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DEVELOPMENT OF A NEW ENGLAND SALT MARSH[1]

ALFRED C. REDFIELD[2]

Woods Hole Oceanographic Institution, Woods Hole, Massachusetts

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ABSTRACT

The salt marsh at Barnstable, Massachusetts, occupies an embayment into which it has spread during the past 4,000 years. It exhibits all stages of development from the seeding of bare sand flats through the development of intertidal marsh to the formation of mature high marsh underlain by peat deposits more than 20 ft deep. Observations and measurements of the stages of its formation are presented. The geomorphology of the marsh is considered in relation to the factors which have influenced its development, i.e., the ability of halophytes to grow at limited tide levels, the tidal regime, the processes of sedimentation, and the contemporary rise in sea level. The rates at which the early stage of development takes place have been determined by observations during a period of 12 years and the time sequence of later stages by radiocarbon analyses.

INTRODUCTION

This paper is an attempt to reconstruct or describe by direct observation the development of a typical New England salt marsh. The observations were made for the most part in the Great Marshes at Barnstable, Massachusetts. This marsh is well suited to the purpose because it occupies an enclosure small enough to be surveyed in its entirety, yet large enough to exhibit all stages in development, from mature marsh several thousand years old to juvenile marsh now invading bare sand flats. Carbon-14 analyses have provided information on the time sequence of events during the earlier periods, and observations continuing over 12 years have indicated the rates of recent processes. Inferences on the formation of the mature marsh may be confirmed by observation of the present processes of development. Previous publications on the Barnstable Marsh are reviewed, and, where relevant, explicit references are given to the more important studies on the salt marshes of the East Coast. Statements on which there appears to be general agreement are made without specific reference. For a review of the literature on marshes in general, see Chapman (1960).

The topography of the area and the names applied to its principal features are shown in Fig. 1. Barnstable Marsh lies in an enclosure formed by a sand spit, Sandy Neck, which is 5.7 miles long. The area of the enclosure west of the termination of Sandy Neck at Beach Point is 5,300 acres. Of this, 3,070 acres are mature high marsh, 280 acres are in the intertidal stage of development, 1,200 acres are occupied by sand flats which bare at low tide; 750 acres of channels remain flooded at all times. The range

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[2] Address: Box 106, Woods Hole, Mass. 02543.

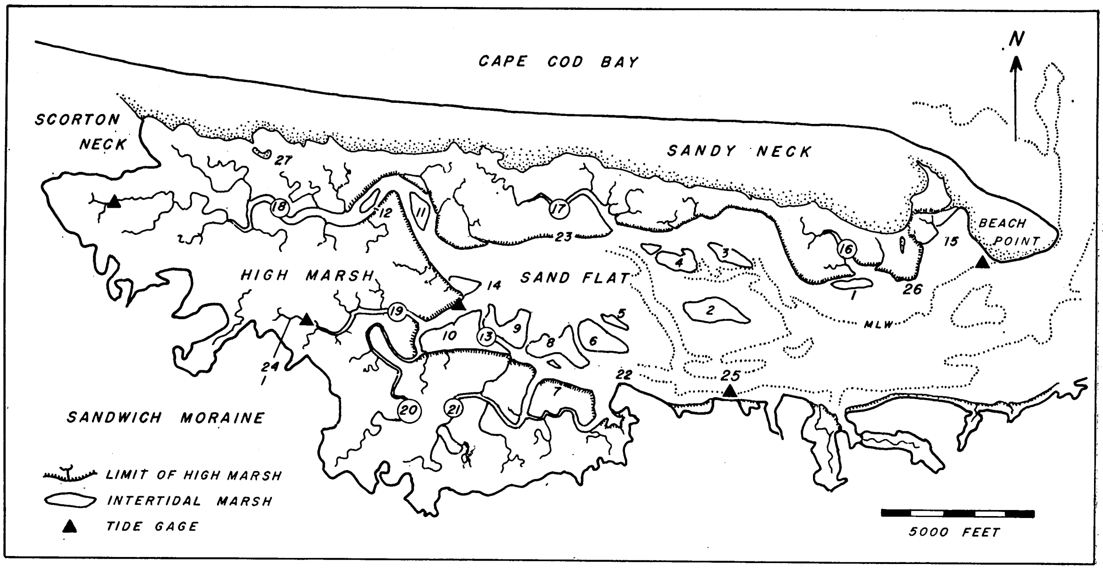

FIG. 1. Barnstable Harbor, 41° 43′ N, 70° 20′ W.

1. Town Island
2. Phillis Island
3. Great Thatcher Island
4. Little Thatcher Island
5. New Island
6. Huckins Island
7. Jules Island
8. Sand Island
9. Duck Island
10. Howes Island
11. Jacksons Island
12. Wicks Island
13. Broad Sound
14. Slough Point
15. The Cove
16. Bass Creek
17. Wells Creek
18. Scorton Creek
19. Spring Creek
20. Bridge Creek
21. Brickyard Creek
22. Calves Pasture Point
23. Black Bank
24. Navigation Road
25. Yacht Club
26. Mussel Point
27. Great Island

of tide is about 9.5 ft and results in the reduction of the volume of water in the harbor at low tide to about 10% of the high tide volume (Ayres 1959).

The geology of the region is treated by Woodworth and Wigglesworth (1934) and Mather, Goldthwaite, and Thiesmeyer (1942); the hydrography of Barnstable Harbor is discussed by Ayres (1959). The rise in sea level during the period of marsh development at Barnstable was studied by Redfield and Rubin (1962), and on the basis of this study the history of the marsh has been reconstructed (Redfield 1965*a*). The vegetation of Barnstable Marsh has been described by Blum (1968), the intertidal fauna by Sanders et al. (1962), and the marsh Foraminifera by Phleger and Walton (1950). Gas transport by *Spartina alterniflora* has been studied at Barnstable by Teal and Kanwisher (1966) and the thermal regime in salt-marsh peat by Redfield (1965*b*).

Place names and terminology

The names applied to geographical features are those shown on the Hyannis Quadrangle of the topographic maps of U. S. Geological Survey and on U. S. Coast and Geodetic Survey Chart 339 of Barnstable Harbor. Other names in local use or which have been coined are as follows:

Black Bank—The marsh bank facing open water west of Wells Creek.

Howes Island—Intertidal marsh lying south of the common trunk of Spring and Bridge Creeks, between Bridge Creek and Broad Sound.

Navigation Road—The roadway extending across the marsh to Spring Creek.

New Island—A thatch island lying northeast of Huckins Island.

Special terms used in the description of the marsh are defined as follows:

Basement—Inorganic deposits of sand, gravel, stone, or glacial till underlying deposits of peat.

High marsh—Marsh in the mature stage of development in which an essentially flat surface lies at approximately the mean high water level.

Intertidal marsh—Stands of *Spartina alterniflora* growing below mean high water.

MHW—Mean high water

MLW—Mean low water

MSL—Mean sea level

Marsh bank—The nearly vertical face of peat deposits produced by erosion.

Neap tides—Tides occurring near the time of the quadrature of the moon, when the range is less than the mean range.

Panne—A shallow pool of standing water interrupting the vegetated surface of marshland.

Panne marsh—A stage in development of intertidal marsh.

Peat—Material formed by mineral sediment deposited among vegetation and containing the roots and other parts of the plants, either living or dead.

Pond hole—The name locally applied to deep pannes which interrupt the turf and consequently have nearly vertical walls.

Slough marsh—A stage in development of intertidal marsh.

Spring tides—Tides occurring near the time of full or new moon, when the range is greater than the mean range.

Submerged upland—Areas in which peat has been deposited over the upland as it has been submerged by rising sea level.

Thatch—The name locally applied to *Spartina alterniflora* growing in the intertidal zone.

Thatch islands—Continuous stands of *Spartina alterniflora* growing in isolation on sand flats.

Turf—The surface layer of peat containing living roots.

Factors in The Development of the Marsh

The development of a salt marsh depends upon the physiology of the local halophytic vegetation, the behavior of the tide, the processes of sedimentation, and changes in sea level relative to the land.

Vegetation

The flora of the marsh at Barnstable, as described by Blum (1968), is similar to that of other parts of the North Atlantic coast as reported by Johnson and York (1915), Knight (1934), Conrad (1935), Taylor (1938), Chapman (1940), Miller and Egler (1950), and Kurz and Wagner (1957). The intertidal zone is occupied almost exclusively by *Spartina alterniflora* reaching heights of 4–6 ft. The plants grow to these heights along the depressed borders of the creeks which drain the high marsh, but at or near the high water level, where the marsh becomes flat, *S. alterniflora* occurs in a dwarfed form only 0.5–1 ft high. The dwarfed form has been designated as the variety *pilosa* by Merrill (1902), but Mooring, Cooper, and Seneca (1970), who have studied the *Spartina alterniflora* of North Carolina marshes, believe that the dwarf form results from environmental factors.

Wherever the high marsh is sufficiently well drained, as throughout its more elevated parts, on the levees which border the greater creeks, and at the margins of ditches, *Spartina alterniflora* is replaced by the *Spartina patens* association consisting of *Spartina patens* and *Distichlis spicata.* Scattered among these species *Limonium carolinianum, Plantago maritima, Aster subulatus, Solidago sempervirens, Atriplex patula, Suaeda maritima,* and *Salicornia* sp. are found. *Juncus gerardi* grows in pure stands at the higher levels along the margin of the marsh or occasionally at places where deposits of sand on the levees bordering the creeks or the presence of submerged sand hills have raised the surface above the general level of the marsh. Pure stands of the glassworts *Salicornia europaea* and *Salicornia Bigelovii* occupy areas surrounding bare pannes and pathways where the grasses have been killed by traffic. Along the margins of the high marsh, where ground water emerges, the typical salt-marsh flora is replaced by plants which can withstand limited exposure to brackish water, such as *Scirpus robustus, Typha,* and, more locally, *Phragmites communis.*

Blum (1968) found that, in unit areas along transects on the high marsh at the western end of the Barnstable Marsh, the angiosperm communities were dominant in the following proportions:

Monospecific dominance	
Spartina patens	39.6%
Spartina alterniflora	32.2%
Distichlis spicata	12.0%
Juncus gerardi	1.1%
Heterospecific dominance	
Spartina alterniflora–S. patens	10%
Spartina patens–Distichlis spicata	1.6%
Spartina alterniflora–Distichlis spicata	0.6%
Panne areas	2.9%

The areas in which the *Spartina patens* association or the dwarfed form of *Spartina alterniflora* dominate the vegetation are shown in Fig. 2. The occurrence of *Distichlis* is not separated from that of *S. patens,* as both grow at similar elevations and are frequently mixed together. Nor are indicated the frequent areas in which *S. patens* and *S. alterniflora* appear as mixtures. The *Spartina patens* association occupies about 38% of the whole high marsh area, the remainder being dominated by *S. alterniflora.* The *Spartina patens* association dominates along the margin where the upland has been submerged by rising sea level. *Spartina alterniflora* occurs, usually in dwarf form, as the dominant in those parts of the high marsh which have developed over sand flats and are underlain by peat formed at intertidal levels. However, *S. patens* has spread to a limited extent into the area which was formerly intertidal, particularly at the western end of the marsh, and occurs

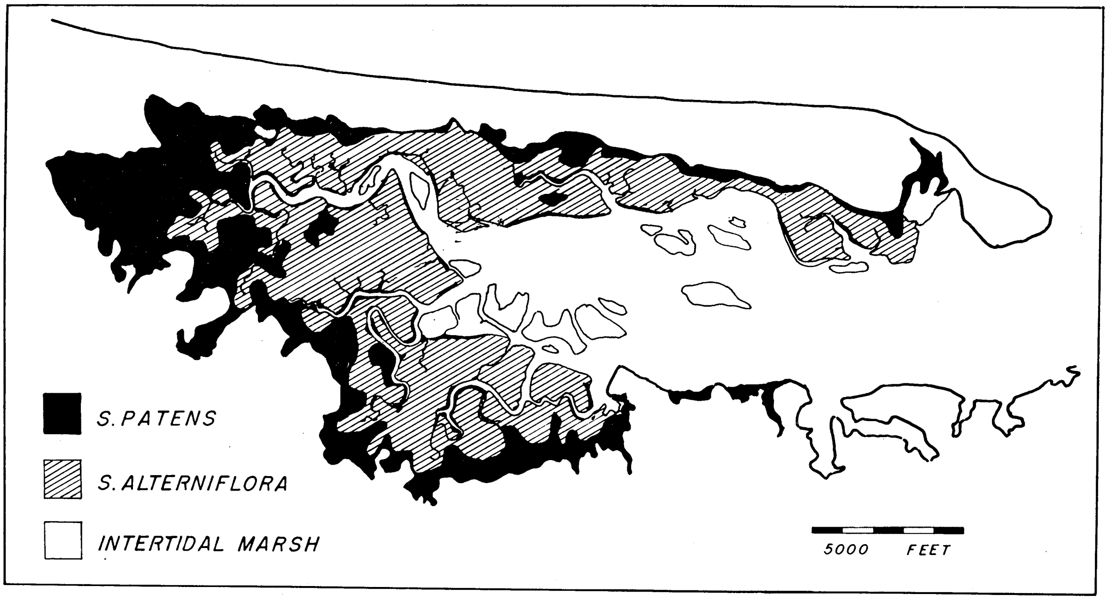

FIG. 2. Areas of high marsh dominated by *Spartina alterniflora* and by the *Spartina patens* association. Monospecific stands of *Spartina alterniflora* occupy the intertidal marsh.

quite generally along the levees on the banks of the creeks. The separation of the areas dominated by *S. alterniflora* and *S. patens* is not clearcut. *Spartina alterniflora* penetrates the *S. patens* zone in many places, particularly along the minor creeks, and *S. patens* occurs in isolated patches in the *S. alterniflora* area. In many places the species are mixed.

The algae of the Barnstable Marsh have been described by Blum (1968). The soil surface under the stands of dwarf *S. alterniflora* of the high marsh is covered almost completely throughout the warm season by a thin layer of filamentous algae, principally *Lyngbia* sp. and *Vaucheria* sp. Algal colonization is sparse or nonexistent under stands of *S. patens* and *Distichlis,* a condition attributed to the exclusion of light by the dense mat of dead plants produced by these grasses. Under the stands of *S. alterniflora* which grow at intertidal levels along the creek banks, the algal layer consists mainly of diatoms.

The development of the marshes of the east coast of the United States depends upon the physiological characteristics of *Spartina alterniflora.* This grass is unique in being able to survive submergence for much longer periods than other halophytes (Chapman 1940). This enables marshland to develop over a substantial part of the intertidal zone and to pioneer in its expansion onto previously barren areas. The plants of the *Spartina patens* association, however, do not grow at levels very much below mean high water and are consequently restricted to the high marsh. Teal and Kanwisher (1966) have shown that uninterrupted spaces in the leaves and roots of *S. alterniflora* permit the diffusion of oxygen to the roots during submergence. However, *S. alterniflora* apparently cannot survive continuous submergence of its roots in standing water. This characteristic accounts for the presence of unvegetated pannes at any level of the marsh, where the surface is inadequately drained.

The germination of seeds of *Spartina alterniflora* and the subsequent growth of the seedlings, as influenced by temperature and salinity, have recently been studied in the laboratory by Mooring, Cooper, and Seneca (1971). They found that the seeds are sensitive to drying, but will germinate if kept moist in sea water at low temperature for 8 months. The percentage of germination was greatest in fresh water and decreased with increasing salinity. Germination was low in 4% NaCl and zero in 8% NaCl. Growth of the seedlings, as judged by height and dry weight, was greatest in 0.5% NaCl and was substantially reduced at salinities greater than 2% NaCl.

At Barnstable successful colonization by seeding takes place on sand flats which (according to Ayres 1959) are submerged twice daily by water of 30‰ salinity and where the salinity in the channels that drain marshland at low water does not fall below 20‰ during spring freshets. Mature stands of *S. alterniflora,* 4–5 ft high, develop on these flats. There is no indication at Barnstable that natural sea water having a salinity of 30‰ is detrimental to germination or growth.

In the Barnstable Marsh, where the mean range of tide is about 9.6 ft, seedlings of *S. alterniflora* become established on aggrading sand flats where the elevation of the surface is about 6 ft below that

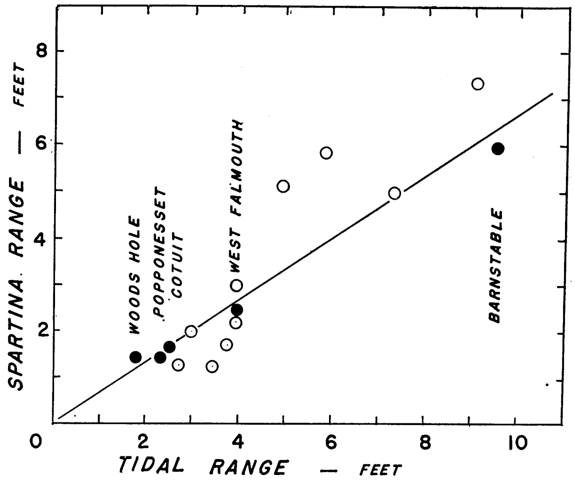

FIG. 3. The vertical range of *Spartina alterniflora* in relation to the range of the tide. Open circles: positions between Massachusetts and Florida after Adams (1963). Solid circles: positions on Cape Cod. The slope of the arbitrary line is 0.7.

of mean high water. The lowest level at which continuous stands of *S. alterniflora* are found is close to this elevation. Thus, growth can occur throughout nearly two-thirds of the mean tidal range.

Johnson and York (1915) proposed that the relative time of submergence limits the vertical range of *S. alterniflora.* Data from positions distributed between Massachusetts and Florida, at which the range in tide differs greatly, have been presented by Adams (1963) in support of this view. It is further supported by data from Cape Cod, where the tidal range differs greatly on the opposite sides of the cape (Fig. 3). The vertical range of the plants is on the average about two-thirds of the mean tidal range, but is subject to local variation.

Salt marshes in general are found in sheltered areas of the seacoast—behind barrier beaches, in the estuaries of tidal rivers, and in other recessions of the upland. Their exclusion from exposed shorelines appears to depend on the instability of the substratum under wave action rather than upon mechanical damage by the waves. On the shores of Cape Cod Bay (at South Wellfleet and Eastham), as in other places, fringes of *S. alterniflora* occur on the foreshore exposed to the full action of waves. In these places the plants are rooted in the peat of former marshes which were buried as the beach receded under erosive forces and which is now found emerging on the foreshore (see Johnson 1925). On the shores of Buzzards Bay patches of thatch also grow in exposed situations among the stones and boulders of the beach. Within sheltered estuaries the movement of sand under the action of tidal currents may limit the distribution of the plants. At Barnstable, sand flats where the sand is in active motion are bare at elevations well above the usual lower limit of *Spartina* growth.

The tide

Tidal influences appear to be the most significant environmental factors responsible for the segregation of salt-marsh vegetation (Miller and Egler 1950). In many coastal lagoons, constriction of the inlets and shallow water reduce the tidal range, delay the time of high water, and modify the form of the merogram in ways which are not indicated adequately by the tide tables.

To determine the characteristics of the tide at Barnstable the portable tide gage described by Redfield (1962) was operated for one complete lunar cycle at four positions shown in Fig. 1. Local bench marks were leveled in to civil bench marks at which the elevation relative to mean sea level is known. Records of the tide at Boston for the periods during which the tide gages were operated were used to determine the general sea level during those periods. Observations over shorter periods were made near the head of Scorton Creek and in Navigation Creek to find the characteristics of the tide in the smaller creeks.

The mean range of tide at Boston was 9.8 ft, as measured in June–July 1959, and was 0.3 ft greater than the value given in the tide tables (Table 1). At Beach Point the mean range was the same as at Boston. On ascending the harbor the mean range decreases to 9.5 ft at the head of Spring Creek. In the smaller creeks in the marsh the range is less because the bottoms of the creeks are above the level of low water in the large creeks to which they are tributary. At the head of such creeks, and in the artificial ditches, the range is reduced to 1–2 ft as these become smaller and shallower.

Although the mean range of tide is less in the creeks than in the open harbor, the elevation at high water relative to mean sea level is about 0.3 ft greater at the Spring Creek tide gage than in the open harbor at the Yacht Club. The elevation at low tide also increases upstream and is 1.11 ft greater at the head of Spring Creek than at Beach Point. This results from restraints to the draining of the channels as they shoal, and particularly to the "weirs" formed by sand bars along their course as described by Ayers (1959).

As is usually the case in shallow estuaries the time of high water is delayed along the channel, and the form of the merogram is distorted so that the tide rises more rapidly than it falls. High water occurs about 0.3 hr later in the larger creeks than at Beach Point and is nearly 1 hr later at the head of Scorton Creek. The delay in the time of low water is much greater. As a result the period of flood becomes increasingly shorter upstream and the period of ebb longer.

TABLE 1. Characteristics of mean tide at Barnstable as given in tide tables and as determined during the periods specified

Position	Latitude (N)	Longitude (W)	Distance (ft)	Mean range (ft)	Elevation re MSL[a] High water (ft)	Elevation re MSL[a] Low water (ft)	Delay re Boston High water (hr)	Delay re Boston Low water (hr)	Duration Flood (hr)	Duration Ebb (hr)
Boston	42° 21′	71° 03′								
Tide tables				9.5	4.75	−4.75	0	0	6.2	6.2
June 19-July 16, 1959				9.8	4.91	−4.88	0	0	6.2	6.2
Beach Point	41° 43.3′	70° 17.1′	0							
Tide tables				9.5	4.75	−4.75				
June 19-July 16, 1959				9.8	5.17	−5.21	0.1	0.3	6.0	6.4
Yacth Club	41° 42.6′	70° 19.0′	9,600							
May 16-June 13, 1959				9.9	5.09	−4.81	0.1	0.8	5.5	6.9
Slough Point	41° 43.2′	70° 20.6′	19,200							
July 23-August 20, 1958				9.6	—	—	0.2	1.4	5.6	7.3
Spring Creek	41° 30.0′	70° 21.9′	25,500							
June 11-July 10, 1958				9.5	5.40	−4.10	0.3	1.9	4.5	7.9
Navigation Creek	41° 29.9′	70° 21.8′	25,500							
July 25, 1961				7.8	5.40	−2.4	0.3	3.4	3.0	9.4
Scorton Creek	41° 43.0′	70° 24.0′	44,100							
August 16-31, 1963				4.9	—	—	0.9	4.3	2.8	9.6

[a]MSL datum is that determined at Boston for the period 1924–42.

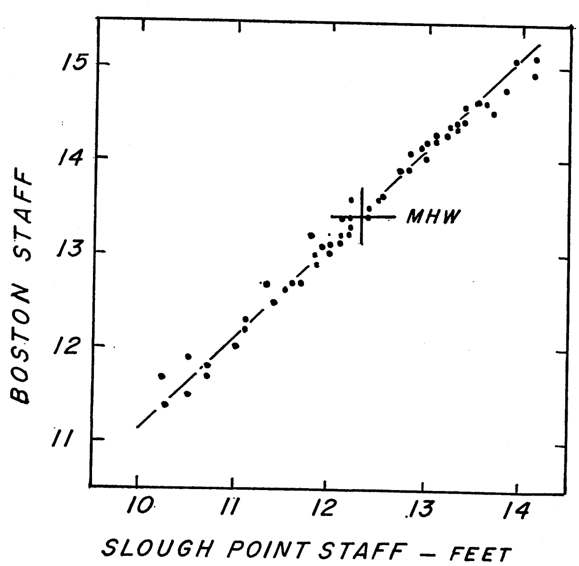

FIG. 4. The variation of the elevation of high waters in the course of the lunar cycle at Boston and at Slough Point, Barnstable.

At high water during spring and neap tides the elevation of the water departs by more than ± 1.5 ft from its mean value. The elevation relative to the local mean high water for simultaneous high waters as recorded at Boston and Slough Point during the period July 23–August 20, 1958, is shown in Fig. 4. Throughout the lunar cycle the variation in elevation at high water from MHW is the same at Slough Point as at Boston. This correspondence indicates that the relative elevations at high water as they change during the month are not distorted in the marsh. It justifies the use of the tidal predictions for Boston in estimating the degree to which the marsh is flooded as the tides vary with time and the use of water leveling at high tides as an approximate means of determining the elevation of the marsh surface near bench marks of which the elevation is known.

At low water during spring and neap tides the elevation of the water relative to the local mean low water is the same for simultaneous tides at Beach Point and at Boston down to the lowest tide recorded which was 1.7 ft below mean low water. Within the harbor and marsh the elevation of the water at low tide does not fall below a certain limit. Above this limit the water at low tide at Barnstable varies with its elevation at Boston, as do the high tides. When the low tides at Boston fall below this limit the low tide within the harbor or marsh remains the same. The limiting elevation increases toward the head of the harbor. At the Yacht Club the limit is reached on tides which at Boston fall to 1.3 ft *below* mean low water. At Slough Point and Spring Creek the limits are reached on tides which fall at Boston to an elevation of 1.7 and 2.3 ft respectively *above* mean low water. Thus, at the lowest tide recorded the elevation of the water at low tide was 4 ft higher at Spring Creek than at the mouth of the harbor. These limits presumably arise from the shoals which obstruct the channels at low water.

The number of tides which flood high marsh of different elevations annually and the volume of water which they supply to be carried off by the creeks

TABLE 2. Number of tides flooding marsh of various elevations annually and resulting volume of flood water and period of submergence of the marsh surface

Elevation of marsh		Number of flooding tides	Volume of flood water	Period of submergence	
re MLW (ft)	re MHW (ft)	(per year)	(ft^3/ft^2 per year)	(hours per year)	(% of year)
9.5	0	316	198	500	5.7
10.0	0.5	170	173	240	2.7
10.5	1.0	83	114	115	1.3
11.0	1.5	43	80	48	0.55
11.5	2.0	18	38	8	0.14
11.7	2.5	1	2.3	0	0

for each square foot of flooded marsh have been estimated from the daily predictions for the tide at Boston. The periods during which marshlands of various elevation would be submerged has been estimated from this information combined with that obtained from tide-gage records made at Slough Point. The estimates are given in Table 2 for marsh increasing in elevation by increments of 0.5 ft at and above the elevation of mean high water. The values decrease rapidly as the elevation of the marsh increases.

Of the 707 tides which occurred in 1968 at Boston 316 were predicted to reach or exceed the height of MHW (9.5 ft re MLW). Marsh at this elevation would be flooded by a volume of 198 ft^3/ft^2 of area in the course of the year. This is the volume of water which must be carried annually by the creeks.

Such marsh would be submerged by the tide for 500 hr during the year or 5.7% of the time. The greater part of the marsh probably does not exceed 10.5 re MLW in elevation. Marsh of this elevation would be flooded by only 83 tides per year or about one-quarter the number flooding marsh of the elevation of MHW. The volume of flood water would be reduced to 114 ft^3/ft^2 per year, or about 0.6 of the volume flooding marsh at the elevation of MHW. Marshland higher than 10.5 ft re MLW is limited to the margin where it rises to meet the upland. The highest tide predicted for the year has a height of 11.7 ft re MLW.

These estimates do not take into account the delay in the movement of water as it floods and ebbs across the vegetated surface of the marsh and are consequently approximate. They indicate, however, the variations which occur as the elevation of the marsh increases. It will be pointed out later that the density of the pattern of small creeks draining the marsh is related to the age and corresponding elevation of the high marsh surface.

The volume of water which floods the marsh annually exceeds greatly that which falls on it as precipitation. The rainfall on Cape Cod is about 4 ft^3/ft^2 per year. The volume of flood water submerging the greater part of the marsh at Barnstable having an elevation of 10.5 ft or less is 114 ft^3/ft^2 per year. This is about 28 times the volume of rainfall. Of the rain falling on the upland much enters the ground water or is lost by evaporation, so that only a fraction appears as runoff. In the marsh, in contrast, these losses are negligible. These considerations account for the dense drainage patterns which characterize salt marshes.

The period of submergence of the high marsh is a relatively small fraction of the total time, about 6% for marsh at the elevation of MHW and 1.3% for the 10.5-ft elevation. Submergence for not more than 1% of the time at infrequent intervals and for periods not greater than about 2 hr is probably adequate to prevent the less salt-tolerant vegetation of the upland from invading the salt marsh.

The critical level below which *Spartina alterniflora* does not grow is approximately 6 ft below mean high water. At Slough Point the average tide exceeds this elevation, submerging the plants for 6.8 hr or 55% of the time. The plants are exposed to the air for 5.6 hr. With a few exceptions, this level marks the elevation of the highest sand flats. On the average tide the highest flats bare about 4 hr after high water and are flooded about 2 hr after low water.

Sedimentation

The obvious source of the sands which have formed Sandy Neck and the sand flats within the harbor is the erosion of extensive sea cliffs which extend from Manomet Point to the Cape Cod Canal, and lesser cliffs at Scorton Neck immediately to the west of Sandy Neck. The eastward drift of sand is interrupted by strong tidal currents in the channel leading into Barnstable Harbor, where a part of the sand is carried into the harbor during the flood. The remainder is carried seaward by ebb currents and has formed a sand bar extending 1 mile seaward from Beach Point. Sand which bypasses the channel has been deposited as extensive sand flats to the eastward which occupy the greater part of the harbor mouth. Erosion of a sea cliff east of the harbor is also contributing sand to these flats and has built a sandspit extending southwestward to enclose marshland. This spit has widened about 450 ft in the past 100 years.

Sandy Neck has grown eastward about 600 ft in this period.

Within the harbor the foreshore along the south side consists of gravel, sand, and glacial clay, on which occasional boulders are scattered, all presumably derived from local erosion of the upland. Patches of scattered stones and gravel are found at a few places along the eastern part of the marsh bordering Sandy Neck, notably at Mussel Point. They are derived from sand spits which marked the termination of Sandy Neck at an earlier period and are now buried in the marsh (Redfield 1965*a*). Elsewhere the open harbor is floored with deposits of quartz sand which has been introduced from offshore by tidal currents.

A comparison of charts going back to 1859 and personal experience of 60 years indicate that the channels of the harbor have shoaled and that the pattern of sand flats and channels, particularly in the western region, has been subject to continual change. The sands are evidently moved freely by the tidal currents which attain velocities up to 2 ft/sec. The surface of the flats is commonly marked by sand ripples giving evidence of its mobility. Analysis of grain size shows that the sands are well sorted and that in their movement the coarser particles tend to lag behind so that the average grain size decreases up harbor (Fig. 5).

The clean white sands of the open harbor do not penetrate very far into the creeks which drain the marsh. At Spring Creek they terminate at its junction with Bridge Creek, about 0.4 mile above Slough Point (see Fig. 13). They extend about 0.7 mile into Scorton Creek. Above them the creek bottoms are of a dark, silty mud, firm enough to be traversed on foot. Deposits of a soft mud are limited to places which are relatively free from tidal motion.

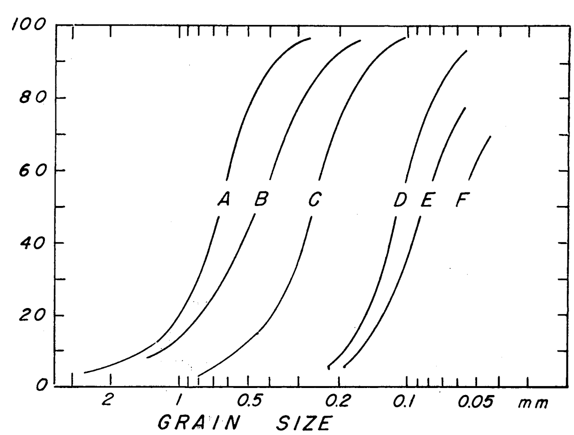

FIG. 5. Cumulative distribution of grain size in sediments of Barnstable Harbor and marsh. A, off Beach Point; B, off Horseshoe Shoal (south of The Cove); C, west of Phillis Island; D, east of Slough Point; E, Spring Creek; F, Wicks Island (intertidal marsh). For positions see Fig. 32.

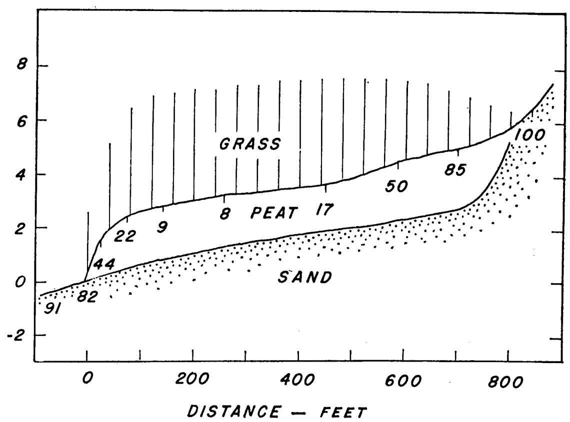

FIG. 6. Thickness of peat, percentage of sand in the peat, and height of *Spartina alterniflora* in August in intertidal marsh bordering The Cove.

At tide levels at which *S. alterniflora* grows, the vegetation acts to reduce the tidal motion and thus to filter out the larger particles of waterborne sediment. The proportion of sand (grain size greater than 0.062 mm) present in the peat deposit of the intertidal marsh on the west side of The Cove is shown in Fig. 6. The sand content of the flat below this marsh was 91%. Within 4 ft of the margin of the flat the sand content of the inorganic sediment of the marsh peat was reduced to 82%. It decreased steadily to a distance of 250 ft from the flat where only 8% sand was present. The proportion of sand increased beyond this point because of windblown sand derived from a sand hill which is encroaching on the marsh. Its effect is evident for 500 ft from the sand hill. The presence of coarse sand in the peats at other positions along the border of Sandy Neck has been noted also, but does not extend very far into the marsh. Windblown sand appears to have a very minor and local effect in supplying sediment for building the marsh.

The mineral matter of the peats formed near the level of MHW is derived ordinarily from sediment particles so small that they remain in suspension in the water which floods the marsh at high tide. Such material collects in the recesses formed when blocks of peat break off and slump into the creeks, where it produces a very soft silty mud (Fig. 49). A sample of mud deposited on a bare area of the high marsh near the margin of Spring Creek contained 41% clay (grain size < 0.04 mm), 32% silt, and 27% sand. A very large volume of fine sediments has been entrapped in the marsh, where deposits of high marsh peat containing 10–15% (by wet weight) mineral matter occur to depths of 20 ft or more. Probably not much of it has been derived from the local upland since the few streams entering the marsh do not carry an appreciable sediment load. Presumably the fine sediments are derived from glacial clays eroded, like the sands, from the coastal cliffs and are similar in origin to the mud deposits which are found offshore in Cape Cod Bay.

Sea level

The level of the sea has been rising since the close of the last glacial period owing to the melting of glacial ice. In addition, the land along the northeast coast of the United States has been subsiding (Redfield 1967). The marsh has preserved evidence of the rise in sea level in the form of (1) a sea cliff on the eastern side of the Scorton Neck, the base of which is covered by peat to a depth of 18 ft; (2) submerged sand hills, one of which, Great Island, is surrounded by 15 ft of peat; (3) sandspits, now buried by marshland, which marked the earlier terminations of Sandy Neck; and (4) buried tree stumps, a fragment of one of which recovered from a depth of 23 ft (7 m) was aged 4,860 years (Redfield and Rubin 1962, Analysis No. W-1093).

The recent change in the level of the sea at Barnstable has been determined from the radiocarbon age of peats, presumed to have been deposited at the mean high water level, and now found at various depths below the high marsh surface. In the past 4,000 years, during which peat has been forming at Barnstable, the elevation of the sea relative to the land has increased by about 25 ft (Fig. 7). The result has been that a substantial area of upland along the southern and western border of the marsh has been submerged and covered by salt marsh.

The combined factors

At Barnstable the factors on which the development of salt marsh depend combine to favor its enlargement. The dominant vegetation, *Spartina alterniflora,* is unique in its ability to withstand submergence and to invade a substantial portion of the intertidal zone. The great range of tide favors a broad intertidal zone suitable for marsh development. The inequality of the tides during the lunar cycle ensures the periodic flooding of the high marsh and thus limits the invasion of the marsh by the vegetation of the upland. Sources of sediment have been ample to build up the elevation of the sand flats to the level at which *S. alterniflora* may grow and to prevent its drowning by the rising sea level. Rising sea levels have enabled the marsh to spread over the bordering upland. They have also prevented the sea cliffs from which sediment is derived from attaining a stable equilibrium, thus ensuring a continuing supply of sediment to the harbor.

These factors obtain along the coast north of Cape Cod, where extensive marshes fill the embayments, for example, at Plum Island, Ipswich, and in many smaller enclosures. On the south side of Cape Cod the conditions for marsh development appear to be less favorable, with many shallow bays remaining as open water. Here the tidal ranges are much smaller, from 1.8 to 4 ft. This limits the area of foreshore on which *S. alterniflora* can grow and reduces the tidal prism so that the size of the inlets and the currents through them are smaller and the supply of sediment to the basins is thus diminished. The result has been that the rate of deposit of sediment has not been sufficient in the face of rising sea level to fill the basins to a level where marsh can develop. Such marsh as was present when sea level was lower has been drowned out as sea level rose, leaving open water over the greater part of the basins.

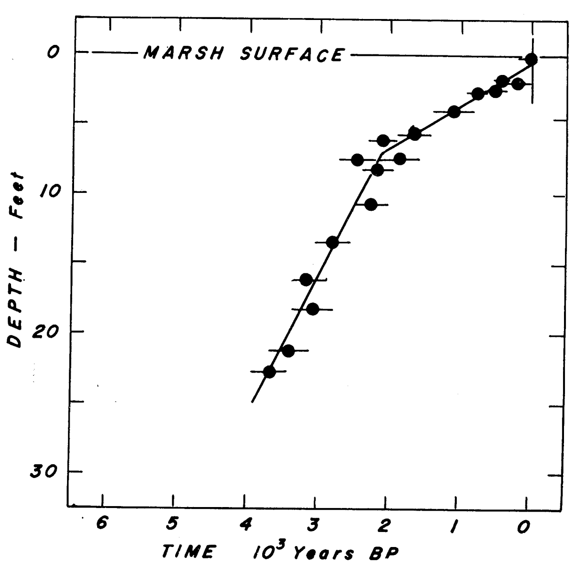

FIG. 7. Age of peat in Barnstable Marsh at depths immediately over the basement. After Redfield and Rubin (1962).

THEORY OF STRUCTURE OF SALT MARSHES

An account of the development of the New England salt marshes was given in 1886 by Shaler. He noted that *Spartina alterniflora,* then known as *S. glabra,* occupied the intertidal zone and was succeeded by other species, the *Spartina patens* association, at the level of high water. With the accumulation of sediment these layers would extend outward over the sand or mud flats. At an earlier period Cook (1857) and Mudge (1858) had pointed out that salt-marsh peat occurred at depths well below the elevation of existing marshes. They concluded that the coastland had subsided.

Johnson (1925) considered that the views presented by Shaler and Mudge were at variance. According to the Shaler theory, if a marsh developed under conditions of constant sea level, it should show a stratification in which layers of peat formed by the *Spartina patens* association would overlay layers of *S. alterniflora* peat which had developed at intertidal levels. These layers in turn would overlay the silty or sandy basement. According to the Mudge theory, if the marsh grew upward during a period of subsidence, a homogeneous layer of peat formed by the *Spartina patens* association would extend to considerable depths. Johnson concluded that the latter theory is correct, and this view was confirmed by Knight (1935) who presented diagrams illustrating the structure to be expected in a marsh formed behind a retrograding barrier beach during a period of rising sea level.

Recently, Chapman (1960) and Redfield (1959) postulated that if a marsh develops during a period of rise in relative sea level, and if sediment accumulates beyond its margin at a rate in excess of that of the rise in sea level, *Spartina alterniflora* will spread over the accumulating sediment whenever its elevation exceeds the lower limit at which this plant may survive. As sea level rises, this critical level will increase in elevation with the result that the basement on which the peat rests will rise toward the outer limit of the marsh. A layer of peat of relatively uniform thickness formed by *S. alterniflora* at intertidal levels will develop over the rising basement. Above this layer, peat formed at the high marsh surface (about MHW) would extend outward as a wedge of decreasing thickness. Such peat alone would occur in regions where the rising sea level had submerged the upland subsequent to the earliest development of the marsh (Fig. 8). Thus, cores of peat taken in the region where the marsh has grown up over the submerged upland would conform to the observations of Mudge; those taken where it has spread out over sand flats would have the stratified characteristic of the Shaler marsh.

An examination of the structure of the marsh at Barnstable has confirmed this speculation. Peats lying at intertidal levels have a water content varying between 30% and 60%, whereas those formed by the high marsh association contain 60–90% water. Using this criterion the structure along a section of marsh was shown to confirm the expectations raised by Chapman and Redfield (Redfield 1965*a*) (Fig. 9).

The History of the Barnstable Marsh

The New England marshes are recent formations which postdate the retreat of the last Quaternary glaciation. The oldest existing marshes which have been studied are not older than about 4,000 years. *Spartina* peat aged 11,000 years has been recovered on Georges Bank from a depth of 193 ft (Emery and Garrison 1967). Presumably the older marshes have been drowned, eroded away, or buried by sediments as sea level rose. Kaye and Barghoorn (1964) suggest that the compaction of peat under its own weight may have limited its rate of vertical accretion and prevented the older marshes from rising as fast as sea level, thus causing them to be drowned out.

A reconstruction of the development of the marsh at Barnstable is shown in Fig. 10. It is based on the depth of the peat, the relation of age to depth of the deposits, and the theory of structure proposed by Chapman and Redfield (Redfield 1965*a*). About 3,000 years ago, when relative sea level was 18 ft

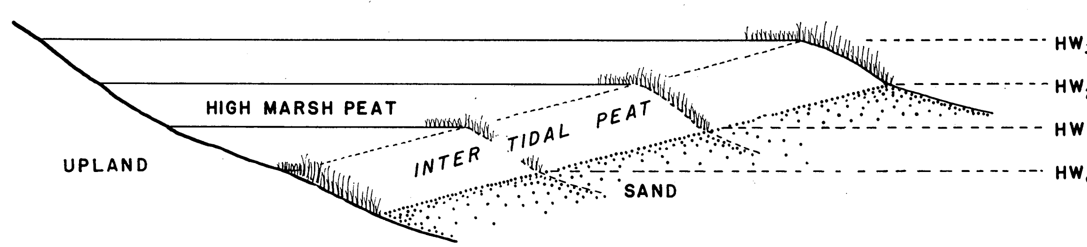

FIG. 8. Theoretical structure of salt marsh which is spreading over accumulating sediment on a sand flat and over the upland in the course of rising sea level. After Redfield and Rubin (1962).

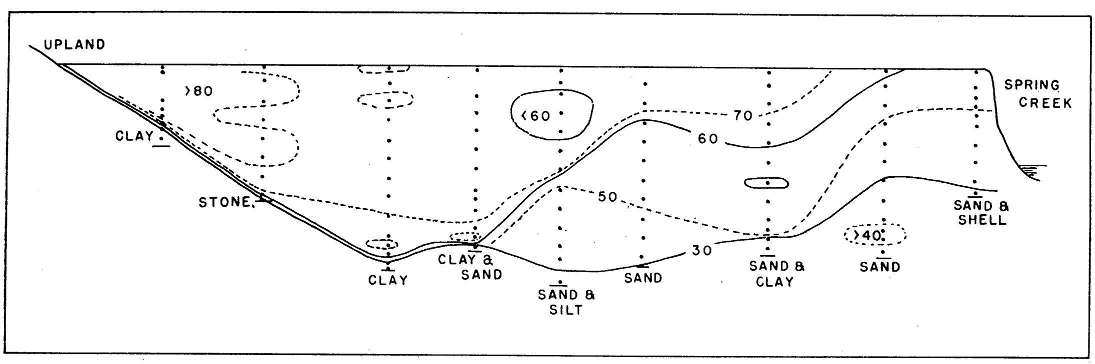

FIG. 9. Water content of peat, as percentage weight, along a section of high marsh extending from upland east of Navigation Road to Spring Creek. Compare with theoretical structure in Fig. 8.

lower than at present, the sandspit which now protects the marsh was much shorter. The marshland was then limited to small patches occupying indentations along the margin of the upland. As time passed the sandspit increased in length, affording protection to the developing marsh. The patches of marsh along the margin became continuous. Meanwhile, sand and silt accumulated within the enclosure fast enough so that, in spite of the rising sea level, the water became sufficiently shallow for *S. alterniflora* to grow out from the margin and to form thatch islands on the higher sand flats. These islands tended to fuse, forming peninsulas of intertidal marsh extending into the basin; later these built up to become high marsh. The result was the division of the open waters into broad sounds occupied by sand flats. As these gradually shoaled they were invaded by marsh and thus narrowed to form the creeks which now drain the high marsh.

The pattern of development appears to have depended on the vagaries of the sedimentary processes which built up the sand flats to the critical level above which *S. alterniflora* can grow. The drainage pattern of the high marsh has been fixed by that of the channels which finally drained the flats in the broad sounds enclosed by the developing marsh. Such channels shift their position continually until stabilized by the turf of the marsh, which then fixes their final position.

The Intertidal Marsh

The processes by which the intertidal marsh is now invading barren sand flats and the steps by which the intertidal marsh rises toward the high marsh level may be observed where the marsh borders the open water of the harbor. Three processes are considered by which *S. alterniflora* may spread onto barren sand flats: (1) seeding, (2) lateral growth of rhizomes, and (3) rafting by ice. Of these, the growth of rhizomes cannot contribute to the origin of isolated patches of marsh since it cannot be effective until the plants have become established.

Spreading by seeding

The seedlings of *S. alterniflora* are inconspicuous. Although seed production is abundant, germination may be reduced by salinity, and few of the seeds which germinate find a place where they can grow. Very limited areas exist above tide levels where the plants may survive which are not already covered by an established stand of grass (Johnson and York 1915, Knight 1934). Seedlings may be found along the margins of the creeks where silt has recently accumulated at the foot of the marsh banks or in the spaces behind blocks of slumped peat, in pond holes which have been drained, and on open sand flats which have recently reached sufficient elevation.

The seedlings may be distinguished from the sprouts which originate from the rhizomes of established clones by their slender leaves and by the absence of rhizomes of their own. They germinate in the spring. At Barnstable they reach a height of 1.5 inches by late May and of 6–8 inches at the end of the growing season. A single stem rises from each root (Fig. 11). In the second year two stems are usually present and a rhizome is formed (Fig. 12). Three-year-old plants reach a height of about 18 inches. The following year the number of stems rising from each clone and the number of rhizomes produced are greater, and the height may exceed 3 ft (90 cm). By the fourth year a fully developed stand of thatch may develop, growing to 4–5 ft in height (Fig. 15).

The seeding and subsequent vegetation of a sand flat has been observed from its inception. A small thatch island situated off the mouth of Broad Sound and due south of Slough Point was selected for the study of the lateral spread of *Spartina* and the vertical accretion of the turf. A concrete benchmark was set at the summit of the island in August 1959, at which time it rose from an extensive area of sand flat and was separated from the nearest marsh by muddy silt for a distance of 200 ft (Fig. 13). The elevation of this flat was lower than 6.2 ft below MHW. The surface on which the thatch grew rose about 2 ft above the surrounding flat and was covered by *S. alterniflora* 5 ft tall.

In September 1960 scattered seedlings were noted on the flat near the west end of the island and to the east and southeast of it. By October 1961 isolated plants were present over an extensive area south and east of the island and along the margin of the nearby intertidal marsh. Most of the plants were seedlings of the year, but a few in which the stems had doubled or trebled probably were the survivors of the previous year's seeding. Where the density was greatest, one plant was present on the average for each 1.25 ft^2 of area. The elevation of the flat around the margins of the vegetated area varied between 5.5 and 6.1 ft below MHW. The plants tended to be absent from areas of the flat where standing water remained at low tide. None occurred on the flats to the north.

In the third year after the first appearance of seedlings, the new growth stood out as a distinct mass of vegetation visible from a distance (Fig. 14). Three year-classes of plants could be distinguished: seedlings of the year, plants in the second year with rhizomes, and plants in the third year with multiple stems and rhizomes. In much of the area the individual plants were widely separated. In the fourth year, 1963, the grass had become more dense and reached a height of 4 ft (Fig. 15). Scattered seedlings continued to appear around the margin. By 1964 the

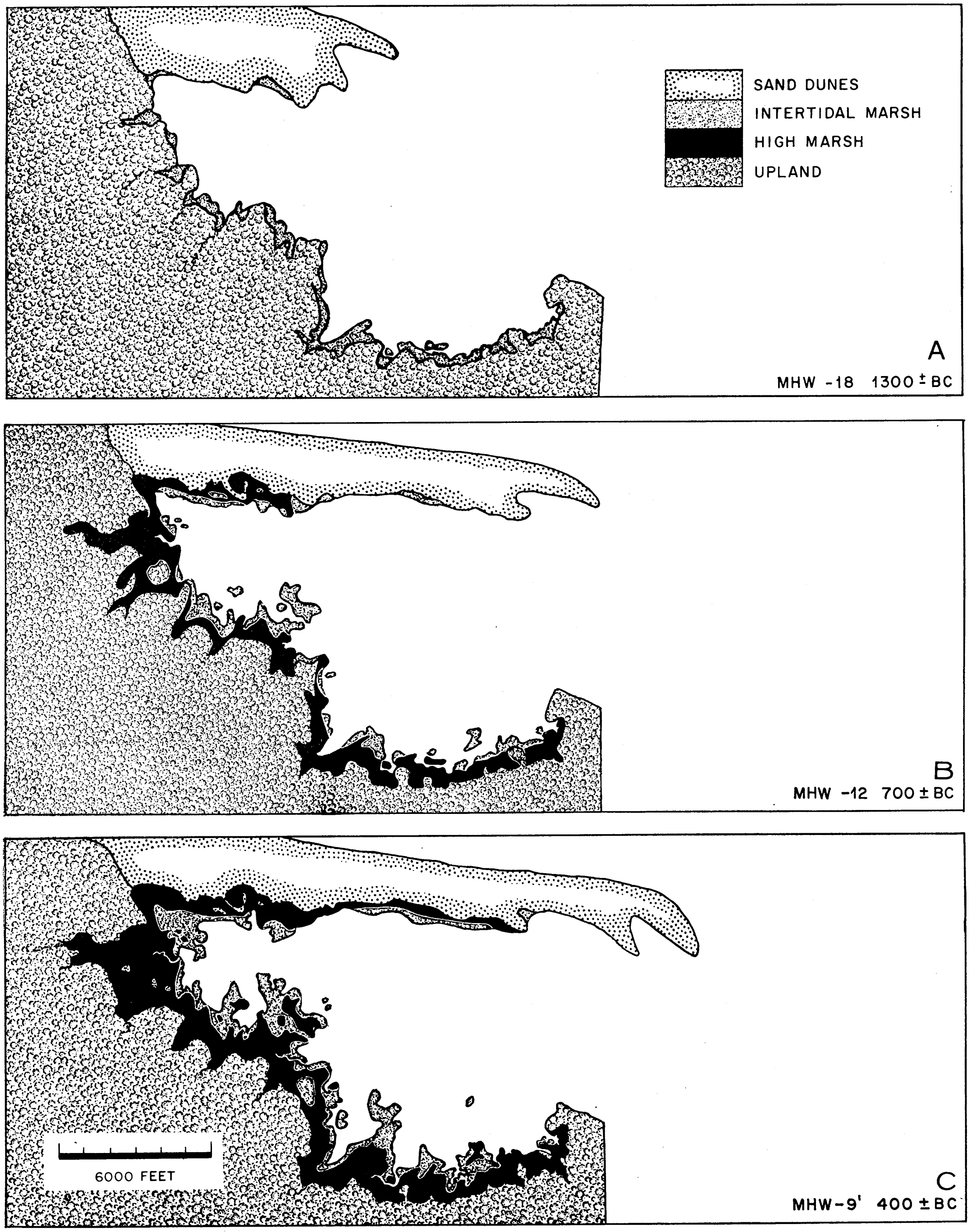

FIG. 10. Reconstruction of the history of the Barnstable Marsh. The date and contemporary elevation of mean high water, relative to the present elevation, are indicated in the lower right-hand corner of each reconstruction. After Redfield (1965*a*).

plants were equal in height and density to the older growth on Broadway Island. Thus not more than 5 years were required after the first appearance of seedlings for the development of a fully mature coverage.

In 1961 scattered seedlings were noted on the flat north and west of Broadway Island. By 1964 these had developed into prominent patches of grass scattered over a distance of 500 ft (Fig. 16). By 1968 these patches had become consolidated and the grass

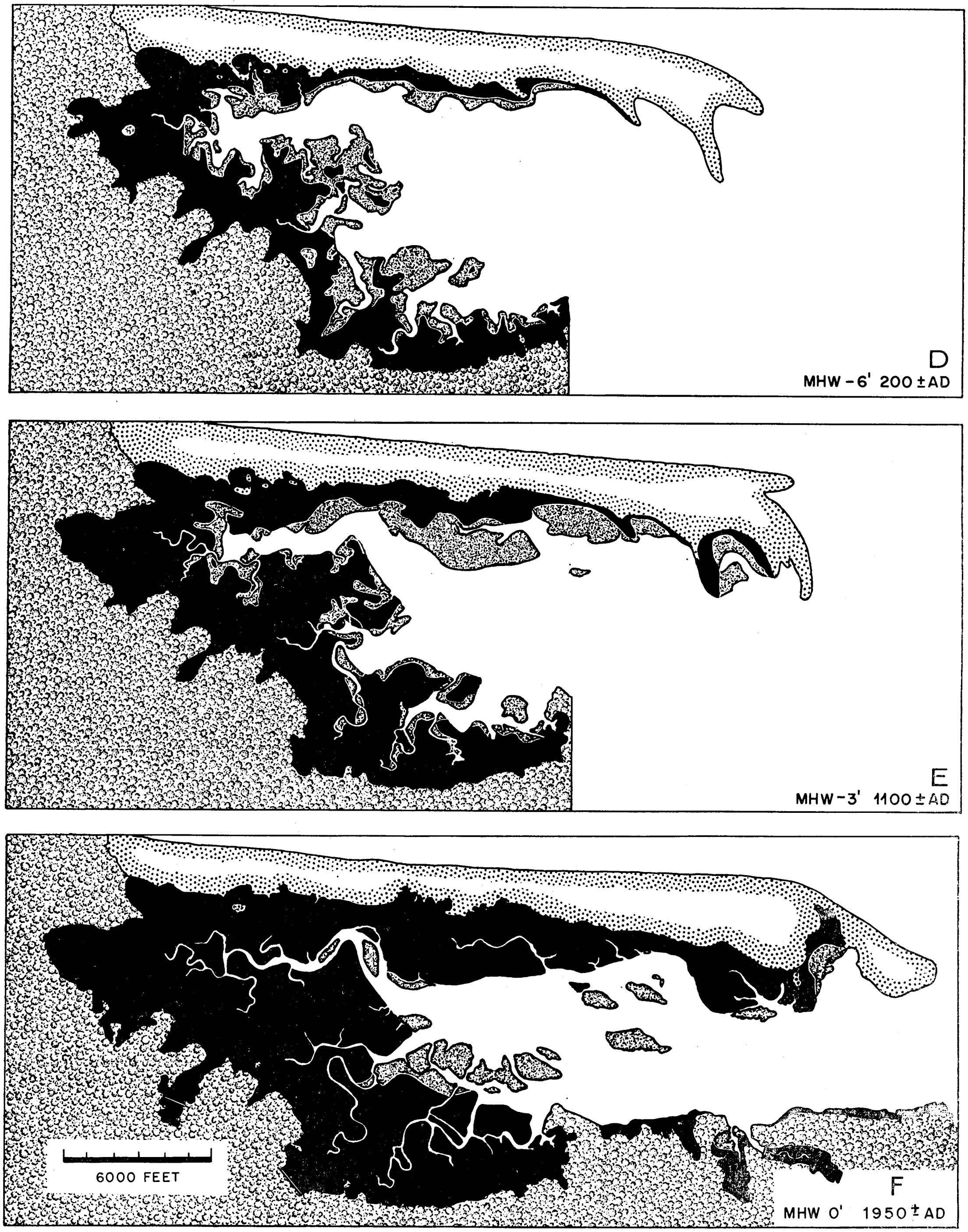

FIG. 10 (continued). Reconstruction of the history of the Barnstable Marsh.

had attained a height of 4–5 ft (Fig. 17). The total extent of the new growth about Broadway Island between 1959 and 1967 is shown in Fig. 18.

The elevation of the flat surrounding Broadway Island at the time seedlings appeared on it provides a measure of the lower limit at which successful germination can occur. One hundred measurements of the elevation of the flat at the outer margin of the vegetated area in 1961 varied between 4.9 and 6.4 ft below MHW. Eighty per cent fell between 5.5 and 6.1 ft with a mean value of 5.8 ft below MHW. This is about the elevation of the outer limit of growth of the intertidal marsh in several places where it was measured with less precision.

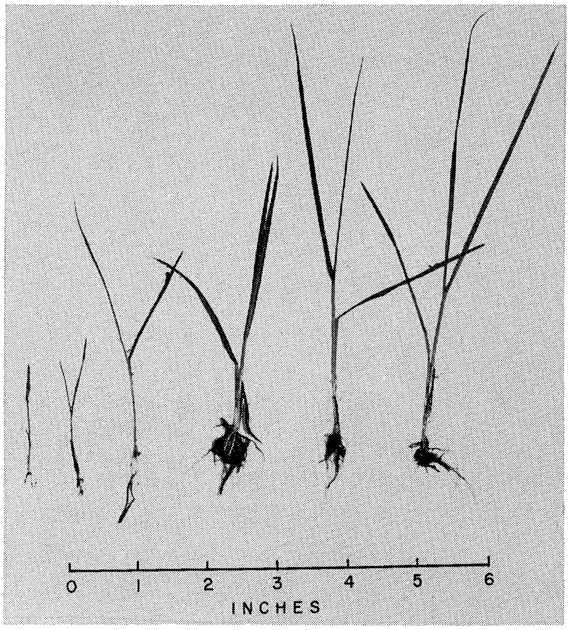

FIG. 11. Seedlings of *Spartina alterniflora*. June 18, 1968.

FIG. 12. *Spartina alterniflora* in the second (right) and third (left) year. Seedlings of first year above. Broadway Island, October 1961. The plant at the left is about 18 inches in length.

The germination and survival of *S. alterniflora* clearly depend on sedimentation to bring the flat to a critical elevation. The development of the vegetation is effective in leading to a further elevation of the sand surface. Isolated clumps of grass usually stand on mounds of sand which appear to be created by disturbances in the flow of water by the plants (Fig. 16).

Levelings across the area surrounding Broadway Island show the influence of the vegetation on the sedimentation (Fig. 19). Broadway Island in 1959 rose about 2 ft above the surrounding flats which had an elevation somewhat lower than 6 ft below MHW. In the subsequent 6 years nearly 0.5 ft of sand accumulated at the summit and eastern end of the island. On the western end, which faces the ebb current, the accumulation was as much as 1.0 ft in thickness. North and west of the island, where the flats are bare, they rose only 0.1–0.2 ft.

During the period in which the seeding at Broadway Island occurred, *S. alterniflora* established itself on extensive areas on the bare flats between Jules Island and Huckins Island and between Jules Island and Calves Pasture Point. In other places seedlings appeared which did not survive. It is clear that large areas of flat may become vegetated and develop into mature intertidal marsh in the course of 4–5 years, once their elevation has risen to that at which *S. alterniflora* can survive.

Spreading by rhizomes

Thatch islands originate chiefly by the establishment of small patches of *S. alterniflora* by seeding followed by the consolidation of these patches by the outgrowth of rhizomes. The latter process is illustrated by a small clump of grass which had become established between New Island and a nearby islet. When first observed in 1960, it consisted of 13 stems. The number of stems approximately doubled each following year, being 23, 56, and about 100 in 1961, 1962, and 1963 respectively. In 1964 the number of stems had increased nearly fourfold, to about 387. By 1966 the patch had spread over the entire area between New Island and the adjoining islet, a width of about 10 ft. The plants were about 4.8 ft tall, slightly greater than in the older areas which they joined, and were of similar density (Fig. 20, 21, and 22).

The rate at which *Spartina alterniflora* spreads over adjacent sand flats by the outgrowth of rhizomes is limited by the length of the rhizomes produced each year (Johnson and York 1915). To determine this rate, measurements were made of the dimensions of three small thatch islands lying off the eastern end of New Island and of one southeast of Huckins Island. The east-west diameter, in the direction of tidal flow, of the islet off Huckins Island increased at an approximately uniform rate of 2.4 ft/year during a period of 10 years (Fig. 23). Thus, at each end, the spread of the margin of the vegetation was at an average rate of 1.2 ft/year. The east-west diameter of the three islets off New Island increased at very nearly the same rate. The average rate of spread for the four

FIG. 13. Airphoto of region about Broadway Island. The region may be located on Fig. 1 as lying east of the junction of Spring (19) and Bridge (20) Creeks which enter from the left, south of Slough Point (14), and east to include a part of Duck Island (9). It includes the intertidal marsh of Howes Island (10) and that bordering on Broad Sound (13) which enters from the lower right. The position of Broadway Island is indicated by an arrow on the sand flat between Slough Point and the entrance to Broad Sound. Scale, ca. 1:14,000. Fairchild Aerial Surveys, Inc. April 20, 1960.

islets was 1.33 ft/year. At this rate it would require nearly 4,000 years for marsh to spread over a distance of 1 mile.

The north-south, cross-current diameter of the two smaller islets off New Island increased at about the same rate as the east-west dimension. At Huckins Islet the increase was less during the earlier years. The cross-current dimension of the larger of the islets off New Island increased very little during the 6 years of observation. Broadway Island increased in width by only 7 ft during 10 years in which it lengthened by more than 130 ft. These observations are explained by depressions caused by the deflection of tidal flow by the islets, which intensifies the current along their sides and scours out the stand. The water standing in the depressions retards the spread of the grass. This accounts for the form, elongated in the current direction, which small thatch islands frequently have. The presence of these pools is shown in the north-south section across Broadway Island in Fig. 19.

The pattern of invasion of Poole Harbor on the

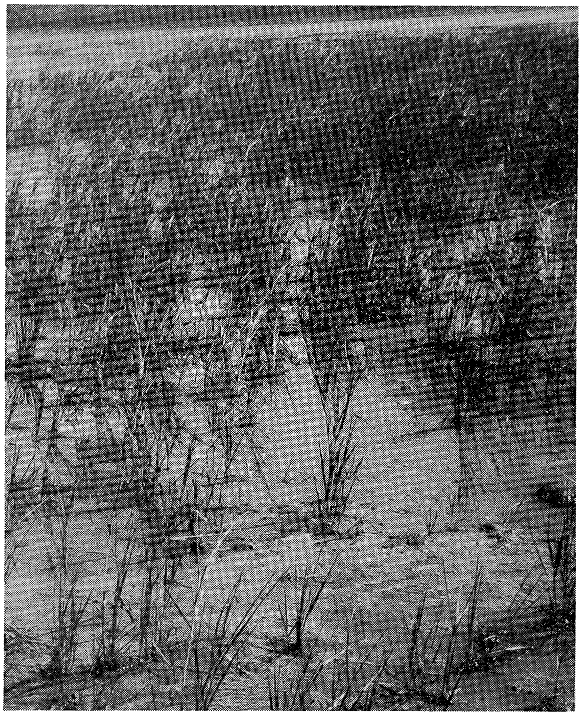

FIG. 14. *Spartina alterniflora* in second and third year of growth on flat south of Broadway Island. October 1962.

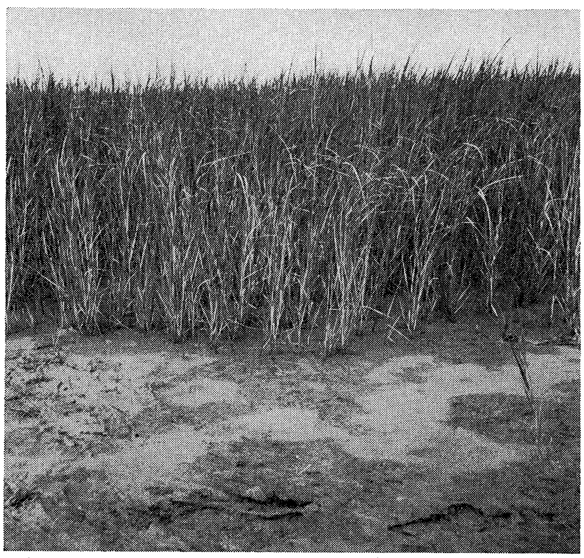

FIG. 15. Fully developed stand of *Spartina alterniflora* on flat south of Broadway Island in fourth year of growth. October 1963. The height of the plants is about 4 ft.

southern coast of England, where *Spartina townsendii* has recently occupied large areas of previously barren flats, has been described by Hubbard (1965). There the relative roles of seeding and the lateral growth of rhizomes are essentially the same as described above.

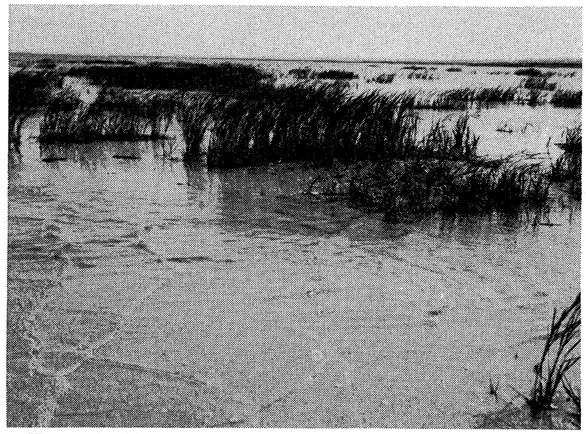

FIG. 16. Clumps of *Spartina alterniflora* on flat northeast of Broadway Island. October 1964. The taller plants are 2–3 ft tall.

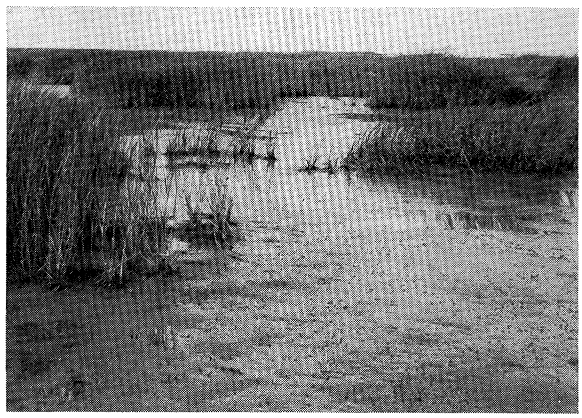

FIG. 17. Intertidal marsh developed from clumps of *Spartina alterniflora* shown in Fig. 16 on flat northeast of Broadway Island. October 1968. The taller plants are 4–5 ft tall.

Spreading by ice rafting

During unusually cold winters substantial quantities of ice form in Barnstable Harbor and move back and forth with the tide. Ice is capable of rafting material frozen into it as evidenced by the appearance following the exceptionally cold winter of 1961 of a boulder, estimated to weigh several tons, at the foot of the marsh bank of Jules Island (Fig. 44). The nearest source of such boulders is at the foot of the cliff at Calves Pasture Point, at a distance of 1,000 ft, where it was presumably frozen into the ice to be transported into the marsh. Masses of salt-marsh turf, 10 or more feet across, are occasionally found resting on the surface of the high marsh where they presumably have been floated during exceptionally high tides, after being lifted by ice (Fig. 24).

Smaller blocks of ice-rafted turf, usually not more than 2–3 ft long, are frequently found on the bare sand flats. If the flat has sufficient elevation, plants may survive and provide a nucleus from which

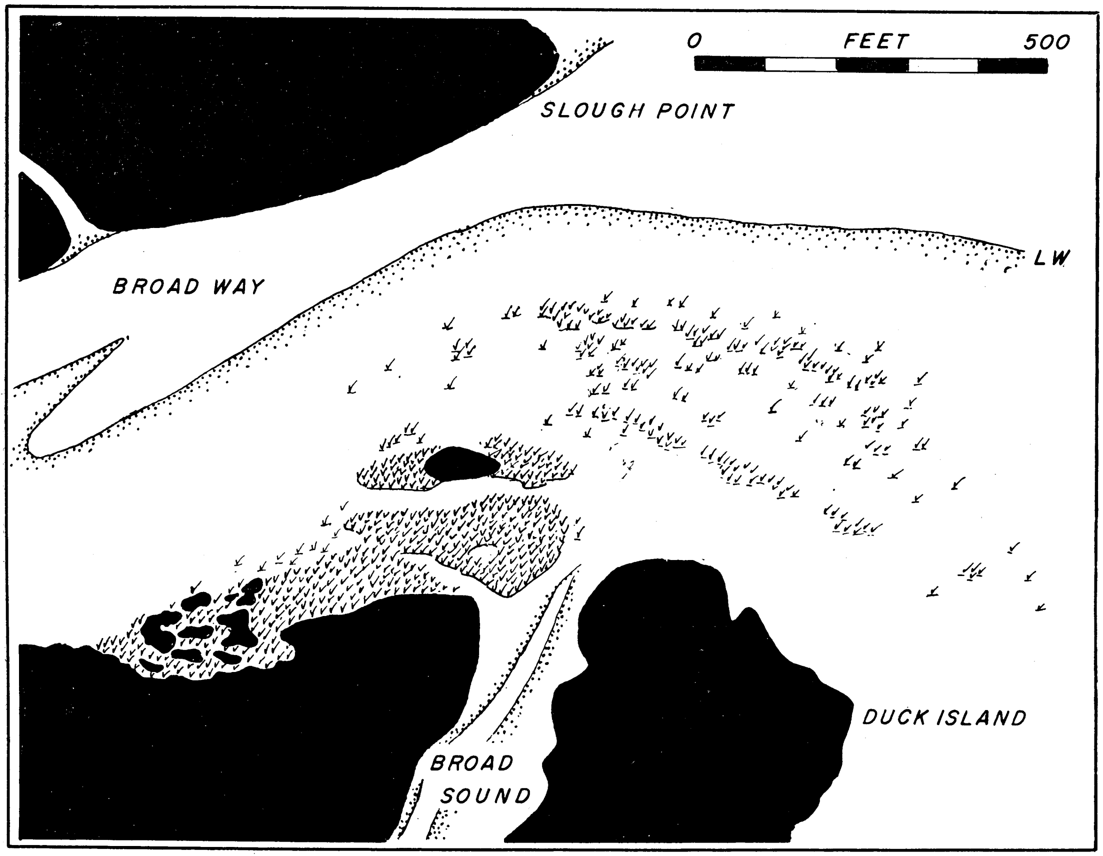

FIG. 18. Map showing extension of intertidal marsh onto flats surrounding Broadway Island in the course of 8 years. Black areas show intertidal marsh present in 1959. Checks show subsequent spread of *Spartina alterniflora* as of 1967. Broadway Island is the elongated black area above the mouth of Broad Sound.

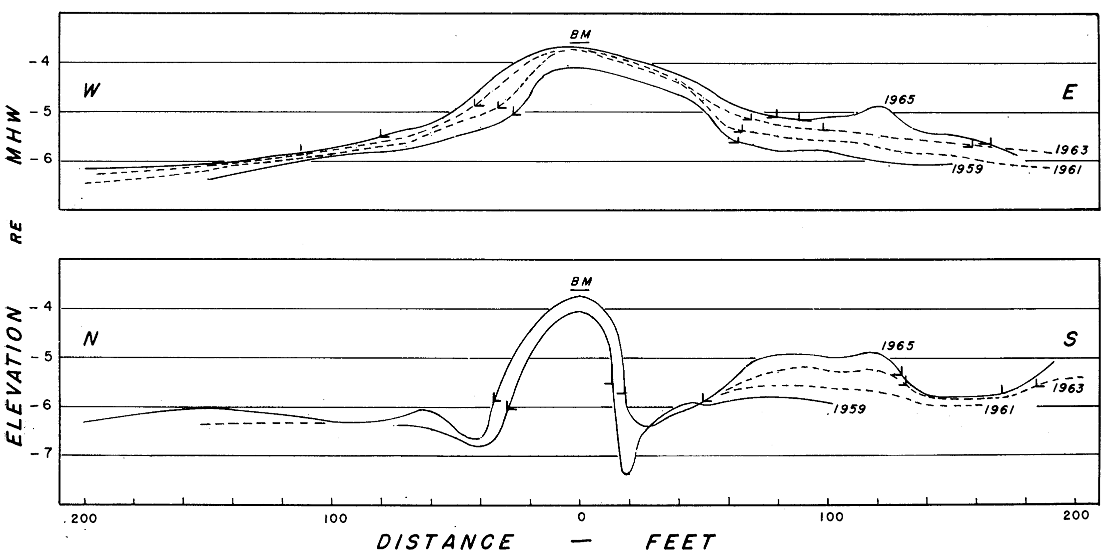

FIG. 19. Elevation of sand surface re MHW at Broadway Island, 1959 to 1965. Above, west-east transect along direction of tidal flow. Below, north-south transect across direction of flow. Checks show outer limit of growth of *Spartina alterniflora.*

FIG. 20. Clump of *Spartina alterniflora* near east end of New Island. The plants are in third year of growth. July 14, 1962.

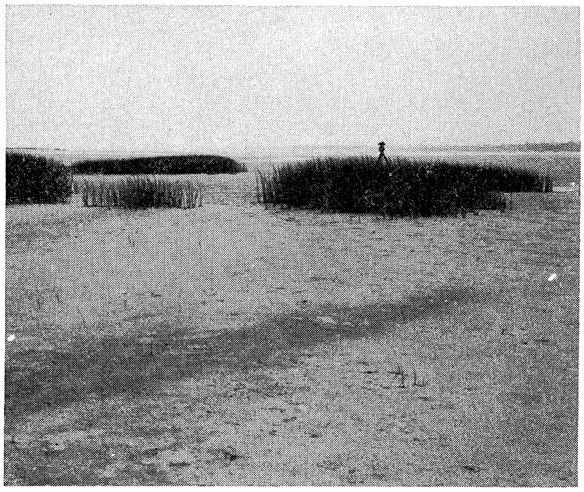

FIG. 21. Small thatch islands on flat at east end of New Island. The clump shown in Fig. 20 is in left foreground. July 26, 1963.

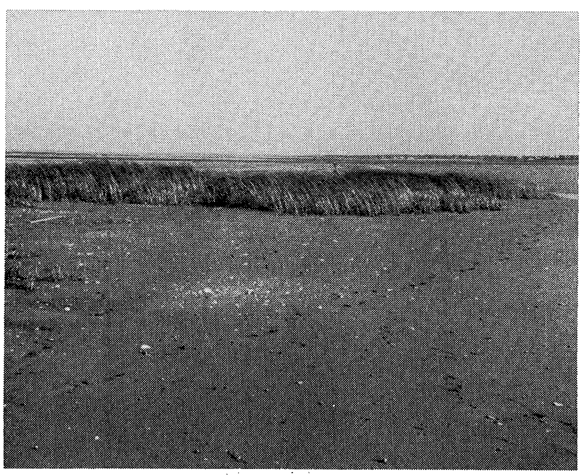

FIG. 22. The growth of *Spartina alterniflora* shown in Fig. 21 as it appeared 3 years later, on October 20, 1966. The clump shown in Fig. 21, the nearby small thatch islands, and New Island have become continuous. The plants are 4.8 ft tall.

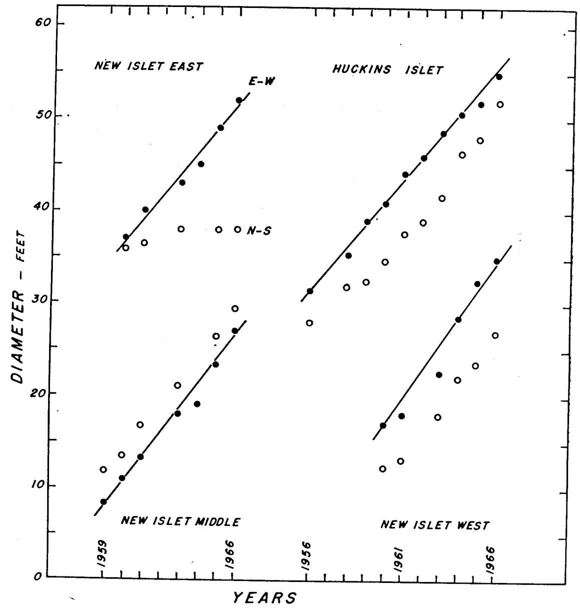

FIG. 23. Increase in diameter of four small thatch islands. Solid circles show diameter of islands in direction of tidal flow, open circles in direction across tidal flow.

FIG. 24. Mass of peat rafted onto the high marsh by ice.

growth may spread. Such a block was dropped near Broadway Island in the winter of 1961. Although the plants survived, the block was surrounded in a few years by plants originating as seedlings. The contribution of the ice-rafted material was negligible compared to the vegetation initiated by seeding. Since ice-rafted turf can survive only on flats of the critical elevation, it is probably a minor factor in the spreading of intertidal marsh.

Vertical accretion of intertidal marsh

At Barnstable an extensive area of intertidal marsh lies between Calves Pasture Point and Slough Point. On the north and east it is bounded by sand flats, on the south by high marsh, and on the west by Bridge Creek. The boundary between high marsh and intertidal marsh is distinct and may be traced from a little east of Brickyard Creek to a point 1,000 ft above the mouth of Bridge Creek (Fig. 13 and 25). Apparently this area was occupied by bare sand flats or open water some 900 years ago (compare Fig. 10 E and F). Erosion of the high marsh had produced an abrupt peat bank along its margin similar to that still present at its continuation along the north side of Jules Island (Fig. 44). The subsequent sedimentation of the flats permitted the intertidal marsh to develop and gave rise to the thatch islands now present. A broad, shallow thoroughfare, Broad Sound,

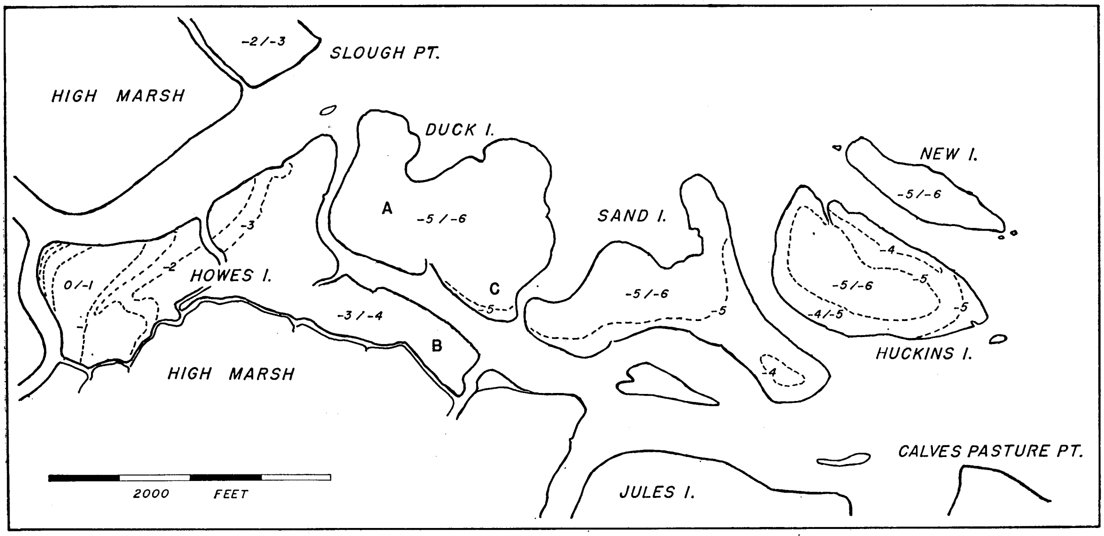

FIG. 25. Map of intertidal marsh between Slough Point and Calves Pasture Point, showing elevation of surface re MHW in feet. The area may be located in Fig. 1 as including the islands numbered 5 through 10. An airphoto of the region west of Duck Island is shown in Fig. 13. The positions where other photographs were taken are indicated by letters: A, Panne Marsh, Fig. 27; B, Slough Marsh, Fig. 28; C, Duck Island from air, Fig. 29.

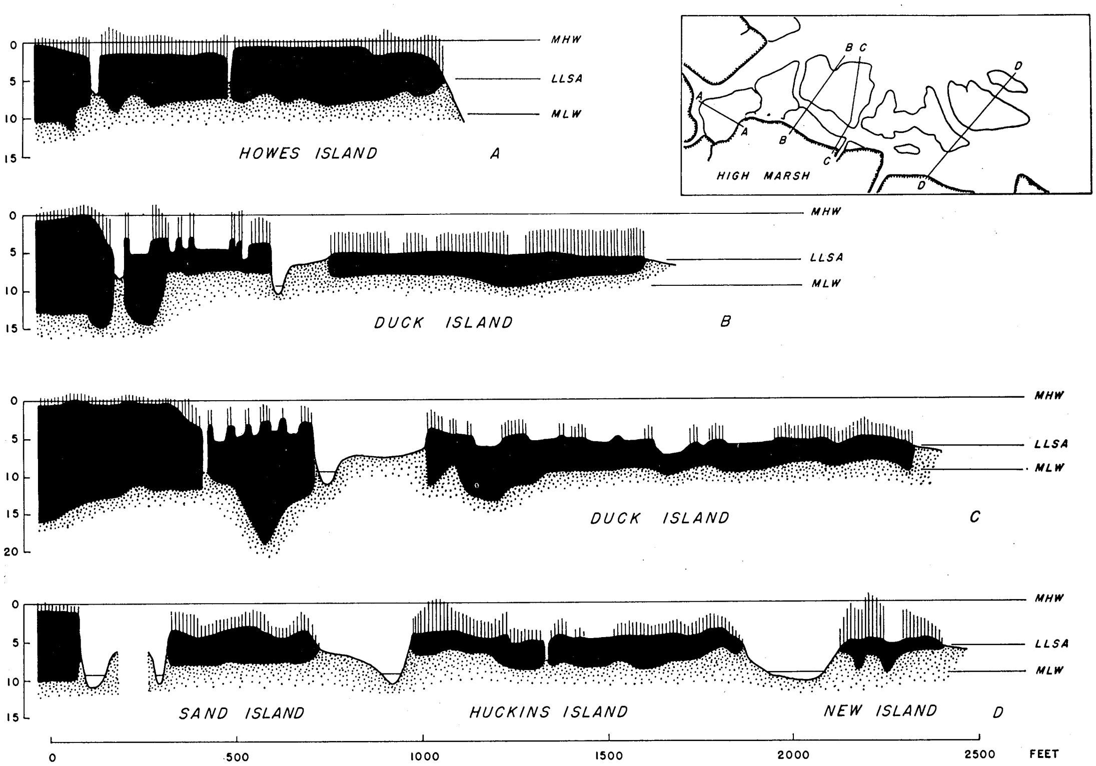

FIG. 26. Sections across intertidal marsh between Slough Point and Calves Pasture Point. Black areas indicate peat; vertical lines indicate general height of grass. LLSA indicates elevation of lower limit of growth of *S. alterniflora*. Abscissa, distance in feet; ordinate, depth in feet below MHW.

traverses the area, and smaller thoroughfares which bare at low tide separate the several thatch islands.

The elevation of the marsh surface in this area was found by leveling along the sections shown in Fig. 26. The levels were tied in to a benchmark on Slough Point, where the elevation of mean high water was known. The contours shown in Fig. 25 are based on the elevations measured along the sections, inspection in the field, and the character of the marsh shown in airphotos.

The greater elevation of the marsh surface and the thickness of the peat layer in the western part of the area (Fig. 26, section A) indicate that development began with the deposition of a sand flat in the wide sound lying between Slough Point and the high marsh to the south, into which Spring Creek and Bridge Creek then entered separately. The development of a thatch island on this flat extended the channel of Bridge Creek to its present junction with Spring Creek. In this area the elevation of the marsh has risen to within 1 ft of MHW. Subsequently sand was deposited and marsh developed to the eastward along the present border of the common trunk of Spring and Bridge Creeks. This development is continuing at present leading to the formation of intertidal marsh about Broadway Island as described above.

The early development of marsh along the course of Bridge Creek and its extension eastward appears to have led to the formation of an embayment between it and the high marsh to the south in which the deposit of tideborne sediment was reduced, with the consequence that the elevation of the surface rose more slowly. Later still, sediment accumulated over an extensive area lying between the present border of Broad Sound and the older high marsh, in which intertidal marsh has developed to a level 3–4 ft below MHW.

The four thatch islands lying north and east of Broad Sound appear to have developed more recently. They occupy the southern border of an extensive flat which is being invaded by *S. alterniflora* along the outer boundary of these islands. The first marsh to appear on this flat was presumably at the eastern end of Sand Island and at Huckins Island, where the surface is 4–5 ft below MHW. Such elevations appear as levees surrounding Sand Island and along the border of Broad Sound on Sand and Duck Islands.

New Island, Duck Island, and the greater part of Sand Island, where the elevation of the marsh surface is 5–6 ft below MHW, i.e., not more than 1 ft above the level at which *S. alterniflora* may grow, appear to have become vegetated very recently. Coast and Geodetic Survey Chart 339 of Barnstable Harbor, based on topographic surveys in 1859, shows the presence of only the eastern half of Duck Island. New Island is not shown. New Island was well developed as early as 1910 when to the author's recollection it was much smaller than at present. Its age may be placed between 60 and 100 years.

The elevation of the marsh surfaces is not an altogether reliable indication of their relative ages because the surface will rise at a rate dependent on the availability of waterborne sediment. This is evidenced by the frequent occurrence of levees along the borders of the larger creeks. The greater elevation of the eastern and southern part of Sand Island may be due to the greater availability of sediments rather than to a greater age.

Sand Island appears to illustrate this relation in another way. The central part of the island is enclosed by a well-defined levee which confines its drainage channels to a single creek which cuts through the levee near its northwestern end. The central area receives only such sediment as this creek carries, and its surface has risen more slowly as a result.

The topography of the intertidal area as a whole confirms the view (Redfield 1965*a*) that the extension of the marsh onto sand flats results from the establishment of islands of marsh grass which subsequently become continuous. The channels which separate the islands are shunts between the tidal streams and consequently are subject to a reduced tidal flow. This has caused the shoaling of these channels, which are no longer flooded at their northern ends at low tide. Unlike the more active creeks, Broad Sound is floored by soft silty mud. The development of new marsh about Broadway Island promises to close its northern entrance in the near future as the first step in the consolidation of the present intertidal islands into the continuum of the existing high marsh.

Stages in development of the intertidal marsh

The intertidal marsh in this area appears to have developed on a nearly level surface. The relief of the marsh changes markedly with increased elevation in a way which appears to be related to imperfect drainage and to differ from that observed on sloping surfaces. Although there is much local variation because of differences in exposure to tidal currents, the availability of sediment, and its sorting as it is transported into vegetated areas, the following successive stages in development may be distinguished and related to elevation:

1) Colonization of bare sand flats by seeding, consolidation of the clumps of grass so formed, and expansion of the margins of the marsh by the lateral extension of rhizomes results in the development of juvenile marsh.

2) Juvenile marsh, characterized by a uniform

stand of *S. alterniflora* reaching a height of about 4 ft, which is not substantially interrupted by bare areas or drainage channels. Juvenile marsh is found along the margins of thatch islands which are spreading onto the surrounding flats, as at Broadway Island, along the northern border of Duck and Sand Islands, and at the eastern end of Huckins Island. New Island is entirely composed of marsh of this character (see Fig. 15 and 22). Characteristic elevation is 5–6 ft below MHW.

3) Panne marsh, characterized by the presence of localized bare areas in which shallow water stands at low tide. Frequently the dead roots and projecting stems of *S. alterniflora* are present, indicating that a former vegetation has died off (Fig. 27). This condition appears to have resulted from unequal deposition of sediment in juvenile marsh, which has created poorly drained areas in which the grass does

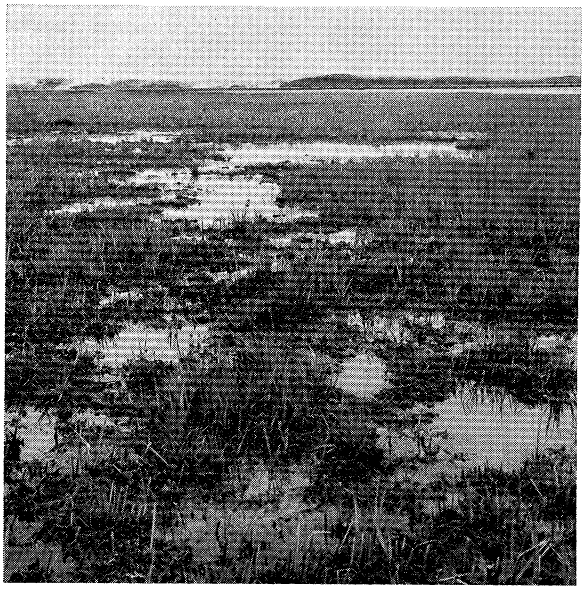

FIG. 27. Panne Marsh on Duck Island. June 1967. For location see Fig. 25. The foreground is 8–10 ft across.

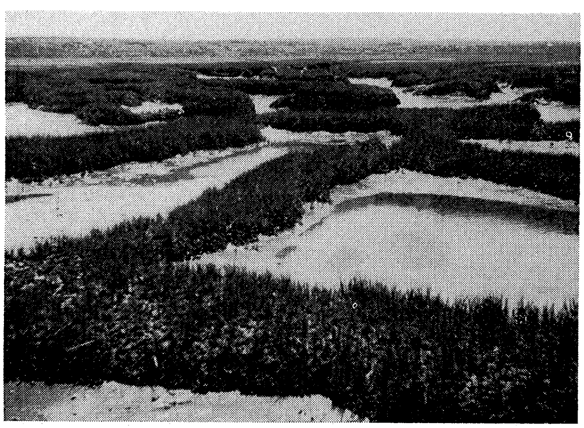

FIG. 28. Slough Marsh in spring. For location see Fig. 25. The ridges rise about 1 ft above the surrounding mud.

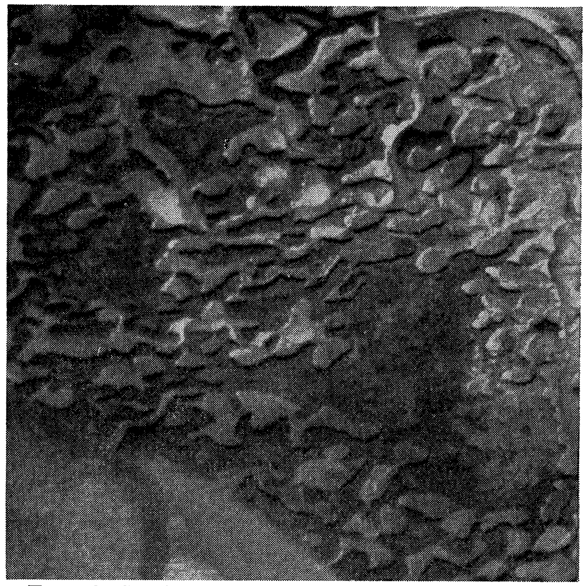

FIG. 29. Southeast part of Duck Island from the air, showing distribution of pannes and ridges of Slough Marsh in the more elevated part of the island. The apparently bare areas at the right are panne marsh in which the relatively sparse vegetation does not show in the photograph which was taken in early summer.

not survive. At a later stage the pannes consist of a large area of soft silty mud, devoid of vegetation, separated by gentle ridges on which the *Spartina* grows. Panne marsh occupies the greater part of Duck Island and the northern part of Sand Island where the elevation is between 5 and 6 ft below MHW. The relief of the area is about 0.5 ft.

4) Slough marsh, characterized by narrow ridges of turf that separate pannes and rise abruptly 1–2 ft above the surface of the pannes (Fig. 28 and 29). The ridges appear to have arisen from the vertical accretion of the turf which separated the pannes during the panne marsh stage at a rate greater than the accumulation of sediment in the unvegetated pannes. The pannes are floored with very soft silty mud. If occupied by standing water, they are bare. If drained at low tide, they may be invaded by *Spartina* by extension of rhizomes from the ridges or by seeding. Where slough marsh has been cut into by erosion along the margin of Broad Sound, horizontal layers of dead *Spartina* roots alternating with layers of silty mud may be exposed indicating that drowning of the vegetation followed by draining and revegetation has occurred repeatedly. The ridges are an exceptionally favorable place for the growth of *S. alterniflora* which may reach a height of 6 ft. The maximum development of slough marsh occurs in the area south of Broad Sound, where the tops of the ridges are 3–4 ft below MHW. Slough marsh in various stages of development is found on the island which forms the extremity of Slough Point (from which the designa-

tion is suggested), on Phillis Island, and on much of the Thatcher Islands.

5) Transition to high marsh. Where the elevation of the vegetated ridges separating the pannes is less than 3 ft below MHW, the ridges tend to broaden, reducing the size of the pannes. Many pannes appear to have been filled with sediment and become vegetated. The relative area of continuous vegetation thus increases leaving the surviving pannes as definite pond holes which are often distributed in rows along the course of drainage channels. With increasing elevation to less than 2 ft below MHW, the process of consolidation of the vegetated surface continues leaving scattered pond holes separated by level areas. These pond holes are surrounded by grass 4–5 ft high. As the elevation of the marsh approaches MHW, fewer pond holes are present, and at these elevations *S. alterniflora* does not generally grow to a height of more than 1–2 ft.

Intertidal marsh on sloping foreshores

The intertidal marsh described above has developed on sand flats where the low relief of the surface has not favored the drainage of tidal water at low tide, and where inequalities in sedimentation have led to the development of pannes and pond holes. Where marsh has developed on sloping foreshores, juvenile marsh, consisting of continuous stands of *Spartina alterniflora,* covers the surface and is infrequently interrupted by pannes or pond holes. Such is the situation where marsh is developing near the termination of actively growing sand spits, at places where sediment is accumulating at the foot of previously eroded marsh banks, as along the foreshore of the open water of the harbor, and at the bends of some of the larger creeks.

Intertidal marsh which has developed on a previously barren slope occurs near the termination of Sandy Neck. The eastern 2,400 ft of the point is exposed to strong tidal currents and is unvegetated. On the foreshore facing The Cove isolated lenticular patches of *S. alterniflora* occur. These do not extend upward to the high water level nor downward to the level which usually limits the growth of *Spartina.* At the high water level *S. patens* and *Salicornia* form a narrow band of vegetation separated from the *S. alterniflora* by bare gravelly sand. Evidently its development has not taken place as a succession from previously established *S. alterniflora.* Near the head of The Cove, the cover of *S. alterniflora* is wider and joins the *Spartina patens* association.

On the western side of The Cove, intertidal *S. alterniflora* marsh slopes upward from bare flats to the high water level at the foot of sand hills. Its vertical rise is about 5.7 ft (Fig. 6). The sloping surface is devoid of pond holes. A narrow band of *S. patens* and *Distichlis* occurs near the level of high water. This gently sloping marsh provides information on the conditions of growth of *Spartina* influenced by elevation and distance from the margin. On August 14, 1959, the height of the grass at the outer margin was about 2 ft, but increased rapidly to about 4 ft within 100 ft. It grew to about this height over the greater part of the slope, at levels increasing from 3.5 ft to 1.5 ft below MHW. Above these levels the height of the grass decreased and became about 1.2 ft high near the upper limit of the marsh where the elevation was 0.5 ft or less below MHW, thus approaching the dwarf form characteristic of high marsh. Under the uniform conditions of slope and presumably of drainage at this location *S. alterniflora* grew most vigorously in the intermediate part of its vertical range.

The peat underlying this marsh could be probed to a depth of about 2 ft. The radiocarbon age of a sample of peat from immediately over the basement was reported as "recent," indicating that it was deposited not more than 200 years ago (Stuiver, Deevey, and Rouse 1963, analysis No. Y-1184). The entire structure thus appears to be of very recent formation. The composition of sediment has already been described.

The stages in the development of the intertidal marsh described above are those of a land form which have led to a rise in the marsh surface to the elevation at which the high marsh community can grow. During the process the composition of the intertidal vegetation, which consists of a pure stand of *S. alterniflora,* does not change. *Spartina alterniflora* has been an agent in hastening the rise in the marsh surface, but it does not appear to be an obligate precursor to the development of the high marsh community. This is indicated by the presence of such plants on recently developed sand spits at levels at which *S. alterniflora* is absent and along the margins of the marsh where, with rising sea level, the *patens* association is spreading over the upland. The transition between the pure stands of *S. alterniflora* and the *patens* community is very sharp along the borders of the creeks where the elevation of the marsh surface changes abruptly. It is less abrupt along the inner margins of the levees which border the creeks or on the body of the marsh, but generally appears to be associated with small differences in elevation and drainage. The invasion of the *patens* community into the dwarf *S. alterniflora* which occupies much of the high marsh is presumably a slow process. It appears to have occurred along the margins of the ditches which drain parts of the marsh dominated by the dwarf form of *S. alterniflora.* The change in the vegetation might profitably be studied where the drainage of a marsh has been altered by a newly cut ditch.

Rate of vertical accretion of intertidal marsh

In the initial stage of the development of intertidal marsh at Broadway Island, the surface of the sand on which the grass grew rose as much as 1 ft in 6 years (0.17 ft/year). The subsequent rate of accretion as the elevation increases toward the high water level is suggested by the structure of the peat where it is exposed by erosion along the creek banks. In many places such peat has a stratified structure. On the north side of Scorton Creek, opposite the west end of Wicks Island, the structure of the bank has been exposed exceptionally well because the blocks of peat which break off as the result of erosion fall into a deep channel close to the bank, leaving its vertical extent fully exposed.

The bank consists of layers of fibrous material alternating with layers of nearly pure sand and silt (Fig. 30). The former resist erosion and stand out several millimeters. The thicker strata may be traced for many feet and depart from the horizontal as though deposited on a slightly convex surface. At the foot of the column the pairs of alternating layers are about 0.1 ft thick. Their spacing decreases upward until as the high water level is approached they are not distinguishable. The cumulative number of pairs of layers present with increasing elevation above the sand on which the column of peat rests are shown in Fig. 31.

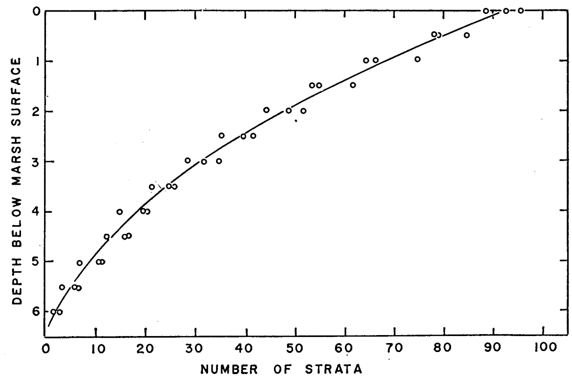

FIG. 31. Number of strata in the bank shown in Fig. 30 above a point 6.5 ft below the high marsh surface.

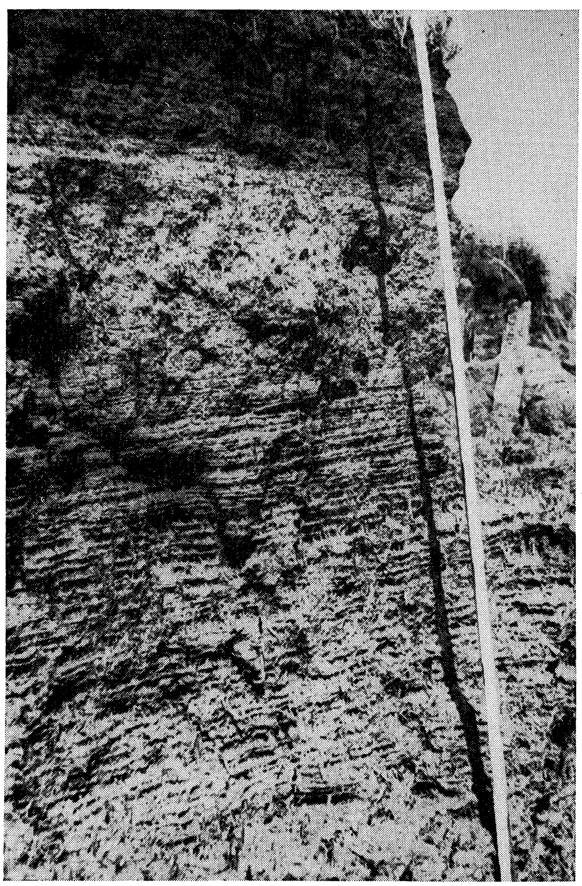

FIG. 30. Stratifications of marsh bank on Scorton Creek, opposite south end of Wicks Island, showing the upper 3 ft of a bank 6.5 ft in height.

The structure may be attributed to an annual change in the conditions of sedimentation. The fibrous layers may have been laid down in summer by the algal mat which forms at the surface and by the subsequent concentration of root fibers in these layers. At that season the stand of grass and the reduced winds would decrease the access of waterborne sediment. The sandy layers may have been deposited in winter, after the *Spartina* stems have broken away and when strong gales increase the sediment load of the creek water. On this assumption, the stratification provides a record of the annual vertical accretion of the marsh. The rate of vertical accretion decreased as the surface rose (Fig. 31). The average rate of accretion was about 0.06 ft/year.

A somewhat lower value for the average rate of accretion is given by the historical record from Nauset Harbor in Eastham, Massachusetts, which is now almost completely occupied by islands of intertidal marsh vegetated by *S. alterniflora*. The peat is about 4 ft thick, and its surface has an elevation slightly less than MHW. Champlain visited the harbor in 1605 and drew a remarkably precise chart which shows the present areas of marsh explicitly marked as "bancs de sable," except for one small area, now destroyed by the retreat of the beach, where symbols indicate the presence of marsh grass (Ganong 1922). A crude map prepared by the selectmen of the Town of Eastham, dated 1795, shows an area in Nauset Harbor marked Salt Meadow. Hitchcock (1841) quotes an intelligent writer in *The Barnstable Journal* who states that in Nauset Harbor the salt marsh has so much increased within 40 years that 300 tons of salt grass are now cut where prior to that time only flats existed. Apparently, the vertical accretion of the Nauset marsh occurred at an average rate of 0.01–0.03 ft/year.

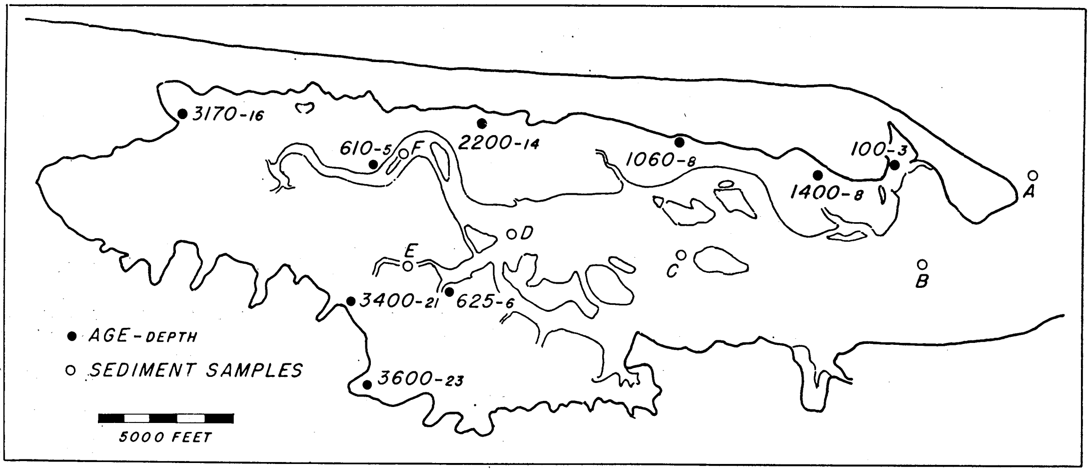

FIG. 32. Radiocarbon age of peat from immediately above the basement in Barnstable Marsh. The large numbers give age in years; the subscripts the depths of sample in feet below the marsh surface. The open circles marked by letters show the position of the sediment samples referred to in Fig. 5.

TABLE 3. Average rate of vertical accretion of intertidal marsh

	Increase in thickness (ft)	Time (years)	Average rate of accretion (ft/year)	Time to rise 6 ft (years)
Broadway Island[a]	1	6	0.17	
Scorton Creek[a]	6	100	0.06	100
Nauset Harbor[b]	4	150–350	0.026–0.011	230–550
Howes Island[c]	5.6	625	0.009	620
Along Sandy Neck[c]	6	950	0.007	950
	6	1,250	0.005	1,250

[a]Based on number of strata.
[b]Based on historical data.
[c]Based on radiocarbon age.

Much lower values for the average rate of vertical accretion of intertidal marsh are given by the radiocarbon age of peat collected from immediately over the sandy basement at positions shown in Fig. 32. A sample from Howes Island, where the marsh surface is still 1 ft below MHW, indicates that the accretion was 5.6 ft in 625 ± 95 years or at an average rate of 0.009 ft/year. At positions in the high marsh bordering Sandy Neck, at greater distances from the open water the age of samples from immediately over the basement indicate that from 950 to 1,250 years were required for the formation of 6 ft intertidal peat (Stuiver, Deevey, and Rouse 1963), corresponding to an average rate of accretion of 0.007 and 0.005 ft/year respectively.

These results are summarized in Table 3. The rate of accretion is evidently variable depending on the elevation which the intertidal marsh has reached, the availability of waterborne sediment, and the distance from open water. Presumably accretion is rapid along the margins of the marsh where levees are formed, less rapid in the body of the marsh. As the margins of the marsh increase in elevation, the accretion rate will diminish providing an opportunity for the interior of the marsh to catch up so that the entire surface ultimately becomes nearly level.

THE HIGH MARSH

The distinction between high marsh and the upper levels of the intertidal marsh cannot be clearly drawn. In general, the high marsh has a flat surface at about the level of mean high water and has more varied vegetation than the intertidal marsh where pure stands of *S. alterniflora* occur. However, intertidal marsh may be essentially flat as its elevation approaches the high water level. Moreover, more than 60% of the Barnstable Marsh is covered by nearly pure stands of *Spartina alterniflora* in the dwarf form, so that the presence of this species is not distinctive.

Surface relief

That the high marsh at Barnstable is not absolutely level may be seen by viewing the marsh from an elevation in winter when the grass has been broken down or flattened and on a day when spring tides occur. As the tide rises the eastern part of the marsh, which was formed more recently, becomes flooded

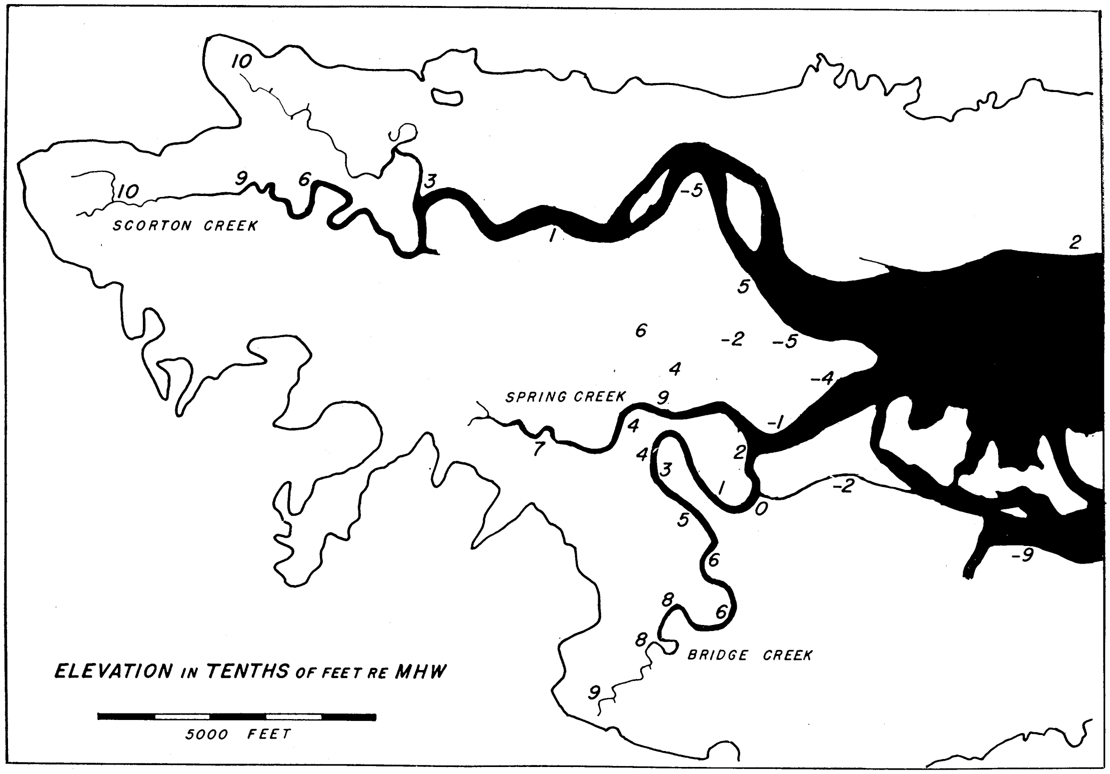

FIG. 33. Map showing elevations of high marsh relative to that of the water at MHW at Barnstable. Numbers indicate elevations in tenths of a foot.

one-half hour before the western end is covered by water. The time lag may be due in part to delay in flow, but that it is not entirely so is shown by measurements of the relative elevation of the marsh along the major creeks.

Elevations of the marsh relative to the local height of the tide at high water were determined by placing stakes painted with soluble ink along the banks of the creeks during spring tides and measuring the height to which the ink was washed away after the tide had fallen. These measurements were compared with a similar one made at Slough Point where the surface of the marsh surface was about 0.4 ft below MHW. Although the absolute elevation of mean high water may vary along the creeks, the measurements show the local variation in the elevation of the marsh relative to the local mean high water. The local elevation increases by about 1.5 ft along the course of the creeks (Fig. 33). The elevation is greatest near the margin of the upland and in the western part of the marsh, which was the first region to develop. In these regions its elevation may exceed 1 ft above mean high water. It is clear that the high marsh has increased in elevation at a rate which exceeded the general rise in sea level during the several thousand years of its existence.

Leveling across the apparently flat surface of high marsh shows a local relief of about 0.5 ft. Relatively low areas frequently occur near the heads of the smaller tributaries. These are areas where the water draining the marsh, after its surface has been flooded during spring tides, flows with high velocity and retards the accumulation of sediment.

A feature characteristic of the high marsh is the presence of levees along the margins of the larger creeks. These are a few tens of feet wide and rise about 0.5 ft above the general elevation of the surface behind them. They presumably arise from the deposition of waterborne sediment as the velocity of the water is decreased as it flows through the vegetation when the tide floods the marsh. Along the larger creek the levees may be interrupted by channels about 1 ft in depth and width which have apparently been cut by water flowing off the marsh following flooding tides (Fig. 34).

The levees are vegetated by *S. patens* and *Distichlis* in contrast to the general surface where dwarf *S. alterniflora* usually occupies the region behind the levees. At several places in the upper reaches of Scorton Creek there are very pronounced levees, formed of coarse sand which has been deposited over the peat surface to a depth of about 1 ft. They occur at the bends of the creek where southeasterly winds have a long fetch along the channel and were pre-

FIG. 34. Small channel cut in levee in bank of Spring Creek. Similar channels appear as closely spaced shadows above the slumped area on the far side of the creek. May 1963. The area in the foreground is about 6 ft across.

FIG. 35. Depressed area resulting from slumping along banks of Navigation Creek. Spring 1958. At the left an area nearly as broad as the creek lies more than a foot below the high marsh, is separated from it by an abrupt bank, and is vegetated with coarse grass, *S. alterniflora*. At the right the slumped bank is narrower and slopes gradually to the water level. Below the water, shown at half tide, abrupt banks separate the slumped regions from the creek bottom. The foreground shows undisturbed high marsh vegetated with *S. patens*.

FIG. 36. Airphoto showing slush ice deposited in winter on the depressed areas bordering the creeks and in the mosquito ditches. The area shown may be located in Fig. 1 immediately west of number 18 which identifies Scorton Creek. It is 1,500 ft by 2,500 ft.

sumably deposited during recent hurricanes. These levees stand out prominently because they are covered by *Juncus Gerardi,* which commonly grows only along the margin of the marsh adjacent to the upland.

Drainage

The high marsh is drained by creeks which interrupt the turf and have nearly vertical walls, the height of which increases with the size of the creek. Except in the smallest channels these unsupported walls have slumped producing a band along both sides which is lower than the general high marsh surface (Fig. 35). *Spartina alterniflora* grows to a height of 4–5 ft on these slumped areas and in summer stands high above the vegetation on the high marsh proper. The continuity of these bands of lower elevation is shown in Fig. 36, an airphoto made when slush ice was deposited on the slumped margins of the creeks.

The smaller creeks are less numerous in the western end of the marsh than in the more recently formed portion eastward (Fig. 37). This indicates that they have tended to fill up and disappear in the course of time. The load of water to be carried by the drainage system during spring tides has decreased as the elevation of the marsh has increased causing the depth and frequency of flooding to diminish.

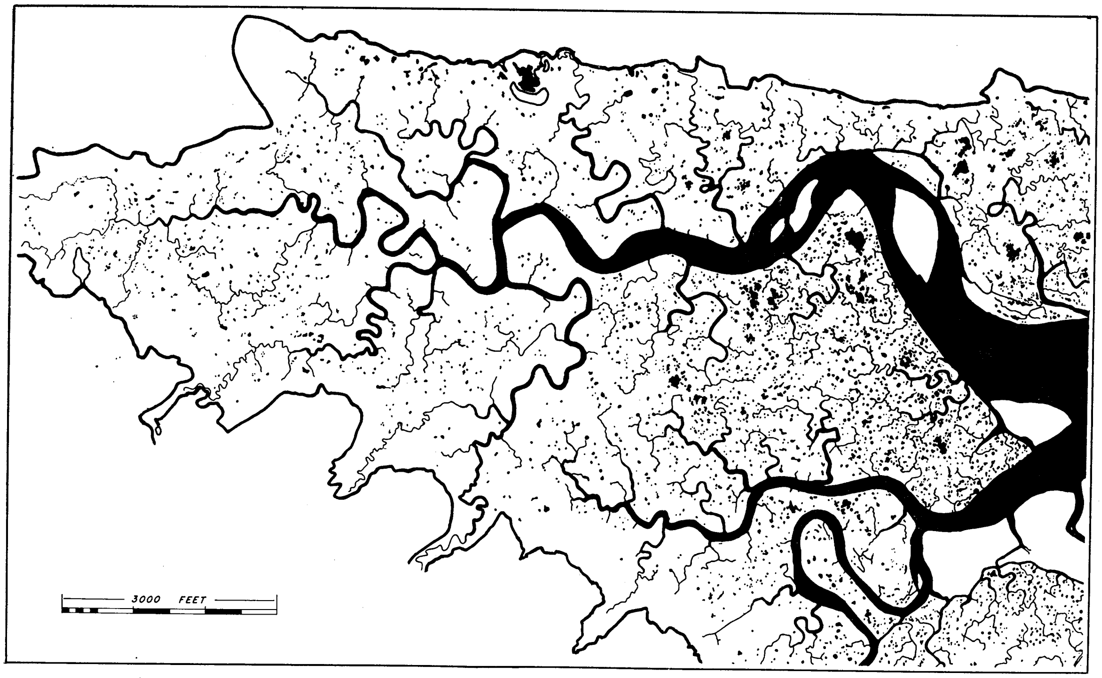

FIG. 37. Distribution of pond holes and creeks in the high marsh at Barnstable. Traced from enlarged airphotos.

The estimates shown in Table 2 indicate the reduction in the number of tides which flood the marsh and the volume of water per unit area which must be carried by the drainage system as the elevation of the marsh increases. Marsh at an elevation of 1 ft above MHW such as occupied the western region would be flooded about one-quarter as frequently and its creeks would carry about six-tenths as much water as a marsh at the elevation of mean high water. When compared with the eastern region, where much of the marsh is 0.5 ft below mean high water level, the difference would be greater. With the reduction of flow in the creeks of the more elevated part of the marsh, the balance between the deposition of sediment and its erosion would be changed so that the creeks would tend to fill with sediment and to disappear as they are invaded by *S. alterniflora.*

In the central part of the marsh, between Scorton and Spring Creeks (where the elevation is about 0.5 ft above MHW) there is an average of one creek head for 14,000 ft^2 of marshland. This is the average area from which sufficient water drains with the falling tide to keep the head of a creek open. The necessary area may be expected to increase as the elevation of the marsh relative to the effective reach of the tide increases, since the volume of water to be carried off by the creek would diminish.

Pond holes

The pannes of the New England high marsh are locally known as pond holes. Pond holes are small pools which occur where the turf is interrupted. Their walls are vertical or undercut below the surface layer of turf. Their depth is variable, but is greater than the thickness of the surface of living turf. The bottom is soft. They are filled by flooding during spring tides. They are stable features since the depth of the standing water usually precludes invasion by *Spartina* either by the growth of rhizomes or by seeding.

Pond holes are most frequently round or oval. Pear-shaped and eight-shaped ponds suggest the union of two nearby circular features following their enlargement by decomposition of the surrounding turf. Large ponds of irregular shape and usually surrounded by many small pannes are found in regions relatively remote from the drainage creeks. The distribution of pond holes in the high marsh is shown in Fig. 37. An airphoto of the portion of the marsh shown in the lower right-hand corner of this figure is reproduced in Fig. 13.

If pond holes become drained as the result of erosion of nearby marsh bank, capture by drainage creeks, or artificially, sedimentation may permit the ponds to become vegetated (Fig. 38) and finally to disappear. Circular areas of *S. alterniflora* in the *Spartina patens* marsh appear to be pond holes which have become filled and revegetated. Sometimes a small pool remains in the center of such an area. The minor creeks frequently terminate in pond holes, which, however, they may not drain completely. Other ponds occur as enlargements along the course

FIG. 38. Relict pond hole in high marsh which has become drained and is being revegetated by *Spartina alterniflora*. June 1967. The pond is about 10 ft in diameter.

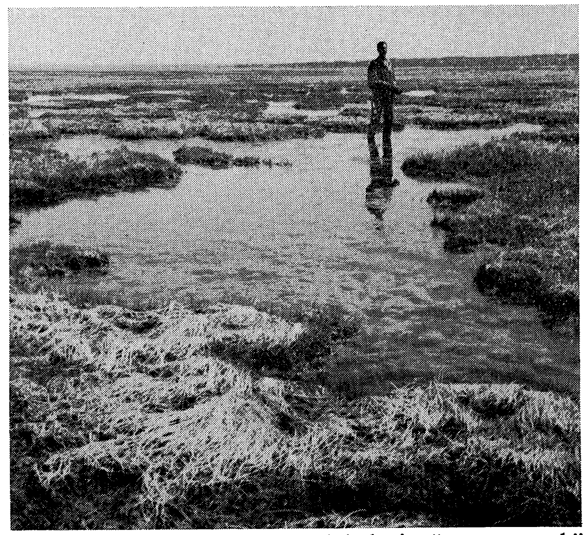

FIG. 39. Large shallow pond hole in "rotten marsh" area. May 1963.

of such creeks. Elongated ponds, sometimes serpentine in shape, are often distributed in linear array, suggesting the course of an earlier drainage channel.

The occurrence of deep pond holes in the New England marshes is apparently associated with the firm turf which covers the surface. In the Georgia marshes where such turf does not usually form they are rarely present.

Three different processes may be postulated to account for the development of pond holes at Barnstable. A fourth applies to those in other regions.

1) Ponds formed as relicts of intertidal pannes. These are produced in the transition from slough marsh to high marsh as described above. They are more or less circular in shape. Such ponds are not to be expected in regions where the high marsh has spread over the submerged upland and has not passed through the intertidal stage. Nor are they to be expected where intertidal marsh has developed on sloping foreshores.

2) Ponds formed as the result of blocking of creeks. Many pond holes occur associated with the smaller creeks. They presumably arise from the blocking of the creeks by slumping of the bank and the retention of water in the creek, followed by subsequent enlargement by the decomposition of the surrounding turf. The resulting pond holes may occur at the head of the creek or along its course, where they are frequently elongated and serpentine in shape. The circular pond holes frequently found at the head of small creeks may be relict pond holes which have been captured by a creek.

3) Ponds formed by decay of surface turf. Large pond holes of very irregular shape, surrounded by many smaller pannes, occur between the systems of drainage creeks (Fig. 39). In these areas, sometimes referred to as "rotten spots," pannes are present which appear to represent successive stages in the development of the large pond holes. Small areas a few feet across occur in which the grass has died. Such pannes may become coated with salt crystals during periods of neap tide. Larger pannes are present in which water stands at a depth of 0.5 ft or so, under which the turf is so firm that one may wade in them with impunity. These vary from a few feet to as much as 100 ft across. In many of the larger pannes the surface layer of turf has disappeared leaving a deep pond, indistinguishable in the form of its bank from those pond holes which are relicts of the pannes of intertidal marsh. Occasionally pannes may be observed in which the shallow bottom has been perforated locally to form a deeper hole (Fig. 40).

Pond holes of this class appear to result from inadequate drainage. The presence of standing water, and perhaps the concentration of salt by evaporation leads to the death of the vegetation and the subsequent decomposition of the turf. The slight depressions in which standing water accumulates may be due to the inaccessibility of the regions where they occur to waterborne sediment or to compaction of the underlying peat.

The formation of rotten spots has been attributed to the killing of the turf by an accumulation of trash on the marsh surface (Warming 1904). Miller and Egler (1950) concluded that at the Wequetequock-Pawcatuck Marsh such trash disintegrates and is washed away so that the affected areas do not remain

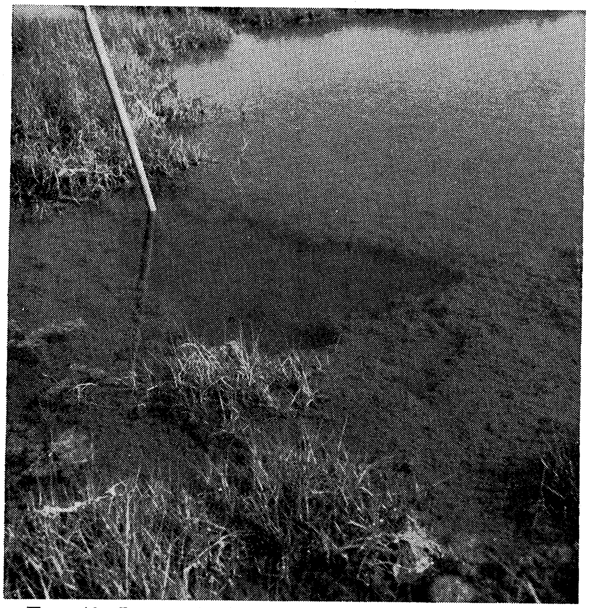

FIG. 40. Large shallow pond in "rotten marsh" area. The peat flooring the pond has broken through in the region of the oar to produce a deeper area with soft bottom.

FIG. 41. The Quaise Marsh, tributary to Nantucket Harbor, 41° 18′ N, 70° 04′ W. The four large pond holes at the termination of the creeks are attributed to the failure of sufficient sediment, introduced from the harbor, to decrease the depth of the water to that at which *Spartina* may grow as the basin was flooded by rising sea level. Scale, ca. 1:3,700. Fairchild Aerial Surveys, Inc.

bare. At Barnstable accumulation of trash is not observed in the areas where those ponds occur.

4) Ponds due to the local failure of marsh to develop. Such ponds persist as relicts of open water in places where the supply of sediment has been insufficient to decrease the depth of water to that where *Spartina* may grow. Ponds of this type have not been observed at Barnstable, but are exemplified by marshes at Nantucket Island and those bordering Great Pond in Falmouth. In these regions a small tidal range and the development of a barrier beach have limited the supply of sediment with the result that the growth of the marsh has not kept pace with the rising sea level. On Nantucket the ponds lie at the head of the drainage creeks where they are remote from the inlet which introduces the sediment (Fig. 41).

The pannes of the Dovey Marsh in England have been classified by Yapp and John (1917) as primary pannes and secondary pannes. Primary pannes are those formed coincidentally with the original development of the marsh. They would include the pannes of the intertidal marsh and their relicts in the high marsh, and those due to the local failure of marsh to develop. Secondary pannes are those formed in pre-existing marsh such as those formed by the blocking of creeks (channel pannes) and those due to the decay of the marsh surface (rotten spots). Yapp and Johns include as secondary pannes those formed in secondary marsh which has arisen by the revegetation of debris eroded from primary marsh along the borders of creeks. Such marsh is analagous to that of the slumped margins of creeks at Barnstable, where pannes are not commonly observed. At the bends of creeks, where intertidal marsh is developing on accumulating sediment, elongated pond holes paralleling the channel are found which may have been formed behind masses of peat previously slumped from the high marsh bank. Yapp and Johns also describe as residual pannes the remnants of larger pannes which have been recolonized. Pannes evidently of this origin have not been noted at Barnstable.

Dionne (1968) has attributed the formation of pannes on the south coast of the St. Lawrence estuary to erosion by ice. The occurrence at Barnstable of large masses of turf which have apparently been rafted onto the high marsh indicates that ice may interrupt the surface and lead to the formation of pond holes but only in places where the turf is not well consolidated. No direct evidence of such action has been found, and apparently ice action is not an important factor in the formation of pond holes at Barnstable.

Distribution of pond holes

Pond holes are most numerous in the eastern part of the marsh where high marsh developed most recently. The highest concentration is found in regions bordering the intertidal marsh in the neighborhood of Slough Point (see Fig. 13 and 37). From there the concentration tends to decrease proceeding westward toward the older regions. In the eastern region the ponds tend to be round or oval in shape and may be considered to be relicts of the pannes formed in intertidal marsh. Associated with them are the larger ponds attributed to the decay of the surface turf. Some ponds of which the shape or association with creeks indicate an origin by the blocking of drainage channels are found in minor numbers in this region.

Pond holes are scarce or absent throughout the portion of the marsh bordering the upland. In this area high marsh has spread over the submerged upland. This area has not passed through the intertidal stage and consequently would not be expected to contain relicts of intertidal pannes. It corresponds roughly with the area in which *Spartina patens* dominates the vegetation (Fig. 2).

In the western region, where the marsh first developed, the number of pond holes and of tributaries to the major creeks is greatly reduced as compared with the eastern part of the marsh. The elongated shape, the linear array, and the relation to the existing creeks suggest that these pond holes have arisen from the blocking of creeks which have subsequently disappeared. Groups of ponds, such as are attributed to the decomposition of surface turf in the eastern region, are absent, but the few large ponds present may be survivors of the larger ponds formed by this process at an earlier period.

Between the extreme conditions at the eastern and western parts of the marsh there is a gradual transition in which the number of pond holes decreases without much change in their relative size. The variation in density of pond holes in local areas may be attributed to conditions which have influenced the production of pannes at an early stage in the development of the intertidal marsh. In particular, pond holes are scarce surrounding the upper reaches of Scorton Creek where the creek was formed by the filling in of a broad sound.

Effect of ditching

The Barnstable Marsh has been extensively ditched for mosquito control. Since the purpose of the ditches is to drain the surface and reduce the standing water in which mosquitos breed, the ditches may be suspected of altering the drainage pattern of the creeks and of influencing the pond holes. Ditches occur in the entire southern and western border of the marsh at intervals of 100–200 ft (Fig. 36) and less extensively bordering Sandy Neck. This area includes the *Spartina patens* zone and extends substantially into the dwarf *Spartina alterniflora* zone. In the latter area *S. patens* usually occupies the borders of the ditches, and dwarf *S. alterniflora* dominates between them. The ditches result in an overdrainage of the marsh, as evidenced by their tendency to fill with sediment which needs to be removed periodically. The general effect of ditching is to reduce the natural drainage system by providing an alternate route for the flow of water. Where the ditches interrupt the course of the minor creeks, a portion of the latter may be abandoned. Isolated parts of the abandoned channels may remain as pond holes. Where the ditches drain a pond hole, the latter may fill with sediment, become vegetated, and disappear.

About half of the salt marsh at Barnstable remains unditched. Airphotos from such regions do not indicate any clear effect of the ditching on the distribution or size of the pond holes. The effect of ditching probably is small. It may accelerate the reduction in the number of pond holes which occurs naturally with time. It probably hastens the abandonment of the minor drainage creeks and leads to the development of pond holes along their former courses.

Erosion

The development of the marsh has not proceeded in an uninterrupted manner. Where it faces open water or bare sand flats and borders creeks, erosive processes are destroying pre-existing marsh and tend to interrupt its orderly development. The changes in topography resulting from the balance of development and erosion during the past 100 years is shown by a comparison of charts made in 1859 and 1957. In Fig. 42 the areas which have not changed since 1859, those apparently lost by erosion, and those into which marsh has spread are distinguished. The outer beach of Sandy Neck appears to have receded about 200 ft along its entire length. This recession is confirmed by the recent emergence of a tree from the foredune of the beach, which must have grown in a low area behind the dune when it stood several hundred feet north of its present position. The extremity of Sandy Neck has been extended about 600 ft eastward. Erosion has also occurred along the south side of Beach Point extending westward into The Cove. The patches of *Spartina* in this area may be remnants of an earlier vegetation. Erosion within the harbor has not been sufficiently extensive along the border of the upland or of the high marsh to be shown by a comparison of the charts.

The intertidal islands within the harbor have changed substantially during the 100-year period. The area of the Thatcher Islands and Town Island have been reduced by about one-half. Two small islands in the sound between Slough Point and Little Thatcher Island have disappeared, as has a large area at the western end of Phillis Island. The area of Phillis Island and of the intertidal islands lying between Slough Point and Calves Pasture Point has

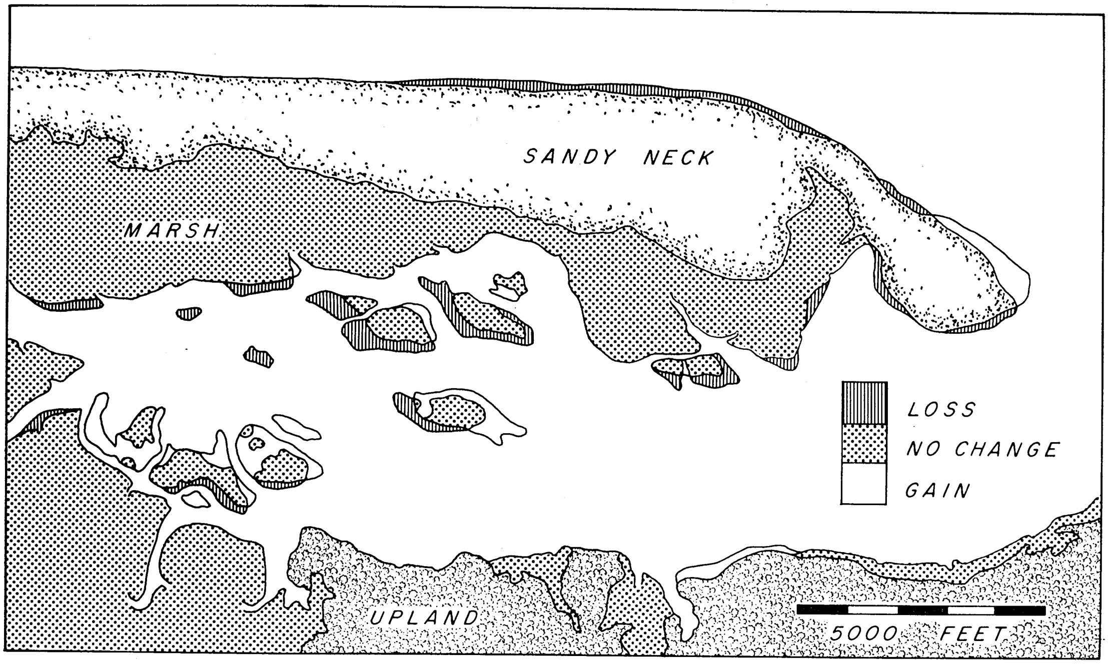

FIG. 42. Changes in the marsh and beach at Barnstable between 1859 and 1957, based on U.S.C. and G.S. charts No. 339. Losses by erosion since 1859 shown by cross hatching; gains by subsequent development of marsh by outline of blank area; stippled areas have not changed during the period.

FIG. 43. Erosion of intertidal marsh by undercutting of sand basement due to shifting channel. The peat at the upper left has been undermined and overhangs the sand by 2–3 ft. In the foreground masses of peat which have broken off after being undercut lie in the sand at the foot of the bank. The layer of peat is about 2 ft thick.

increased. New Island and the western half of Duck Island are not shown on the earlier chart. On the whole the gains and losses in intertidal marshland appear to be approximately equal.

Erosion of intertidal marsh

Intertidal thatch islands are subject to ready destruction by erosion if the channels which drain the sand flats shift so as to impinge on their margins. If the channels are deeper than the peat layer, the underlying sand is washed away leaving the peat to overhang, sometimes by 2–3 ft. The overhanging peat ultimately breaks off leaving a low vertical bank at the margin of the island (Fig. 43). This process has been observed to destroy several small islands formed on sandbars in the major creeks and accounts for the disappearance of the two thatch islands which formerly existed on the flats east of Slough Point.

Erosion of the margin of the intertidal marsh appears in many places to have alternated with its farther expansion. The surface of the marsh is broken into "terraces," each marked by a small, abrupt change in elevation where an eroded bank formerly existed and where subsequent accumulated sediment has permitted the extension of the vegetation. An extreme example of this process has been described in which the intertidal marsh bordering the south side of Broad Sound has been built upon sediments accumulated at the foot of a high marsh bank produced by erosion at an earlier period (see Fig. 26).

Erosion of high marsh

Where the peat of the high marsh extends to depths greater than that of the adjoining deposits of

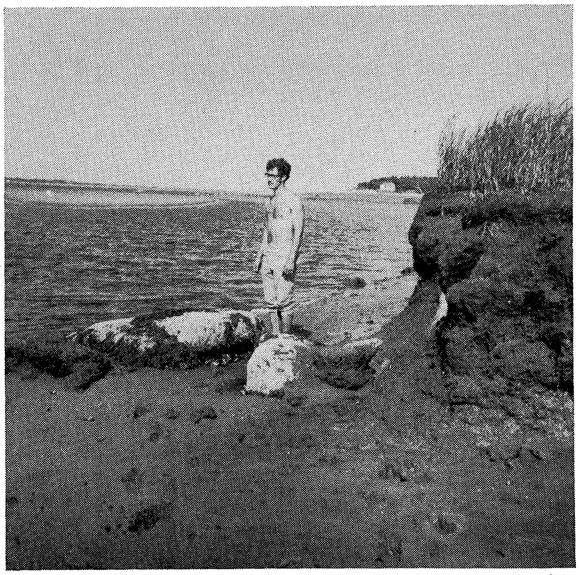

FIG. 44. Erosion of a high marsh bank on north side of Jules Island. The large boulder was rafted to its position by ice.

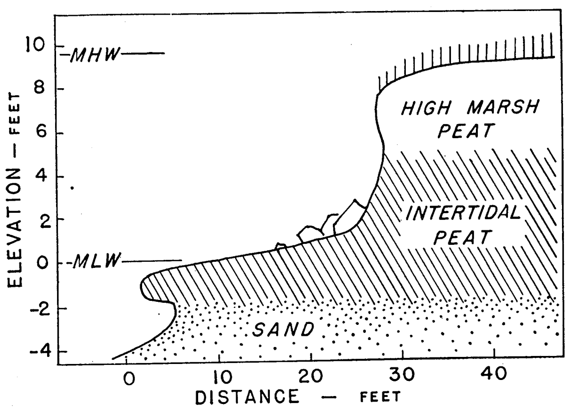

FIG. 45. Diagram of the structure of Black Bank.

sand, undercutting of the exposed bank is retarded by the cohesion of the peat. Erosion of the peat at or below the midtide level ultimately causes the bank to become mechanically unstable with the result that blocks of peat break off leaving a vertical bank 5–6 ft high (Fig. 44). If a deep channel impinges on the bank, the blocks fall into deep water. Otherwise the foreshore below the bank may consist of a deposit of silty clay that is a remnant of the marsh which extended beyond its present limit before its upper layers were removed by erosion. This foreshore may be littered with blocks of peat which have fallen from the bank as it underwent erosion.

The latter condition is illustrated by Black Bank which faces open water west of Wells Creek. The structure of Black Bank it shown diagrammatically in Fig. 45. Note that erosion has removed the peat in the intertidal zone (by wave action) leaving a shelf of intertidal peat extending out from the bank. This shelf has been undercut by tidal currents which have removed the sand basement underlying the peat deposit.

Similar evidence of erosion may be seen along the Barnstable shore, facing the open water of the harbor. Near the Barnstable Yacht Club the foreshore beyond the peat bank consists of a layer of soft peaty clay which appears to be a remnant of the eroded bank. It is now covered by a thin veneer of sandy gravel. At several places in this region the salt-marsh peat lies above deposits of fresh-water peat which had developed on the upland before its submergence.

The surface of the marsh banks facing open water, or along the larger creeks, usually slopes downward for 20–30 ft so that the margin of the bank is a foot or two below the general elevation of the high marsh. This suggests that compaction has taken place as the result of the ease with which water and other material may be squeezed out through the face of the bank. At one point at Black Bank a fluid silty clay, similar in water content to that at similar depth within the marsh, was seen to be oozing out from the face of the bank.

In many places where banks of high marsh have been cut by erosion, sediment is accumulating at their base, and where it reaches sufficient elevation the deposit becomes revegetated with *Spartina.* The effects of erosion are thus compensated for by the further extension of the marsh.

Stability of creek banks

The banks of the smaller creeks appear to be undergoing active erosion, but this is evidently being counterbalanced by their reconstruction. Goldthwait (1936) concluded that the salt-marsh creeks at Salem, Massachusetts, have not changed from the position shown on old charts. This is confirmed by a comparison of the detailed chart of 1859 with recent air photographs of the Barnstable Marsh. In spite of the tortuous pattern of the creeks of the high marsh only two places have been found where meanders have been cut off to form oxbow loops. This argues for the stability of the pattern and is surprising in view of the appearance of active erosion almost everywhere along the creeks.

The creeks have not been formed by recent erosion of the surface, but appear to be relicts of drainage channels which were formed at an earlier time. As the marsh builds upward with rising sea level the margin of the creek becomes unstable so that the peat tends to break off and slump into the channel, producing a band depressed 0.5 ft or more along the creek bank (Fig. 35). Where the peat is deep, cracks may be formed between the slumped margin and the undisturbed high marsh behind it. These cracks may extend for many feet and open to a width of a foot

FIG. 46. A crack in the marsh surface due to the slumping of the bank of Navigation Creek. Spring 1955. The crack is about 1 ft wide and 30–40 ft long.

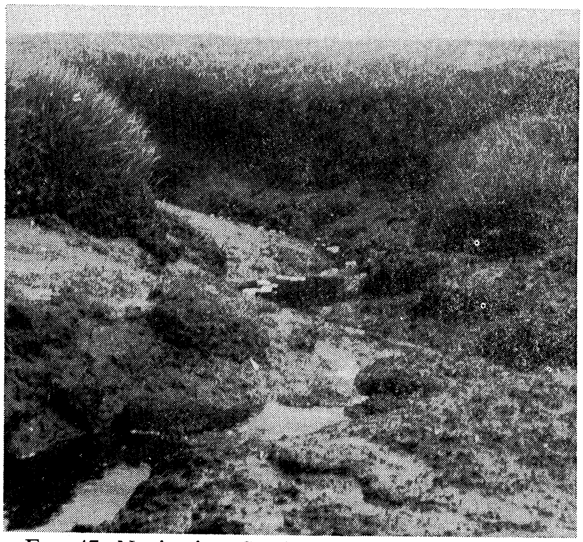

FIG. 47. Navigation Creek at low water, showing accumulation of eroded peat on the creek bottom. The bottom of the creek is about 7 ft below the high marsh surface.

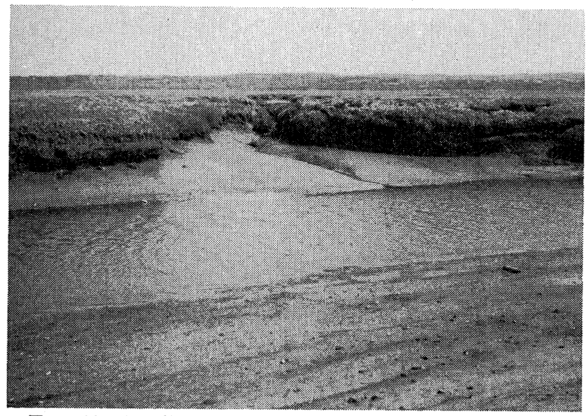

FIG. 48. A tributary entering Spring Creek as a hanging valley. The bottom of the tributary is about 4 ft above the water level in Spring Creek at low tide.

FIG. 49. Deposit of silty mud behind a block of peat which has broken off and slumped into Spring Creek. *Spartina alterniflora* has invaded the distant end of the mud deposit. Seedlings were growing at the nearer end, beside the crack in the mud, which may be due to drying or to continuing movement of the block.

or more (Fig. 46). Blocks of peat break off from the face of the slumped margin and fall into the channel where they decompose. The products of their decomposition and other sediments accumulate in the creek bottom (Fig. 47). As a result, the bottom of the creek tends to rise as the marsh increases in elevation and, except in the larger creeks, to stand well above the low water level. Smaller tributaries enter the larger creeks as hanging valleys, their discharge at low tide flowing down over the sloping bottom of the latter (Fig. 48).

Sediment accumulates in the cracks formed by the slumping of the bank and becomes vegetated by the outgrowth of rhizomes and by seeding (Fig. 49). It is deposited also on the slumped surface and the blocks of peat which break off from it, tending to counteract the effect of slumping. Thus turf is formed which reconstitutes the marsh and counteracts the effects of erosion. A healing process takes place which tends to keep the creek in very much the same position and to adjust its size to that required to carry its load of tide water.

It is observed in sounding the marsh that the peat

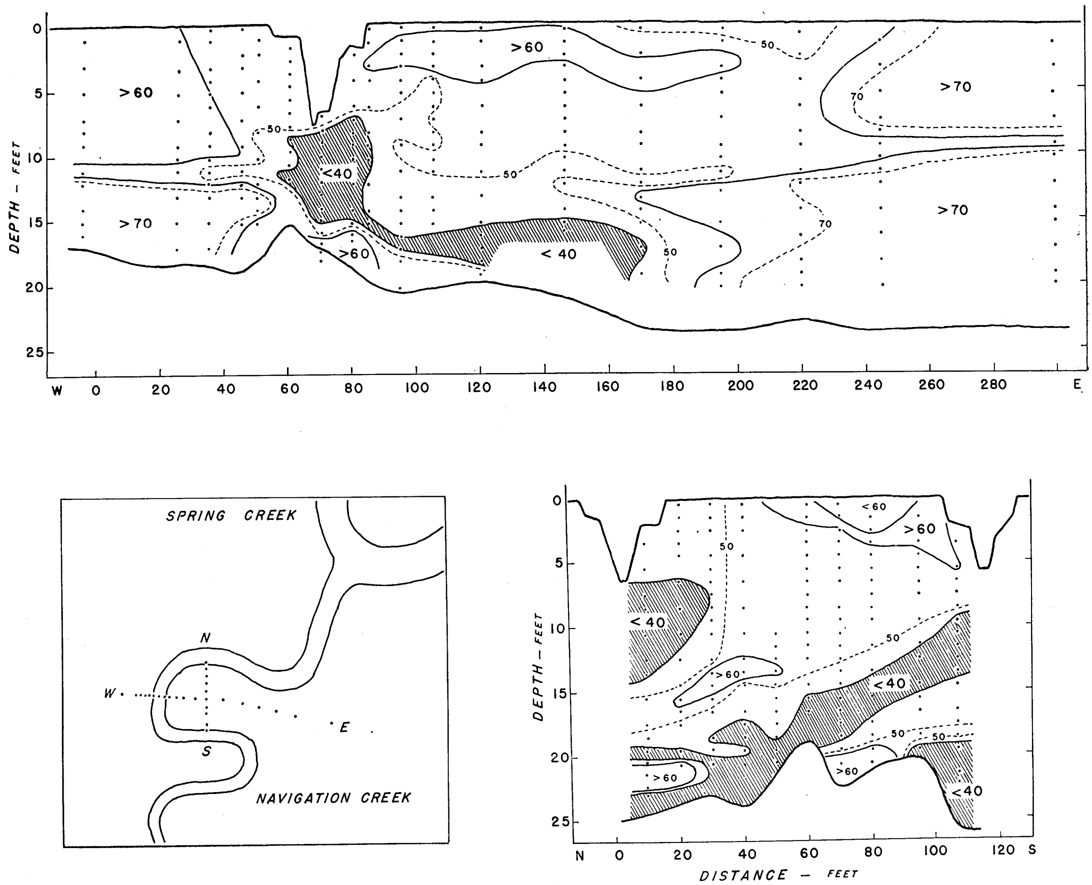

FIG. 50. Sections across a meander of Navigation Creek showing water content of peat as percentage wet weight. Deposits containing more than 60% water are interpreted as undisturbed high marsh peat; those of 40–60% water as peak reworked following erosion; those of less than 40% water as sediment deposited in the creek bottom. Above: west-east section; lower right: north-south section.

of the undisturbed high marsh is soft and easily penetrated by the sounding rod. As the borders of the creeks are approached the peat becomes very much more compact. Presumably this compact material has been formed by the reworking of the peat at the margin of the creek as it has shifted its position.

A detailed study of the structure of the peat surrounding Navigation Creek, a small creek lying east of Navigation Road, was made. Water content of the peat was used as an indicator of its character. A section across the creek from the western extremity of a meander is shown in Fig. 50. The peat underlying the high marsh beyond the general course of the creek has a water content greater than 60%, characteristic of undisturbed high marsh peat. Peat having a water content between 60% and 40%, interpreted to represent that formed by reworking following erosion, extends into the marsh for about 30 ft beyond the present position of the creek. Such peat also extends across the entire area enclosed by the meander, indicating that this region has been reworked by the movement of the stream along the axis of the meanders. The deposit immediately below the present position of the creek has a water content of 40% or less. It is interpreted to be sediment deposited in the creek bottom from which the finer sediments and organic debris have been winnowed by the motion of the water. This deposit extends to a depth of about 7 ft below the bottom of the channel and indicates that the channel has occupied the same position as its bottom has risen with the rising marsh surface. For the creek bottom to rise 7 ft with increasing sea level would require some 2,000 years.

A section along the axis of the meandering creek is shown in Fig. 50 at the lower right. It crosses the creek at two points—above and below the section described above. A deposit containing less than 40% water underlies the bottom of the downstream arm of the creek, but does not extend into the enclosed loop or to the basement. A second deposit of this character lies close to the basement at this point and extends across the loop, rising as it does so to lie immediately below the upstream arm of the creek. A third deposit of low water content is present under the upstream arm close to the basement. The distribution of the sediment of low water content, considered to be deposited in the creek bottom, suggests that the meander has shifted upstream in the course of time and that the upstream arm of the creek once occupied the present position of the downstream arm. This is compatible with the conclusion that the entire area within the loop has been reworked following its erosion by the shifting channel.

The surface of the marsh enclosed by this meander also suggests that the meander has shifted upstream, being lower along the upstream arm as though the marsh has not been fully reconstructed in the area more recently occupied by the creek. Although this meander appears to have moved, the shift appears to have been mainly in the axial direction, and the creek has not encroached far into the high marsh beyond the envelopes of the meanders. The surface features of many other meanders in the Barnstable Marsh do not show such evidence of migration. It may be that because Navigation Creek drains an indentation of the upland, which has enlarged as sea level has risen, the volume of tide water carried by the creek has increased. This may have disturbed the hydraulic balance on which the meander pattern depends and may have caused the meander to migrate upstream.

Observations of the marshes at Southport, North Carolina, and at Sapelo Island, Georgia, suggest that the creeks in the marshes of the southern coast of the United States are much less constant in position than those of New England. Usually, in these regions the marsh is not covered by a dense turf, but consists of a soft muddy surface sparsely vegetated by *Spartina alterniflora*. At Southport, cores of apparently undisturbed, coherent fibrous peat were found in a recession of the margin of the upland. Beyond the limit of this recession cores consisted of silt containing fragments of *Spartina*. This suggests that the deposit had been reworked by the changing position of the creek. Old maps indicate that substantial changes in the creek pattern at Sapelo Island have taken place within historic times (R. A. Ragotskie, *personal communication*).

Chronological Summary

The development of the Barnstable Marsh may be summarized according to its chronology.

The enclosure in which the marsh lies was formed by the development of the sandspit, Sandy Neck. The time required for the growth of the sandspit may be judged by the age of the peat formed in its shelter. The age of the deepest peat found along its margin is shown in Fig. 32. There the oldest peat, aged 3,170 years, was found at the base of the spit. Somewhat older peats were found along the southern margin of the marsh. The oldest existing features are probably not more than 4,000 years old. About 1,000 years were required for the sandspit to grow to one-half its present length, and an additional 1,000 years were needed for it to extend to Mussel Point. Beyond this point the growth of the spit in the past 1,200 years has been much slower, and most of the marsh is still in the intertidal stage.

The earliest marshland presumably developed in the intertidal zone along the margins of the upland and of the sandspit. This stage in development may now be seen near the end of Sandy Neck, bordering The Cove. Along the southern border of the marsh where the upland consisted of glacial deposits, the marsh presumably developed first in the indentations of the shore line, where peat is found up to 3,600 years old. The spreading of the marsh along the borders of the enclosure took place chiefly by seeding. Nearly 20,000 years would have been required for it to extend along the length of Sandy Neck by the outgrowth of rhizomes.

About two-thirds of the area enclosed by Sandy Neck is now occupied by marshland, of which 92% is high marsh. The filling of the enclosure by marsh has taken place only as fast as the deposit of sand has raised the elevation of the flats to the lower level at which *S. alterniflora* can grow. When this level is reached the flats become vegetated by seeding. The clumps of grass so produced become consolidated by the outgrowth of rhizomes to form thatch islands and these in turn become joined to produce larger continuous areas of intertidal marsh and ultimately of high marsh. The initial stages are rapid—only about 4 years are required for established seedlings to develop a dense stand of grass. Such stands spread, sedimentation permitting, by the outgrowth of rhizomes. As the marsh has spread from its margins it has enclosed broad sounds of open water which have subsequently narrowed to leave the present creeks to drain the marshland (Fig. 10). The area about Slough Point is now passing through this stage of development.

The vertical accretion of intertidal marsh, by which it is ultimately transformed to high marsh, is dependent on the availability of sediment. When a flat is first vegetated, sand may be deposited among the grass stems to a depth of 1 ft in 6 years. As the intertidal marsh increases in elevation and extent it becomes less accessible to sediment and its surface rises more slowly. The time required for the intertidal marsh to rise to the high water elevation appears to vary greatly with the local availability of sediments and may be a few hundred to a thousand years. It has probably averaged about 600 years.

Once the high water level is reached the accretion of peat depends primarily on the rate of rise of sea level relative to the land; recently this has been about 3 ft in 1,000 years in the Cape Cod region. As sea level has risen, the marsh has spread over the inundated upland. Along its southern border layers of high marsh peat more than 20 ft thick, resting on glacial deposits of sand or clay, have been formed during the past 3,600 years.

The vertical accretion of the high marsh has been at a somewhat greater rate than the rise in sea level, exceeding it by as much as 0.5 ft in 1,000 years. This has resulted in a reduction of the quantity of water to be drained off by the creeks and has led to a decrease in the number of small creeks in the older parts of the marsh, accompanied by the filling in of many of the pond holes.

Barnstable Harbor is silting-in rapidly. On the basis of the reconstruction of its past history and the present position and depth of the channels draining the sand flats, one may venture to predict the changes to be expected in the future. In perhaps another thousand years the intertidal islands lying between Slough Point and Calves Pasture Point may become consolidated as high marsh. Broad Sound is already closed at its western end at low tide and may be expected to fill in to join this future high marsh area to the present high marshland. Intertidal marsh should develop over the extensive flats lying in the wide sound east of Slough Point leaving a channel only sufficient to carry off tide water from Scorton, Spring, and Bridge Creeks. The thoroughfare separating Jules Island from the continuous marsh to the south is now nearly dry at low tide at its western end and may be expected to close at that point.

The Thatcher Islands and Phillis Island may be expected to form another unit of high marsh, drained by a creek entering east of Phillis Island and extending northward between Great and Little Thatcher Islands. The channels separating these islands are already closed at their western ends at low tide. Intertidal marsh should also develop on the flats west of Mussel Point and in The Cove.

These changes would nearly complete the filling of the enclosure within Sandy Neck with marshland, as is now the condition of the smaller estuaries facing Cape Cod Bay. The creeks draining the future marsh will probably follow the course of the present deeper channels.

In view of the present concern with the destruction of salt marshes a few remarks on their rate of development and restoration are appropriate. High marsh has taken 500–1,000 years or more to develop, and if filled, will not be restored. Nor will dredged channels become vegetated during the many years required for siltation to reduce their depth. On the other hand, the development of intertidal marsh may be rapid if the elevation of the foreshore is sufficient. *Spartina* may revegetate areas from which the turf has been removed to provide sand bathing beaches in a few decades if left undisturbed. Its growth along the margins of dredging spoil and landfill soon serves to stabilize the banks. In most estuaries intertidal marsh is now as extensive as the prevailing depths will allow and in many marshlands already occupies the greater part of the sheltered area in which it could develop.

The extension of marshland into estuaries now occupied by sand or mud flats will depend on the rate at which sedimentation raises the level of the flats to that at which the plants may grow. In embayments which are freely open to the sea and where sources of sand are available for introduction by tidal currents, or where river waters are depositing great quantities of mud in the enclosures, the rise in elevation of the flats may be relatively rapid, as measured in generations of men. In most of the coastal estuaries of the Atlantic States, however, the inlets are so restricted and the sources of terrestrial sediments so limited that it may be a matter of millenia before the basins now open are substantially occupied by marshland.

Acknowledgments

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