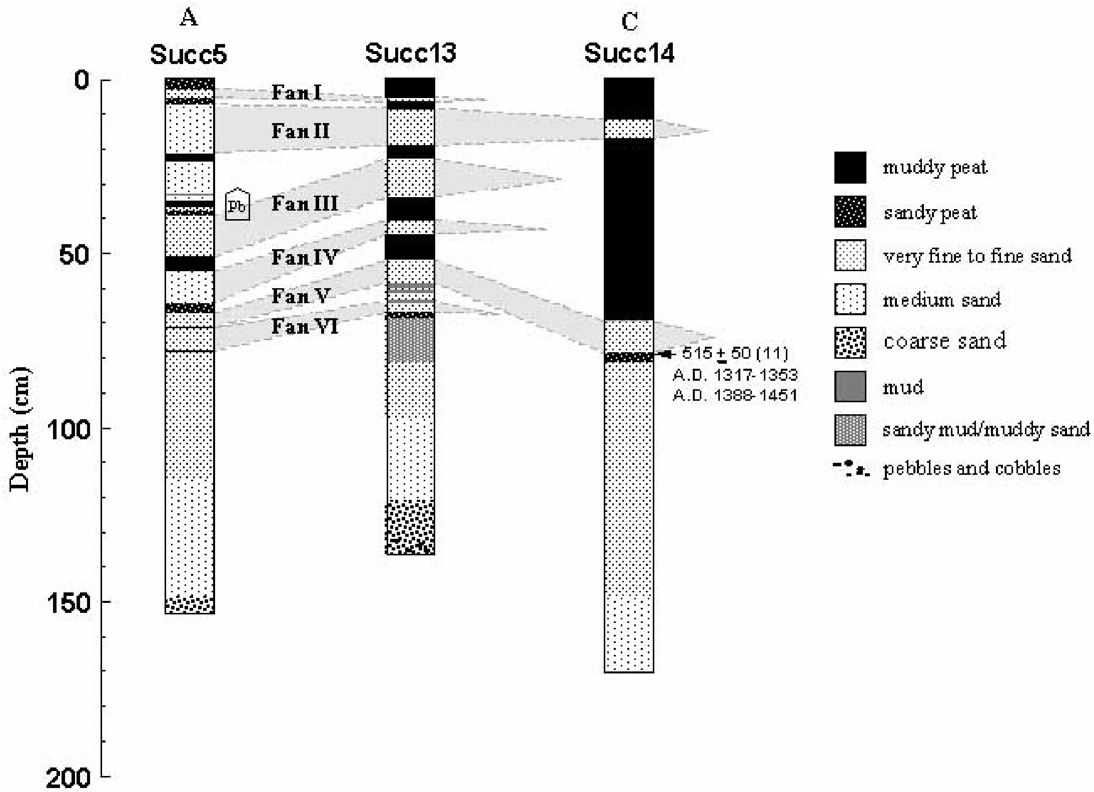

Figure 8. Logs of cores from transect A−C. Overwash fans have been correlated between cores (shaded in gray) and labeled fans I−VI. Solid arrows mark the location of radiocarbon-dated samples, the dates of which are presented with 2σ calibrated age ranges (sample numbers noted in parentheses correspond to those presented in Table 1). Large arrows labeled Pb denote the stratigraphic interval where the concentration of Pb increases over background levels associated with the industrial revolution (see Fig. 10).

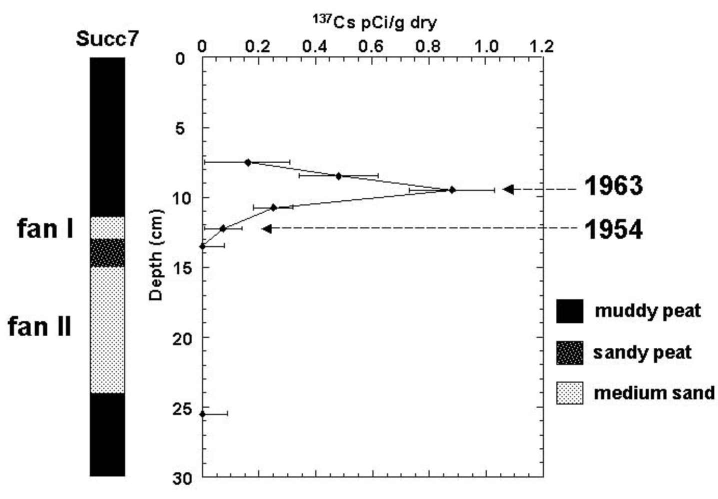

Figure 9. Activity profile of ^{137}Cs and core log from the upper 30 cm of core 7 (see photo in Fig. 4). Note the initial rise in ^{137}Cs attributable to A.D. 1954 occurs in the sample between 12 and 13 cm. The peak in ^{137}Cs activity occurs in the sample between 9 and 10 cm and represents A.D. 1963.

pean-style agriculture below indicate the age of this fan to be late eighteenth or early nineteenth century. These chronological controls and our inference that deposits above this fan in transect A−B are associated with the activation of the adjacent channel by the 1815 hurricane are consistent with fan III also being associated with the hurricane of September 23, 1815.

The age of fan IV is delimited by two radiocarbon dates (5, 10) and the increase in *Rumex* pollen abundance within the peat layer above the fan. Sample 5 produced the calibrated ranges A.D. 1518–1596 and A.D. 1621–1662 and sample 10 produced the calibrated ranges A.D. 1494–1500, A.D. 1515–1599, A.D. 1616–1671, A.D. 1779–1798, and A.D. 1945–1945. The mutual overlap between these dates is A.D. 1518–1596 and A.D. 1621–1662 (Fig. 12). The elimination of the younger ranges from sample 10 is further supported by the lack of *Rumex* pollen within this peat layer, indicating that this peat layer was deposited prior to widespread European-style agriculture ca. A.D. 1700. Although the A.D. 1518–1596 range cannot be eliminated, that

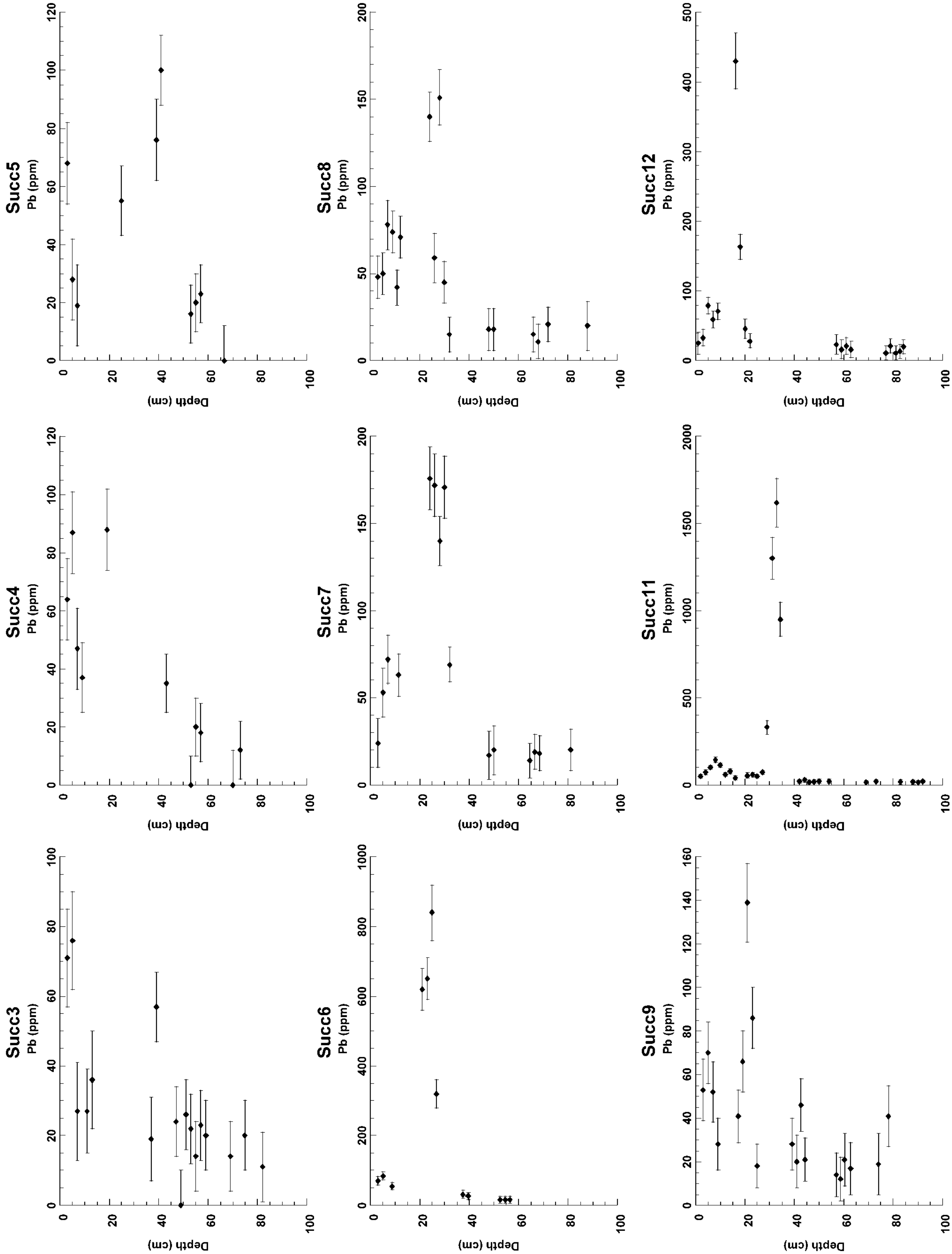

Figure 10. Pb concentrations from peat intervals within cores 3, 4, 5, 6, 7, 8, 9, 11, and 12. We infer that the increase in Pb concentration between 42 and 20 cm depth indicates that this sediment was most likely deposited in the mid- to late nineteenth century A.D.

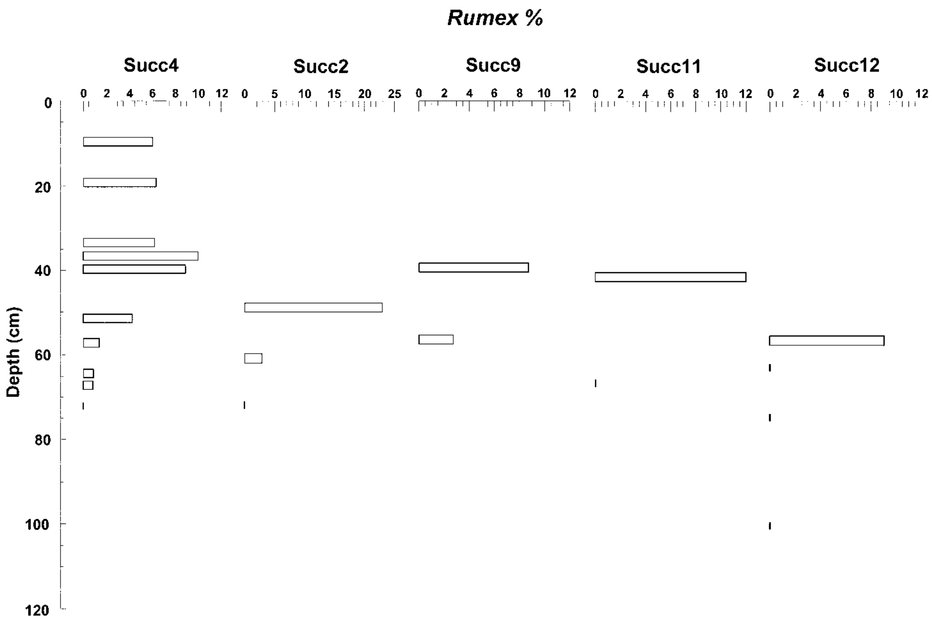

Figure 11. Abundance of *Rumex* pollen relative to total tree pollen in samples selected from cores 4, 2, 9, 11, and 12. Dashes indicate that no *Rumex* was observed in samples from that depth. We infer that the increase in *Rumex* abundance between 60 and 40 cm depth represents the onset of widespread European-style clearance and agriculture (ca. A.D. 1700).

Rumex increases within the peat interval above fan IV in cores 4, 11, and 12 and the intercepts with the calibration curve at A.D. 1641 and 1645 indicate that the most likely age of this peat layer is A.D. 1621–1662 (Fig. 12). The age of fan IV is between A.D. 1621 and ca. A.D. 1700. This age is consistent with deposition associated with the great colonial hurricane of 1635 or possibly the hurricane of August 13, 1638. A radiocarbon date (300 ± 50) from below an overwash fan at Wells, Maine (Kelley et al., 1995), calibrates to a similar age range (A.D. 1470–1672) with an intercept of A.D. 1637 (Fig. 12), and given the coastal track of the 1635 hurricane (Fig. 2), may also be the result of that storm.

Six samples from the peat at the base of fan V were radiocarbon dated. Five of six radiocarbon dates (1, 3, 4, 8, and 11) yielded 2σ calibrated age ranges in the fifteenth century A.D. (Fig. 12). Sample 9 from core 12 yielded a slightly older calibrated age, but overlaps significantly with the other five samples. The slightly older age may reflect some erosion of the marsh surface at the time of overwash deposition or contamination of the sample with older carbon. Excluding sample 9, the mutual overlap of the 2σ ranges for these samples produces a best estimate range of A.D. 1411–1446 for the age of the peat directly below fan V (Fig. 12). If sample 9 is included, the mutual overlap produces a range of A.D. 1411–1433. This age of the peat layer below fan V, combined with the age of the peat deposit above fan V, its age defined as seventeenth century A.D., limits the age of fan V to the fifteenth and sixteenth centuries A.D. The reproducibility of the calibrated radiocarbon age of the peat deposit directly below fan V indicates that little erosion of the marsh surface took place as this fan was deposited. Therefore, the age of the radiocarbon samples likely represents the age of the marsh surface at the time fan V was deposited. Fan V was most likely deposited between A.D. 1411 and 1433.

Two radiocarbon dates (2, 7) from the peat at the base of fan VI yielded 2σ calibrated dates of A.D. 1295–1436 and A.D. 1285–1407, respectively (Table 1; Fig. 12). The mutual overlap of the 2σ ranges from samples 2 and 7 produces a best estimate range of A.D. 1295–1407 for the age of peat deposit directly below fan VI (Fig. 12). Given that the age of fan VI should be older than the peat layer above it, which dates to A.D. 1411–1433, the age of fan VI is roughly fourteenth century A.D.

Implications and Limitations

The cores therefore contain a record of six overwash fans deposited since A.D. 1300. Photos, dates, accretion rates, and recorded storm surge heights show that fans I and II were deposited by the 1954 and 1938 hurricanes. Written historical accounts, radiocarbon dates, lead concentrations, and increased abundance of *Rumex* pollen indicate that fans III and IV were probably deposited by the 1815 and 1635 (8) hurricanes. The likely association of historic intense storms and overwash fans makes it also likely that fans V and VI also arose from intense prehistoric hurricanes.

Mapping and dating of overwash fans provide a record of historic and prehistoric storms. Our interpretation of the stratigraphic record at Succotash Marsh requires caution, however, in light of several uncertainties inherent in sediment records. The dynamic natures of back-barrier salt marshes and adjacent coastal environments often make it difficult to interpret the sedimentary record. As a result, back-barrier salt marshes can be imperfect recorders of hurricanes. A comprehensive historic record of storms, local geomorphology, and regional landscape changes is necessary to provide a framework for understanding the sedimentary record. Changes in the sensitivity of the site to overwash deposition associated with changes in barrier position and height as well as inlet formation can be taken into account if sufficient historical information regarding the geomorphology exists. After a barrier has been overwashed it may take years or decades before the barrier regains its former height. Storms resulting in relatively minor storm surge may be able to overtop a barrier recently flattened by a large storm surge. An approach using multiple study sites can be used to minimize the influences of local changes in beach geomorphology on the interpretation of the sedimentary record of intense storms. Overwash deposits at multiple sites, dated to the same time interval, within a region would provide more compelling evidence of an intense hurricane strike.

Overwash fans from two storms that occur within a few years of one another may not be able to be distinguished within the sediment record if the sediment source is similar and not enough time has passed for marsh deposition to occur. In this case the second overwash fan would likely be composed of reworked sediment from the first overwash fan and other additional sediment of similar character. For example, historical accounts indicate that both the great colonial hurricane of August 25, 1635, and the hurricane of August 13, 1638, likely overtopped the barrier at Succotash Marsh, but only one overwash fan (fan IV) is preserved at the site for this time interval. It is possible that fan IV could be the result of both the 1635 and 1638 hurricanes, but there is no sedimentological evidence that fan IV represents deposition by two distinct overwash events. Therefore, multiple intense storms within a brief period may be difficult to resolve using these techniques.

The activation of the inlet at Succotash Marsh in the nineteenth century increased the sensitivity of the site to overwash deposition. As a result of this increased sensitivity a complex series of sand layers was deposited at this site adjacent to the channel. If a storm of intensity similar to that of the 1938 or 1815 hurricane struck this coast while the inlet was active it might be difficult to differentiate deposits associated with that storm from other deposits from less intense storms. For example, the 1869 hurricane may have caused storm surge high enough to overtop the barrier at Succotash Marsh when the inlet was closed and the marsh was more protected by the barrier, but because it struck when the inlet was open, we cannot identify any consistent overwash fan attributable to this storm at the site. In addition, the presence of an active channel may make overwash deposits more susceptible to reworking by tidal currents. Additional records from back-barrier environments nearby are needed to attempt to replicate the record from Succotash Marsh and possibly fill in some of the potential gaps in the Succotash record.

CONCLUSIONS

This study demonstrates that reconstructing the overwash history of back-barrier salt marshes can provide a sedimentary record of intense storms. Six distinct, large-scale overwash deposits are identified within the deposits of Succotash salt marsh. Careful dating and linking to the historical record provide means of determining how sensitive the site is to overwash deposition and a framework for interpreting prehistoric events. The timing of the four overwash fans within the historical period is consistent with the timing of intense historical hurricane strikes resulting in significant storm surge on this coast. Overwash deposits anticipated that were based on aerial-photographic evidence in association with the 1938 hurricane and hurricane Carol (1954), are evident in the top 25 cm of marsh peat at the site. The upper, less extensive overwash fan (fan I) was deposited by hurricane Carol on August 31, 1954, while fan II was deposited during the hurricane of September 21, 1938.

AMS radiocarbon dating of salt-marsh peat underlying overwash fans combined with other stratigraphic dating tools delimits the age of historic and prehistoric overwash deposits.

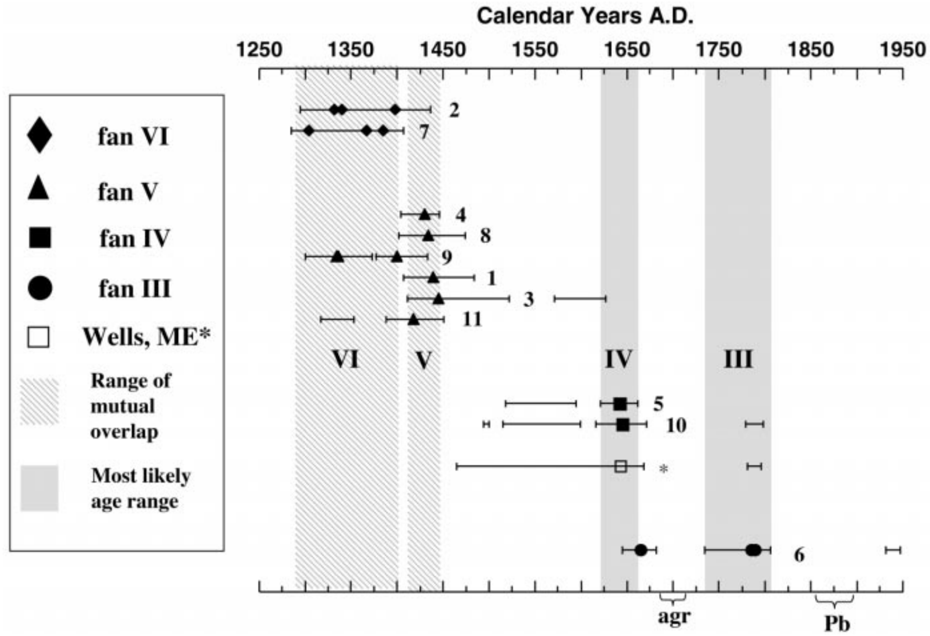

Figure 12. Plot of calibrated (2σ) radiocarbon age ranges for 11 radiocarbon dates for peat intervals directly below overwash fans at Succotash Marsh. The data are arranged in groups according to the overwash fan that overlies each sample: e.g., diamonds are dated peat sample directly underlying fan VI, and triangles are dated peat samples directly underlying fan V. These symbols represent the intercepts of the radiocarbon date with the calibration curve. Time intervals shaded with diagonal lines denote the mutual overlap of dates constraining the age of that peat interval. Time intervals shaded with solid gray denote the most likely age range based on the calibrated radiocarbon dates and other stratigraphic data. The intervals denoted by agr and Pb represent the time of the onset of widespread European-style clearance and Pb pollution, respectively. Asterisk indicates calibrated radiocarbon date from a peat deposit at the base of a large-scale overwash fan at Wells, Maine (Kelley et al., 1995).

Two other large-scale overwash fans have covered much of this area of Succotash Marsh since European settlement of the region (A.D. 1620). Fan III, its age defined as early nineteenth century, was likely deposited during the hurricane of September 23, 1815. This interpretation is further supported by the initiation of channel-levee and/or dredge-fill deposits in several cores following the deposition of this fan, which is consistent with the opening of the tidal inlet adjacent to the study site during the 1815 hurricane. Delimited in age to the nineteenth century A.D., fan IV was likely deposited by the August 25, 1635, and/or the August 13, 1638, hurricane.

The overlapping 2σ calibrated radiocarbon ranges suggest that fans V and VI were deposited between A.D. 1411–1446 and A.D. 1295–1407, respectively. Given that the sediments at Succotash probably recorded only intense hurricanes during the historic period makes it likely that the older overwash fans (fans V and VI) represent intense prehistoric hurricanes making landfall to the west of Succotash Marsh, similar to the 1815 and 1938 storms. This record of overwash deposition, coupled with historical records, indicates that at least seven hurricanes of intensity sufficient to produce storm surge capable of overtopping the barrier beach at Succotash Marsh have made landfall in southern New England in the past 700 yr.

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