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Elizabeth A. Allen

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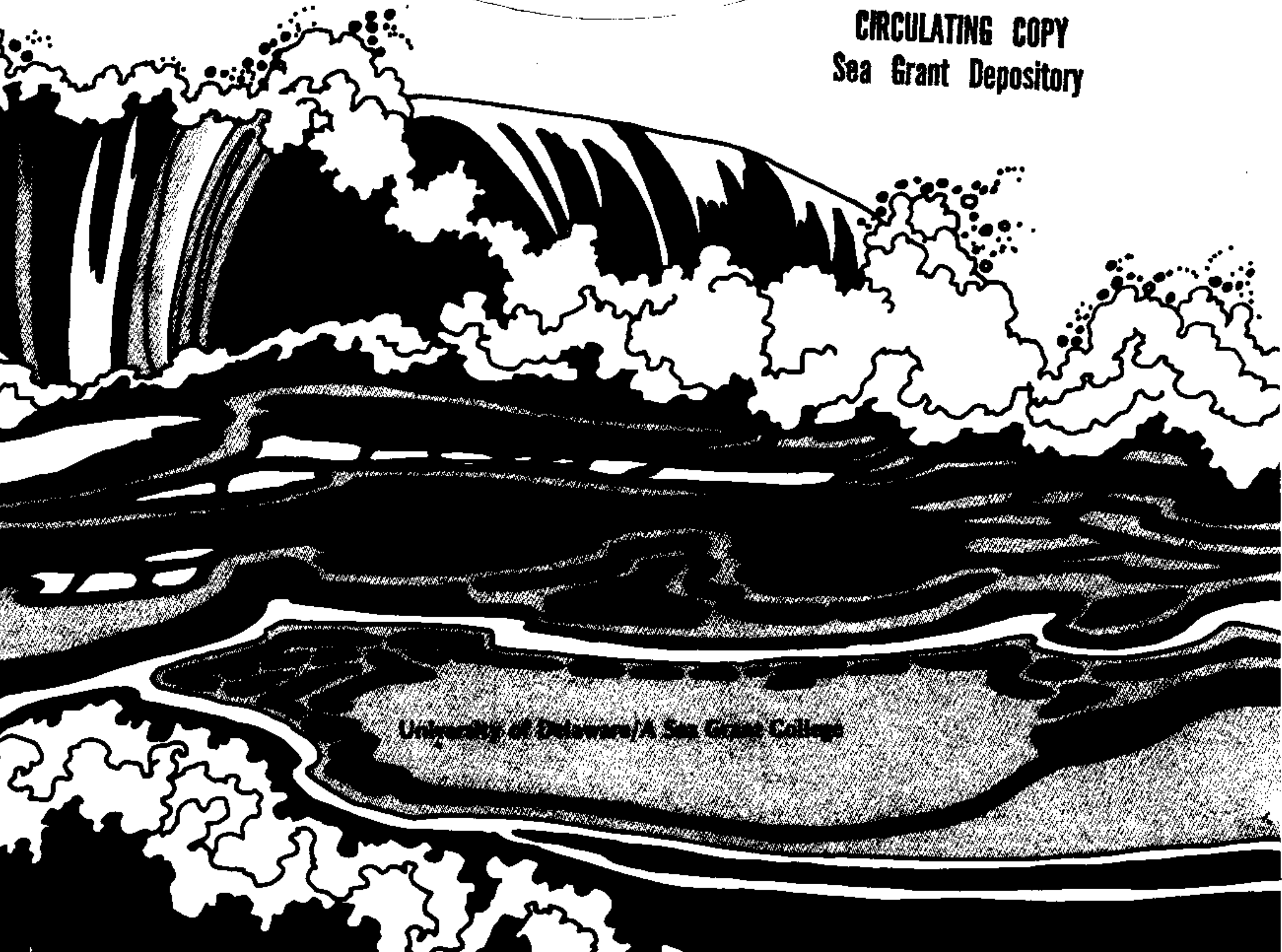

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This study of coastal-marsh sediments is part of a project undertaken by John C. Kraft and his colleagues at the University of Delaware to investigate the Holocene geology of the Delaware coast. Consequently, the study benefits greatly from the research of many students and faculty members working on the geology of the coast during a period of more than ten years. Research support was granted by NOAA Sea Grant to John C. Kraft, principal investigator, and Elizabeth A. Allen and

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ABSTRACT

Seventeen marsh facies and subfacies from temperate-zone marsh deposits along the western shore of Delaware Bay are defined, based on microscopic analyses of microtome sections of surficial and subsurface sediments and plants, megascopic observations of sediments, and observations of surficial marsh environments.

Facies are distinguished primarily by species identification of plant fragments in microtome section. Second order features used in classification include: Type, size, and preservation state of plant organs; predominance of framework or matrix material; matrix color; and the distribution of a variety of components such as diatoms, cell fillings, fusinite, micrinite, and pyrite. Degradation of plant fragments can be related to surface conditions in depositional environments rather than to changes that occur at depth. Maceral compositions of these marsh sediments show low amounts of pre-resinites, pre-sclerotinites, and fusinites, and high amounts of pre-micrinites. The highest pre-vitrinitic, pre-resinitic, pre-micrinitic, and pre-sclerotinitic compositions are found in brackish-marsh facies. Fusinitic compositions are highest in high-marsh facies.

Subsurface distributions of marsh facies are related to sea-level changes, compaction, shoreline configuration, drainage, sediment supply, and other factors. The overall factor controlling marsh deposition in coastal Delaware is relative sea-level rise. This produces a transgressive sequence of fresh- to brackish- to salt-marsh deposits. Compaction occurring in thick stratigraphic sections affects the distribution of marsh environments. Repetitive facies sequences common in these thick stratigraphic sections reflect the interaction of sea-level change, compaction, and sediment supply. Stratigraphic sections containing single facies indicate a balance between depositional conditions and relative sea level. The evolution of one marsh facies to another with a slightly higher elevation commonly, but not necessarily, occurs in young or developing low marshes and can be attributed to characteristic high sedimentation rates of low marshes.

Although most basal marsh deposits contain remains of salt-marsh or brackish-marsh plants, some deposits contain fresh-water fern remains. These fresh-water fern deposits are not related to tidal deposition, and radiocarbon dates on these deposits should be used with extreme caution in constructing sea-level curves.

Three typical stratigraphic sequences are developed for the Delaware Bay shoreline: broad marsh-continuous barrier sequence, broad marsh-discontinuous barrier sequence, and tidal-river marsh sequence. The first two sequences contain predominantly high- and low-marsh sediments. Brackish-marsh sediments may be common, but fresh-water marsh sediments are a minor component. Sandy washover fan deposits occur at irregular intervals. The tidal river sequence contains thick sections of brackish-marsh sediments. Fresh-water and salt-marsh sediments may contribute significant and relatively equal amounts to the sequence.

Finally, from observations of the aerial dimensions and internal variability of Holocene deposits along western Delaware Bay, a model is constructed to predict the characteristics of similar features in ancient analogs and to predict the preservation potential of particular marsh sediments.

INTRODUCTION

Coastal marshes commonly border many of the world's estuaries and sheltered marine embayments. A relatively small number of vascular plants populate these marshes and many of these plants are zoned in response to environmental differences within marshes. Subsurface coastal-marsh sediments record long-term changes in these vegetated environments. Information about such changes can elucidate the history of coastal areas in both local and regional extent.

The major purposes of this study are to characterize the principal depositional environments of middle-latitude marshes along the western shore of Delaware Bay and to differentiate their corresponding environmental facies in subsurface Holocene sediments. The broad marshes and large deposit of organic-rich sediments in Delaware provide an ideal opportunity for this study.

Undisturbed, oriented microtome sections are the principal means of studying these marsh sediments. By providing detailed information on the *in situ* organization of organic and inorganic constituents that cannot be obtained from hand-specimens or sieved sediments, these microtome sections facilitate accurate identification of environmental facies and thereby improve interpretations of the genesis of coastal-marsh deposits. This technique involves three steps. First, it is necessary to develop a thorough knowledge of the plant anatomy and morphology of potential plant contributors to coastal-marsh sediments in order to identify plant fragments in marsh sediments. Second, it is necessary to know the variation in surficial marsh environments and to recognize unique characteristics, including plant species distribution, of these environments in microtome section. The third step involves identification of marsh facies in the subsurface based on information gained from the first two steps. These analyses then establish the basis for determining the evolution of coastal-marsh sediments in Delaware and their Holocene stratigraphy.

In the past, marsh sedimentological characteristics have been based largely on general textural features observed in hand specimen, sediment color, and sediment size (see Allen, 1974). An exception to this is the paleontological marsh study of Basan (1975). Yet, there has been growing recognition that marsh sediments cannot be distinguished confidently without microscopic study (Barghoorn, 1949b; Smith and Coleman, 1967; Stewart and

Durno, 1969; Cohen, 1968; and Allen, 1974). For instance, the vegetational variety that exists on marshes has not been well documented in marsh facies. In fact, many sediments that appear uniform megascopically actually have very different microscopic characteristics and represent different marsh depositional environments. Also, the same environment may produce sediments that have different megascopic characteristics.

It is hoped that this study will provide information on the diversity of coastal marsh sediments and will show how detailed coastal-marsh analyses can be of use to coastal geologists and stratigraphers.

REGIONAL SETTING AND STUDY AREA

Introduction

The mid-Atlantic region of the east coast of North America, located on a mid-plate continental margin geosyncline (Moore and Curray, 1974),is characterized by a broad continental shelf and coastal plain (Figure 1). Delaware Bay lies on the partially emerged northwest flank of the subsiding Baltimore Canyon trough of the geosyncline (Sheridan, 1974). Sediments reach thicknesses of as great as 12,000 m in the geosynclinal basins and 2,000 m in Delaware (Minard and others, 1974).

Cretaceous, Tertiary, and Quaternary sediments are exposed in Delaware. The coastal plain surface has little relief and elevations rarely exceed 30 m. Pleistocene sediments cover much of the state and crop out along the shorelines of the bay and ocean. Late Pleistocene landforms partly control the distribution of Holocene depositional environments. Some of the major Pleistocene features are the deeply-incised tributary valleys to the ancestral Delaware River and Bay (Kraft and others, 1976). Pleistocene units form a surface over which the Holocene sedimentary

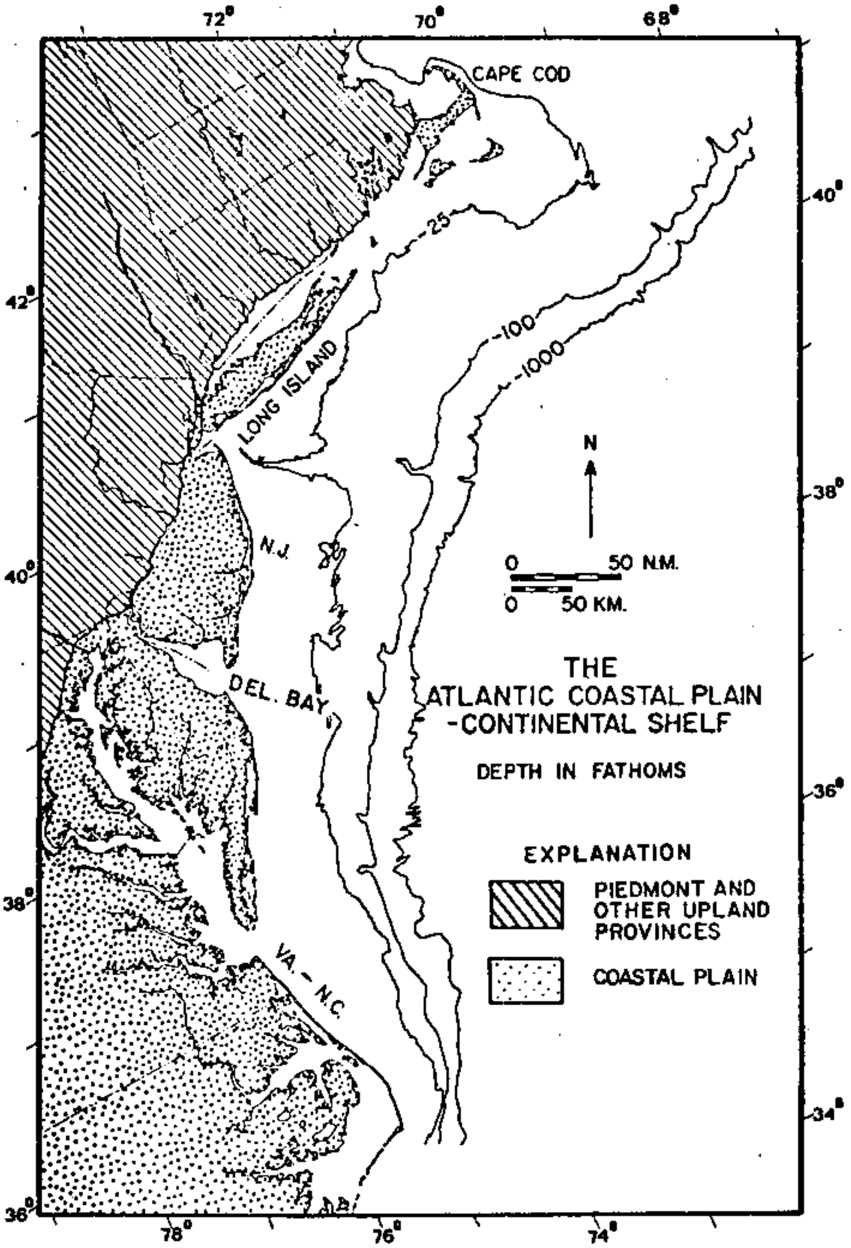


Figure 1. The Atlantic coastal plain and continental shelf (after Kraft and others, in press).

environments migrate and provide a major source of sediment to the Holocene during the transgression (Kraft and others, 1973).

Holocene coastal environments in Delaware include nearshore shallow marine sands; the Atlantic Coast barrier systems with beaches, dunes, washover fans, marshes, lagoons, inlets,and tidal deltas; the Cape Henlopen spit complex with beach ridges, marshes, and simple spit; the Delaware Bay estuary; and estuarine washover barriers and broad marshes along the Delaware Bay shoreline (Kraft, 1971a,b). These coastal units have been migrating across the continental shelf and coastal plain in response to relative sea-level rise. Documentation of this transgression in the Delaware area has been made by Kraft and others (1971), Kraft and Allen (1975), Swift and others (1972), and Belknap and others (1976). The oldest post-glacial coastal-marsh sediments in Delaware are dated at 11,000 years B.P. and are buried at 30 m below present sea level in the channel of the ancestral Indian River along the Atlantic Delaware coast (Kraft and others, in press). Marsh deposits at a depth of 27 m at South Bowers are dated at nearly 10,000 years B.P. indicating that coastal sedimentation was occurring in the vicinity of at least part of the present bay shoreline by this time (Belknap and Kraft, 1977).

Belknap and Kraft (1977) constructed a local relative sea-level curve for the Delaware coast from radiocarbon-dated coastal-marsh sediments. The smooth curve consists of three segments: the first indicates sea level rising at rates of 29.6 cm/century before about 5,000 years; the second indicates sea level rising at about 20.7 cm/century from about 5,000 to 2,000 years ago; and the third indicates sea level rising at 12.5 cm/century from about 2,000 years ago to present. It is possible that this curve may ignore low-amplitude fluctuations in sea levels. For instance, Hicks and Crosby (1974) record a present sea-level rise of up to 39 cm/100 years based on tide-gage records in the mid-Atlantic region. This area may be undergoing a recent increase in rate of sea-level rise,or this may be in fact a short-term rise that may be compensated for by a later short-term drop or steady stage of sea level (D.F. Belknap and J.C. Kraft, oral communication, 1977). Such short-term changes in sea level could greatly modify sedimentary processes and deposits in coastal areas.

Delaware Bay

Delaware Bay is exposed to a temperate zone climate. The most severe storms are "northeasters" and hurricanes which can cause severe coastal erosion and extensive wash-over fan deposition. On the average, one major storm strikes the coast every 3 years (Maurer and Wang, 1973). High astronomical tides coupled with strong onshore winds can also cause significant erosion and washover-fan deposition. The dominant winds come from the northwest, but during major storms the winds generally blow from the northeast (Mather, 1968).

The large fetch of Delaware Bay allows wind to generate large waves within the estuary. A comparison of shoreline erosion rates and a wave frequency rose diagram for Delaware Bay suggests that most shoreline erosion in Delaware is caused by local wind-generated waves (Weil, 1977). Waves in Delaware Bay are less than 0.6 m 80% of the time (Maurer and Wang, 1973).

Mean tidal range generally increases from approximately 1.3 m in the lower part of the bay to 2.0 m in the upper portion of the bay (Zeskind and Le Lacheur, 1926). There is a gradual reduction in tidal range from the mouth of tidal rivers to the headward limit of tidal water intrusion. Also, duration of tidal inundation is drastically reduced along the upper limit of marsh growth where the marsh is inundated by only the highest portion of the highest tides.

Tide is the main factor controlling currents and sediment transport in most of the bay (Maurer and Wang, 1973). Both ebb and flood currents occur simultaneously in different parts of the bay due in part to the great length of the bay and the low velocity of tidal currents (Weil, 1977).

Salinity varies geographically and seasonally (Mather and others, 1973). Bay water salinities generally range from 35 $^{o}/_{oo}$ near the mouth to 6 $^{o}/_{oo}$ in the upper part of the bay. Significantly higher and lower salinities occur within the coastal marshes and will be discussed in greater detail. Much of the existing data on salinity, tidal patterns, current velocities and directions in Delaware Bay has been compiled by the U.S. Army Corps of Engineers (1973).

Shoreline sediments of Delaware Bay are probably derived from many sources. One source includes Delaware Bay sands in the baymouth and linear shoals and channels, and fine sands and muds of subtidal flats (Weil, 1977). Eroding subcrops and outcrops of pre-Holocene sands and pebbles provide an irregularly spaced but locally very important source of sediment to the shoreline. The Delaware River, its tributaries, and tidal rivers tributary to Delaware Bay carry loads of predominantly fine-grained (silt and clay) sediments into the estuary (Mansue and Commings, 1974). The shelf and Atlantic Coast is also a potential sediment source as sediment is transported into the mouth of Delaware Bay. The shoreline itself provides sediment to other parts of the shoreline through erosion and littoral transport of sediment and overwash processes. Erosion of relict-marsh tidal flats, and wind- and water-borne sand from beaches contribute significant amounts of sediment to back-barrier marshes.

Weil (1977) notes that shorelines formed of marsh sediments erode at greater rates than sandy shorelines or the even more resistant shorelines formed of pre-Holocene sediments. Some marsh shorelines are located over deep pre-Holocene valleys and the higher rates of erosion may be due in part to subsidence of the surface related to compaction of underlying fine-grained sediments.

Study Area and Coastal Marshes

An index map showing study areas and sample locations along the western Delaware Bay shoreline is illustrated in Figure 2. This shoreline shows several major geomorphic variations (Figure 3). In the southern portion of the bay shoreline, the washover barrier is wide and continuous; the marshes are typically poorly drained, contain large ponds, some brackish vegetation, and few tidal creeks (Figure 3A). In areas where inlets breach the barrier, marshes are well drained. To the north, the sandy barrier is discontinuous (Figure 3B). Where present, it separates relict marsh surfaces commonly forming the tidal flat from well-drained tidal marshes with dendritic creek systems. Farther north, the barrier is rarely present, and marshes form the shoreline edge (Figure 3C). Coastal marshes also fringe numerous tidal rivers which empty into Delaware Bay (Figure 3D). The sandy barrier is essentially

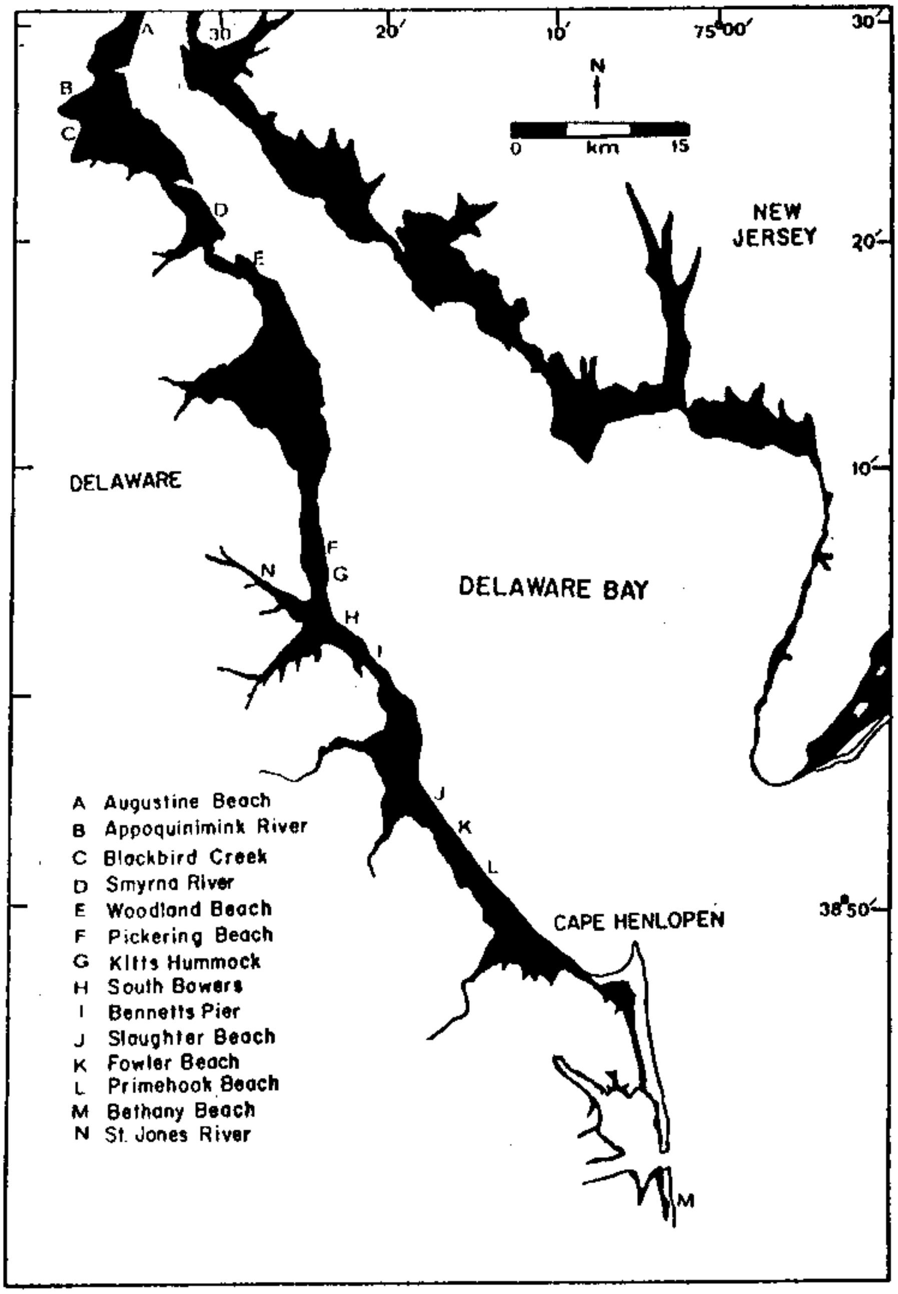


Figure 2. Study areas and sample locations along the western Delaware Bay shoreline. Marshes are shown in black. Wilmington, Delaware is located approximately 20 km north of Augustine Beach.

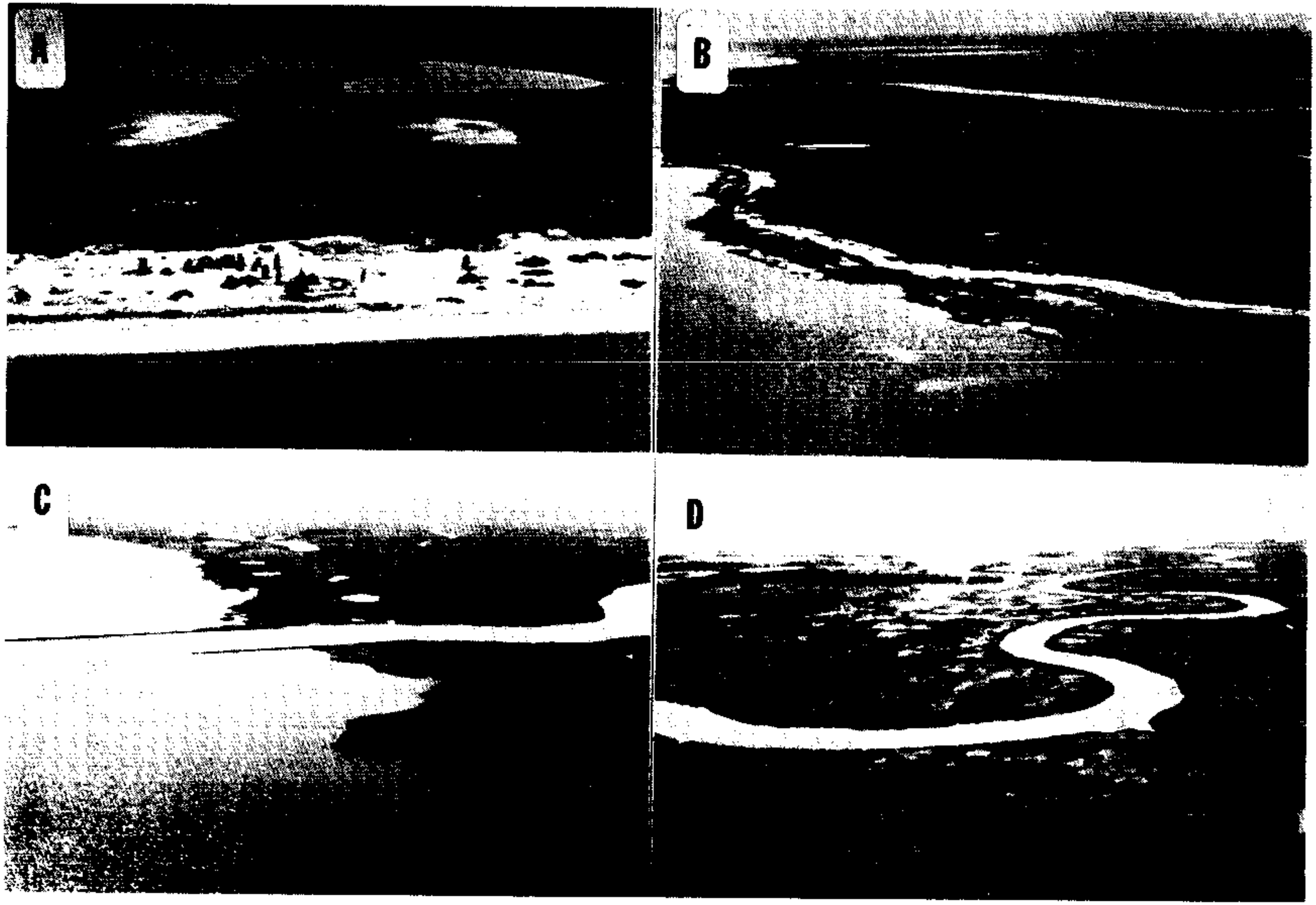
Figure 3. Delaware Bay shoreline.

A. Oblique air photograph of the wide and continuous washover barrier in the southern portion of Delaware Bay shoreline. The marshes are poorly-drained, contain large ponds, brackish vegetation,and few tidal creeks.

B. Oblique air photograph showing the discontinuous, perched sandy barrier shoreline north of A. A relict-marsh surface forms the tidal flat and a well-drained tidal marsh with dendritic creek systems exist landward of the barrier.

C. Oblique air photograph showing the marsh shoreline north of B. The sandy barrier is rarely present and marshes form the shoreline edge.

D. Oblique air photograph looking towards the bay and showing the Smyrna River, one of many tributaries to Delaware Bay. This river and others are situated in the vicinity of pre-Holocene river valleys.


A
B
C
D

continuous south of South Bowers and discontinuous north of South Bowers. A more detailed description of the geomorphic subdivisions of Delaware's bay coastline is presented by Kraft and others (1976).

Beach slopes are generally steep and average 1:10, and barrier widths vary from 10-100 m with the widest ones occurring along the southwestern bay shoreline (Allen and others, 1977). Dunes, if present at all, have maximum elevations of 1-2 m above mean high water. Some tidal flats are nearly 1 km wide. Shoreline-erosion rates range from 1-8 m/yr from 1843 to 1954(U.S. Army Corps of Engineers, 1956).

A block diagram illustrating the three-dimensional characteristics of the broad, transgressive marshes and narrow, sandy barriers is shown in Figure 4. The thickness of marsh sediments varies greatly along the shoreline due to the highly irregular pre-Holocene surface, but marshes form the most common Holocene sedimentary deposit along the coast and reach thicknesses up to 30 m in some Pleistocene valleys. South of South Bowers,some of the subsurface Holocene deposits consist of mud representing lagoons along a former shoreline (Kraft, 1971b; Elliott, 1972; Allen and Kraft, 1974). To the north of South Bowers along the shore, the sequence consists entirely of organic muds representing continuous coastal-marsh deposition. Richter (1974)

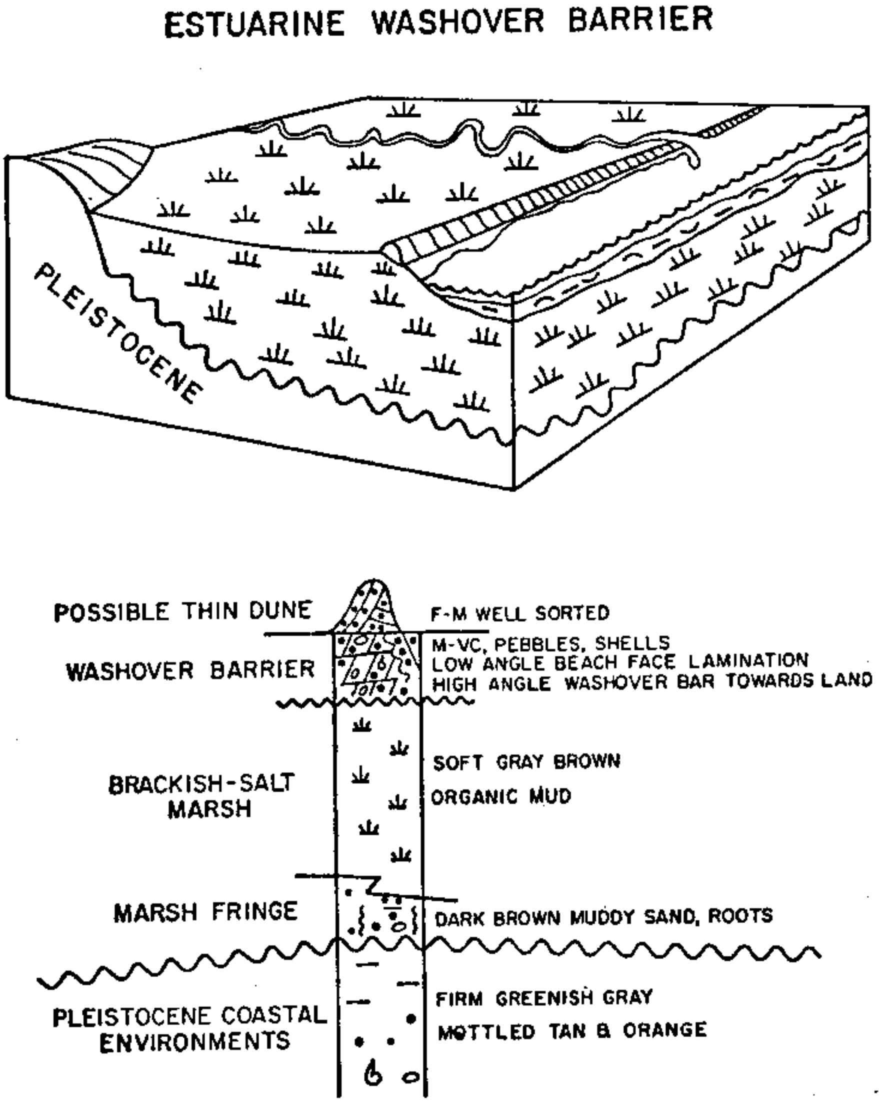


Figure 4. Diagrams showing the typical sequence of facies beneath the broad, transgressive marshes and narrow, sandy barriers fringing Delaware Bay (after Kraft and others, 1973). Block diagram (top) illustrates the overall relationship between the subsurface sediments and the modern depositional environments, and the stratigraphic column (bottom) provides details of the vertical sequence of sediments beneath washover barriers.

determined that the median thickness of Holocene sediments is approximately 5 m and 50% of these sediments have been deposited within the last 3,900 years.

Approximately 29,600 hectares of marshes form along the shoreline edge of western Delaware Bay (Daiber and others, 1976). The marshes vary in width from several hundred meters to nearly 8 kilometers and extend almost continuously from Cape Henlopen in the south to Wilmington in the north, a distance of approximately 150 km. Of these marshes, 55% (16,000 ha) are populated by *S. alterniflora*, 16% (4,760 ha) by *D. spicata* and *S. patens*, 3% (1,020 ha) by *Baccharis* and *Iva*, 9% (2,720 ha) by *P. communis*, 15% (4,420 ha) by a wide variety of brackish-marsh species such as *Scirpus* and *Panicum*, and 2% (680 ha) by fresh-water marsh species such as *Pontederia* and *Peltandra* (Daiber and others, 1976). Many other species also populate these marshes. Those plant species collected and examined in this study are listed in Table 1.

Marsh environments are distinguished primarily by community associations of angiosperms. Zonation of seed-plants is controlled largely by elevation with respect to tidal range, salinity of water and sediment, and drainage. However, marshes are complex systems,and a great variety of other factors also control vegetation distribution.

Consequently, such terms as salt marsh, high marsh,

FAMILY	SPECIES	COMMON NAME
Araceae	Peltandra virginica (L.) Kunth	Arrow arum
Caryophyllaceae	Spergularia marina (L.) Griseb.	Sand spurrey
Chenopodiaceae	Atriplex patula L. var. hastata (L.) Gray	Marsh orach
	Salicornia europaea L.	Scarlet samphire
	Salicornia virginica L.	Glasswort
	Sueda maritima (L.) Dumort.	Sea blite
Compositae	Baccharis halimifolia L.	Sea myrtle
	Iva frutescens L. var. oraria (Bartlett) Fern. and Grisc.	Marsh elder
	Pluchea purpurascens (Sw.) DC. var. succlenta Fern.	Salt marsh fleabane
	Solidago sempervirens L. var. mexicana (L.) Fern.	Seaside goldenrod
Cyperaceae (sedges)	Scirpus americanus Pers.	Three sqnare rush
	Scirpus robustus Pursh	Bulrush
Gramineae (grasses)	Distichlis spicata (L.) Greene	Spike grass
	Panicum virgatum L.	Switch grass
	Phragmites communis Trin.	Reed
	Spartina alterniflora Loisel	Smooth cordgrass
	Spartina cynosuroides (L.) Roth	Salt marsh grass
	Spartina patens (Ait). Muhl.	Salt hay
Juncaceae	Juncus gerardi Loisel	Black grass
Malvaceae	Hibiscus palustris L.	Marsh mallow
	Kosteletzkya virginica (L.) Presl. var. aquilonia Fern.	Seashore mallow
Plumbaginaceae	Limonium carolinianum (Walt.) Britt.	Sea lavender
Polygonaceae	Polygonum punctatum Ell.	Perennial smartweed
	Rumex altissimus Wood	Water dock
Pontederiaceae	Pontederia cordata L.	Pickerel weed
Typhaceae	Typha angustifolia L.	Narrow leaved cattail
	Typha latifolia L.	Common cattail

Table 1. Common coastal-marsh plants of Delaware examined in microtome section during this study.

low marsh, brackish marsh, and fresh-water marsh cannot be precisely defined by physical, chemical and/or biological factors. A continuum of environments with a whole range of conditions exists. For this reason, I use the term coastal marsh to encompass all the marsh environments,and I name the sub-environments without providing rigorous definitions.

Marshes exhibit both lateral and longitudinal zonations. Lateral zonations occur from low elevations along creeks and rivers to higher elevations along the upland border of the marshes. Longitudinal zonations occur along tidal-river systems and are controlled primarily by salinity. Plants tolerant of higher salinities populate marshes near the river mouth and plants tolerant of lower salinities populate marshes upstream.

For a more detailed description of marsh plants, their habitats, primary productivity and associated flora and fauna in Delaware see the publication of Daiber and others (1976).

METHODS OF INVESTIGATION

Introduction

A variety of field and laboratory techniques have been employed to study marsh environments and their sediments. Field investigations provided information on the geomorphic variability of marsh environments and on the physical and biological processes occurring within these environments. Laboratory investigations, particularly microscopic studies, provided information necessary to distinguish marsh facies and to recognize a wide range of marsh sedimentological characteristics.

Field Methods

Plant collection. Twenty-seven species of coastal-marsh plants were collected in Delaware marshes (Table 1). Taxonomic classification was based on the new Britton and Brown illustrated flora (Gleason, 1963) and Gray's manual of botany (Fernald, 1950). The morphology of each plant was described and sketched. Plant specimens were dried and pressed for use as a herbarium collection. Individual organs of fresh, living plants were cut into small pieces and stored in a solution of formaldehyde, acetic acid, and alcohol (50 parts 95% ethanol, 40 parts water, 5 parts acetic acid, 5 parts formaldehyde).

Sediment sample collection. Samples were taken from the surface of the marsh, from outcrops, and from cores. The following surficial marsh environments were samples: 1.)tidal creeks, 2.)creek banks, 3.)*S. alterniflora* low marshes, 4.)*S. patens* high marshes, 5.)*D. spicata* high marshes, 6.)mixed *S. patens*-*D. spicata* high marshes, 7.) *Salicornia* marshes, 8.)rotten spots, 9.)*P. communis* marshes, 10.)*Baccharis*-*Iva* marshes, 11.)tidal-river levee brackish marshes, 12.)back-levee brackish marshes, and 13.)*Peltandra* and *Pontederia* marshes.

Surface samples were collected from four relict-marsh exposures on Delaware Bay tidal flats. Fourteen hand-driven cores were taken with plastic tubing (5.7 cm in diameter) to maximum depths slightly greater that 5 m following the method described by Kraft (1971b). A hand-operated Dutch coring device, made by the Eijkelkamp B.V. soil auger and machine factory, provided additional cores (2.8 cm in diameter). This device was used to field check interpretations at the end of the study. Several other samples at depths of up to 30 m were obtained with the University of Delaware's truck-mounted auger drill rig.

Field observations of marsh environments. Surficial environments were studied between 1972 and 1977 and observations were made on: vegetation patterns including seasonal and longer term changes, vegetation density, depth of living roots, surface litter, animal activity, grain size, general elevation with respect to tidal range, degree of exposure, drainage, energy conditions and geomorphology. In addition, water salinity was recorded with a refractometer (Behrens, 1965).

Laboratory Methods

Storage and sample preparation. All sediment samples were frozen, or preferably, refrigerated until processed. Refrigerated cores were stored in an upright position. Cores were split lengthwise using a hand-held electric power saw. One half was sampled, and the other half was studied in hand specimen. No estimates were made of compaction.

Megascopic study. The following characteristics of each sediment sample were recorded when possible: plant species, kinds of plant organs, texture of organic materials, structure, color, and degree of preservation of plant fragments. Plant fragments were removed from the sediment, washed and described as to shape, color, size, organ and, if possible, identified to species or genus. A smooth sediment surface was prepared with an electric knife so that the interrelationship of organic and inorganic particles could be observed with only a minor amount of distortion. Reference samples of surficial marsh sediments were wrapped in plastic sheets and refrigerated.

Microscopic study. One hundred and fifty-two microtome sections of modern plants, 53 microtome sections of surficial marsh sediments and 190 microtome sections of subsurface and outcrop marsh sediments were prepared for microscopic study.

Plant organs were dehydrated, embedded in paraffin, cut in 15μ thick sections on a sliding microtome and stained in safranin 0 and fast green following a standard botanical procedure (Johansen, 1940).

A modified version of this procedure was used to prepare sections of organic-rich sediments 15μ thick and 1 cm^2 (Cohen, 1968; Cohen and Spackman, 1972). Cubes of sediment approximately 1.5 cm on a side were cut at 5 cm intervals from organic-rich cores using a razor blade. Then the cubes were carefully transferred to 100-mesh copper wire gauze cages. Orientation of samples was maintained throughout the procedure. These "cages" of sediment were dehydrated, embedded in paraffin,and sections were cut perpendicular to the original sediment surface on a sliding microtome. Sections of sediments were not stained because of the adequacy of natural color variation in the sediment. Organic-rich sediments containing sand could not be sectioned well because of the softness of paraffin and the cutting procedure. When samples contained too much sand for proper sectioning, individual plant fragments from the sediment were embedded and sectioned. All microtome sections were mounted in Canada Balsam.

Observations and point counts. Microtome sections of sediments were scanned under transmitted light at magnifications of 50X, 125X and 500X. The following observations were recorded:

SAMPLE: DEPTH: ORIENTATION: %F/M:

- I. FRAMEWORK (constituents greater than 100μ in diameter)
  - A. PLANT ORGANS — Roots / Rhizomes — Stems / Leaves — Other
  - B. FUSINITE
- II. MATRIX (constituents less that 100μ in diameter)
  - A. BIOLOGICAL COMPONENTS
    - 1. Plant Fragments
      - a. cells and cell fragments
      - b. cell fillings
      - c. silica cells
      - d. fine granular debris
      - e. other
    - 2. Microorganisms
      - a. forams
      - b. diatoms
      - c. fungi
      - d. other
    - 3. Miscellaneous
      - a. sponge spicules
      - b. pollen spores
      - c. fecal pellets
      - d. micrinite
      - e. other
  - B. MINERAL COMPONENTS
    - 1. Pyrite
      - a. crystals
      - b. spheres, framboids
    - 2. Other Minerals
- III. STRUCTURE
  - A. MICROBEDDING
  - B. COMPACTION

C. OTHER

IV. IDENTIFIED PLANT GENERA OR SPECIES
   A.
   B.
   C.
   D.

V. DEGRADATION AND OTHER COMMENTS

Point counts were made of one hundred or approximately one-half of all microtome sections of sediments. Three hundred to five hundred point counts at 500X were made per slide. Spacing was consistent from slide to slide and the entire section was scanned in each case. For other slides the letters A (abundant), C (common), P (present), R (rare) and N (not present) were used to denote qualitative amounts of components.

Diameters of foraminifers, fecal pellets, and plant organs such as roots and rhizomes were recorded for each section. Color was recorded for cells and cell fragments, cell fillings, fine granular debris, and fecal pellets. Observations were made with a microscope containing a daylight blue filter and Tungsten lamp light source; therefore, colors are somewhat artificial.

Method check. Since sediment thin sections were to be identified to particular marsh environments, it was necessary to determine if thin sections reflect characteristics of the original depositional setting accurately.

Cohen (1968) had found that analysis of surficial sediments gave a good indication of the nature of the actual environment (i.e., plant community and sedimentary processes) but did not always reflect actual percentages of various plant species populating an environment. This could cause errors in interpretation if a quantitative reconstruction of the original environment were attempted.

In order to guard against possible misinterpretations, several tests were performed in this study and the following observations were made:

A. Thin sections of surficial marsh sediments contain plant species and other components that can be attributed to living vegetation on these sediments. This is in agreement with Cohen's observations cited above.

B. Thin sections prepared from different cubes of sediment taken at the same horizon contain similar, if not identical components.

C. Cores taken 50 meters apart contain similar stratigraphic sequences that can be correlated.

Therefore, unknown samples can be correlated to particular marsh environments with confidence.

Percent carbon. Ignition-loss tests were made on sediment samples to obtain estimates of organic content (Ball, 1964). Duplicate splits of samples indicate that ignition-loss values are reproducible within ±2 percent.

Cores were sampled every 5 cm for ignition loss. Surficial marsh and outcrop samples were examined also.

Ten of these samples, representing the range of ignition-loss values observed in the sediments, were tested on a 185B Hewlett-Packard Carbon-Hydrogen-Nitrogen analyzer to determine the abundance of carbon. A regression analysis provided a formula for converting all ignition-loss values to percentages of carbon. This equation, $y = 0.518x + 1.087$, where y = percent carbon and x = percent ignition loss, produces slightly higher percent carbon values than the regression analysis curve given by Ball, $y = 0.458x - 0.4$.

GENERAL CHARACTERISTICS OF MARSH SEDIMENTS AND THEIR DEPOSITIONAL ENVIRONMENTS

Introduction

In order to interpret the distribution of the microscopic components of marsh facies, environmental and sedimentary parameters of marshes were examined. These parameters, such as salinity, drainage, and substrate consistency, provide information on sediment forming processes. Some of the common components of marsh sediments observed in microtome section, such as grass roots, foraminifers, and diatoms, are also described. As a preface to this discussion, some general comments are made on the preservation and degradation potential of plant remains.

Preservation and Degradation of Plant Remains

In general, plant material that is exposed on or above the marsh surface is less likely to be preserved or is preserved in a highly decayed state, while material that is intruded into the sediment such as roots and rhizomes has a greater chance of preservation in recognizable form. Characteristics of the original material affect its preservation potential. For instance, Barghoorn (1949b) noted preservation of fine details in cuticular and epidermal cellulosic fragments of monocot roots and rhizomes in contrast to decay of secondary wall tissue such as vascular tissue. He attributed these differing rates of decay to fundamental chemical differences between tissues. Thus, primary cellulosic cell walls are more likely to be preserved than thick lignin-inpregnated secondary walls. Barghoorn observed that most of the granular amorphous material in his marsh sediments was derived from lignin-impregnated secondary walls. Also, similar material may undergo many different paths of degradation depending upon its history (Cohen, 1968). For example Stewart and Follett (1966) observed that under aerobic conditions the cuticle of plant leaves is highly decayed by microorganisms; yet it is preserved under anaerobic conditions.

Factors such as water level and abundance and types of organisms affect conditions both on the surface and in the subsurface. Because of the great volume of decomposing organic material, marsh sediments typically are acidic and reducing (Hill and Shearin, 1970; Swanson and others, 1972). Grain size is also a strong control on the chemistry and biology of the sediments. Johnson and Calder (1973) observed that fatty acid and hydrocarbon distribution in a 50 cm core from a sandy marsh in Florida could not be related to original marsh environments. Yet Swetland (1975) found excellent correlation between fatty acid-hydrocarbon distribution and fine-grained marsh environments in a Delaware marsh. The differences in observations may be due to grain size differences of the marsh sediments. Microbial activity and chemical alteration of plant matter should be higher in more permeable sandy marsh sediments.

Marsh environments are very complex chemical-physical-biological depositional sites. Sufficient explanation of the resulting marsh sediments requires attention to a wide range of sediment forming processes.

Environmental and Sedimentary Parameters

It was necessary to develop a set of parameters to facilitate description of sediments and their depositional environments, thereby allowing comparison between two or more facies and their corresponding depositional environments. Qualitative and quantitative observations were made in three major categories: modern marsh environments, megascopic sediment samples, and microscopic sediment samples. Most of the parameters used in this study are common and have been used by other investigators.

Some observations are qualitative, others have numerical values. All observations are reduced to descriptive terms such as high, intermediate and low. Ranges of values for the descriptive terms vary from one parameter to another and are related to the ranges in values for a given parameter in these environments. The parameters in this study are defined below.

Environmental Parameters

Salinity. "Low" refers to salinities that range from 2-10$^{o}/_{oo}$ (≅ oligohaline)* and these values occur most commonly in brackish marshes. "Intermediate" salinities range from 11-24$^{o}/_{oo}$ (≅ mesohaline and polyhaline) and occur in salt-marsh and brackish-salt marsh transition zones. "High" salinities range from 25-35 $^{o}/_{oo}$ (≅hyperhaline), and occur in some high-marsh environments.

Exposure Index. This term refers to the percentage of time the marsh surface is exposed to air during the tidal cycle. "Low" values occur in the lower intertidal to subtidal zone. "Intermediate" values occur in the mid-tidal range, and "high" values refer to areas that are covered only by high or spring high tides.

Drainage when exposed. "Poor" values indicate extensive ponding of water. "Good" values indicate some or occasional ponding, and "excellent" values indicate well-drained conditions, usually where the sediment contains some sand.

Substrate consistency. Substrate consistency is dependent upon grain size, drainage, vegetation density, and

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*Salinity terms adopted at the Venice Symposium on classification of brackish waters (1958) are provided in parentheses.

exposure index. Terms used to describe conditions include: very soft, moderately soft, soft, moderately firm, firm and very firm.

Grain size. Grain size was estimated megascopically although information of size variations in Delaware marsh environments is known from previous grain size analyses (Allen, 1974; Elliott, 1972). Most marsh sediments are composed of silt and clay. Sand becomes an important component in marshes near washover barriers and dune systems, upland surfaces, and along some creeks and tidal rivers. Others have noted these same trends (Basan, 1975; Edwards, 1973).

Vegetation density. When the mud surface is visible from a standing position vegetation density is considered "low" to "intermediate." When the surface cannot be seen, vegetation density is "high."

Energy conditions. Wave and current energy is high in marsh environments proximal to tidal creeks and rivers, and in low marshes. It is sporadically high in back-barrier marshes when water levels are raised by extreme high tides and strong onshore winds.

Megascopic Characteristics

Plant organ composition. Organs or organ fragments that may be distinguished megascopically include: small roots, large roots, stems (including both rhizomes and culms), leaf sheaths and leaves. The botanical term stem includes both the aerial stem, or culm, and the subsurface stem, or rhizome. Rhizomes have roots extending from nodes and thus can usually be distinguished from the culm megascopically. The anatomical features of rhizomes and culms are usually indistinguishable. The term stem is used when a fragment can't be positively identified as a culm or rhizome. Since the subsurface plant organs are more likely to be preserved than the aerial organs, most stems in sediment sections probably are rhizomes. The leaf sheath surrounds the stem and often extends along the stem a significant distance. The sheath joins the leaf at the abscission zone. Identifications of some plants can be made with some confidence from the megascopic morphology and anatomy of stems. Niering and others (1977) have employed this technique in a study of salt-marsh sediments in Connecticut.

Texture. In this study, texture refers to the organic portion of the sediment only. "Fibrous" textures describe sediments containing an interlocking network of abundant roots. The modifiers "fine" and "coarse" refer to the relative sizes of the roots. Fiber content (FC) is a qualitative term for the amount of tissue fragments. Textures of "parallel to subparallel orientation of fragments" indicate a lack of roots and a presence of more "sedimentary" particles such as stems and leaves, or detrital fragments. "Granular" textures contain short fragments of uniform size.

Structure. "Massive" sediments show no particular orientation or bedding. "Laminated" sediments show parallel to subparallel orientation of layers. Sediment lenses are distinguished both by grain size (sand or mud) and by color (lighter or darker than surrounding material). Those distinguished by color often reflect differences in preservation state of organics. Dark lenses sometimes contain finely-fragmented plant debris and/or fusinite when viewed in thin section. This was also observed by Cohen (1968).

Color. Sediment color varies from brown or gray to dark brown or gray. Orange and/or black mottles are common.

Carbon. "Very low" values range from 3-5 percent, "low" from 6-10 percent, "intermediate" from 7-16 percent, and "high" from 17-35 percent.

Microscopic Characteristics

Species. This is the single most important determinant of marsh facies. Species distribution in the sediment does not necessarily reflect the actual or quantitative species distribution on the marsh surface. Some species may be preserved in preference to others, so that species represented in the sediment might actually be less abundant in surficial environments than other species which are highly susceptible to decay (Cohen, 1968).

Ratio of framework to matrix (F/M). The terms framework (F) and matrix (M) are used to divide sediment components into two major classes: a coarse fraction and a fine fraction (Cohen, 1968). The coarse fraction includes components with diameters greater than 100μ which is the approximate size of the smallest root observed. Thus roots, rhizomes, culms, leaves and many tissue fragments form the framework or structural part of the sediment, and smaller tissue fragments, cells, pyrite, micrinite, foraminifers, diatoms, and sponge spicules generally form the matrix, or filling material (less than 100μ in diameter) within the framework. Much of the matrix consists of fine granular debris which includes both finely-disseminated plant debris and inorganic material. "Very low" ratios of F/M range from 1-5 percent, "low" from 6-14 percent, "intermediate" from 15-30 percent, and "high" > 30 percent.

Compaction. Compaction observed in thin section commonly consists of compressed stems, roots, and rhizomes.

Framework plant organ composition. This refers to the type of plant organs identified in the framework portion of the thin section and is the major means of identifying plant genera and species.

Framework structure. Microbedding is often present in thin section when no apparent bedding exists megascopically. Sediments that show no orientation of particles in thin section are considered massive.

Abundance of fusinite. Fusinite is dark-brown to black plant tissue which retains its cell structure and is equivalent to charcoal. It usually occurs as fragments greater than 100μ in diameter. Its occurrence is recorded as none (0 percent), rare (1 percent), present (2-3 percent), common (4-6 percent) or abundant >6 percent.

Miscellaneous components. Individual matrix components such as foraminifers, diatoms, sponge spicules, and other small plant and animal fossils may be diagnostic of particular marsh facies. Miscellaneous biological components are present in all marsh facies to some extent.

Fecal pellets. The absence of fecal pellets is more distinctive than their presence. They are a very common sediment component in most marsh sediments.

Matrix color. Matrix colors vary from light to medium to dark brown and from red to dark red brown. Lighter colors generally indicate less decay than darker colors.

Abundance of micrinite and premicrinite. Micrinite is fine-grained dark brown to black plant remains which do not retain any cell structure. Premicrinite is brown to dark brown in color, semi-opaque and may be a possible precursor of micrinite (Cohen, 1968). These two components are represented together in point counts. None (0 percent), rare (1-4 percent), present (5-14 percent), common (15-29 percent), and abundant >30 percent.

Abundance of pyrite. Pyrite is present in all of the marsh facies studied, although its abundance is highly variable. None (0 percent), rare (1 percent), present (2-4 percent), common (5-6 percent) and abundant >6 percent.

Abundances of other minerals. No attempt was made to identify individual minerals other than pyrite. These "other minerals" are recorded together. None (0 percent), rare (1 percent), present (2-4 percent), common (5-10 percent) and abundant >10 percent.

Common Components of Coastal-Marsh Sediments

Some sediment components are found in almost all marsh facies. The most common ones are described in this section. Abundances of some components provide a means of distinguishing marsh facies. Although the occurrence of other components is not as well understood, many appear to have potential use in discriminating facies.

Roots. Roots (Figures 5 and 6) are one of the most common components of coastal-marsh sediments. Roots of different grasses possess very similar anatomy, making them difficult to distinguish in modern section (Metcalfe, 1960). Distinguishing features are also usually lacking in sediment thin section. Figure 5 shows several examples of large grass roots. The cortical cells generally decay into lateral rays of individual cells and cell fragments as the root matures. Well-preserved cortical regions of roots are encountered frequently in the sediment, which suggests some early-stage chemical alteration which enhances preservation (Cohen, personal communication, 1977). Roots with cortical regions that showed high decay or complete absence of cell structure are common. These cortical regions frequently contain fine-grained matrix material, although many lack any secondary filling. Filling material is usually very similar to the general matrix composition common in most thin sections and suggests translocation of fine-grained sediment into the root rather than *in situ* degradation products of the cortex. Some roots maintain their structural framework even at depths greater than 5 m, while others collapse.

Small grass roots (Figure 6) are even more numerous than large grass roots. These roots often represent localized areas of decay in the sediment.

Figure 5. Large grass roots.

A. Photomicrograph of a modern S. alterniflora large root (fixing root) in cross-section. The cortex of mature roots consists of lateral files of cells and cell fragments with large intercellular areas (epidermis, ep; hypodermis, hy; cortex, co; lateral root, lr; endodermis, en; stele, st).

B. Photomicrograph of a large grass root in the sediment (hypodermis, hy; cortex, co; endodermis, en; stele, st). The easily decomposed cortex is well preserved suggesting early-stage chemical alteration which enhanced preservation potential (Cohen, oral communication, 1977).

C. Photomicrograph of a large grass root in the sediment showing decay in the hypodermal (hy), cortical (co), and stele (st) regions. Compare this with the modern root in A.

D. Photomicrograph of a large grass root in the sediment showing elimination of cortical cells and preferential preservation of the hypodermal and stele regions.

E. Photomicrograph of a large grass root compacted under the weight of the overlying marsh sediment (autocompaction).

F. Photomicrograph of several highly-decayed, compressed large roots in the sediment. Cortical regions are filled with sediment, and cells in the hypodermal and stele regions are poorly preserved.

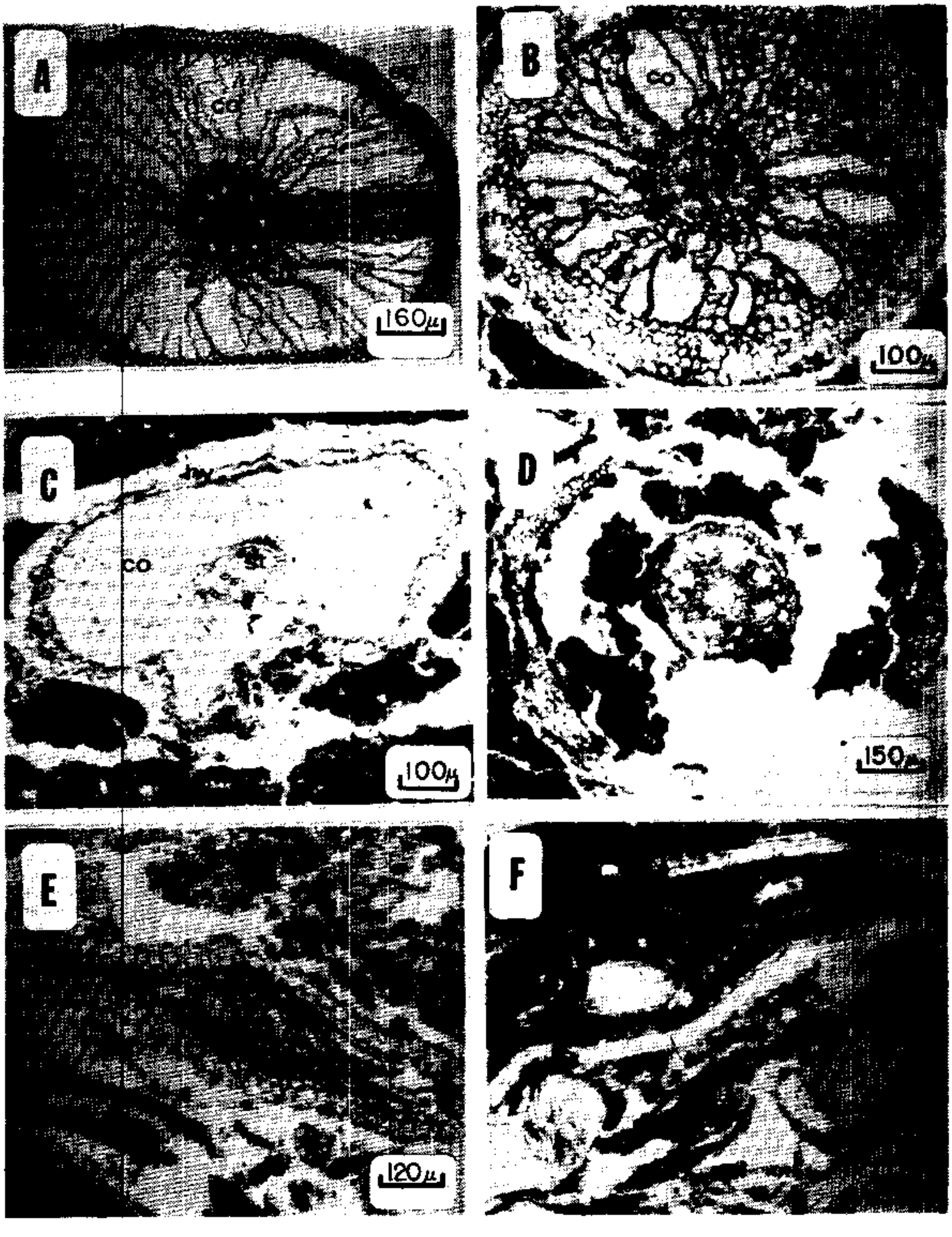
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Figure 6. Small grass roots.

A. Photomicrograph of a modern S. alterniflora small grass root (absorbing root) in cross-section.

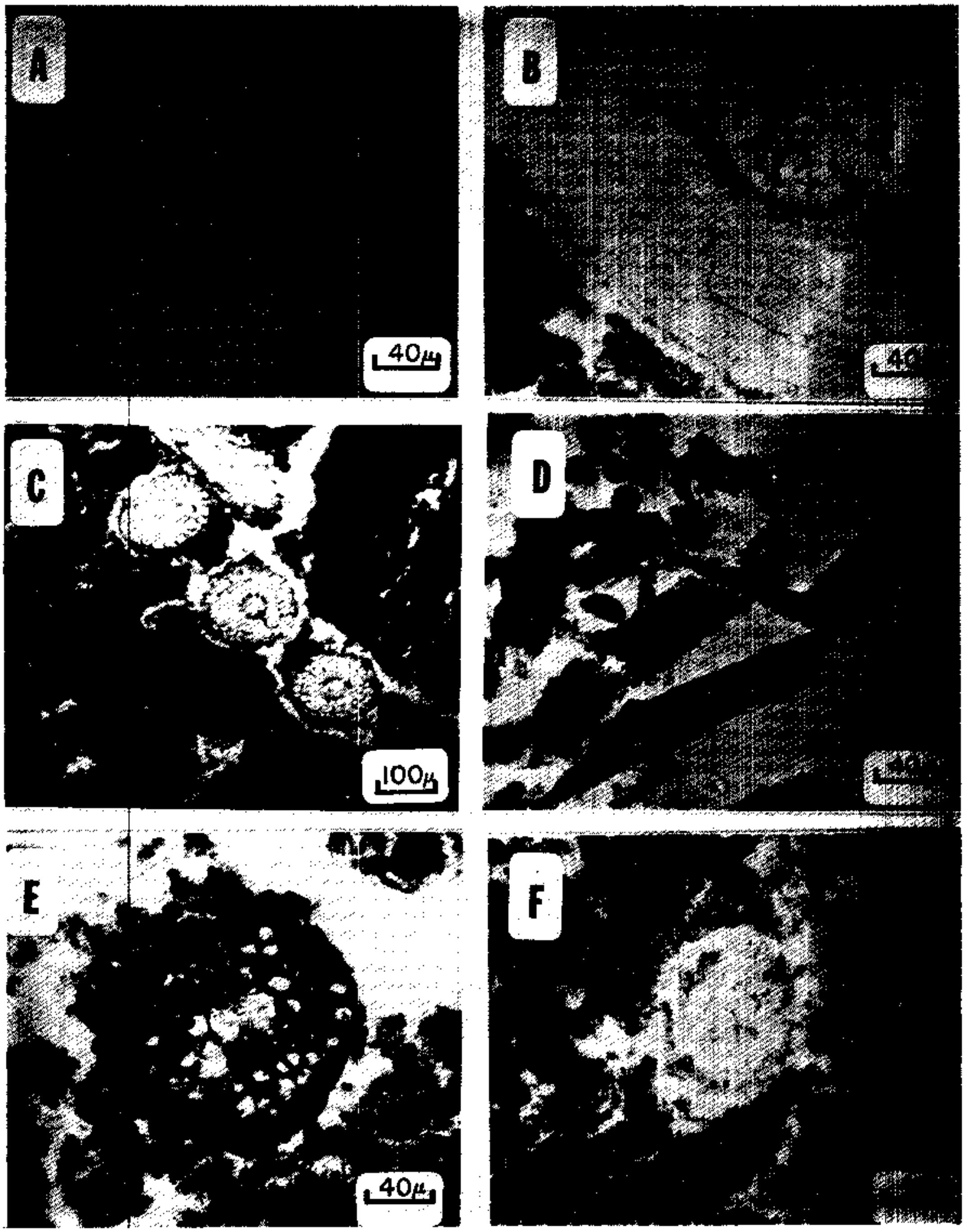
B. Photomicrograph showing a cross-section and a longitudinal-section of small grass roots in the sediment. Compare this with the modern root in A.

C. Photomicrograph showing several cross-sections of small grass roots in the sediment. These roots are usually more numerous than large grass roots.

D. Photomicrograph of detrital fragments of small grass roots in longitudinal section in the sediment.

E. Photomicrograph of a small grass root showing dark-colored decay around and inside root cells.

F. Photomicrograph of a small grass root showing decayed cells which are almost transparent (bleached) in contrast to the type of decay seen in E.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Small grass roots may penetrate the weaker cortex of large grass roots. Such mixing of younger and older material effectively lowers the age of the older horizon, as has been noted by Redfield and Rubin (1962). Belknap (1975) developed a method for compensating for this "contamination." Careful observation of the amount of root penetration is important when samples are to be radiocarbon-dated.

Living roots effectively aerate the sediment and create a particular chemical and microbiological environment. The depth of root penetration and the chemical-biological microenvironment created are important factors in controlling the type of sediment produced.

Root fragments are rare in sediment thin sections but suggest either bioturbation (Cohen, 1968) or erosion and redeposition of marsh sediments.

Foraminifers. Sediment thin sections frequently contain sections of foraminiferal tests (Figures 7 and 8). Foraminifers with agglutinated or interior pseudochitinous wall structures are preserved in preference to those with calcareous wall structures which are dissolved by the acidic pore waters of the sediments. Tentative identifications are made for some specimens (H.A. Curran, written communication, 1977). Diameters range from 70μ to 300μ . Numerous studies record zonation of foraminifers in temperate-zone marshes (Phleger and Walton, 1950; Phleger, 1965, 1970; Parker, 1959; Bradshaw, 1968; Lee and others, 1969; Murray, 1971; Begle, 1973; Clark, 1974). Foraminiferal tests in sediment thin sections may therefore aid in distinguishing marsh facies.

Diatoms. Diatoms are also present in sediment thin sections (Figures 9 and 10). These tiny plants are photosynthetic and thus live at or very near the marsh surface. Sullivan (1971, 1975, 1976) studied the distribution of diatoms on Delaware marshes and identified the diatoms in this study. Other studies of marsh diatoms include those of Round (1960) and Williams (1962).

Sullivan recognized several perennial, distinct, edaphic communities of diatoms within marshes and, although diatoms may be moved around by tidal waters, there is a high probability that their surface distribution will be reflected in the sediment. Also, unlike foraminifers, siliceous diatoms do not appear to undergo dissolution in the sediments.

Sullivan (1975) noted greater diversity and abundance of diatom species in grassy areas than on bare banks or pans, particularly in the winter and early spring. He found that physiological activities and growth habits of grasses, along with other factors such as light intensity and temperature, are important in controlling the distribution of diatoms.

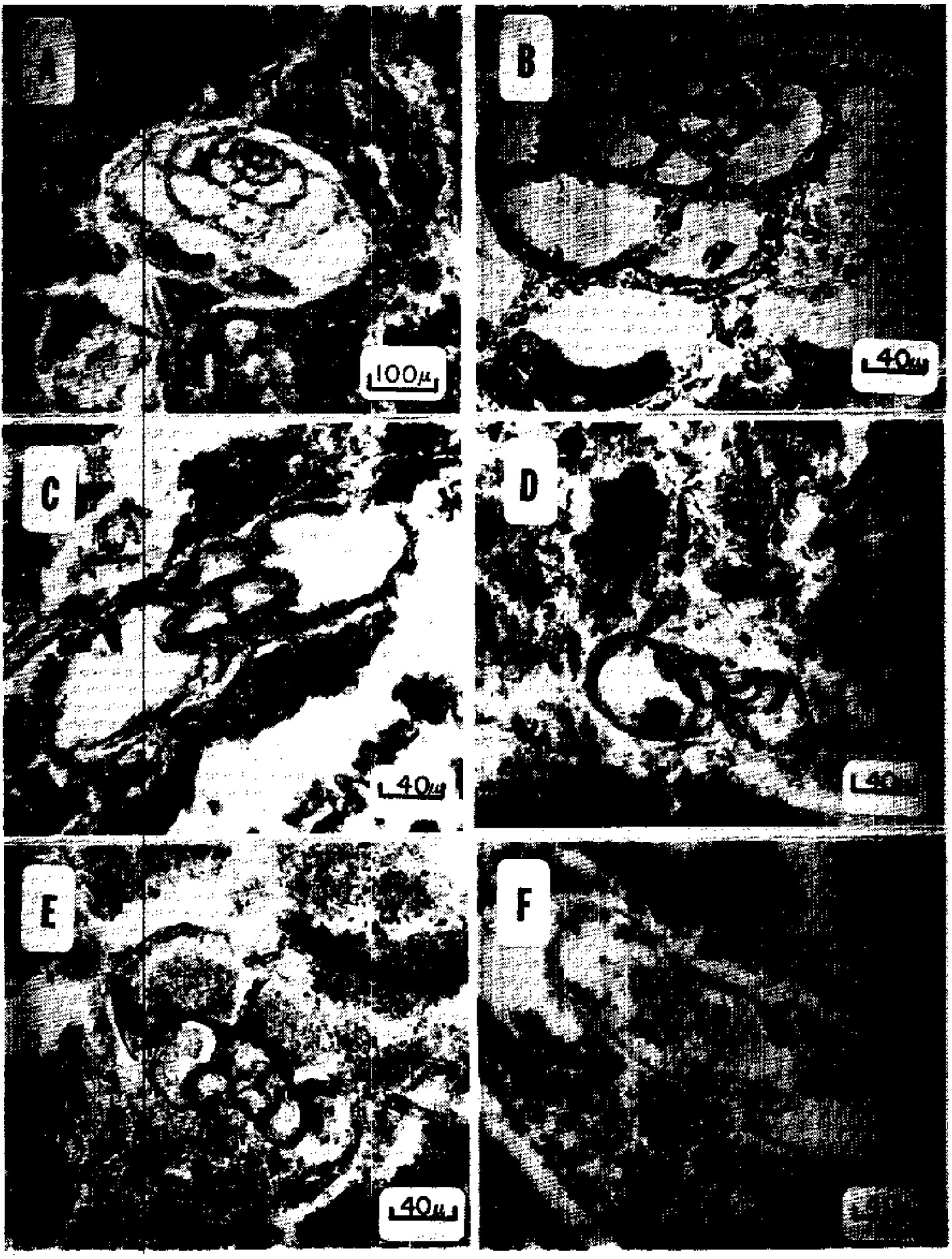
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Figure 7. Foraminifers.

A. Photomicrograph of a *S. alterniflora* sediment thin section showing a *Tiphotrocha comprimata* (Cushman and Bronnimann)(?) foraminifera. This might also be *Trochammina inflata* (Montagu). The distinguishing feature of these two species is the shape of the aperture which is not visible.

B. Close up of the foraminifer in A. Note the thin, fragile agglutinated wall.

C. Photomicrograph of a brackish-marsh thin section showing an unidentified foraminifer.

D. Photomicrograph of a *Salicornia* sediment thin section showing a *T. inflata* (?) foraminifer.

E. Photomicrograph of a *D. spicata* sediment thin section showing an unidentified foraminifer.

F. Photomicrograph of a *D. spicata* sediment thin section showing an unidentified foraminifer.

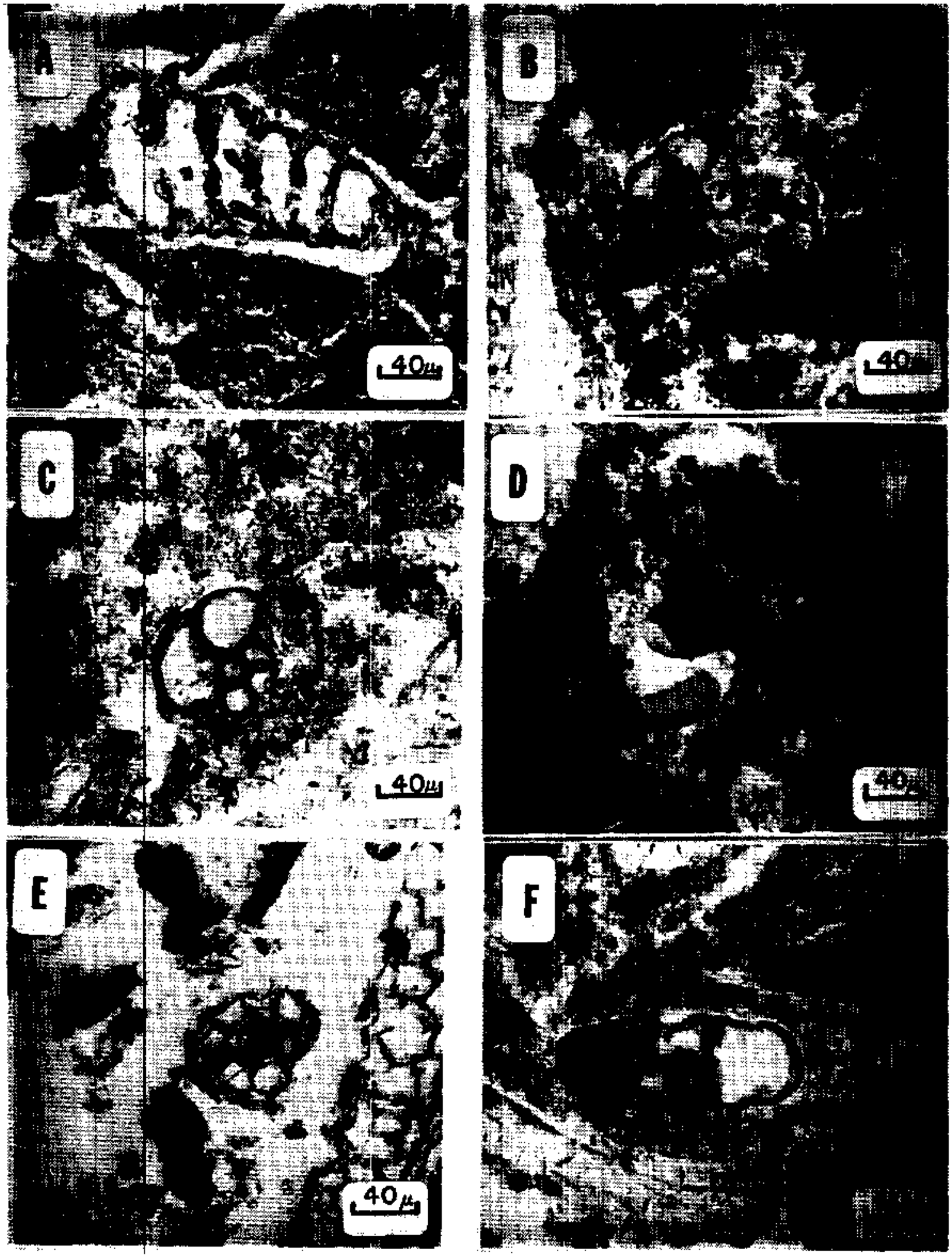
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Figure 8. Foraminifers.

A. Photomicrograph of a brackish-marsh thin section showing an _Ammobaculites dilatatus_ Cushman and Bronnimann (?) foraminifer.

B. Photomicrograph of a high-marsh thin section showing an unidentified foraminifer.

C. Photomicrograph of a _D. spicata_ sediment thin section showing an _Ammonia beccarii_ Linne (?) foraminifer.

D. Photomicrograph of a _Salicornia_ sediment thin section showing an _A. beccarii_ (?) foraminifer.

E. Photomicrograph of a high-marsh thin section showing an _A. beccarii_ (?) foraminifer.

F. Photomicrograph of a _Salicornia_ sediment thin section showing an unidentified foraminifer.

Figure 9. Diatoms.

A. Photomicrograph of a mudbank thin section showing a girdle view of 2 1/2 Melosira sulcata (Ehr.) Kutz. frustules. This diatom is found in most marsh environments.

B. Photomicrograph of a high-marsh thin section showing a valve view of M. (=Paralia) sulcata.

C. Photomicrograph of a low-marsh thin section showing Melosira moniliformis (=M. borrei) (O. Mull.) Ag.

D. Photomicrograph of a D. spicata sediment thin section Diploneus interrupta (Kutz.) Cl. var. interrupta.

E. Photomicrograph of a D. spicata sediment thin section showing Diploneus sp. (1) and an unidentified diatom (2).

F. Photomicrograph of a D. spicata sediment thin section showing Frustulia sp.

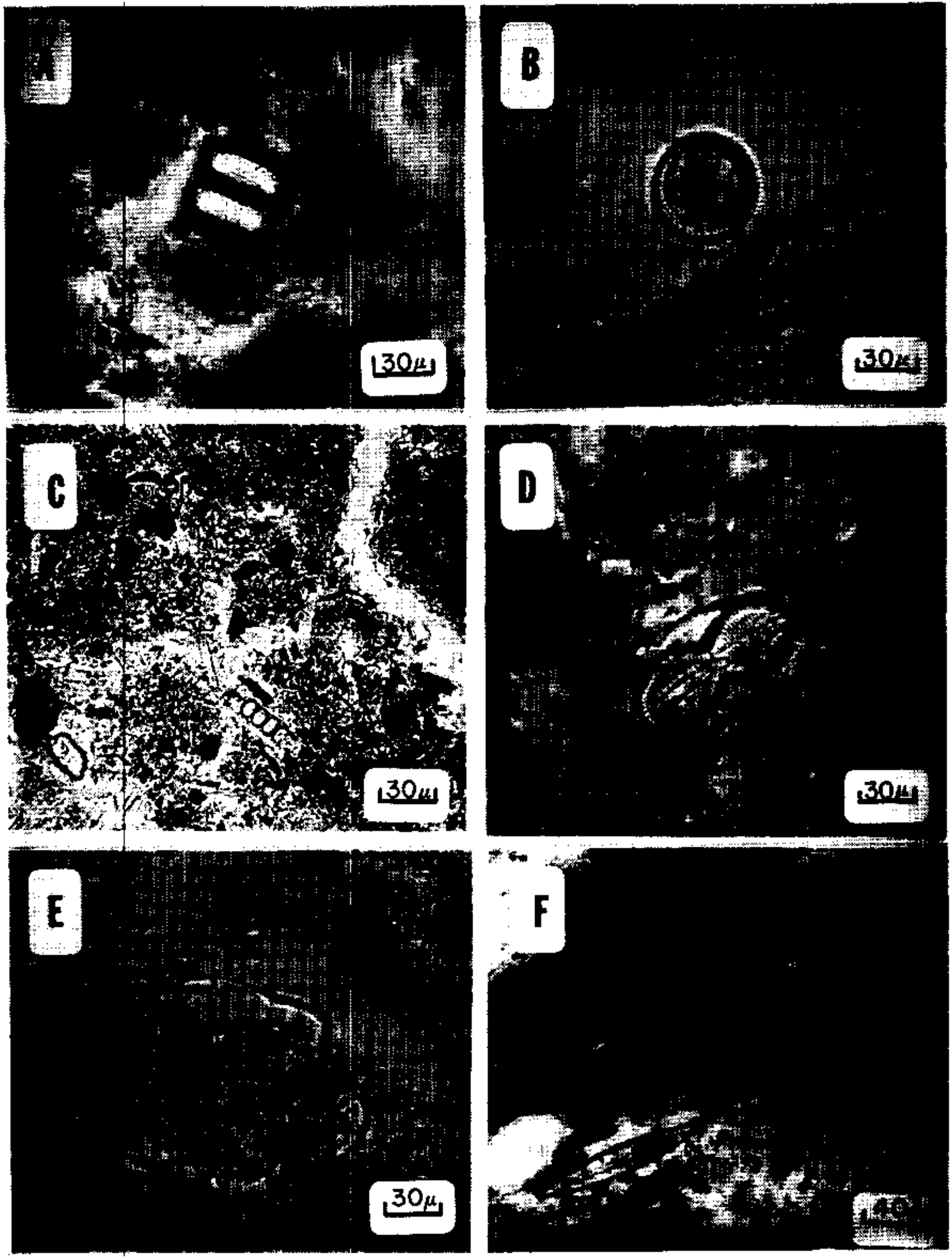
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Figure 10. Diatoms.

A. Photomicrograph of a *D. spicata* sediment thin section showing *Nitzschia* sp. (1) and *Frustulia* sp. (2).

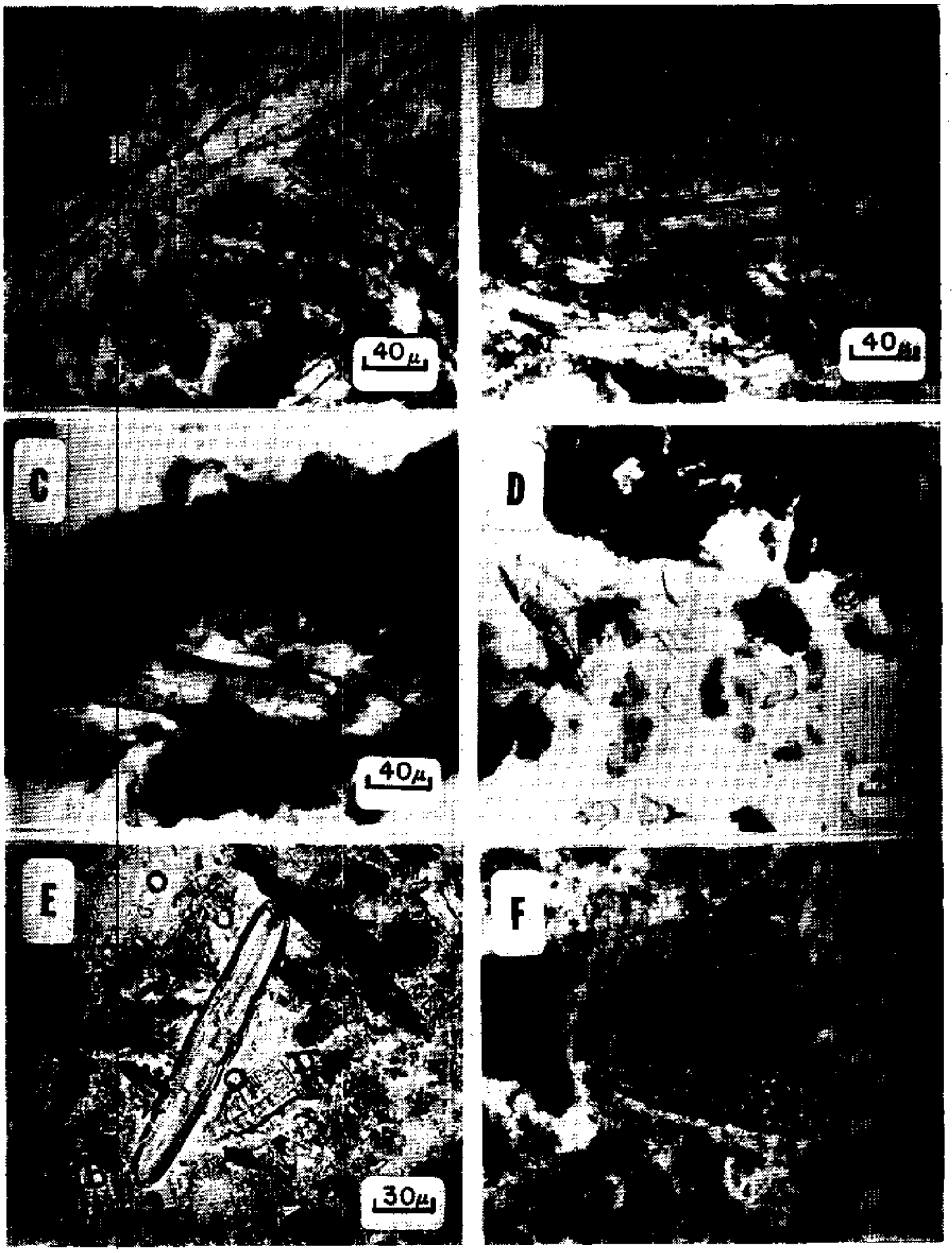
B. Photomicrograph of a *D. spicata* sediment thin section showing *Nitzschia* sp. diatom.

C. Photomicrograph of a *P. communis* sediment thin section showing a very large *Pinnularia* sp. diatom.

D. Photomicrograph of a *P. communis* sediment thin section with *Pinnularia* sp. diatom fragments.

E. Photomicrograph of a high-marsh sediment thin section showing an unidentified diatom.

F. Photomicrograph of a brackish-marsh thin section showing a *Biddulphia favus* (Ehr.) diatom.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A complete study of diatom distribution in sediment thin sections has not been attempted, although it could prove quite valuable. Instead, characteristics such as the degree of fragmentation of tests and general abundance of diatoms have been used to distinguish some marsh facies.

Macroscopic algal remains are not likely to be preserved in marsh sediments in identifiable form. Algal associations are common in marshes (Stewart and Pugh, 1963; Blum, 1968; Gallagher and Daiber, 1974; and Ralph, 1975). Productivity is high so that these plants probably contribute finely-fragmented organic material to the sediment, particularly as digested remains in fecal pellets.

Sponge spicules. Sponge spicules in sediment thin sections all appear to be of the monaxon type, although many are fragmented and may be parts of other types (Figure 11). There is no apparent pattern to the distribution of sponge spicules in the sediment. Sponge spicules and spicule fragments are more common or more easily observed in sediments with high matrix contents.

Silica cells. Silica cells are found in the aerial parts of many plants, especially grasses, sedges and rushes (Bonnett, 1972). Silica is located in walls and lumen of many cells including epidermal cells, vessel elements, and leaf mesophyll cells. The location, size, shape, and surficial features of these resistant plant objects have been studied and to some extent classified (Smithson, 1958; Metcalfe, 1960; Parry and Smithson, 1966; Twiss and others, 1969; and Bonnett, 1972). Bonnett (1972) determined that grass silica cells can be identified to subfamily, but not with certainty to species.

Of the four classes of silica cells: festucoid, chloridoid, panicoid and elongate (Twiss and others, 1969)--most silica cells observed in this study belong to the elongate class which has no subfamily implications and occurs in most grass species (Figures 11 and 12). Further study might reveal distribution patterns useful in distinguishing marsh facies.

Fibers. Sclerenchyma fibers (resistant thick-walled cells) are common in highly-decayed sediments (Figure 12). They tend to concentrate as the residual remains of plant tissues.

Miscellaneous components-animals. Many invertebrates including polychaetes, arthropods, and molluscs contribute to marsh sediments in various ways (Davis and Gray, 1966; Odum and de la Cruz, 1967; Ustack, 1969; Keefe, 1972; May, 1974; Olmstead and Fell, 1974; and many others). There are carnivores, herbivores, and detritus feeders. Some organisms feed directly on both living and dead plants. Others feed on partially decomposed material on the marsh surface. These actions make material more suitable for bacterial

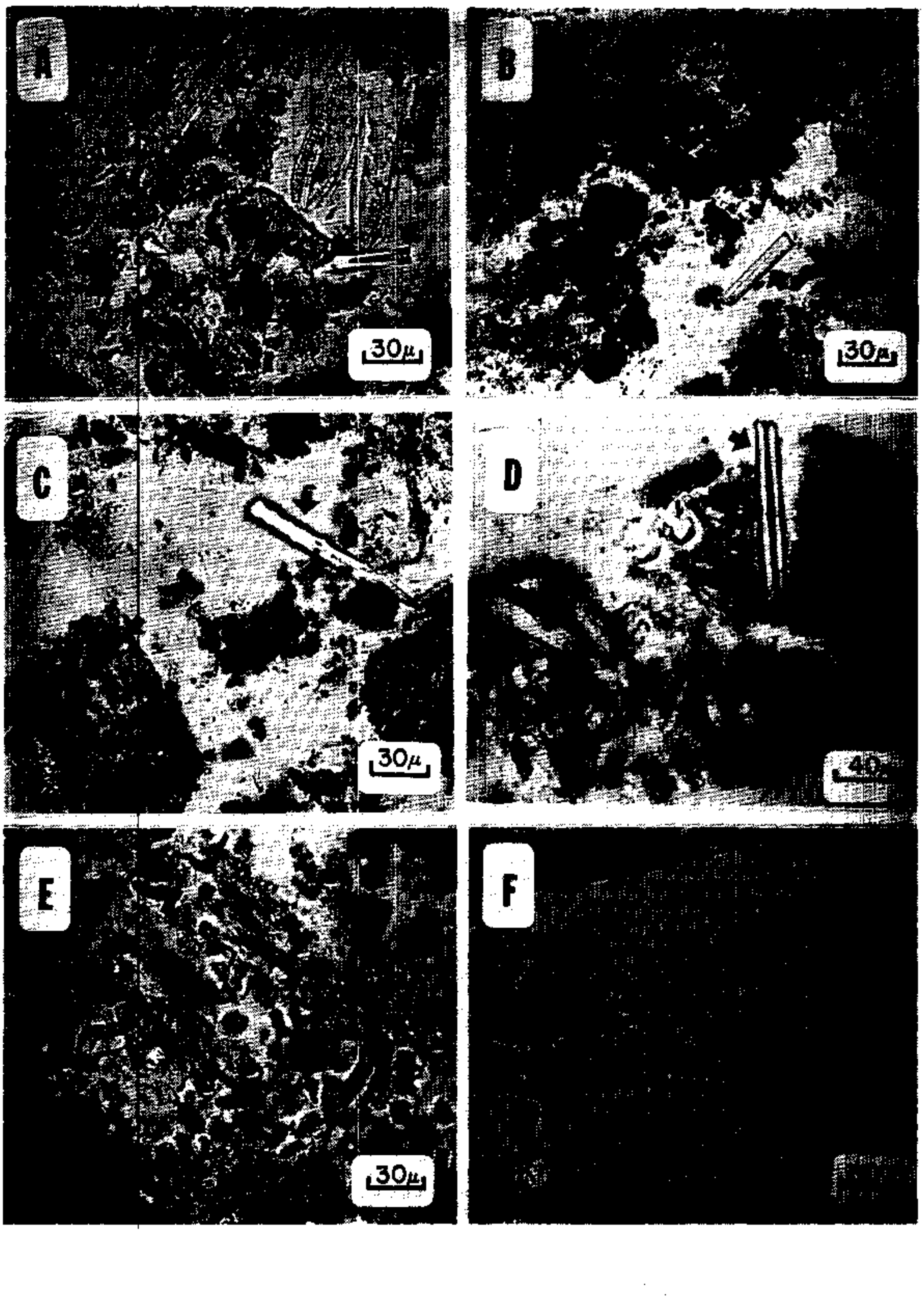
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Figure 11. Sponge spicules and silica cells.

A. Photomicrograph of a sponge spicule noted by arrow. This low-marsh thin section also contains large diatoms (1); mineral grains (2); framboidal pyrite (3); and micrinite (4).

B. Photomicrograph of a sponge spicule in a brackish-marsh thin section (arrow). Note the abundant micrinite.

C. Photomicrograph of a sponge spicule with a pointed terminus in a brackish-marsh thin section (arrow). Double arrow points to fungal hyphae within a fecal pellet.

D. Photomicrograph of a sponge spicule in a *S. alterniflora* sediment thin section (arrow).

E. Photomicrograph of numerous silica cells with slightly sinuous outlines and straight ends. Silica cells often have a granular appearance and dark outline as seen here.

F. Photomicrograph of silicified epidermal cells with very sinuous walls. Arrow points to one cell dislodged from the tissue.

Figure 12. Silica cells and fibers.

A. Photomicrograph of an elongate, perforated silica cell in a mudbank thin section (arrow).

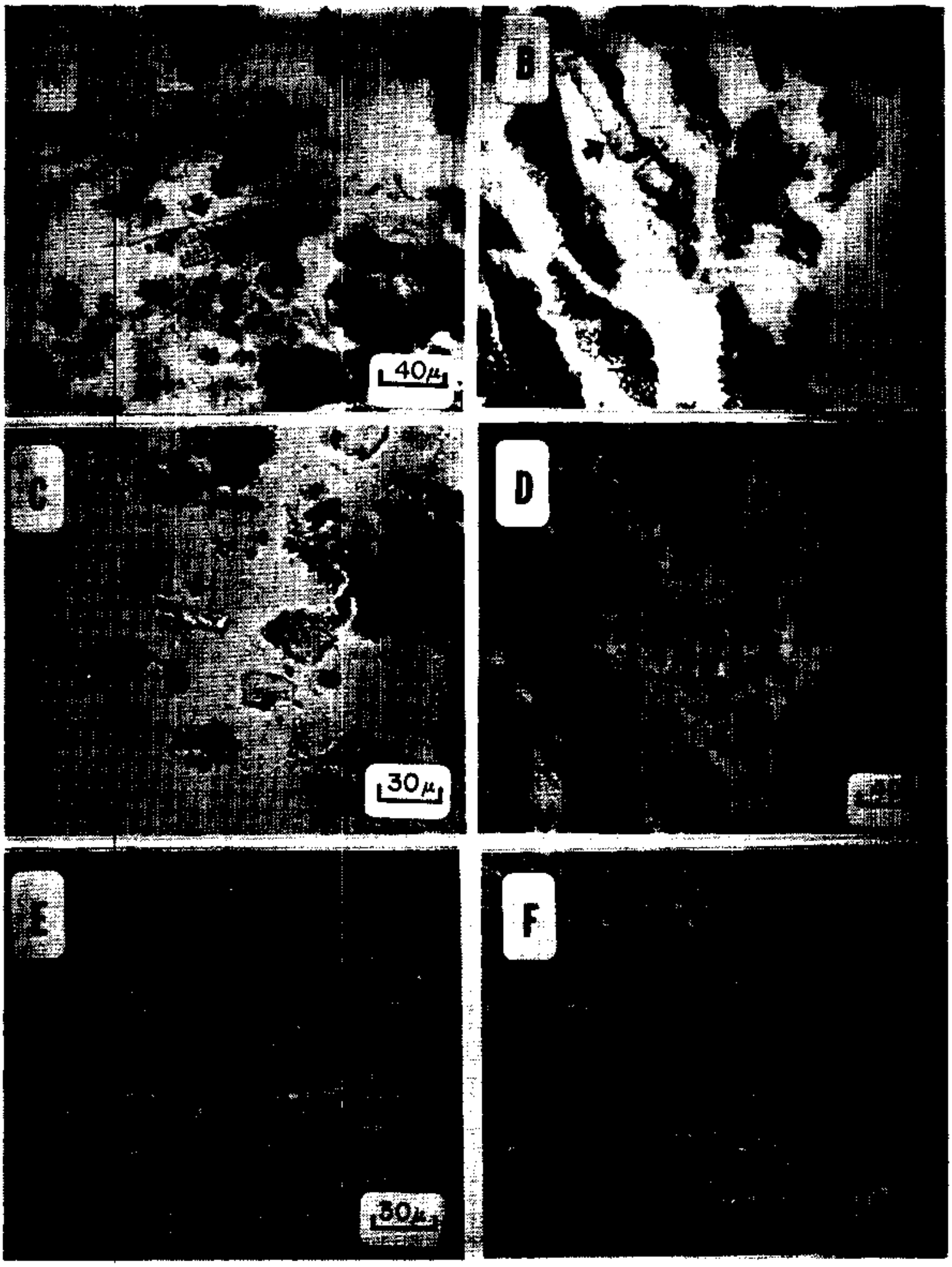
B. Photomicrograph of an elongate silica body with sinuous walls in a rotten-spot thin section (arrow).

C. Photomicrograph of a silicified long cell, or fundamental cell, of the epidermis (brackish-marsh thin section).

D. Photomicrograph of two oblong-shaped silica cells in a *D. spicata* sediment thin section (arrow). The shape suggests that they are trichomes, or epidermal appendages.

E. Photomicrograph of sclerenchyma fibers in a high-marsh thin section. These fibers form beneath the epidermis. Their clear and "glassy" appearance is due to the thick lignin-impregnated walls.

F. Photomicrograph of sclerenchyma fibers in a high-marsh thin section. These are very common in the inner cortex of grass roots, stems,and leaves.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decay (Burkholder and Bornside, 1957). Some animals burrow and most contribute fecal pellets and their corpses to the sediment.

Detritus-forming agents include microbes, macroinvertebrates such as isopods, amphipods, copepods, polychaetes, and nematodes. Insects including beetles, flies, mosquitos, bugs, aphids, leaf hoppers, plant hoppers, ants, crickets,and grasshoppers are extremely abundant.

Some of the more visible invertebrates on Delaware marshes include the snails *Nassarius obsoletus* (Say) in tidal creeks, *Littorina irrorata* (Say) on *S. alterniflora* and *Melampies bidentatus* (Say) in the high marsh; the ribbed mussel *Modiolus demissa* (Dillwyn) in the low marsh and on creek banks; the mud crab *Sesarma reticulatum* (Say); and the fiddler crab *Uca pugnax* (Smith), *U. pugilator* (Bosc) in sandy marshes and *U. minax* (Le Conte) in low-salinity marshes.

Teal (1962) estimates that 55% of the net aboveground primary production of Georgia salt-marsh plants is consumed by bacteria and other organisms. The remaining 45% is either exported off the marsh or incorporated into the sediment.

Odum and de la Cruz (1967) estimated that 1.3% of surface detritus from a Georgia marsh consisted of animal remains. Animal detritus includes fragments of chitinous appendages, fish scales, fragments of molluscan and crustacean shells, fecal pellets, insect wings, eyes and other parts, vertebrate remains such as bird feathers and mammalian hair, and much more. Most unmineralized animal parts decompose very quickly unless buried. Uca shells on the marsh surface decomposed completely after 180 days (Odum and de la Cruz, 1967).

Some possible examples of insect remains are illustrated in Figure 13. The most common evidence of animal activity is fecal pellets which are discussed in more detail below.

Miscellaneous components-plants. Plant reproductive parts such as pollen, spores, seeds, and fern annuli are occasionally seen in thin section (Figures 13 and 14). Cohen (1968) observed that pollen and spores were more abundant in fresh water peats than marine peats in southern Florida. They are not particularly abundant in this study. Pollen, spores, and seeds can be carried by wind or tides and therefore may be misinterpreted as part of a particular sedimentary environment. Nevertheless, studies have been made of pollen distribution in marshes (Butler, 1959) and used for stratigraphic interpretations (Meyerson, 1972). In contrast, the presence of fern annuli in marsh sediments is interpreted to indicate fresh water conditions because the fern annulus is located on the abaxial side of the leaf

Figure 13. Miscellaneous components.

A. Photomicrograph showing possible insect remains in a *Phragmites* sediment thin section.

B. Photomicrograph showing possible insect remains in a rotten-spot thin section.

C. Photomicrograph showing a possible insect eye in a low-marsh thin section.

D. Photomicrograph showing probable fungal spores in a low-marsh thin section.

E. Photomicrograph showing smut (*Ustilago* sp.) spores in a mudbank thin section. This fungus produces a black mass of spores on some marsh grasses.

F. Photomicrograph showing fern spores from a freshwater marsh thin section.

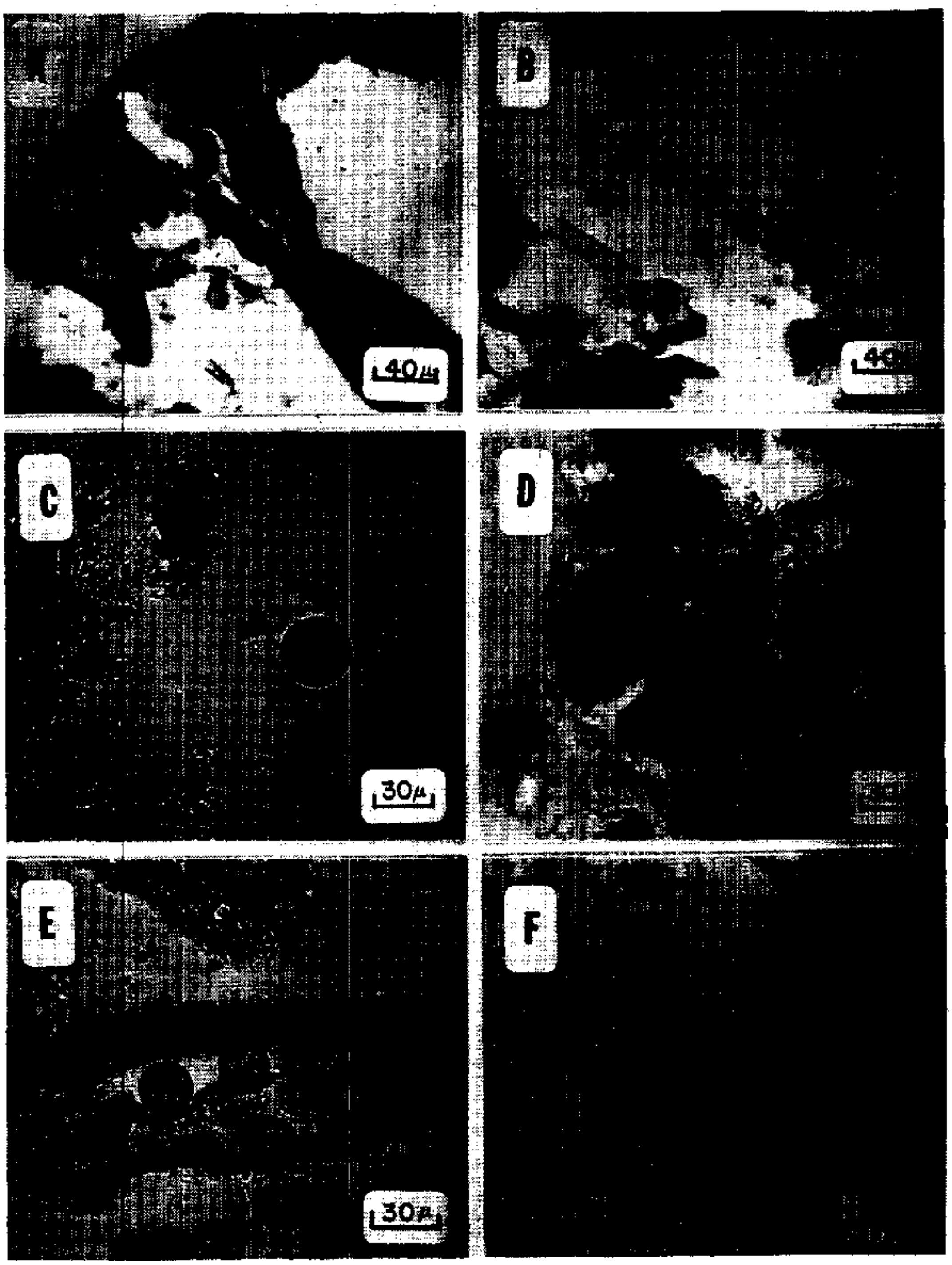
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Figure 14. Miscellaneous components.

A. Photomicrograph of a high-marsh thin section containing a pollen grain (noted by arrow).

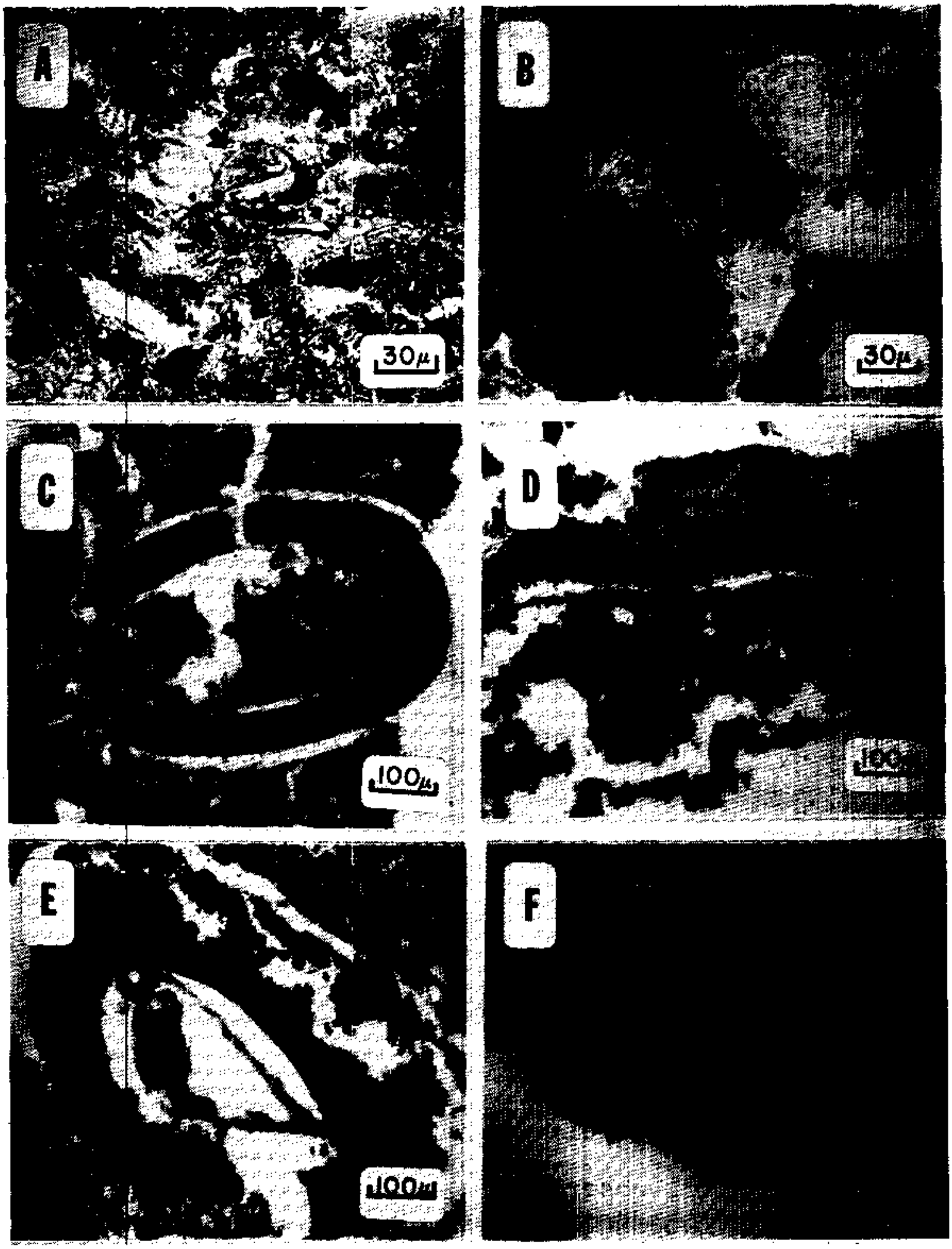
B. Photomicrograph of a low-marsh thin section containing a pollen grain (noted by arrow).

C. Photomicrograph of a smooth-coated seed from a *Phragmites* sediment thin section.

D. Photomicrograph of a seed with an outer coating possessing ridges in a high-marsh sediment.

E. Photomicrograph of a seed from a high-marsh thin section.

F. Photomicrograph of a fern annulus in thin section from a fresh water deposit. The fern annulus is a thickened portion of the sporangium. The sporangium is borne on the abaxial side of the leaf and produces spores.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30μ
B
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D
100
E
100μ
F

and is not likely to be transported.

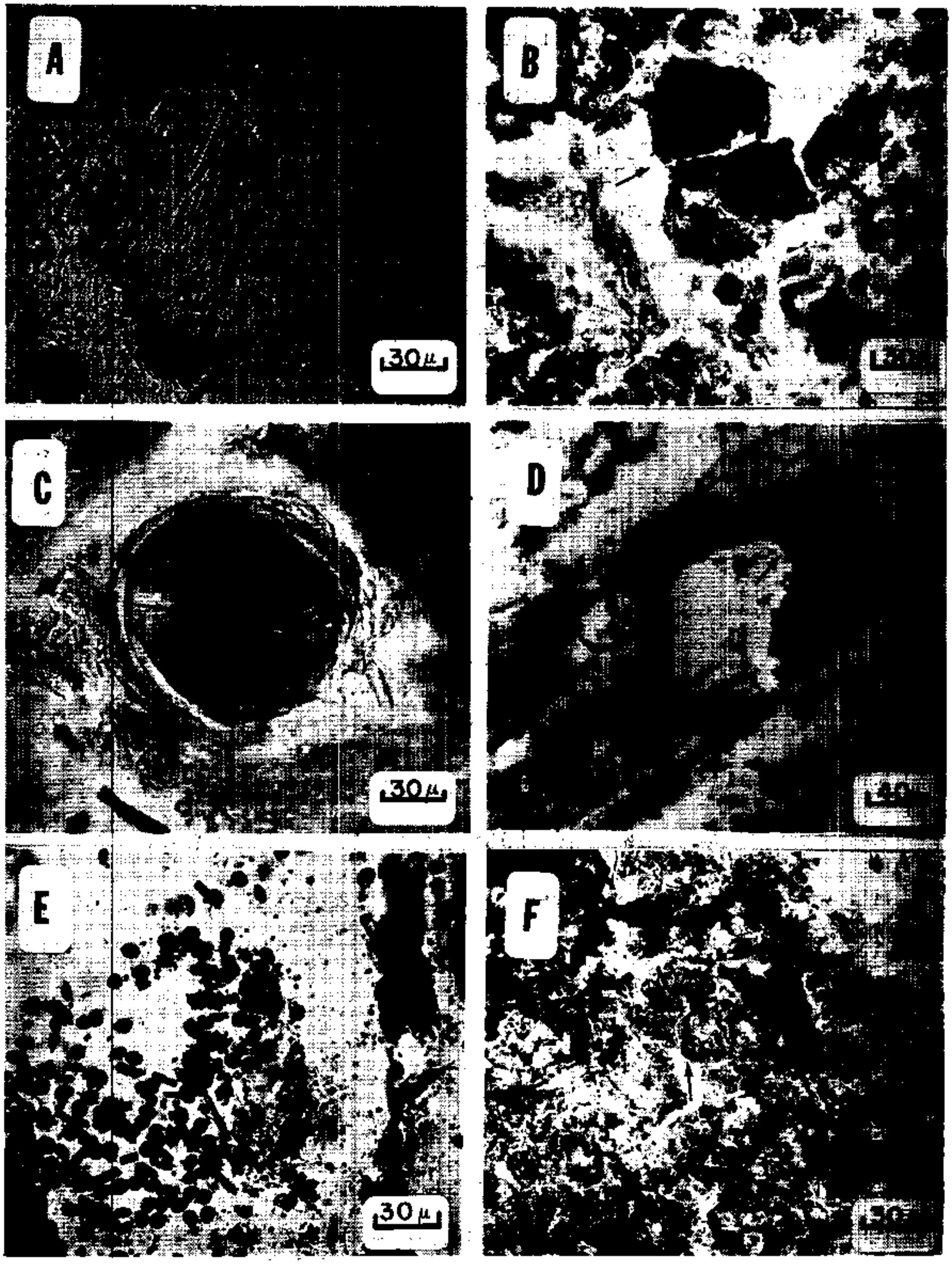
Fungi. Fungal remains are present to some degree in all sediment thin sections studied (Figures 15 and 16). In modern environments they are most abundant under aerobic conditions although they may also occur in the subsurface (Cohen, 1968). Barghoorn (1949a) states that the rate of degradation due to the presence of fungi and bacteria is most rapid under warm, moist, highly aerobic conditions, probably those on or just below the sediment surface. Cohen (1968) observes that sediments with a high percentage of fungal remains also contain a high percentage of fusinite and suggests that this is due to the dryness of the environment. Most of the degradation due to fungal activity appears to occur on the surface before the plant remains are incorporated into the sediment (Cohen, 1968).

May (1974) observed the fungal activity on Spartina during a five-month period. Fungal hyphae first invaded the air passages of leaves and inter-leaf zone of culms, areas where cell walls would not obstruct the growth of fungi. Fungal hyphae then invaded cells. After five months exposure, the leaf epidermis was highly decomposed but much of the vascular system and internal leaf structure remained. Other observations on fungi in salt marsh plants are made by Gessner (1972) and Gessner and others (1972).

May (1974) observed very little bacteria in scanning electron photomicrographs of Spartina. Turner and Gray (1962) found high counts of bacteria in all marsh environments, except bare mud flats.

Fecal pellets. Fecal pellets are very abundant in marsh thin section (Figures 17 and 18). Cohen (1968) notes that fecal pellets are common in marine peats and in drier, fresh-water peats, although they are rare in wetter, fresh-water peats.

Fecal pellets are usually round, elliptical, or oblong in outline, although some are irregular. Some are composed of finer-grained material than the surrounding matrix, while others are composed of cells and other identifiable components larger than surrounding matrix materials. They range in diameter from 10μ to 1 mm and in this study are divided into three classes: small (10-40μ), medium (40-100μ),and large (>100μ). The medium-size fecal pellets are the most common and are usually distributed throughout the entire thin section when present. Small fecal pellets usually occur within a localized area such as the cortex of a root and suggest that the organism producing the pellets may have been eating the plant. Large fecal pellets are found in drier, usually brackish marshes such as the back-barrier Phragmites marsh. Some fecal pellets are darker brown than surrounding material; others are lighter brown in color, and a few are zoned.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D
40
E
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F
50

Figure 15. Fungi.

A. Photomicrograph of fungal spores located in a tissue fragment.

B. Photomicrograph of a fungal sclerotium (arrow).

C. Photomicrograph of a mass of fungal material (mostly hyphae) encased in a spherical structure.

D. Photomicrograph of a fungal sclerotium developed in *Phragmites* tissue. This sclerotium is very common in *Phragmites* sediments, although it also occurs in other marsh facies.

E. Photomicrograph of numerous fungal spores and hyphae in the sediment.

F. Photomicrograph of fungal budding structures (arrow) in the sediment matrix.

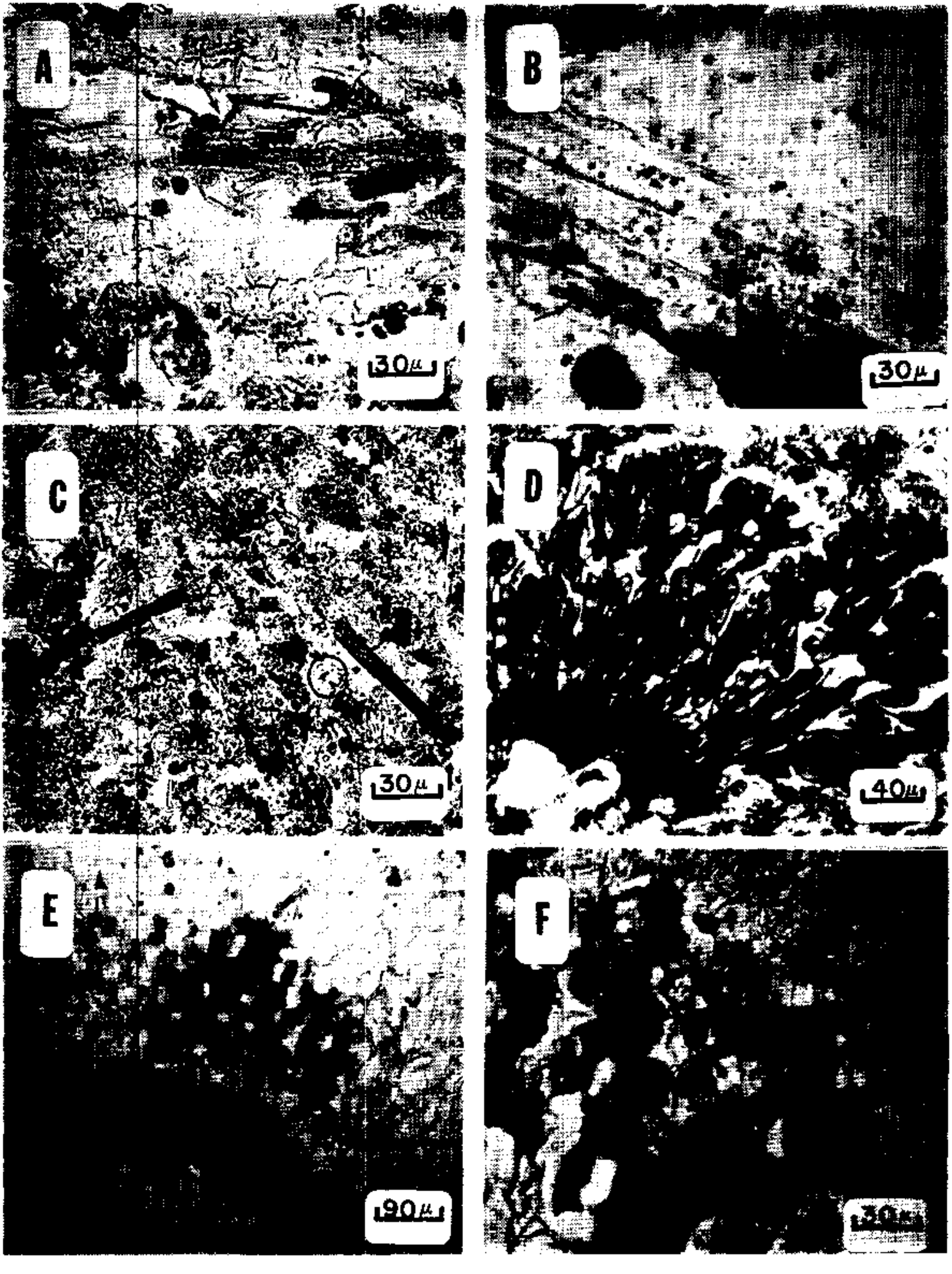
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Figure 16. Fungi.

A. Photomicrograph of fungal hyphae (arrow) penetrating some partially decomposed plant tissues in the sediment.

B. Photomicrograph of fungal hyphae (arrow) penetrating grass epidermal tissue. Fungal hyphae are common in all marsh facies and are most abundant in highly-decomposed sediments and those near the upper limit of the tidal range.

C. Photomicrograph of fungal budding structures in the sediment matrix.

D. Photomicrograph of abundant fungal material in the sediment matrix.

E. Photomicrograph of possible fungi penetrating a tissue fragment. There may also be non-fungal cell fillings here.

F. Detail view showing cells filled with fungal material and/or cell fillings.

Figure 17. Large and small fecal pellets.

A. Photomicrograph of a large fecal pellet consisting of tissue fragments, small roots and other material. A closeup is shown in B.

B. Close-up photomicrograph of the large fecal pellet shown in A. Note clearly-defined cell structure in some tissue fragments.

C. Photomicrograph of small ellipsoidal fecal pellets in the cavity of a tissue fragment. A close-up is shown in D.

D. Close-up photomicrograph of small fecal pellets shown in C.

E. Photomicrograph of small cylindrical fecal pellets in the cortical region of a large grass root. The pellets may have been deposited by an organism which ate the root cortex.

F. Photomicrograph of small cylindrical fecal pellets filling a cavity in the sediment.

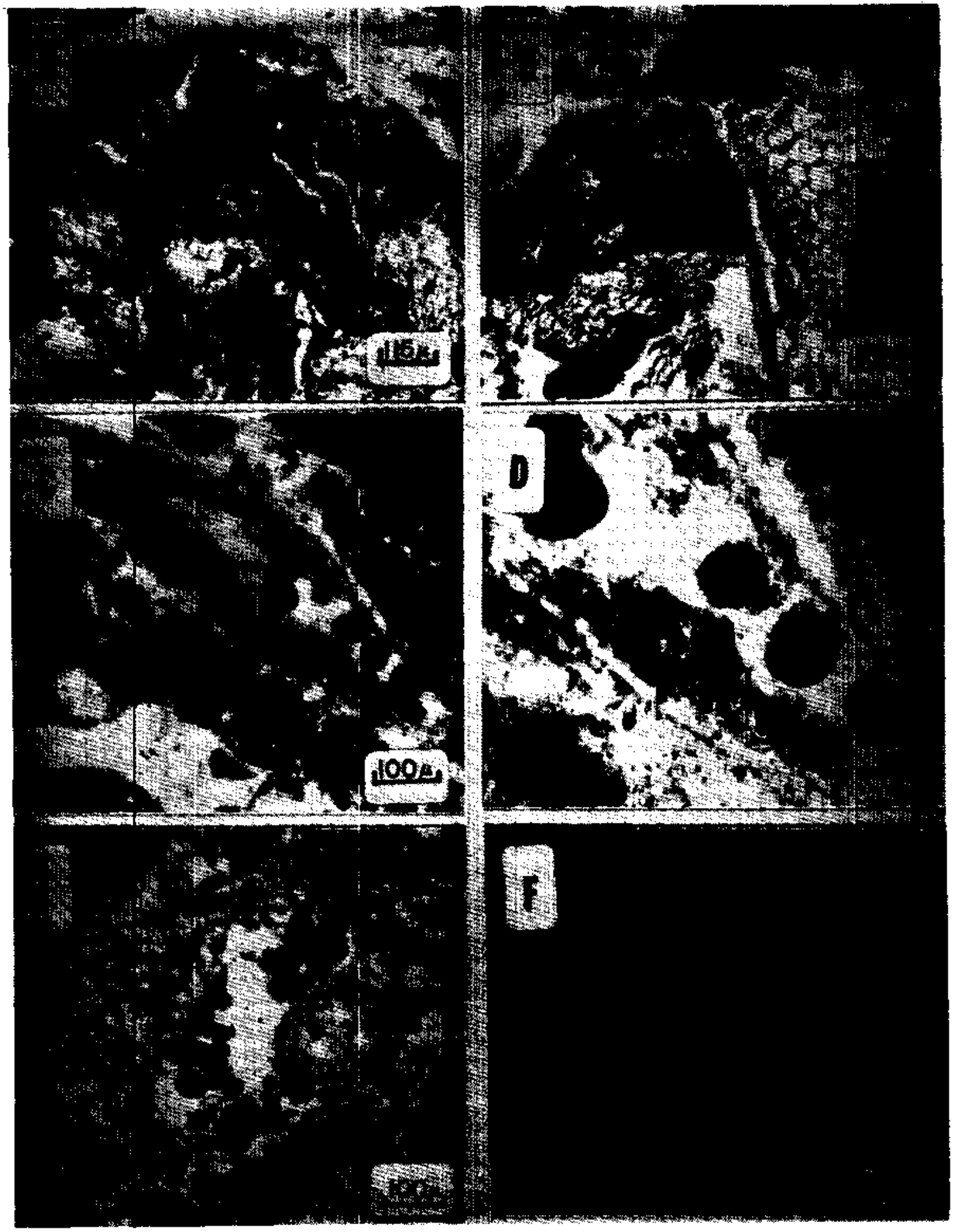

15μ
D
100μ
F

Figure 18. Medium-size fecal pellets.

A. Photomicrograph of a sediment thin section showing medium-size fecal pellets of fine-grained dark material in a coarser-grained matrix.

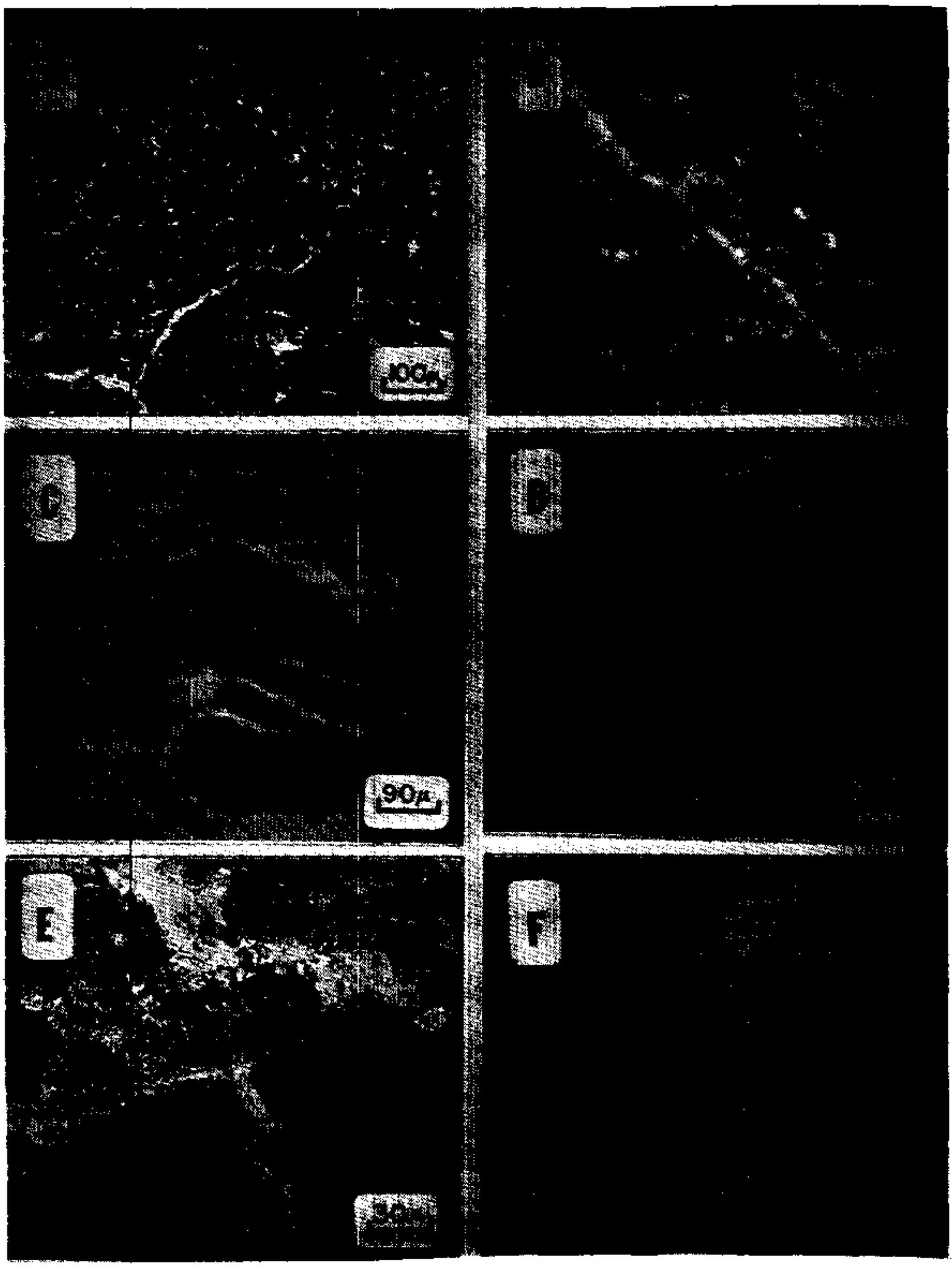
B. Photomicrograph of a sediment thin section showing fecal pellets with poorly defined borders in a coarser grained, dark matrix.

C. Photomicrograph of a sediment thin section showing a fecal pellet. A close-up is shown in D.

D. Close-up of the fecal pellet in C showing the contrast in texture between the fecal pellet and the matrix material.

E. Close-up of a fecal pellet showing the contrast in texture between the finer-grained fecal pellet and the matrix material.

F. Photomicrograph of fecal pellets surrounded by very little matrix material.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The differences in color reinforce the fact that fecal pellets represent a mixing or bioturbation of the sediment. The burrows of organisms ranging in size from small beetles to large crabs and muskrats mixes older sediment with younger sediment and aerates the sediment as roots do. Animal activity is an important control on what actually is incorporated into the sediment and in what form it is incorporated.

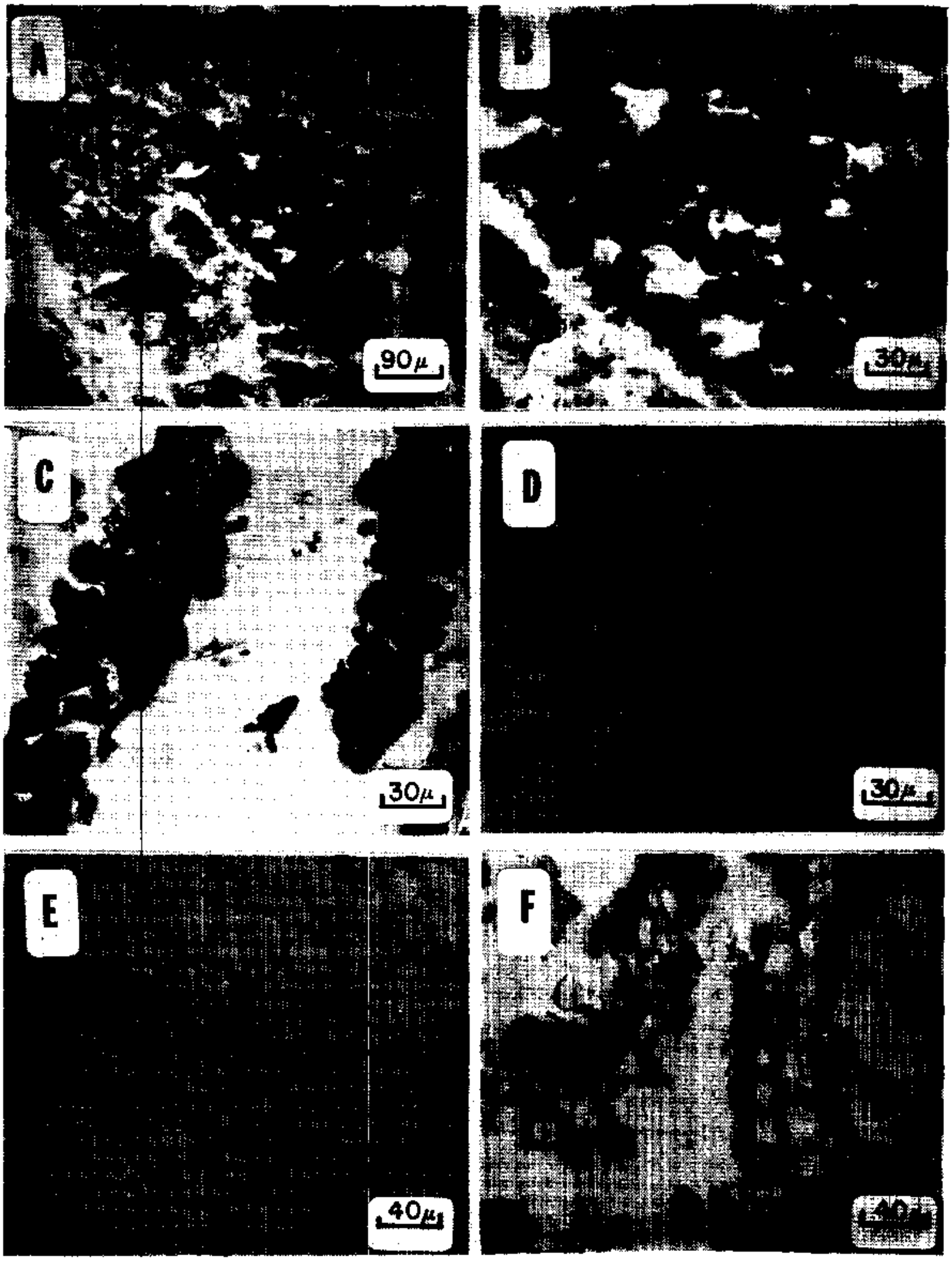
Kraeuter and Haven (1970) made a detailed study of fecal pellets of common estuarine invertebrates. Their results indicate that some medium-size fecal pellets in this study may be produced by the marsh fiddler, U. pugnax. Other pellets could have been produced by many different organisms.

Cell fillings. Cell fillings are relatively resistant organic materials (possibly tannins, Esau, 1965) which occur within the cell lumina of some plants (Figures 19 and 20). Esau (1965) describes these deposits as yellow, red or brown amorphous substances which appear as coarsely- or finely-granular masses, or as bodies of various sizes. They are common in many plant leaves and in vascular tissue. They also are more common in woody material than in herbaceous material (Cohen, 1968). They are especially lacking in monocotyledons (Esau, 1965). Cohen (1968, 1969) notes that cell fillings may dissolve out of one area of cells and be redeposited in another area. Some cell fillings may form during decay, possibly from cell wall material. He also observed that leaves which show effects of exposure to aerobic decay seem to have lost their cell fillings.

Cell fillings occasionally are abundant in sediment thin sections. All are red in color. Shapes observed include: irregular, square to rectangular, and ellipsoidal. The arrangement of some suggests that they are in original position and that the surrounding tissue has decomposed.

Pyrite. Pyrite (FeS_2) is a common authigenic mineral in organic-rich, fine-grained marine and estuarine sediments. Significant investigations of pyrite in modern sedimentary environments include: Pons (1964); Cohen (1968); Cohen and Wiedemann (1973); Berner (1967) and (1969); Chavengsaksongkram (1972) and Czyscinski (1975). Factors necessary for pyrite formation include: The availability of reactive iron compounds, dissolved sulfate, and organic matter suitable for production of H_2S by sulfate-reducing bacteria (Berner, 1971). These factors are not limited in salt- or brackish-marsh environments. Sea water provides a continuous supply of sulfate to marine and estuarine sediments and is necessary for the maintenance of sulfate-reducing bacteria (see Cohen, 1968).

In this study, pyrite was identified in transmitted light by its black opaque nature and its typical shape--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40μ
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40μ

Figure 19. Cell fillings.

A. Photomicrograph of red irregularly-shaped cell fillings in a mudbank thin section. The regular arrangement of cell fillings suggests that they are in place and that the plant tissue has disintegrated completely.

B. Detailed view of irregularly-shaped cell fillings in A.

C. Photomicrograph of red square- to rectangular-shaped cell fillings from a high-marsh thin section. The plant tissue once surrounding these cell fillings is gone.

D. Photomicrograph of large ellipsoidal (1) and subrectangular (2) to oblong shaped (3) red cell fillings in plant tissue from a high-marsh thin section.

E. Photomicrograph of small ellipsoidal cell fillings in plant tissue from high-marsh sediments.

F. Photomicrograph of small ellipsoidal cell fillings in tissue fragments in high-marsh sediment.

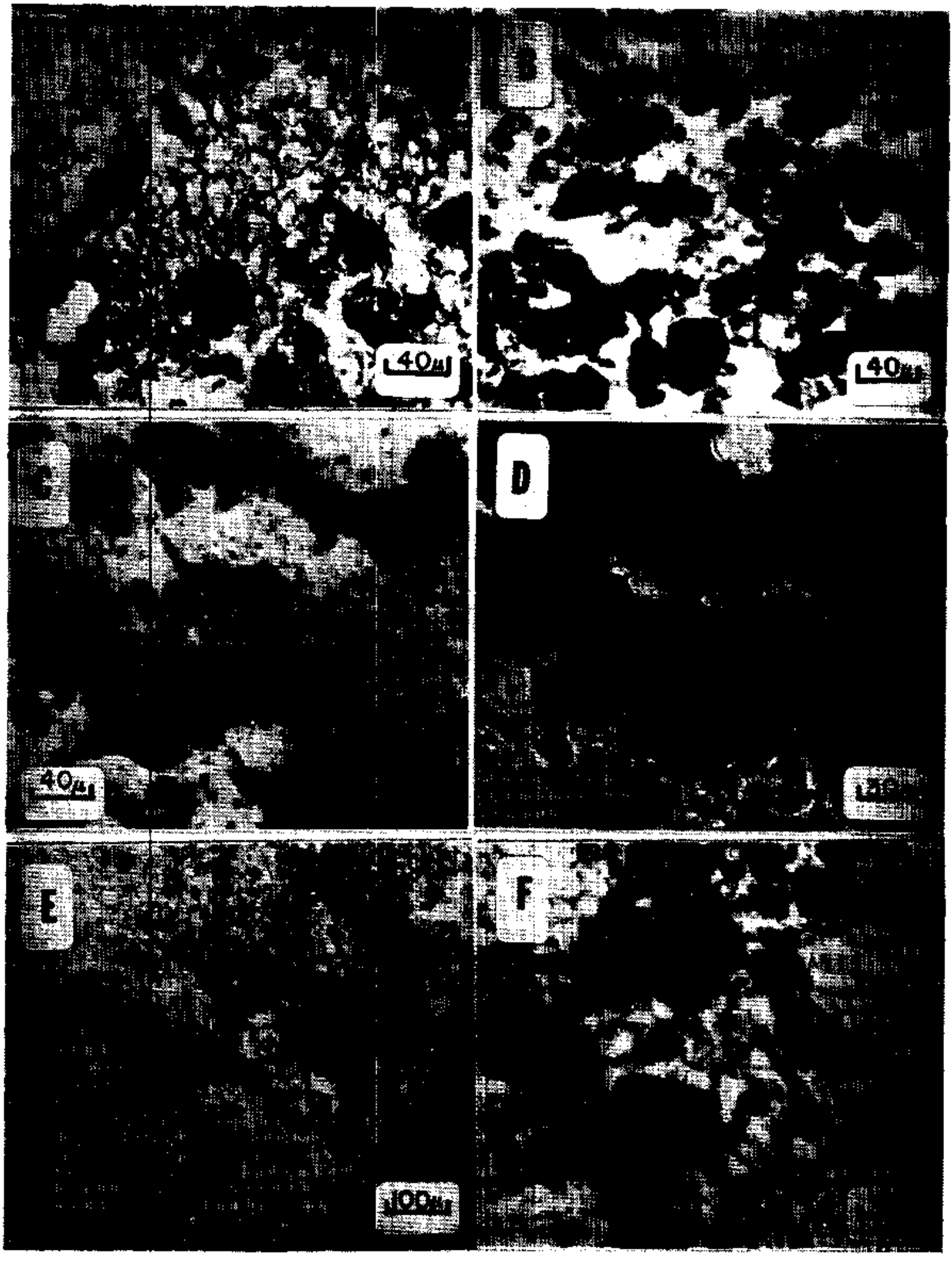
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Figure 20. Cell fillings.

A. Photomicrograph of sub-ellipsoidal to irregularly-shaped large cell fillings and smaller ellipsoidal cell fillings in a tissue containing abundant fungi. Note that fungal hyphae appear to follow the outline of cell walls.

B. Photomicrograph of large and small cell fillings such as those seen in A but lacking tissue remains. These types of cell filling are very abundant in some *Phragmites* deposits.

C. Photomicrograph of rectangular cell fillings in decayed tissue of a low-marsh sediment thin section.

D. Photomicrograph showing a row of sclerenchyma cells which appear to contain small cell fillings in each center. Arrow points to one cell.

E. Photomicrograph of irregularly-shaped cell fillings in a *S. alterniflora* rhizome fragment.

F. Close-up of the cell fillings shown in E.

either in euhedral crystals or framboids (spherical structures usually composed of an agglomeration of small euhedral crystals) (Figure 21). Grain sizes varied from approximately 1 to 50μ . Percentages of pyrite, calculated in this study, may be lower than actual values because other possible forms of pyrite could not be identified in transmitted light.

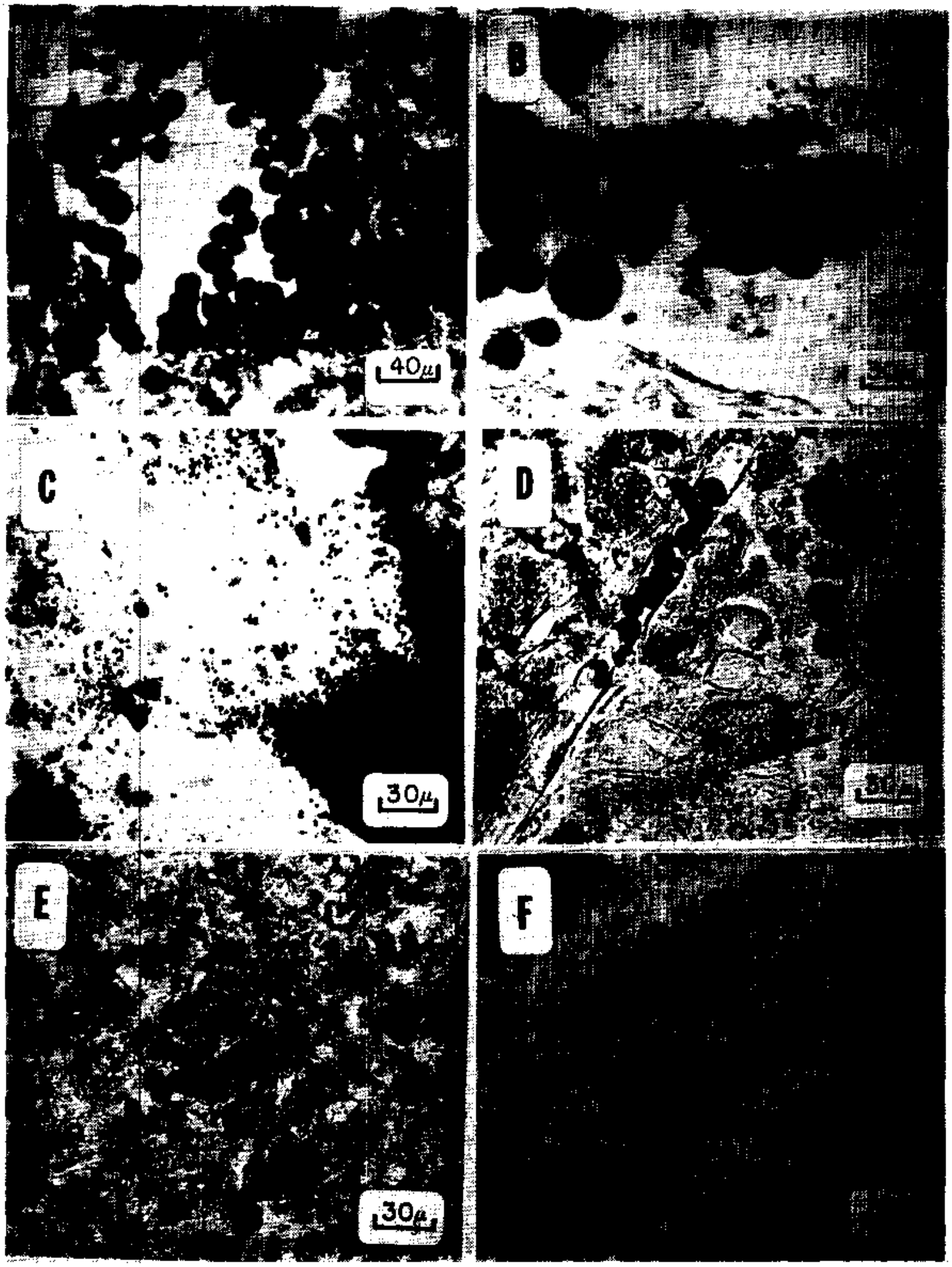
Cohen (1968) observed what he considered to be several stages of pyrite development in a petrographic study of peats from southern Florida. Bacteria and actinomycetes (only a few microns in diameter) were sometimes coated with a low reflectance black opaque amorphous substance. In other cases, bacteria and actinomycetes seemed to be covered by small crystals and spheroids of high reflectance interpreted as pyrite. The low reflectance stage may precede the formation of pyrite crystals. In addition, Cohen noted that samples with low percentages of pyrite had pyrite localized in root tissues. Samples with greater percentages had pyrite distributed in other tissues, coating various objects, or randomly distributed throughout the sediment. These patterns were noted in this study also.

Others also have observed particular characteristics of pyrite distribution. Pestrong (1972) reported pyritized diatoms in California marsh sediments, and Czyscinski and others (1977) noted pyritic masses shaped like foram tests in South Carolina marsh sediments, suggesting that the organisms had been loci for pyrite formation. Similarly, pyrite was found within diatoms and forams in this study.

Cohen (1968) not only observed that pyrite content is greater in marine peats than in nonmarine peats but also that pyrite content is controlled strongly by post-depositional conditions. When a bed is overlain by a marine deposit, that bed contains a greater percentage of pyrite than when a similar horizon is overlain by a fresh water deposit. Others have related pyrite contents in coals to similar post-depositional conditions (Caruccio and others, 1977; Horne and others, unpublished manuscript).

The absence of pyrite from the upper 15-30 cm of marsh sediments has been noted in southern Florida by Cohen (1968) and along the northeastern Gulf of Mexico by Swanson and others (1972). In this study, pyrite also was absent in the upper 30 cm of marsh sediments. Interstitial water chemistry in Delaware marshes show high levels of $SO_4^{=}/S^{=}$ in the top 30 cm which is consistent with the above observation that pyrite is not present (C. Lord, oral communication).

Laboratory experiments indicate that metastable iron sulfides such as mackinawite and greigite (both black) crystallize first and are converted to pyrite during early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40μ
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30μ

Figure 21. Pyrite.

A. Photomicrograph of pyrite framboids filling a cavity in a high-marsh thin section.

B. Photomicrograph of polyframboidal pyrite in a high-marsh sediment thin section.

C. Photomicrograph of a large mass of euhedral crystals of pyrite from a high-marsh thin section.

D. Photomicrograph of framboidal pyrite within a large diatom (?) from a low-marsh thin section.

E. Photomicrograph of a row of pyrite framboids in the sediment. The size and arrangement of framboids suggests the filling of an object which is no longer present.

F. Photomicrograph of pyrite (many of them euhedral crystals) lining the cell walls in a tissue fragment from a high-marsh thin section.

diagenesis (Berner, 1971). This observation is corroborated by the fact that the black color tends to disappear with increasing depth (Van Straaten, 1954; Biggs, 1967). Marsh sediments in this study often contain black mottles which may be localized areas of iron sulfide formation. The low reflectance amorphous substance observed by Cohen (1968) to be a precursor of pyrite may be, in fact, these metastable iron sulfides.

Variations in pyrite content and their possible causes will be discussed under appropriate marsh facies and in stratigraphic interpretations.

Fusinite. Fusinite (Figure 22) is defined as charcoal material that retains its cell structure. Its formation is attributed to highly oxidizing conditions on the marsh surface, including fires (Stach and others, 1975). Observations in this study agree with those of Cohen (1968) that percentages of fusinite are higher in high, dry marsh environments. Although fusinite was found to some degree in all marsh facies, the most favorable location for fusinite formation in temperate zone marshes is the high marsh environment of D. spicata and S. patens.

Micrinite. Micrinite (Figure 22) is defined as fine-grained opaque organic material that does not retain its cell structure. Most micrinite is less than 100μ in diameter. Larger micrinite is called massive micrinite.

Its formation is attributed to biological decay (Cohen, 1968), although it also may form inorganically. It is present in varying amounts in all marsh facies. High micrinite contents are interpreted as indicating thorough degradation.

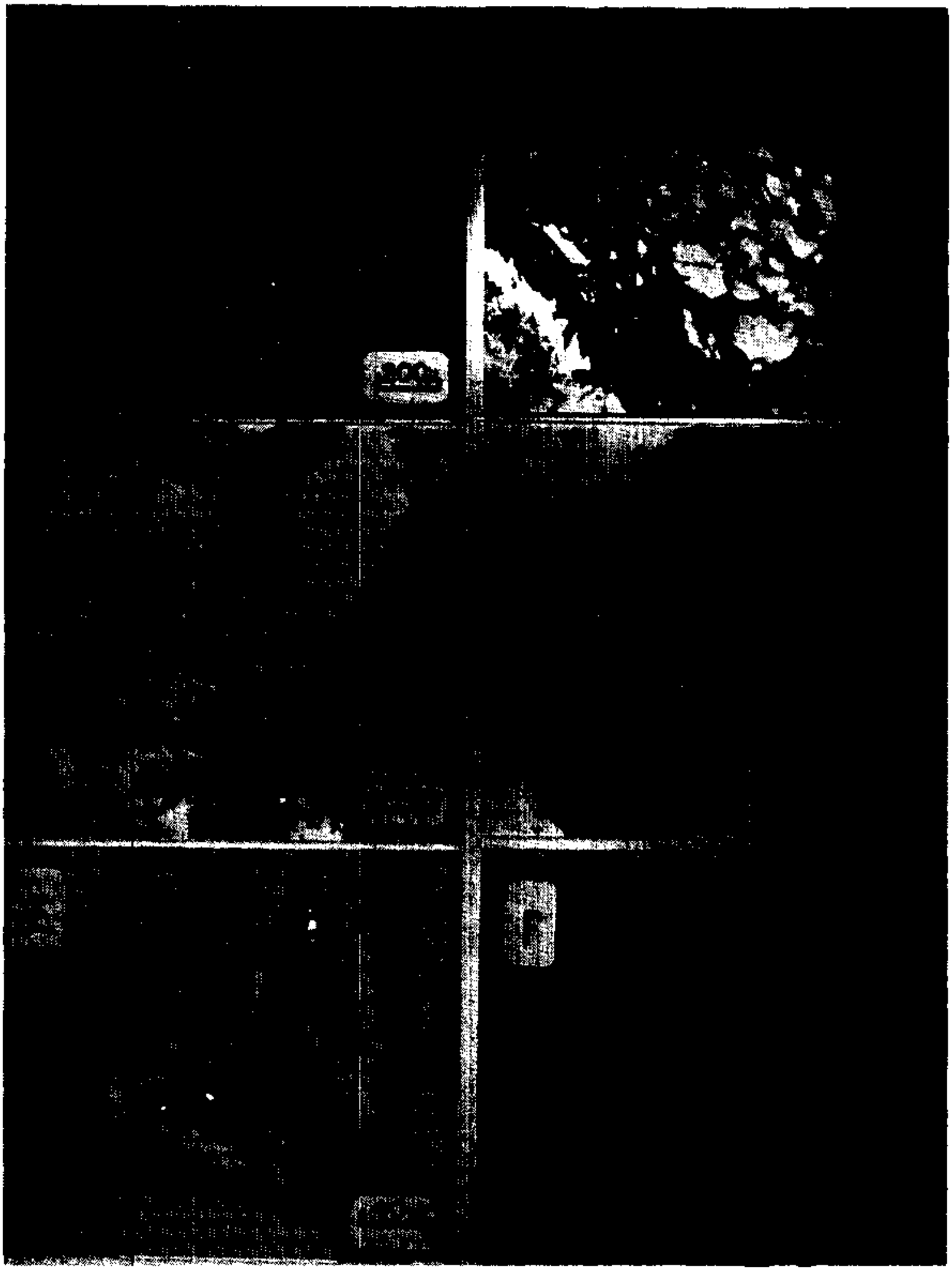


Figure 22. Fusinite and micrinite.

A. Photomicrograph of a cross-section of a fusinized portion of a S. alterniflora stem. Note the large intercellular cavities (ic) of the cortex which are characteristic of this species and the detailed preservation in the hypodermal layers (hy). A close-up is shown in B.

B. Detail of photomicrograph A. Cell structure is preserved.

C. Photomicrograph of longitudinal sections of fusinized grass tissues.

D. Photomicrograph of a fragment of fusinized grass tissue in longitudinal section. Characteristic long and short cell pattern of grass tissue is visible. Stach and others (1975) describe this material as fine fusinitic splinters. Thin-walled fusinites of herbaceous plants shatter easily.

E. Photomicrograph of micrinite decay in plant tissue. Cell structure is not preserved.

F. Photomicrograph of micrinite in the sediment. Its formation is attributed at least in part to biological decay (Cohen, 1968).

ENVIRONMENTAL FACIES OF MARSHES

Introduction

The following classification of environmental facies is based primarily on vascular plant remains, but also on other constituents and properties of the surficial and subsurface deposits. Each of the 17 facies and subfacies corresponds to a modern depositional environment distinguished by a community of plants. Although these environments are generally distinct, they locally grade into one another, so facies likewise may not always be distinct.

In situ marsh facies and subfacies are presented in order of those representing saline conditions to those representing fresh-water conditions. One detrital-organic facies is discussed. Subfacies are discussed under the following categories: Low-Marsh, High-Marsh, Marsh-Pond, *Phragmites*, Brackish-Marsh, Fresh-Water Marsh and Detrital-Organic Facies. Discussions of megascopic characteristics, microscopic characteristics, and depositional environment are presented for each facies and subfacies. When sufficient information is present, degradation patterns of particular species are discussed. The patterns do not necessarily indicate a path of decay or any time framework. Much of the detail on decay is presented also in captions for figures. Table 3 on page 188 summarizes the important characteristics of each subfacies and facies and the corresponding environment in which it is formed.

I. Low-Marsh Facies

Low-marsh environments include low-marsh *S. alterniflora* zones, creek banks both vegetated and unvegetated, and tidal creeks (Figure 23).

The dominant species associated with low-marsh environments is *S. alterniflora*. The tall form which grows on tidal-creek banks and often invades creeks as they aggrade reaches heights up to 2 m. The short form covers more extensive areas of the low marsh in greater plant density, and is rarely more than 50 cm tall. The plant has long, broad (10-15 mm) leaves, and a thick, rigid sheathing base with numerous layers of sheaths, some partially decayed and dark brown to black in color. The hollow culm is very short and elongates with the inflorescence. The large rhizome (2.5-10 mm dia.) is hollow (except at nodes) and possesses leaf scales. Large and small adventitious roots extend at least 50 cm below the surface.

A. *S. alterniflora* low-marsh subfacies

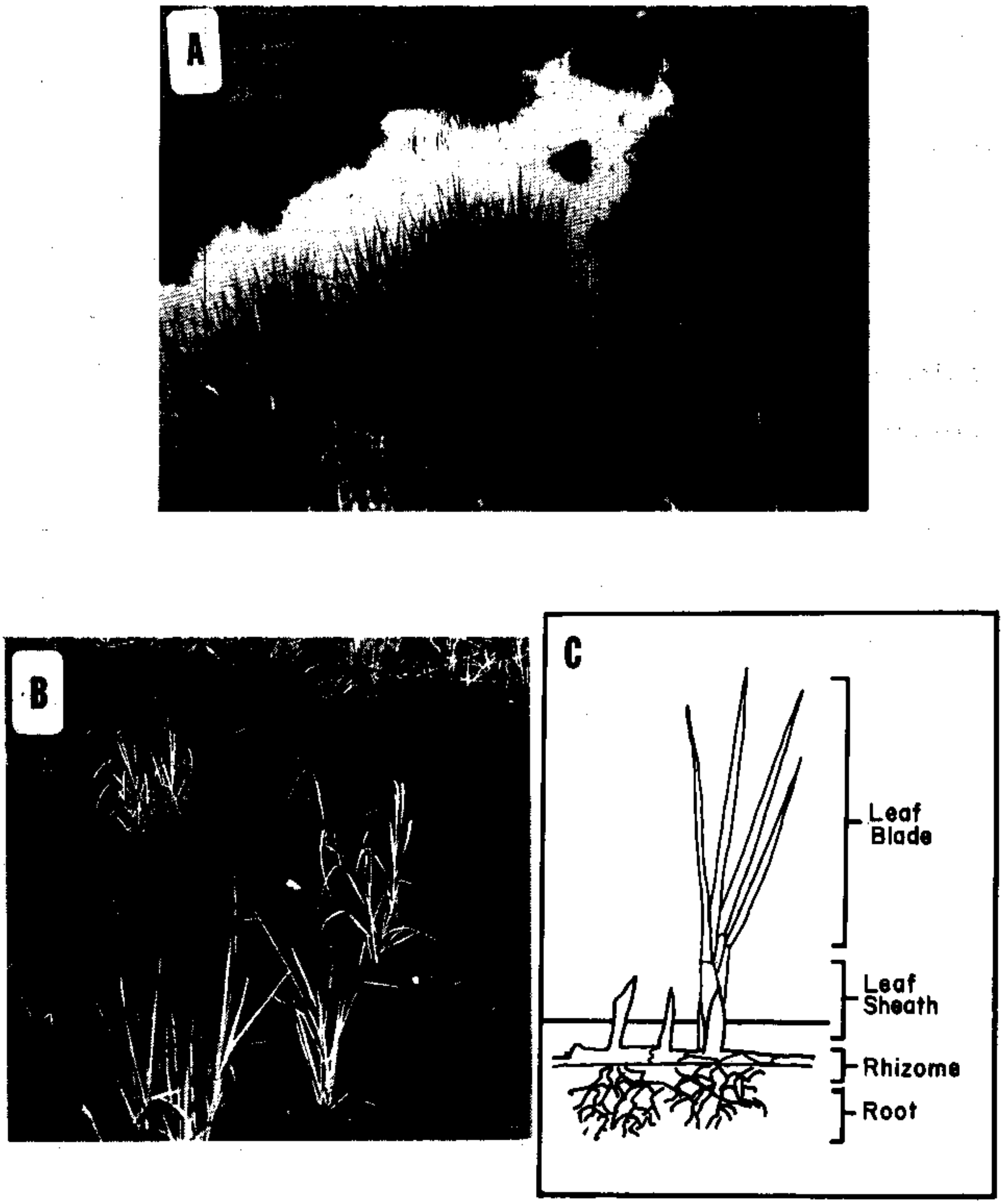
Megascopic characteristics. *S. alterniflora* low-marsh sediments are finely fibrous and have fiber contents

Figure 23. Vegetation and environments of the low marsh.

A. Photograph showing *S. alterniflora* low marsh and aggrading tidal creek with tall *S. alterniflora*.

B. Photograph of a bare creek bank and tidal-creek floor (*S. alterniflora* approximately 30 cm tall). The bank is densely-populated by the mud fiddler crab, *Uca pugnax*.

C. Line drawing of the morphology of *S. alterniflora* (15 cm to 2 m tall).


A
B
C
Leaf Blade
Leaf Sheath
Rhizome
Root

that range from intermediate to high. The sediments are brown and locally show bright orange mottles around roots. Structure is generally massive because of the dense network of roots, but there are occasional lenses or laminae of sand, mud, or fine organic debris that suggest periods of rapid deposition. Roots cannot be identified to species based on their morphology but the presence of orange mottles around the roots strongly suggest a S. alterniflora environment. Rhizomes can be identified by size and the presence of a hollow interior in cross-section. The colors of roots and rhizomes are tan to transparent and sometimes dark orange to black. Broad sheet-like fragments which are common in the sediment were identified as leaf sheaths in microtome sections. These are brown to black.

Microscopic characteristics (Figures 24, 25, and 26). Framework composition consist of roots, rhizomes, and occasionally, leaves. Leaf sheaths, separated from the culm or rhizome, are very common, and are present in various stages of decomposition. Many plant organs are fragmented, and isolated sections of organs such as a solitary vascular bundle can be identified. Small roots are by far the most common organ present. Root cells are often highly decayed and decomposition is also present locally in the sediment around the root. This sediment zone around the root is dark orange to red. In thin section plant organs are light brown to pale yellow, orange, or dark brown to black.

Cells and tissue fragments are present in various degrees of preservation. Larger fragments consist of rows of long and short cells characteristic of grasses. Most smaller fragments are unidentifiable and highly decomposed. Fecal pellets are common as are other matrix components such as diatoms, foraminifers, sponge spicules, and minerals. Matrix color is light brown in those sediments containing abundant roots and few plant fragments. The majority of fine granular debris appears to be composed of inorganic particles rather than plant debris. This is further suggested by the lack of common fungal remains which are usually associated with degraded plant debris (Cohen, 1968).

Evidence of surface litter such as leaves is rare. Tidal currents and waves apparently carry such material away. F/M ratios are low to intermediate, again indicating the importance of tides in transporting and depositing inorganic sediment in low marsh and in carrying organic material out of the marsh. Micrinite and fusinite contents are variable. Pyrite is common and sometimes abundant below 30 cm.

The *Spartina* marsh sediments of Cohen (1968) were probably formed in a higher, drier environment in southern Florida than those in Delaware. They show a greater abundance of both fungi and fusinite.

Degradation (Figures 24, 25, and 26). Tissues of

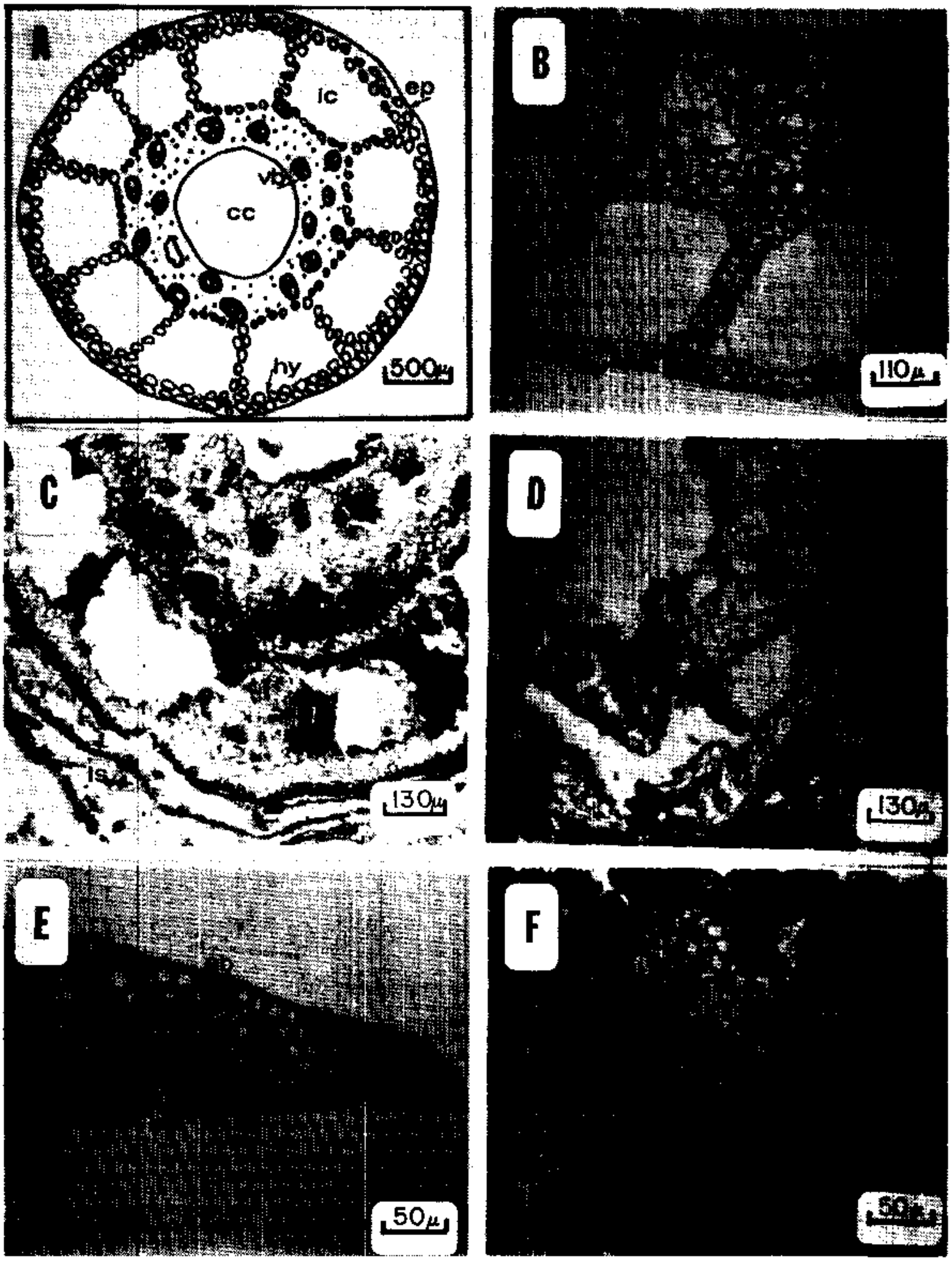

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Figure 24. Stems and leaves of Spartina alterniflora.

A. A line drawing of a S. alterniflora stem showing the large central cavity of the stele (cc), vascular bundles of the stele (vb), cortex with large intercellular spaces (ic), a multi-layer hypodermis (hy) and an epidermis (ep).

B. Photomicrograph of a portion of a modern S. alterniflora stem (rhizome) showing some of the features illustrated in A.

C. Photomicrograph of a portion of a S. alterniflora stem in the sediment. Note that the vascular bundles of the stele are filled with dark-colored material. The epidermis clearly retains its cell structure and several leaf sheaths (ls) are visible in the lower left hand corner. Compare this with the modern section in B.

D. Photomicrograph of a portion of a S. alterniflora stem in the sediment. Note that the vascular bundles of the stele are gone and cavities remain.

E. Photomicrograph of a portion of a modern S. alterniflora leaf. The adaxial surface of the leaf consists of ridges and furrows (adaxial surface, ad; abaxial surface, ab; vascular bundle, vb).

F. Photomicrograph of a portion of a S. alterniflora leaf in the sediment. Vascular bundles (vb), epidermis (ep) and the adaxial ridge and furrow structure (ad) can still be recognized. Compare these features with those in modern section in E.

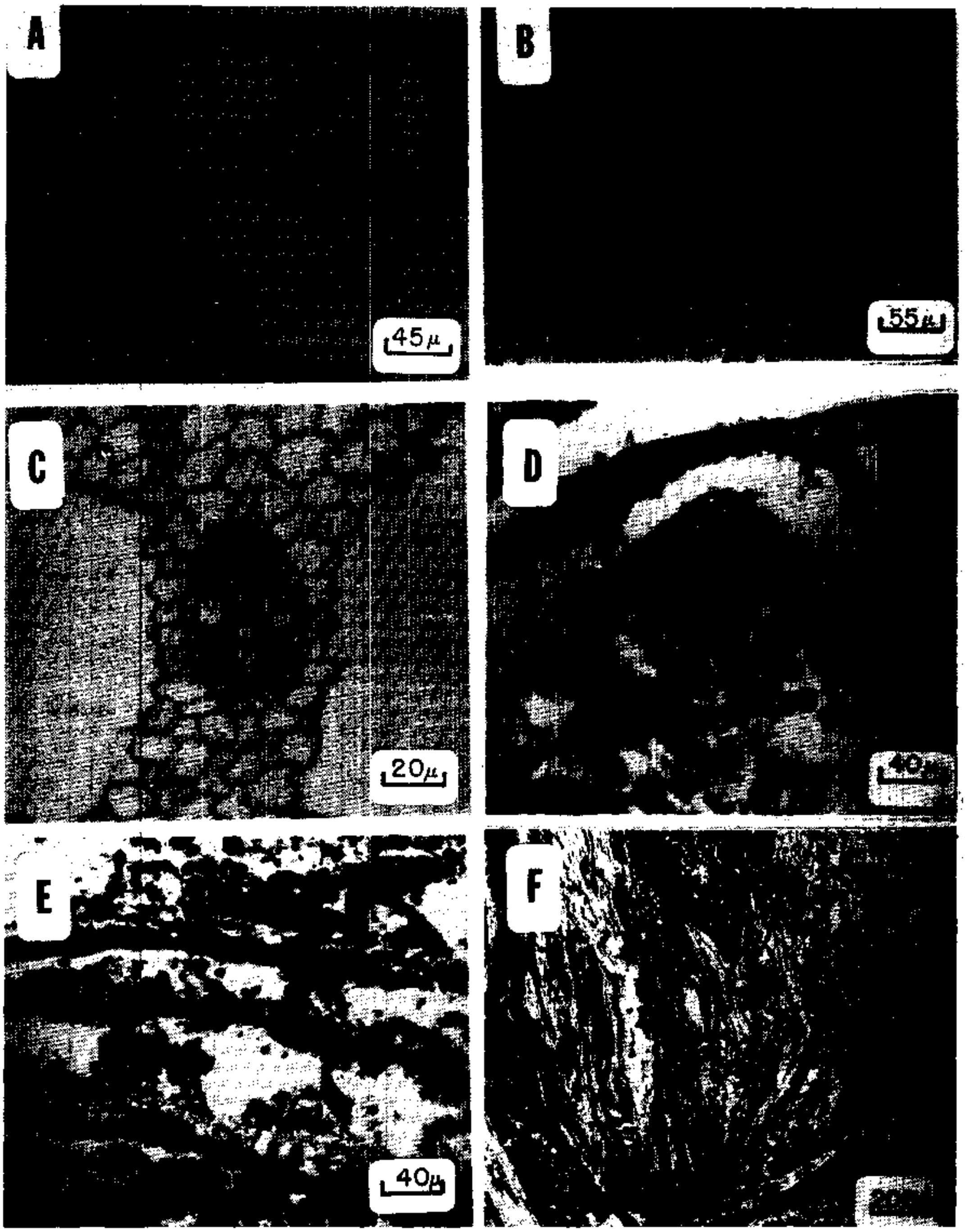
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Figure 25. Leaf sheaths and vascular bundles of *Spartina alterniflora*.

A. Photomicrograph of a modern section of a *S. alterniflora* leaf sheath. Note the central position of the vascular bundle (vb); this position aids in distinguishing *S. alterniflora* leaf sheaths from those of *P. communis*.

B. Photomicrograph of a *S. alterniflora* leaf sheath in the sediment. Compare the vascular bundle (vb) with the modern one in A.

C. Detailed view of the vascular bundle in A (bundle sheath, bs; phloem, ph; xylem, xy).

D. Detailed view of an isolated *S. alterniflora* vascular bundle in the sediment (bundle sheath, bs; phloem, ph; xylem, xy). Compare this with the modern bundle in C.

E. Photomicrograph of several *S. alterniflora*? leaf sheath fragments in the sediment.

F. Photomicrograph of a mass of *S. alterniflora*? leaf sheaths in the sediment. These leaf sheath masses are characteristic of this marsh facies.

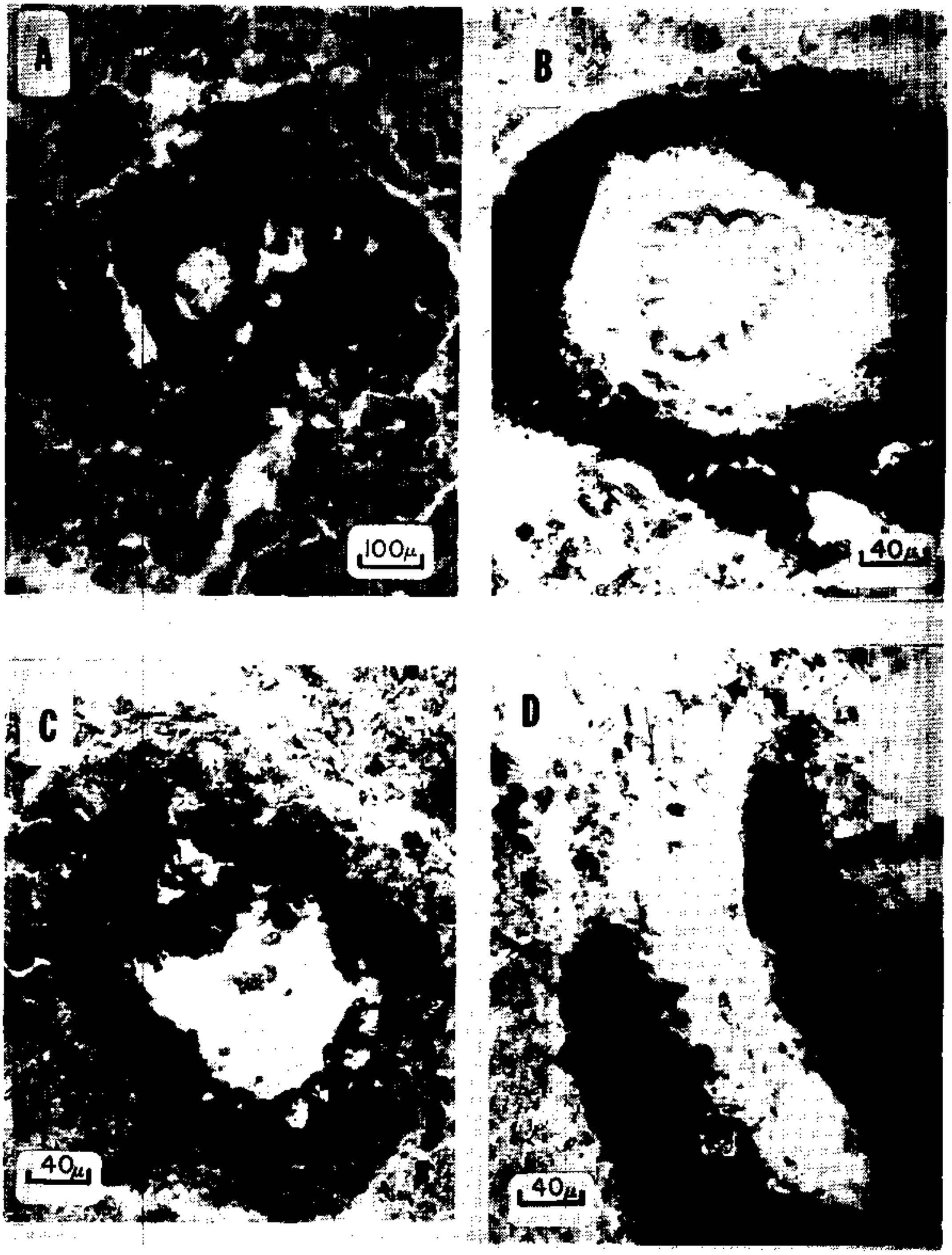
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Figure 26. Roots of *Spartina alterniflora*.

A. Photomicrograph of a cross-section of a *S. alterniflora* small root in the sediment showing zones of decay surrounding the root.

B. Close-up photomicrograph of a *S. alterniflora* small root with a zone of decay. This root appears to have shrunk in size, probably as a result of the decay.

C. Close-up photomicrograph of a decay zone of a small root of *S. alterniflora*. The root has been completely removed.

D. Close-up photomicrograph of a longitudinal section of a *S. alterniflora* small root showing decomposition of cells in the dark decay zone and retention of cell structure outside the decay zone (note arrow).

S. alterniflora are rarely preserved as whole organs and identifications are based not only on fragments bearing anatomical features characteristic of S. alterniflora but also on knowledge of the physical processes occurring in the depositional environment.

As noted by Barghoorn (1949b), tissues with lignified secondary walls such as vascular tissue are highly susceptible to decay (Figure 24C). Yet, in some instances, tissue fragments of isolated vascular bundles retained well-defined cell structure (Figure 25D). These tissues may have been torn from the relatively weak cortex and stele by the mechanical action of tidal currents or the burrowing activity of organisms.

Well-preserved leaf sheaths associated with stems are rare, and those that are present probably originated from basal culms beneath the sediment surface (Figure 25B). Highly-decayed leaf sheaths are abundant and usually fragmented (25 E,F). Some fragments contain partially preserved cell structure, but most are brown to orange and associated in masses. Hypodermal layers of the stem also may be associated with leaf sheaths. During decay thin rows of fundamental cells between the large intercellular spaces in the cortex weaken and the hypodermis becomes separated from the stem.

Decay of small roots is characteristic of

S. alterniflora and suggests the presence of an organism which may be causing or contributing to the decay (Figure 26).

Depositional environment. S. alterniflora low-marsh sediments show little degradation of organic material because the sediment consists mainly of subsurface components (roots and rhizomes) and inorganic particles. Surface litter forming processes are not important as most of the detritus is washed away by tides.

Most of the S. alterniflora low marshes studied are well drained, with numerous tidal creeks and/or drainage ditches. Some, though, are poorly drained and often ponded. Well-drained marshes have a level, relatively firm surface produced by a dense framework of plant roots. Marshes with uneven surfaces and ponded water contain areas of dense mats of roots alternating with areas of loose, soft sediment and few roots and rhizomes. These poorly-drained marshes are not immature or youthful, however, because they rest on several meters of marsh sediment.

Variations within one type of environment such as this produce variations within the subfacies.

B. S. alterniflora creek-bank subfacies

Megascopic characteristics. Vegetated creek-bank sediments are very similar to those of S. alterniflora low-marsh sediments, except that the fiber content is lower and sand lenses and laminae occur more commonly in creek-bank sediments.

Microscopic characteristics (Figure 24, 25, and 26). These have the same general characteristics as *S. alterniflora* low-marsh sediments except that there are fewer roots and other framework components in creek-bank sediments. The inorganic content of the matrix is high and the matrix also contains foraminifers, diatom fragments, sponge spicules, fine organic debris, and cells and tissue fragments.

Some of the roots appear torn or more highly decayed than those in *S. alterniflora* low-marsh sediments. This may be due to the greater activity of burrowing fiddler crabs on the creek bank.

Depositional environment. Sedimentation on creek banks can be high due to trapping of sediment by plants. Detrital layers of plants and plant fragments often pile up on the creek bank around the culms of living plants. Creek-bank erosion exposes roots and rhizomes along the cut bank. Organic and inorganic material eroded from the bank may be deposited along another portion of the bank or in the tidal creek as tidal currents erode, transport and deposit sediments into and out of the marsh system.

C. Unvegetated creek-bank subfacies

Megascopic characteristics. These sediments contain few organics and those present show parallel to subparallel orientations and appear to be on bedding planes. Sand and mud laminae are common, and dark mottles of the sediment occur occasionally. These sediments are not as cohesive as other low-marsh sediments. Sometimes a very **fine network** of thin, delicate roots, probably from nearby S. alterniflora plants, is present.

Microscopic characteristics (Figure 27). Tissue fragments often show well-preserved cell structure and suggest mechanical-breakup of plant tissues during transport rather than biological decay. They also display parallel to subparallel orientations which suggest microbedding. Tissues are difficult to identify to species. S. alterniflora remains, especially leaf sheaths, are most frequently identified; although remains of other plant species are present also. Some tissues are highly degraded, while adjacent ones are well preserved. Roots are rare.

Fecal pellets are abundant and dominate most sediment thin sections. Some sections are composed entirely of fecal pellets. Fragmented diatoms, foraminifers, and sponge spicules are characteristic. Cell fillings are locally abundant which suggests that detrital fragments may have decomposed on the bank leaving residual cell fillings.

Depositional environment. The creek banks in this study consist almost entirely of silt and clay, with very little sand. Creek banks show slump structures and laminae of intercalated mud and sand. These sedimentary structures

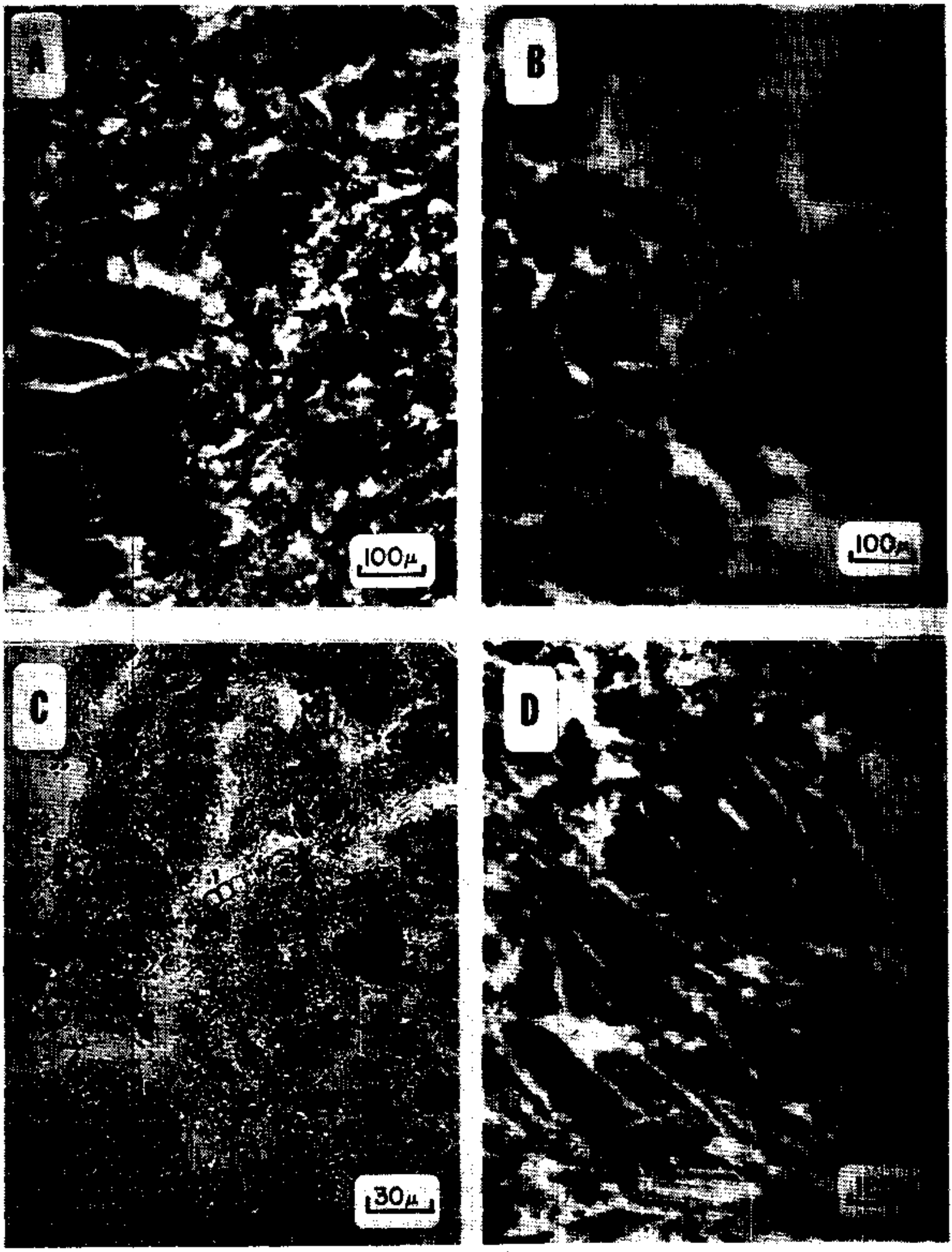
Figure 27. Mudbank sediments.

A. Photomicrograph of a mudbank thin section showing a possible burrow structure filled with fine-grained sediment.

B. Photomicrograph of a mudbank thin section showing abundant fecal pellets.

C. Photomicrograph of a mudbank thin section showing a variety of matrix components (diatom, diatom fragments, 1; micrinite, 2; tissue fragment, 3; mineral grain, 4).

D. Photomicrograph of a mudbank thin section showing parallel to sub-parallel laminations of highly decayed plant tissues, the result of creek bank deposition.


A
100μ
B
100μ
C
30μ
D

are at least partially disrupted by the great number of burrowing organisms, particularly fiddler and mud crabs, that populate creek banks. Some burrows remain open at great depths, others become sand- or clay-filled (Allen, 1972). Edwards (1973), Basan (1975) and Frey (1976) describe creek banks and point bars in Georgia marshes which contain laminations, discontinuous to contorted bedding, shell remains, bioturbation structures, and varying grain-size distributions. Redfield (1972) has noted similar sedimentary structures in Barnstable marshes in Massachusetts.

Detrital layers of plants pile up on unvegetated banks as well as vegetated banks. Unvegetated banks undergo desication and are exposed to wide variations of salinity (Sullivan, 1971). These extreme conditions are suitable for high decay. The presence of root fragments, particularly highly decayed fragments in thin section (which do not appear to be _in situ_), is interpreted as resulting from deposition of organics during creek-bank sedimentation.

D. Tidal-creek subfacies

Megascopic characteristics. Tidal-creek sediments may be difficult to distinguish from unvegetated creek-bank sediments in megascopic study; although tidal-creek sediments usually contain more dark brown to black mottles.

Microscopic characteristics. Tidal-creek sediments are very similar to unvegetated creek-bank sediments. Both contain more cells and tissue fragments than S. alterniflora low-marsh and vegetated creek-bank sediments. Some of these fragments are highly decayed, while others retain well-defined cell structure. Leaf sheaths, probably from S. alterniflora, are the most common framework component. F/M ratios are very low and matrix components consist of fragmented debris and inorganics. There are four basic associations recognized in thin section that represent tidal-creek and unvegetated creek-bank environments:

1. Thin sections consisting entirely of fecal pellets;
2. Thin sections consisting of fine granular debris (mostly mineral) with occasional cells and tissue fragments;
3. Thin sections with leaf sheaths, root fragments, and other large plant fragments in parallel to subparallel orientations; and
4. Thin sections with a fine-grained matrix and small roots that appear to be in growth position.

Depositional environment. At low tide the tidal-creek surface is light brown due to the presence of diatoms which rise to the surface to photosynthesize. Detrital organics are common as are large concentrations or mounds of fecal pellets. These fecal pellets appear to be sorted by currents. Some creek sediments contain a very fine network of roots and occasionally, S. alterniflora seedlings are rooted in the creek bottom, even in well-drained creeks. Frequent slumping occurs along the cut bank of the channel and contributes bank sediment to the creek.

In a study of hydrocarbon and fatty acid distribution in marsh sediments, Swetland (1975) determined that tidal-creek sediments in his study area received most of their organic matter from marsh-plant detritus. This appears to be true in my study area also. Yet it is possible for tidal creeks to contain sediments derived from bay waters also. Factors such as distance from inlets and tidal-flushing patterns control the sources of tidal-creek sediments. Banks and tidal creeks are both areas of frequent erosion and deposition.

Low-marsh sediments contain the following characteristics in common:

1. Usually, they contain a light-colored matrix, which suggests little decay and a high percentage of inorganics.
2. They all have low percent carbon values (4-10%) related to other marsh sediments. S. alterniflora low-marsh sediments contain the highest percent carbon of this group (6-10%).
3. They contain high percentages of inorganics (5-12% "other minerals").

4. Burrowing organisms play a dominant role in sediment formation by: a. contributing fecal pellets to the sediment; b. eating or mechanically tearing plant organs as they burrow, and c. aerating the sediment.

II. High-marsh Facies

High-marsh environments include *S. patens* zones, *D. spicata* zones, mixed *S. patens*-*D. spicata* zones, *Salicornia* patches, rotten spots and transitional zones of *Baccharis*, *Iva*, and *Limonium* (Figures 28, 29 and 30).

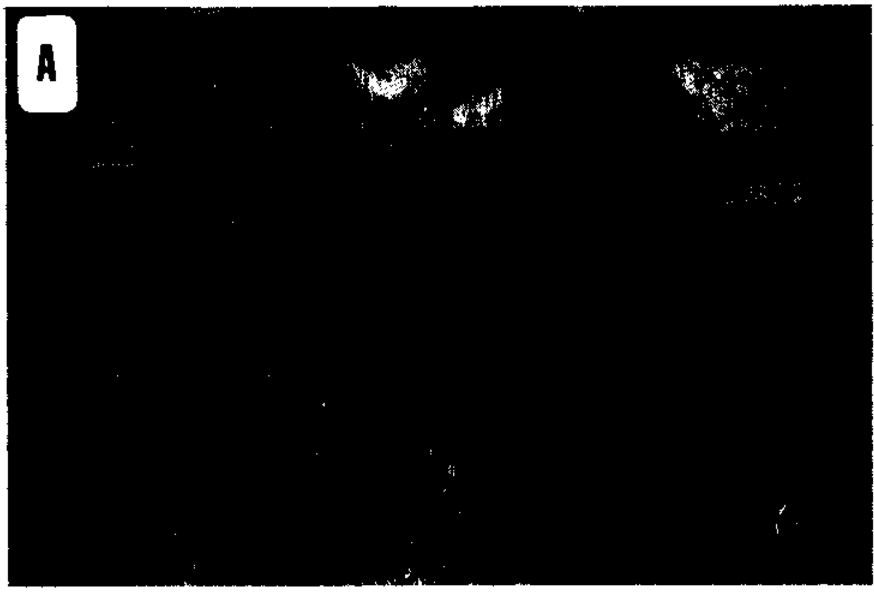
S. patens is a slender, stiff grass with short (20-35 cm), thin (1-3 mm) leaves and a pronounced sheathing base. The rhizome is slender and hollow (except at nodes), and the root system is adventitious and fibrous. *D. spicata* has similar dimensions. Plant height is approximately 20-50 cm, and leaf blades are 2-3 mm wide. The rhizome has a solid center in contrast to *S. patens* and is more "gnarled" with abundant leaf scales. The dense living root system of both plants extends approximately 10 cm into the sediment. These plants create a "cowlick" pattern late in the growing season as they are bent over by the wind. *Salicornia virginica* forms extensive perennial mats. The rhizome is stout and roots consist of a short, fine network which penetrates to depths of 5-10 cm. The stem is jointed, fleshy, and branched. Leaves are reduced to scales at the

Figure 28. Vegetation of high-marsh environments.

A. Photograph showing a high-marsh cowlick environment formed by *S. patens* and *D. spicata*.

B. Line drawing of the morphology of *S. patens* (15 to 35 cm tall).

C. Line drawing of the morphology of *D. spicata* (15 to 50 cm tall).


A

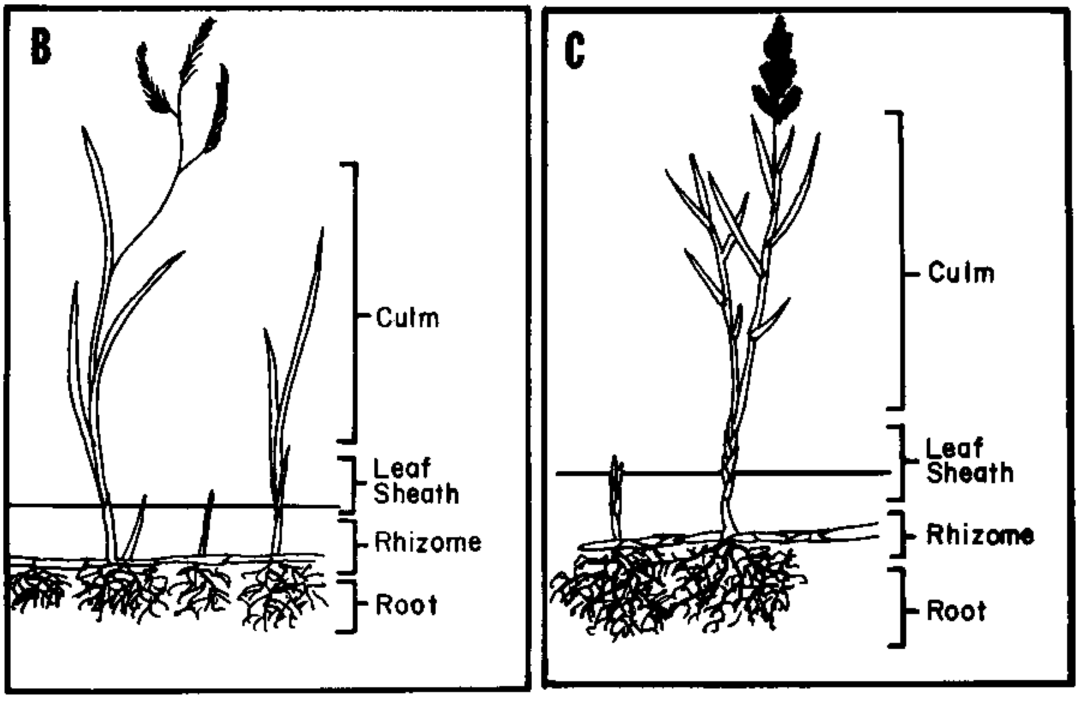

B
Culm
Leaf Sheath
Rhizome
Root
C
Culm
Leaf Sheath
Rhizome
Root

Figure 29. Vegetation of high-marsh environments.

A. Photograph of a rotten spot showing dead culms of *S. alterniflora*. The surface is covered with blue-green algae. Scale is 25 cm long.

B. Close-up photograph of a rotten spot showing the blue-green algal crust and dark brown to nearly black sediment beneath. Scale is 25 cm long.

C. Close-up photograph of a stand of *Salicornia* sp.

D. Line drawing of the morphology of *S. virginica* (10 to 15 cm tall).

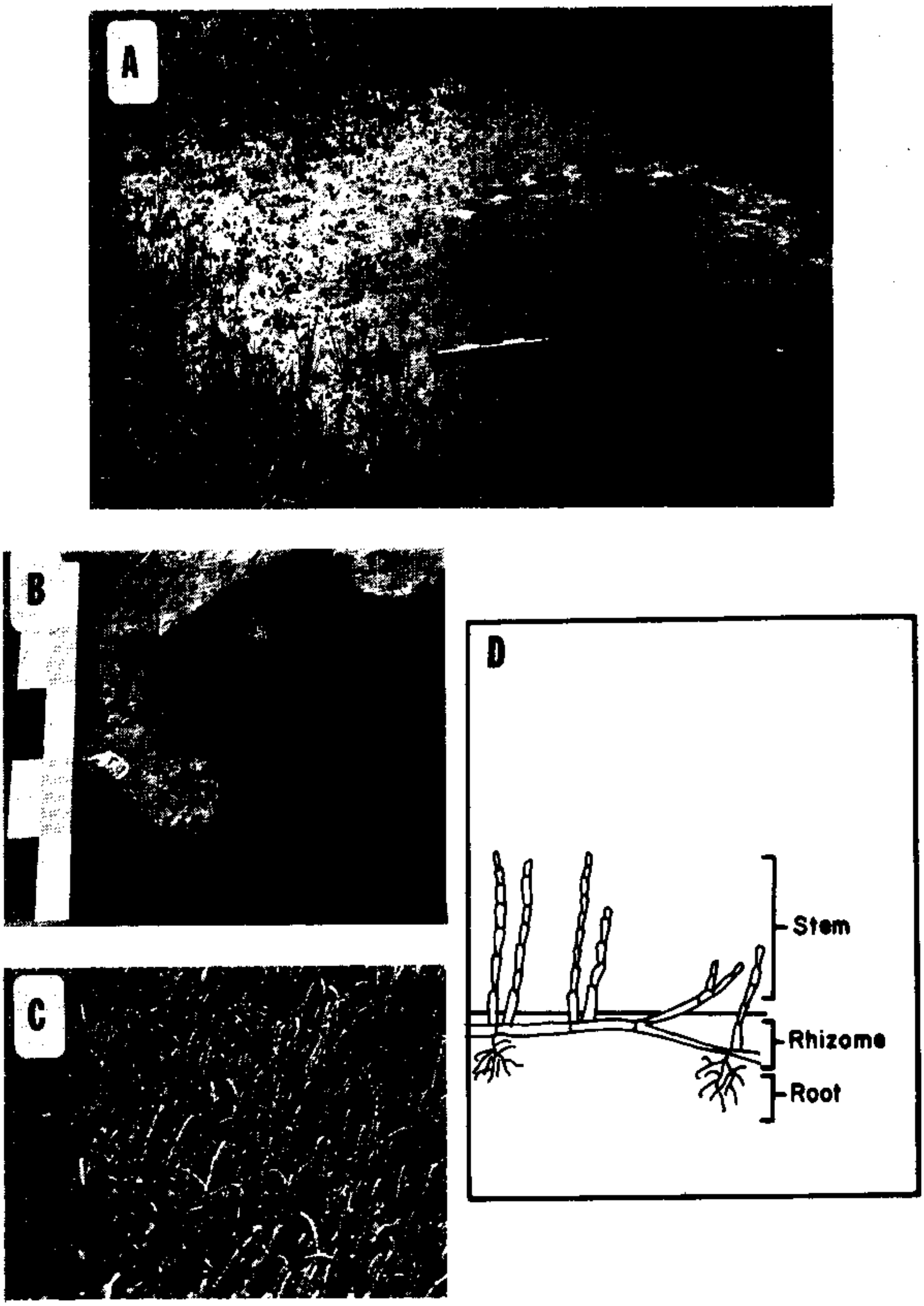

A
B
C
D
Stem
Rhizome
Root

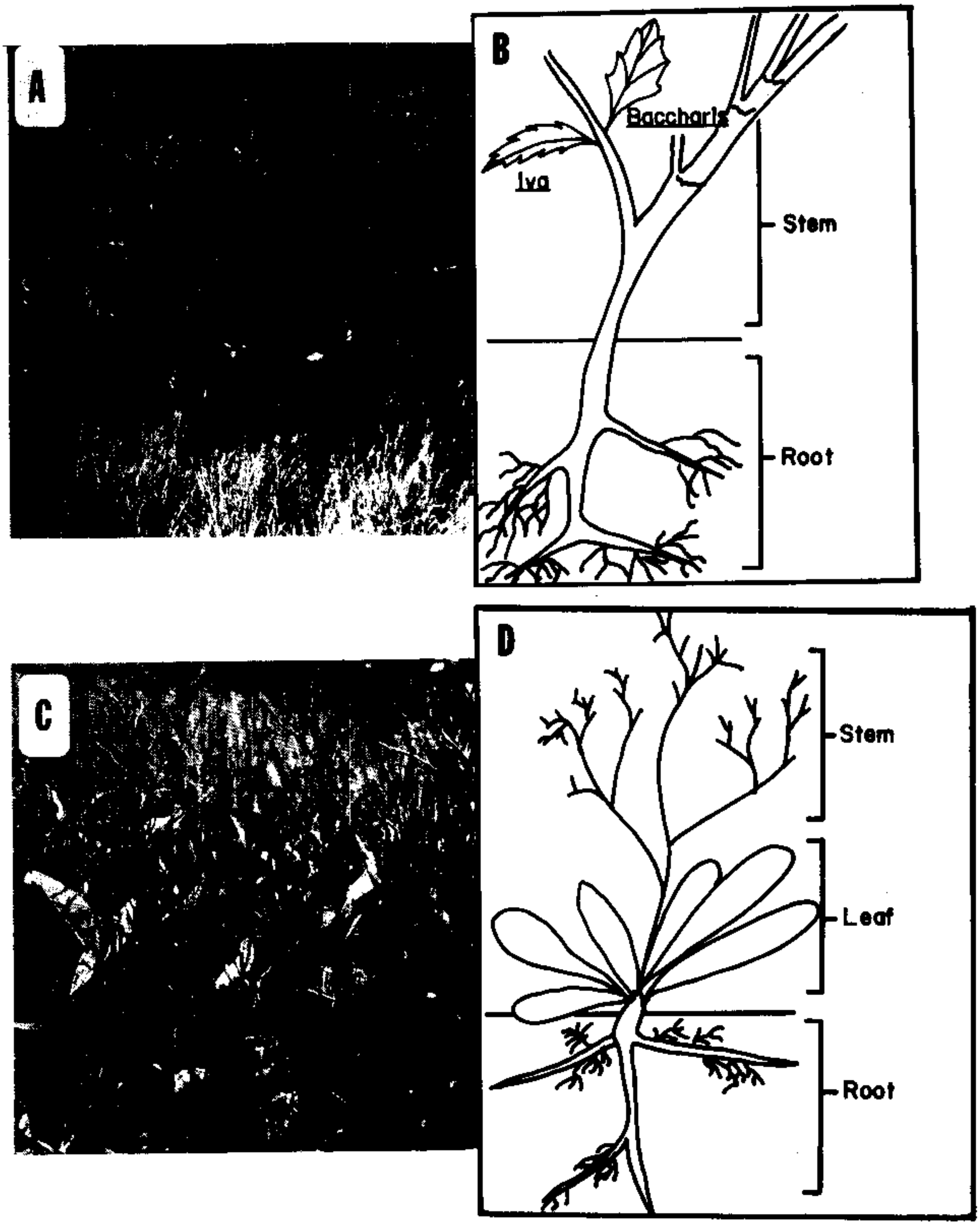
Figure 30. Vegetation of the transitional environment between high marsh and upland.

A. Photograph of I. frutescens bushes along the landward border of the high marsh.

B. Line drawing of the general morphology of I. frutescens and B. halimifolia (1 to 3 m tall).

C. Photograph of L. carolinianum.

D. Line drawing of the general morphology of L. carolinianum (30 to 60 cm tall).


A
B
Baccharis
Iva
Stem
Root
C
D
Stem
Leaf
Root

nodes. The plant is 10-15 cm tall. The annuals S. bigelovii and S. europaea are more common in Delaware marshes, but they possess less robust root systems and therefore, are less likely to be preserved in the sediment. Baccharis and Iva are woody shrubs which may reach heights of approximately 3 m. They have tap root systems. Limonium is a perennial herb which possesses a branched stem, a basal rosette of thick, broad leaves, and a tap root which penetrates the sediment about 30 cm with a lateral spread of 50 cm (Purer, 1942).

A. High-marsh cowlick subfacies

Megascopic characteristics. Cowlick sediments are not cohesive, they tend to part along planes or fall apart. Broad sheets identified as leaf sheaths in thin section are common. Short (5-15 mm) cylindrical fragments are abundant and interpreted as culms. Rhizomes are scarce and can be distinguished from culms by the presence of roots at nodes on rhizomes. Fragments of S. patens culms are slender and hollow in the center. Fragments of D. spicata culms are solid in the center. The brown to dark-brown sediments may contain pockets of darker-colored fine-grained organics, or black mud. In thin section, these areas are highly decayed. Orange mottles are not common around roots as in S. alterniflora sediments.

Microscopic characteristics (Figures 31, 32, 33, and 34). Composition is dominated by stems and leaf sheaths of

S. patens and D. spicata. Roots are conspicuously rare or absent. Leaves may be present, and are often fusinized. These fragments characteristically show parallel to subparallel orientations in thin section which reflects their position or arrangement in the cowlick environment. The weaker or more highly-decayed culms are compressed under the weight of the overlying culms and sediment.

Matrix texture is coarse and suggests very little inorganic composition. Cell and tissue fragments are common. Fungal remains are abundant. Cell fillings are occasionally present. Usually, matrix components such as foraminifers, diatoms, and sponge spicules are unfragmented in contrast to those found in low-marsh sediments. Matrix color is highly variable even within one slide and ranges from light brown to dark-red brown. Fecal pellets are common. The presence of plant fibers indicates high decay.

Two subtypes of high-marsh cowlick sediments are identified:

1. High-decay cowlick sediment: Low F/M ratios. Matrix consists of fine granular debris, cells and tissue fragments, and large amounts of fungal remains. Large tissue fragments are highly decomposed. Matrix colors are red to dark-red brown. Fusinite and micrinite are very common.
2. Low-decay cowlick sediment: High F/M ratio.

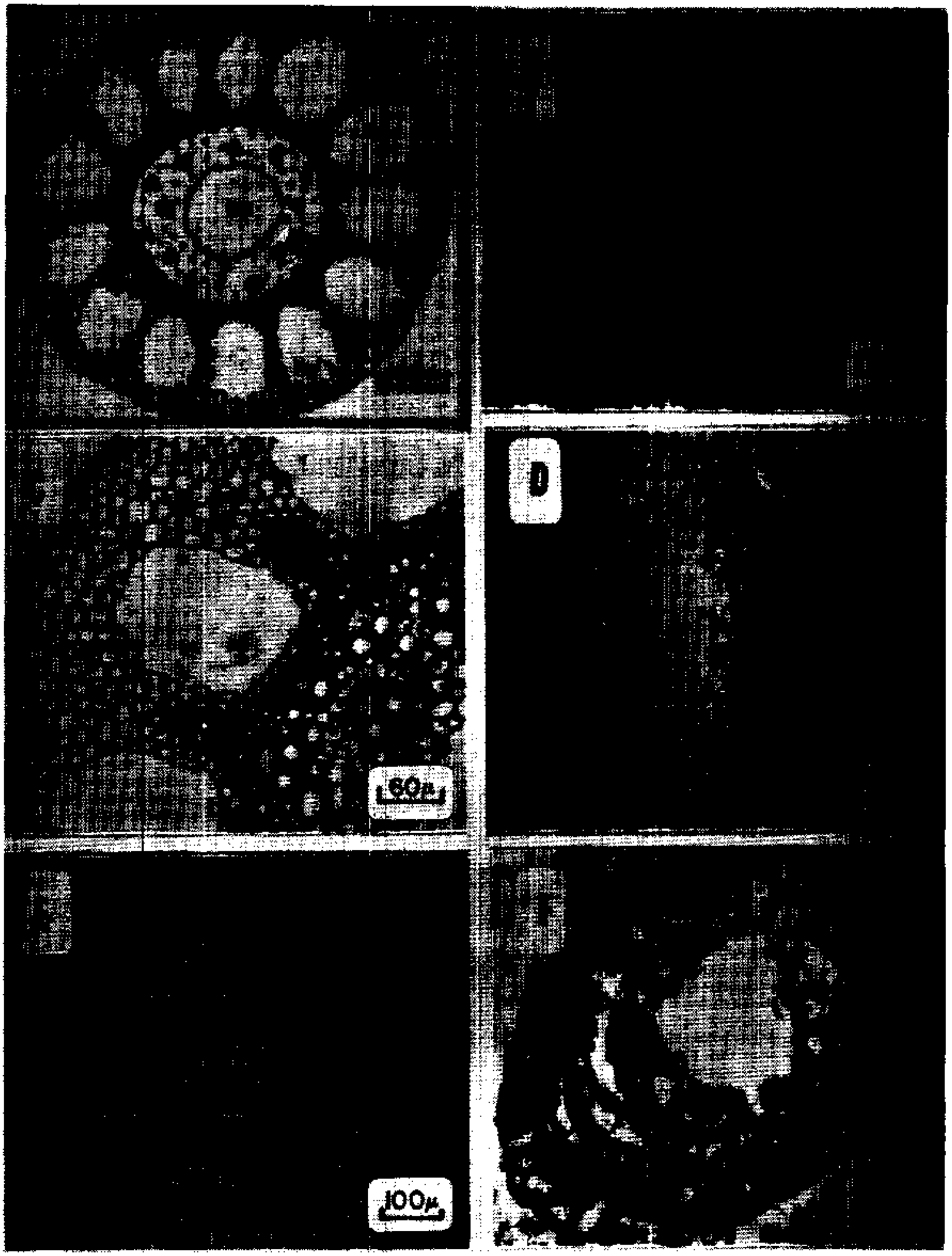

D
60μ
100μ

Figure 31. Stems and leaf sheaths of *Spartina patens*.

A. A line drawing of a *S. patens* stem showing the large central cavity of the stele (cc), vascular bundles of the stele (vb), mechanical tissue (mt), cortex with large intercellular spaces (ic), a multi-layer hypodermis (hy) and an epidermis (ep).

B. Photomicrograph of a *S. patens* stem in the sediment. Compare this with the line drawing in A. The shrivelled outline of the plant suggests desiccation. Warm, dry conditions which commonly occur on the high marsh are a probable cause.

C. Detailed view of a modern *S. patens* stem (rhizome). The dark band of cells is mechanical tissue (the dark color is the result of biological staining). Mechanical tissue often darkens "naturally" in the sediment and is a diagnostic feature of *S. patens*.

D. Detailed view of a *S. patens* stem in the sediment. Compare the vascular bundles (vb) with modern ones in C. Vascular bundles in the sediment are filled with dark material, or cell fillings.

E. Photomicrograph of *S. patens* leaf sheaths in the sediment. These tightly wrapped leaves form the basal culm of the plant at the sediment-air interface.

F. Photomicrograph of fusinized *S. patens* leaf sheaths. Compare this with the section shown in E.

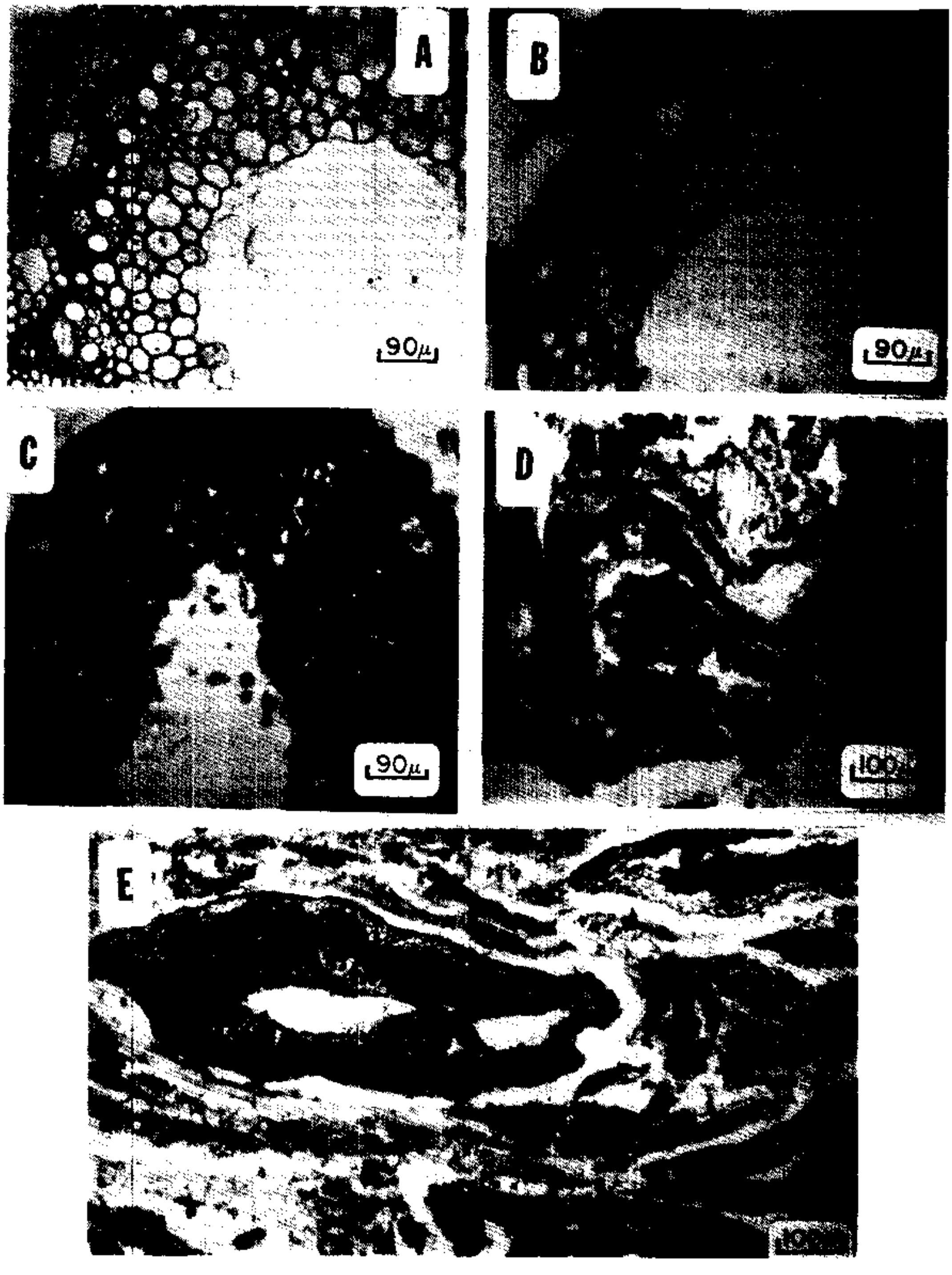

A
90μ
B
90μ
C
90μ
D
10μ
E
10μ

Figure 32. Stems and leaf sheaths of *Spartina patens*.

A. Photomicrograph of a modern section of a *S. patens* culm, the aerial stem. Compare the anatomy shown here with the line drawing of the stem in the previous figure. Although the anatomy is fundamentally the same, a range of features such as shown here does exist within most species.

B. Photomicrograph of a *S. patens* stem in the sediment. Compare this with the modern section in A.

C. Photomicrograph of a fusinized *S. patens* stem in the sediment. Diagnostic cell structure is retained. Compare this with sections in A and B.

D. Photomicrograph of leaf sheath fragments in a *S. patens* sediment thin section.

E. Photomicrograph of portions of five compressed *S. patens* stems in the sediment. This "cowlick" formation is a common feature of the high-marsh *S. patens* environment.

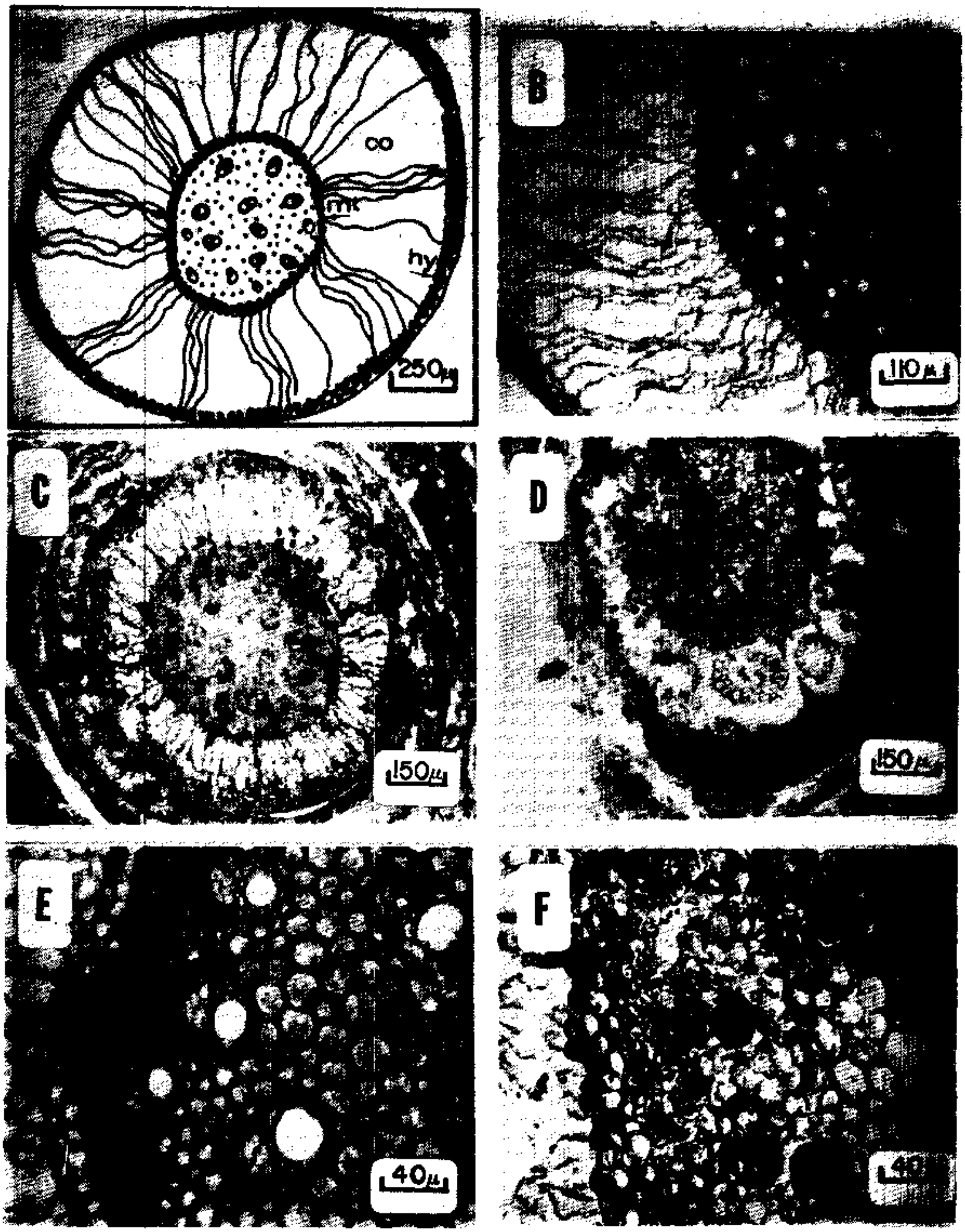

co
nk
hy
250μ
B
10μ
C
150μ
D
150μ
E
40μ
F
40

Figure 33. Stems and leaf sheaths of *Distichlis spicata*.

A. Line drawing of a *D. spicata* rhizome showing the solid stele with scattered vascular bundles, the cortex with lateral rays of cell fragments and large intercellular spaces (co), mechanical tissue (mt), hypodermis (hy) and epidermis (ep).

B. Photomicrograph of a portion of a modern *D. spicata* rhizome showing the features identified in A.

C. Photomicrograph of a *D. spicata* stem with several leaf sheaths (ls) in the sediment. The vascular bundles are filled with dark material. Note that the cortex is well preserved; this is an uncommon feature and suggests early infiltration of cells with some material that enhanced preservation.

D. Photomicrograph of a *D. spicata* stem in which younger roots have penetrated the weak cortex of the stem.

E. Detailed view of the modern stele of *D. spicata* showing vascular bundles and dark band of the endodermis (the dark color is due to biological staining).

F. Detailed view of a *D. spicata* stele in the sediment showing the same type of vascular bundles seen in E. As shown here, these bundles frequently contain cell fillings. Although the endodermis is not darkened in this photomicrograph, it often becomes "naturally stained" in the sediment.

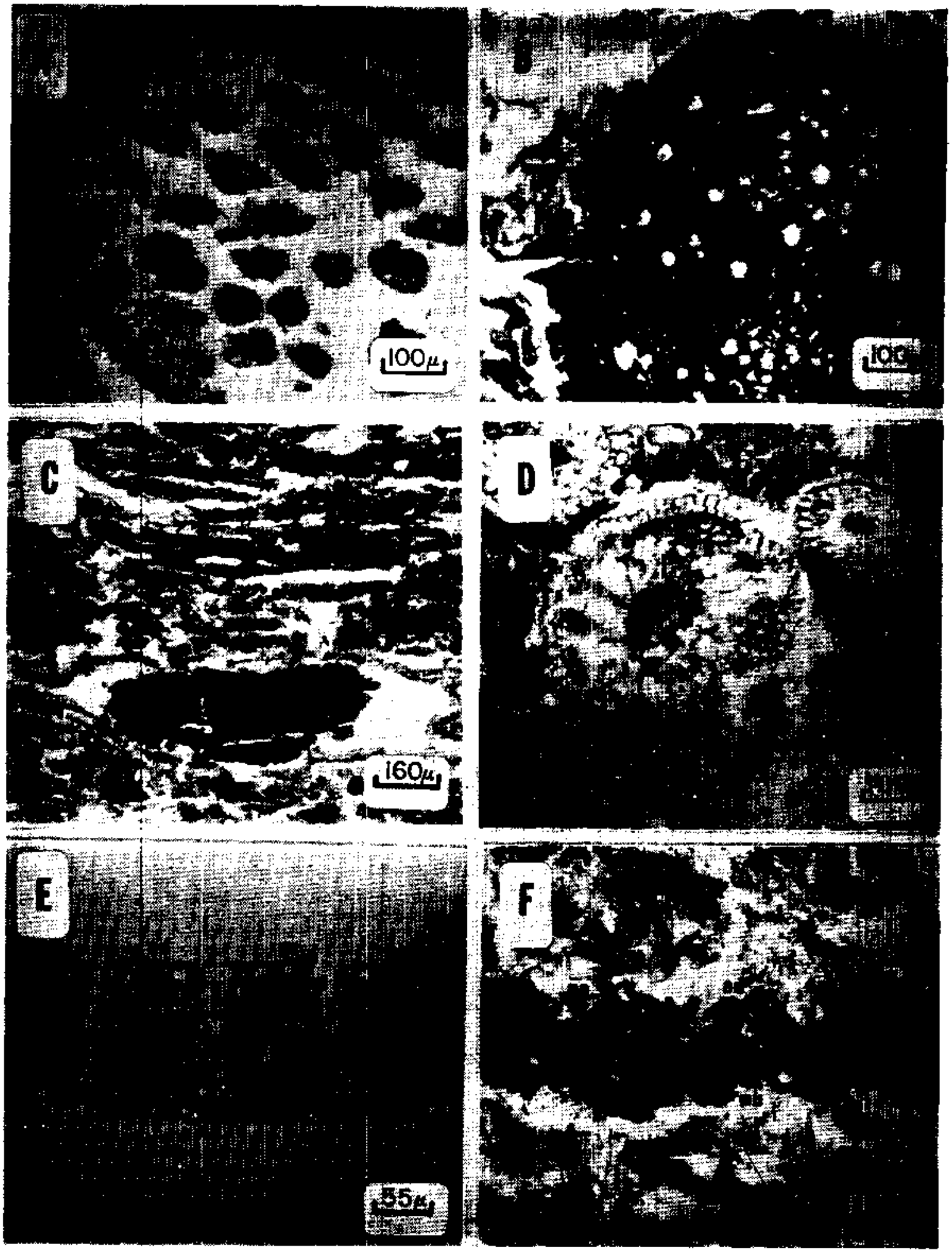

100μ
100
C
160μ
D
E
55μ
F

Figure 34. Steles, stems, roots, and leaves of Distichlis spicata.

A. Photomicrograph of an isolated stele of a D. spicata stem from a washover deposit of detrital organics. Fragments of organs, such as this, are often enough to allow positive identification of species.

B. Photomicrograph of a fusinized stele of a D. spicata stem showing vascular bundle cavities.

C. Photomicrograph of portions of four compressed D. spicata stems in the sediment. This "cowlick" formation is a common feature of the high-marsh D. spicata environment.

D. Photomicrograph of the high density of D. spicata roots characteristic of the high-marsh environment.

E. Photomicrograph of a modern leaf of D. spicata (abaxial surface, ab; adaxial surface, ad; papillae, pa).

F. Photomicrograph of a fusinized D. spicata leaf in the sediment. Compare this with the modern leaf in E and note the papillae (pa). Leaves are rarely present in high-marsh deposits.

Major components consist of stems and leaf sheaths. Fusinite is rare, and micrinite is rare to abundant.

Depositional environment. The high-marsh environments are covered only by spring high tides; thus they are exposed to aerobic oxidizing conditions during the greater portion of the tidal cycle. Also, they are less likely to receive sediment from tidal action than low-marsh environments. The high-decay cowlick sediment probably develops when tidal sedimentation is very low, conditions are dry (water table is low) and aerobic decay therefore is very high. The low-decay cowlick sediment is developed when the rate of accumulation of plant matter and/or inorganic sediments is high enough that surface litter is buried before it is highly decomposed. These conditions appear to be seasonal on the marsh. They could also be typical of longer-term climatic changes (in terms of years) or they could exist simultaneously on different portions of the high marsh. Preservation conditions are controlled by surface processes. The effects of tides are less than on the low marsh so that surface litter is less likely to be carried off, but the amount of aerobic decay is greater.

B. High-marsh root subfacies

Megascopic characteristics. These finely fibrous, strongly bound sediments contain a very dense network of large and small tan grass roots. The root morphologies are not well enough preserved so that they can be distinguished as to species, but the texture produced is very characteristic of this subfacies. A similar but distinctive texture is produced by brackish-marsh _Panicum_ sediments. Rhizomes and leaf sheaths of _S. patens_ and _D. spicata_ are common to abundant. Sediment color is brown to dark brown and mottles due to organic or inorganic inhomogeneity may be present. Organic mottles contain finely-fragmented organic debris such as that produced in the cowlick environment.

Microscopic characteristics (Figures 31, 32, 33, and 34). Framework composition consists of roots and rhizomes of _S. patens_ and _D. spicata_. The F/M ratio is consistently high. Most roots are very well preserved; yet some are highly decayed even though they appear to be in growth position.

Matrix is light brown to dark brown and finer-grained than in cowlick sediments. Light-brown matrices indicating low amounts of decay are very common. Fecal pellets are common. Fungal remains are common and cell fillings may be common locally.

Depositional environment. This sediment is a product of the subsurface high-marsh environment. Variations in preservation of roots in growth position may be related to the amount of oxidation of the sediment. Increased sediment oxidation can be caused by burrowing activity of organisms or lowering of the water table either due to seasonal or yearly dry conditions. Water-table fluctuations have been observed in this study and also by Redfield (1965) and Chapman (1940, 1974).

High-marsh root sediments may be interbedded with cowlick sediments or they may form a continuous sequence. The presence of interbedded sediments suggests a balance between surficial and subsurface sediment-forming processes. The continuous sequence indicates that surface litter either is being greatly reduced by high rates of decay or is being carried off the marsh.

Degradation. Types of degradation in *S. patens* and *D. spicata* are described in captions for Figures 31-34. Stems (culms and rhizomes) show the greatest variety of degradation. There are many similarities in decay patterns between *D. spicata* and *S. patens*. One major difference, though, is due to the basic anatomical differences in the cortex. Cortical cells in *D. spicata* break down readily even when the plant is living, and they are highly susceptible to decay. Cortical cells in *S. patens* have very different structure and are more resistant to decay.

Several stages of decay observed in stems and associated leaf sheaths are presented below:

1. Well-preserved sections of leaf sheaths are

tightly wrapped around the stem (Figures31E, 33C). The band of mechanical tissue between the cortex and stele darkens (Figure 32B). Vascular bundles retain distinct structure.

2. Stem and leaf sheaths become dissociated. Vascular bundles contain dark-red material (Figures31D, 33F). This material may migrate from another part of the same organ or it may be introduced from the outside. At this stage, the mechanical tissue may lose its color, and there may be some connection between the presence of filling material in vascular bundles and the lack of it in mechanical tissue. These patterns of degradation are very common.
3. The stele region of stems decay (Figure 33C). Cell structure is lost and tissue darkens. Compaction may occur (Figures32E, 33C). The entire vascular bundle may be removed from the tissue. Leaf sheaths fragment, lose their cell structure, and are orange brown.
4. Leaf sheaths appear as masses of strands in the sediment with very little to no cell structure preserved (Figure 32D).
5. Hypodermal layers appear to be very resistant to decay. The epidermis may be separated from

the hypodermis at an early stage or it may be retained until later stages of decay.

C. High-marsh and low-marsh transitional subfacies

Megascopic characteristics. These sediments contain roots and rhizomes of *S. alterniflora*, *S. patens* and *D. spicata* in varying proportions. They do not belong to either the *S. alterniflora* low-marsh subfacies or the high-marsh root subfacies. They possess characteristics of both, although they usually have a higher fiber content than *S. alterniflora* low-marsh sediments.

Microscopic characteristics. These sediments contain *S. alterniflora*, *S. patens* and *D. spicata* plant remains. Usually they are well-preserved, although fusinite is occasionally abundant and its presence suggests a burning of the marsh.

Depositional environment. Although *S. alterniflora* usually forms a monospecific community and *D. spicata*-*S. patens* associations are relatively pure, they do coexist. This association appears to be most common as a transition from low marsh to high marsh. Blum (1968) noted in a study of community structure on the Barnstable marsh, Massachusetts that *S. alterniflora*-*S. patens* were associated on 10% of the marsh and *S. alterniflora*-*D. spicata* on 0.6% of the marsh. Pure stands of *S. alterniflora*, *S. patens*, and *D. spicata* populated 32.2%, 39.9% and 12.0% of the marsh, respectively.

D. Rotten-spot subfacies

Megascopic characteristics. Rotten-spot sediments consist of a surficial layer or mat of blue-green algae 1-3 mm thick underlain by blue-black, highly-reduced sediment about 2 cm thick. Orange mottles may be present.

Microscopic characteristics (Figure 35). The most characteristic microscopic feature of rotten-spot sediments is the presence of masses of pennate diatoms. Laminations attributed to interbedded mud and blue-green algae occur also. Other matrix components include fecal pellets, mineral grains, cell and tissue fragments, cell fillings, and an occasional foraminifer. Pyrite is present 1-3 cm below the surface in rotten-spot environments, the only surficial environment in which it is consistently observed. Yet, fusinite and highly-decayed plant fragments are also common. Their presence may be due to dry, oxidizing conditions at the very surface of the rotten spot or they may be detrital. The first theory is favored because layering in this environment suggests that very different conditions exist within a distance of centimeters.

Depositional environment. The rotten spot is a type of salt-marsh pan (Chapman, 1974). These are areas in which the angiosperm vegetation dies off and is replaced by blue-green algal mats. Various theories as to why this occurs include: a. excessive salinity; b. water-logging

Figure 35. Sediments of rotten spots.

A. Photomicrograph of a rotten-spot thin section showing a mass of pennate diatoms.

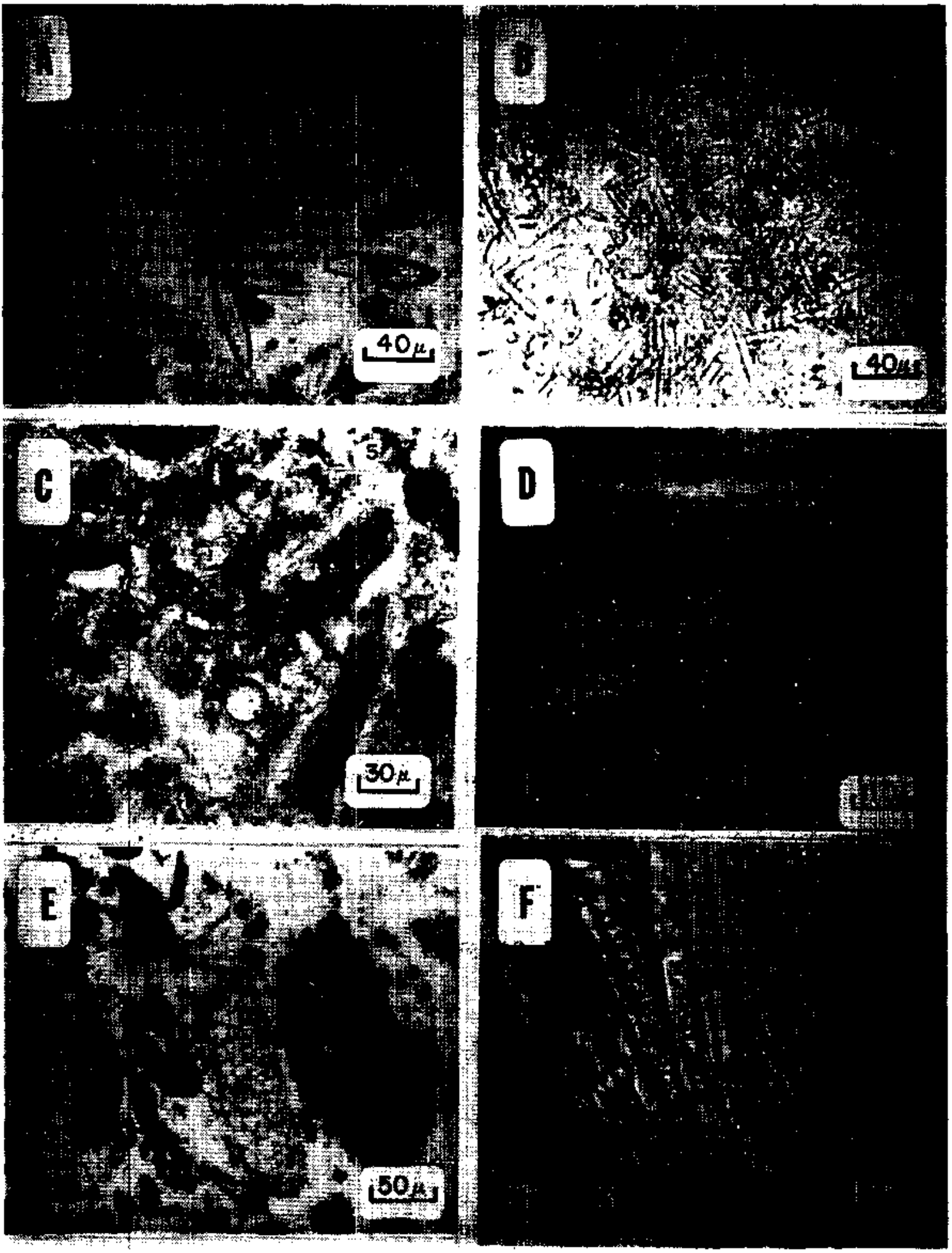
B. Photomicrograph of a rotten-spot thin section showing the abundance and low diversity of pennate diatoms.

C. Photomicrograph showing a variety of matrix components found in rotten-spot thin sections (centric diatom, 1; mineral grain, 2; iron sulfide coated bacteria?, 3; pyrite framboid, 4; tissue fragment, 5 .

D. Photomicrograph of a vertically-oriented thin section showing laminations, attributed to interbedded mud and blue-green algae.

E. Photomicrograph of a rotten-spot thin section showing cell fragments adjacent to fusinized plant fragments. Fecal pellets are also present here.

F. Photomicrograph of residual fiber cells in sediment thin section indicating the high amount of decay in the rotten-spot environment.


A
40µ
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D
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F

of roots in slightly depressed areas, especially where creek systems are poorly developed; c. vegetation trash that remains on the marsh and kills underlying plants; and d. wind-matted patches of flattened grass, ie., cowlicks (Chapman, 1974). It is difficult to determine what actually causes them. None of the above theories can be used confidently to explain rotten spots observed in this study. They do show extreme ranges in salinity but probably this is a secondary effect rather than a cause. They do develop on marshes which are poorly drained, but many poorly-drained marshes do not have rotten spots. There is contradictory evidence for the other two theories as well.

In any case, rotten spots are underlain by sediments of an earlier marsh environment. Rotten-spot sediments contain few macroscopic plant fragments. Erect dead basal culms of the previous marsh environment protrude through the algal mat. Rotten spots in this study have persisted for at least 5 years and show no signs of disappearing; yet they are considered "ephemeral" features compared to other marsh environments. Stratigraphic evidence of this environment would tend to be destroyed by roots of the overlying environment, although some evidence of the abundance of diatoms might persist.

E. Salicornia subfacies

Salicornia environments were sampled and thin sectioned, but there were no remains in macroscopic or microscopic analyses that could be attributed to *Salicornia*. There is never any surface litter accumulation in these environments. The root system is shallow and sparse. Highly-oxidizing conditions and high salinities characterize the environment. *Salicornia* also colonizes a very low percentage of the high marsh. For these reasons, it is highly unlikely that remains of *Salicornia* would be preserved, and if preserved, sampled.

F. *Baccharis* and *Iva* subfacies

Megascopic characteristics. *Baccharis* and *Iva* sediments can be studied best in tidal-flat outcrops of marsh sediments. The root systems and branches of these plants are exposed at low tide and are abundant when they occur.

Microscopic characteristics (Figures 36 and 37). Stems and leaves of *Baccharis*, *Iva* and *Limonium* are found occasionally in sediment thin section. Most are highly decomposed.

Depositional environment. *Baccharis*, *Iva* and *Limonium* populate the upland border of the high marsh. Their tap root systems are the most likely portion of the plant to be preserved. Most leaves decompose on the branches, but those that do fall on the marsh surface may be buried and preserved.

Baccharis and *Iva* are recognized easily in outcrop

Figure 36. Stems of *Baccharis halimifolia*.

A. Photomicrograph of a cross section of a modern *B. halimifolia* stem (cortex, co; xylem, xy; pith, pi).

B. Photomicrograph of a *B. halimifolia* stem in a sediment thin section (xylem, xy; pith, pi).

C. Close-up of xylem of a modern *B. halimifolia* stem.

D. Close-up of xylem of a *B. halimifolia* stem fragment in the sediment. Compare this with the modern section in C.

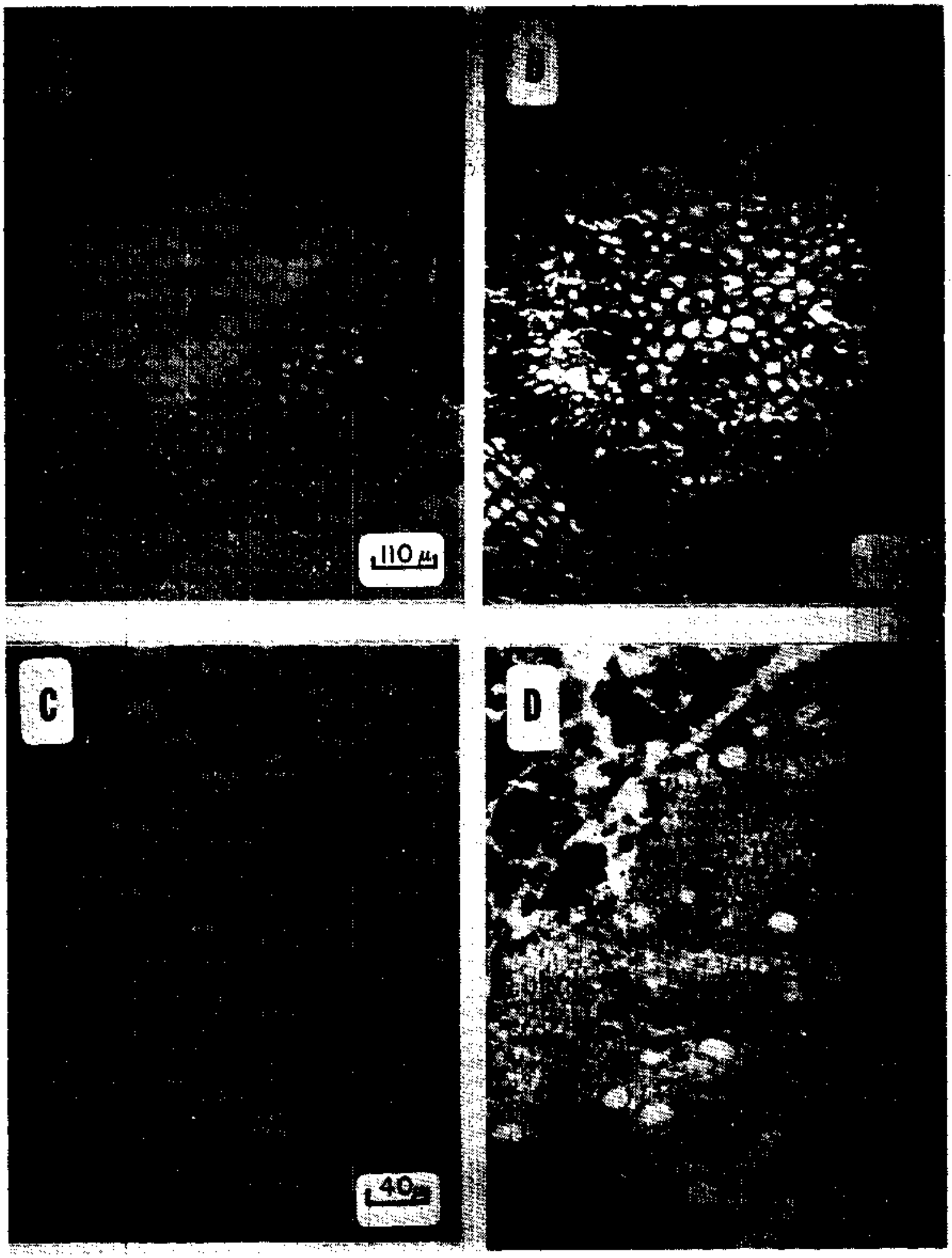

110 µ
C
40 µ
D

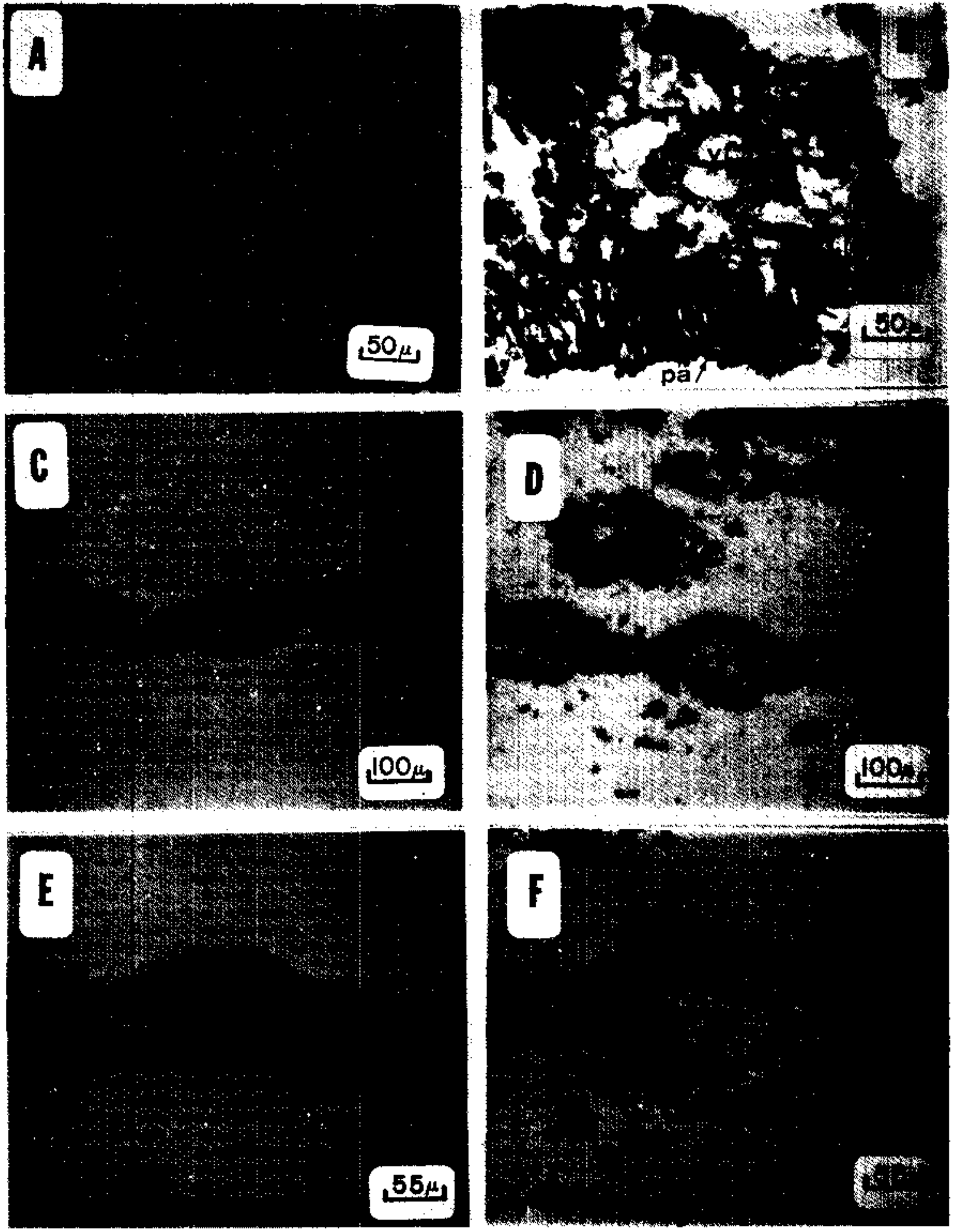
Figure 37. Leaves of *Baccharis* *halimifolia* and *Limonium* *carolinianum*.

A. Photomicrograph of a cross section of a modern *B. halimifolia* leaf (palisade layer, pa; vascular tissue, vt).

B. Photomicrograph of a *B. halimifolia* leaf fragment in the sediment (palisade layer, pa; vascular tissue, vt). Compare this with the modern section in A.

C. Photomicrograph of a cross section of a modern *L. carolinianum* leaf.

D. Photomicrograph of a *L. carolinianum* leaf in the sediment. Compare this with the modern section in E.


A
50μ
y
50μ
pa
C
100μ
D
100μ
E
55μ
F

exposure, yet, they do not actually form a marsh facies that can be described in thin section. Although these plants commonly grow in a narrow border along the upland edge of the high marsh, they actually grow amongst the common high-marsh plants, *D. spicata* and *S. patens*. Therefore *Baccharis*, *Iva* and *Limonium* remains are found usually as a component in high-marsh facies. Their presence is important because it indicates deposition near the upper limit of the tidal range.

III. Marsh-Pond Facies

Marsh ponds form in low-marsh, high-marsh, brackish-marsh and fresh-water marsh systems. They are defined in this study as large (>20 m diameter), usually deep (>20 cm) ponds which contain water during most, if not all, of the year. They do not support any vascular plant vegetation, except around the pond edge. Figure 3A illustrates ponds in the Primehook brackish marsh.

Megascopic characteristics. Marsh-pond sediments consist of layers of detrital organics. These plant fragments appear highly decayed and may be desiccated. Colors range from dark brown to black. Inorganic composition is usually low but strongly related to proximity of other environments such as upland forested regions.

Microscopic characteristics. Plant fragments are highly decayed and rarely can be identified to species.

Remains of Hibiscus, Phragmites and D. spicata have been identified. Micrinite is abundant and fusinite is common, reinforcing the theory that these sediments were desiccated and exposed to oxidizing conditions.

Depositional environment. The marsh ponds studied have firm floors, are 20-50 m in diameter, and contain ponded water 30 cm or more in depth during most of the year. Salinity is no more than 3 $^{o}/_{oo}$. Hibiscus, Phragmites and other vegetation fringe the pond. These ponds are visible on a 1917 topographic map in Primehook marsh and were probably in existence before then.

IV. Phragmites Facies

Phragmites is abundant in coastal marshes (Figure 38). Its distribution does not appear to be restricted by salinity or sediment type. Phragmites is 2-4 m tall, has a stout culm 8-20 mm in diameter, and long, narrow (2-3 cm) leaves. The rhizome system is large, stout (8-20 mm dia.), creeping, and may extend 50 m or longer (Waisel, 1972).

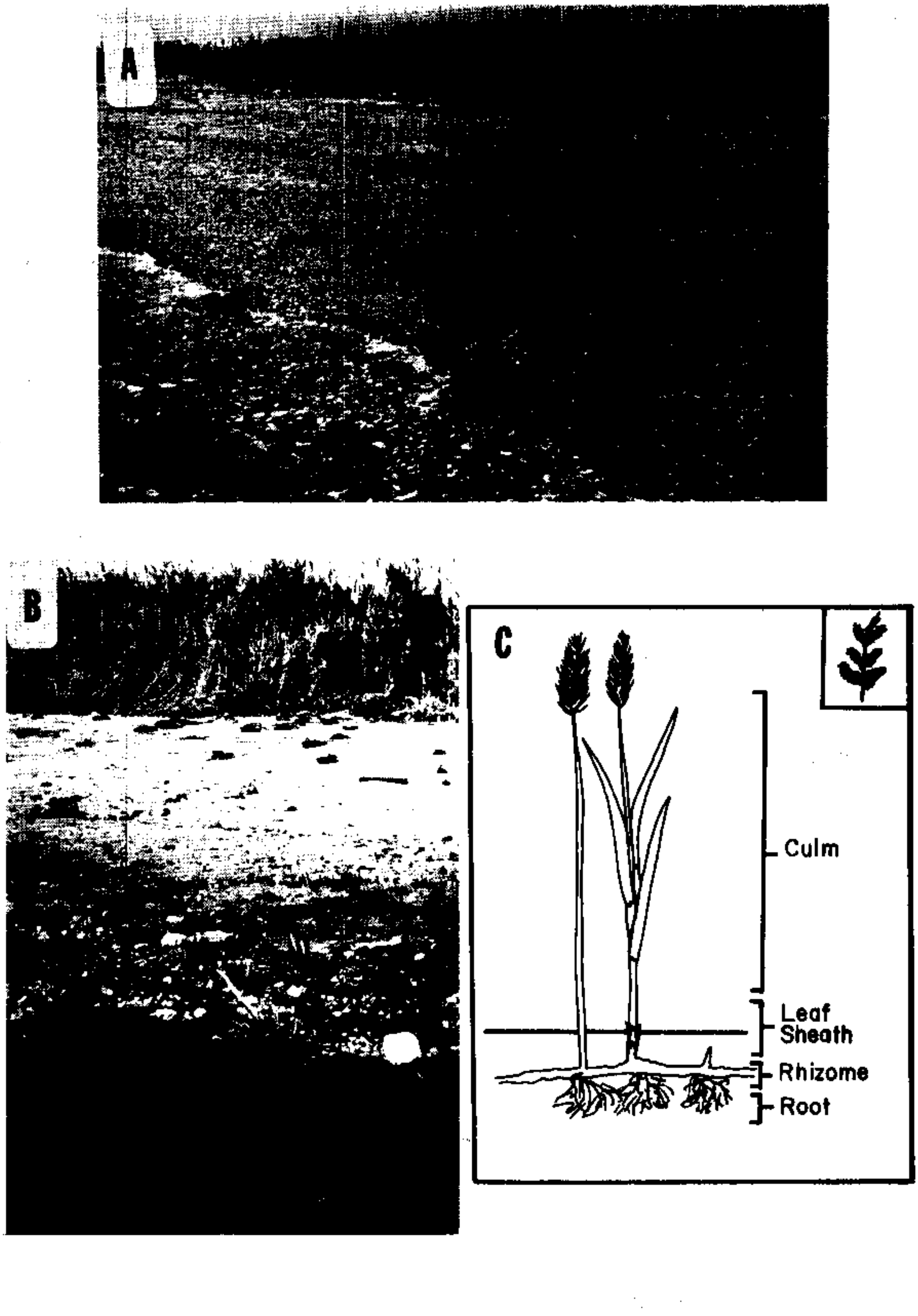
Megascopic characteristics. P. communis sediments are commonly, but not necessarily, sandy. They are coarsely fibrous, yet quite inhomogeneous in composition. Some parts are very cohesive and bound by roots while others are loose and appear composed of highly-decayed organics. There are

Figure 38. *Phragmites communis* vegetation.

A. Photograph showing the fringe of *P. communis* landward of a sandy estuarine barrier along Delaware Bay (plant height approximately 2 m).

B. Photograph showing *P. communis* fringe, sandy barrier and tidal flat consisting of a relict marsh containing *P. communis* roots and rhizomes.

C. Line drawing of the morphology of *P. communis* (1 to 4 m tall). Leaf sheaths extend up along the culm to the abscission zone which marks the junction of the leaf sheath and the leaf. Insert shows the inflorescence of *S. cynosuroides*, a plant of the same dimensions as *P. communis*.


A
B
C
Culm
Leaf Sheath
Rhizome
Root

lenses or pods of sand, mud, and fine organic debris within the fibrous root network. Sandy sediment may contain orange mottles. Leaf sheaths are common and frequently orange. Others are black. Rhizomes are rigid, hollow in the center (except at nodes) and large, up to 20 mm in diameter. Large roots have diameters of 2 mm and are flaccid. Roots and rhizomes are usually tan.

Microscopic characteristics (Figures 39 and 40). Framework composition consists of roots, stems (probably mostly rhizomes) and leaf sheaths of *P. communis*. Leaves are present occasionally. Large tissue fragments with the long and short cell pattern of grasses are common. Roots and rhizomes can be either decayed or well preserved.

The matrix is well developed and contains both abundant organic and inorganic components. Organic fine granular debris with colors ranging from dark gray to dark red brown suggest high decay. This observation is strengthened by the presence of fungal spores and other fungal remains. Sclerenchyma fibers are present as are cell fillings. This sediment type is one of the few that consistently contain cell fillings, which suggests that these cell fillings are derived from *Phragmites*. Fecal pellets are common, especially the large type. F/M ratios are variable. Some sediments are dominated by highly-decomposed, finely-fragmented organic sediment, probably related to surface litter formation, and others contain a high percentage of roots and rhizomes. Pyrite is abundant in samples taken from tidal-flat exposures.

Degradation. Types of degradation are described in captions for Figures 39 and 40. Leaf sheaths show stages of degradation similar to those seen in *S. alterniflora*. *P. communis* stems show degradation patterns similar to those described for *D. spicata* and *S. patens* stems.

In an electron microscope study of *Phragmites*, Stewart and Follett (1966) observed that fresh leaves contained wax projections on the surface. When these wax projections are present, cell-wall outlines and stomata are clearly defined. In year-old leaves on standing culms, wax projections are absent but cell details remain. As soon as the material becomes part of the surface litter, cell-wall features lose considerable detail. Very little change was noted with depth. In decomposition studies of *Phragmites*, Tyrawski (1977) observed that the breakdown of plants into surface litter is due to leaching and microbial activity rather than to physical processes or macroorganism activity.

Depositional environment. *P. communis* forms an elongate fringe of vegetation behind sandy washover barriers along Delaware Bay. It also populates large expanses of marsh in exclusion of other species in many parts of the

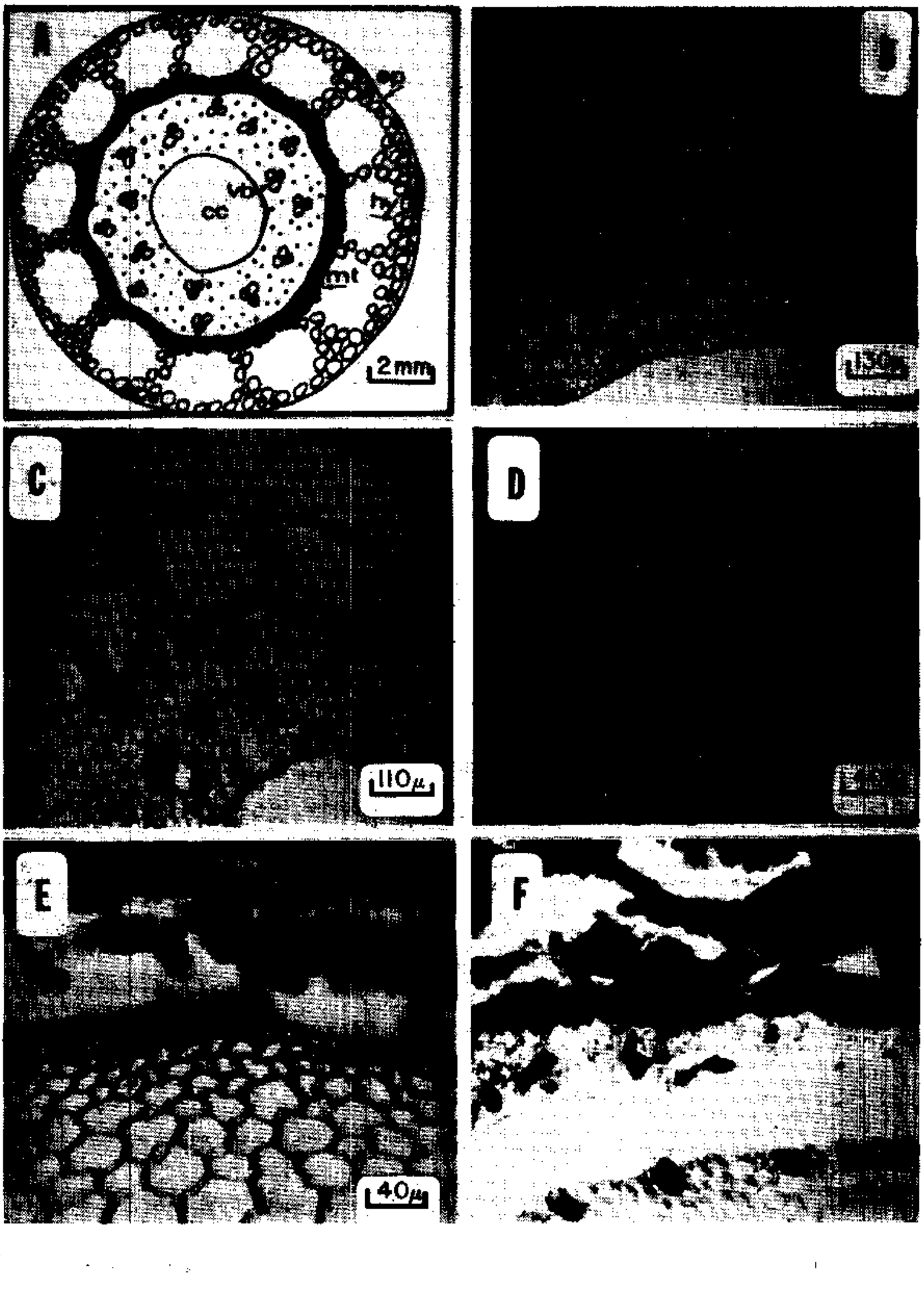

A
vb
cc
hy
mt
2mm
B
130μ
C
110μ
D
E
40μ
F

Figure 39. Stems of Phragmites communis.

A. Line drawing of a P. communis stem showing the large central cavity of the stele (cc), vascular bundles of the stele (vb), mechanical tissue (mt), cortex with large intercellular spaces (ic), a multi-layer hypodermis (hy) and an epidermis (ep).

B. Photomicrograph of a portion of a modern P. communis stem (rhizome). Compare this with the line drawing in A.

C. Photomicrograph of a portion of a P. communis stem in the sediment. Compare this with the modern section in B. Vascular bundles are filled with dark material.

D. Detail of the modern epidermis of a P. communis rhizome showing a single layer of thick-walled cells.

E. Detail of the epidermis of a P. communis stem in the sediment. Many of the thick-walled cells are filled with dark material; these cell fillings are not present in the hypodermis. Compare this with the modern epidermis in D.

F. Detail of the epidermis of a P. communis stem in the sediment. The epidermal cells are all filled with dark material producing a distinctive "beaded" pattern. The thick-walled pattern present in the modern section is not noticeable. The epidermal band is separated from the hypodermis. Compare this with the modern section in D and the earlier stage of degradation in E.

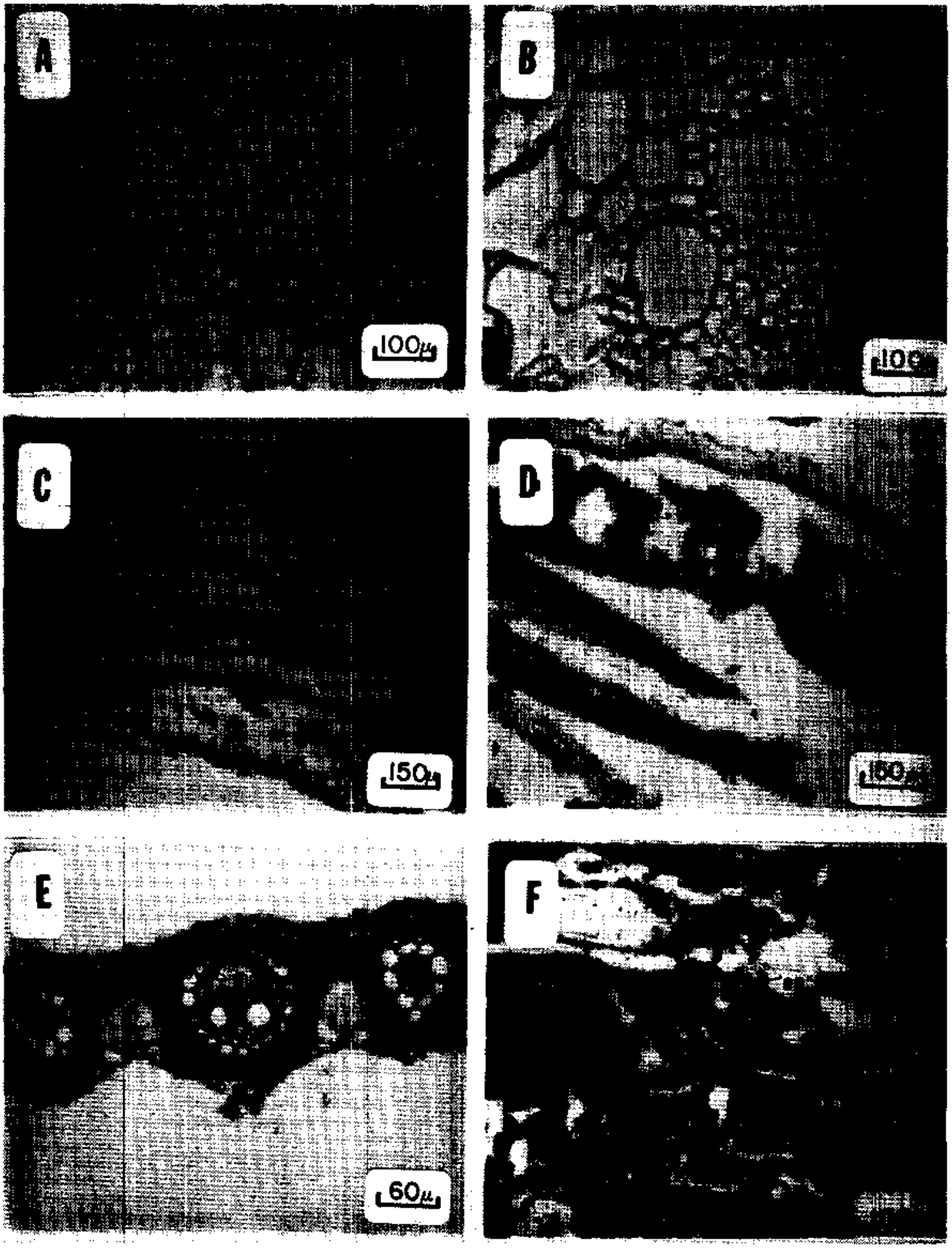

A
100μ
B
100μ
C
150μ
D
150μ
E
60μ
F

Figure 40. Vascular bundles, leaves, and leaf sheaths of *Phragmites communis*.

A. Close-up photomicrograph of a vascular bundle of a modern *P. communis* rhizome.

B. Close-up of an isolated *P. communis* vascular bundle in the sediment. Compare this with the modern section in A.

C. Photomicrograph of modern *P. communis* leaf sheaths. Note the asymmetrical position of vascular bundles on the sheaths in contrast to the central position of vascular bundles in *S. alterniflora* (vascular bundle, vb).

D. Photomicrograph of a *P. communis* leaf sheath in the sediment (vascular bundle, vb). Compare this with the modern section in C.

E. Photomicrograph of a modern *P. communis* leaf.

F. Photomicrograph of a *P. communis* leaf in the sediment. The epidermis (ep) and vascular bundles (vb) can still be recognized. Compare this with the modern section in E.

state. The back-barrier P. communis marsh is dry and experiences sporadic inundation by bay waters during storms, spring high tides, and under strong onshore wind conditions. Surface litter is often 50 cm or more thick and consists of previous years' growth and other detrital material carried in by tides and waves. Culms of Phragmites are structurally rigid and remain standing at least a year. When exposed on the surface, even the more resistant portions of plants are decayed and incorporated as matrix material. This provides a large volume of organic material for aerobic decay. The aerial organs (culms and leaves) provide decomposition products of cells and tissue fragments, cell fillings, and fine granular debris to the sediment containing roots and rhizomes. Some roots and rhizomes show evidence of decay which suggests that oxidizing conditions may exist with the more porous sandy sediment.

V. Brackish-Marsh Facies

Brackish-marsh environments are characterized by a greater variety of species with a more complex species distribution than salt marshes. Brackish-marsh vegetation patterns along Chesapeake Bay have been studied by Kerwin (1966) and Flowers (1973). These studies suggest that Chesapeake Bay brackish marshes have plant associations that are similar, but not identical, to those along Delaware Bay. Some of the most extensive brackish marshes in Delaware form along major tidal rivers tributary to Delaware Bay. The marshes along the tidal rivers support vegetation which is adapted to bay-water salinities near the mouth and progressively less saline waters upstream (Figure 41).

Along much of the tidal river, the low marsh on the stream bank is populated by *S. alterniflora*. The vegetation on the river levee consists of a variety of plants such as *Hibiscus*, *Kosteletzkya*, *Phragmites* and *S. cynosuroides*. The back-levee marsh, at slightly lower elevation, is populated by pure to mixed stands of *Scirpus*, *Juncus*, *Panicum*, *S. patens* and others. *Typha* is found in low areas that have ponded water. In the upper reaches of the tidal river, the leafy marsh plants *Peltandra* and *Pontederia* replace the grasses, sedges and rushes.

Scirpus has a sharply triangular culm 5-10 mm in diameter, a pronounced sheathing base, a solid, round rhizome 4-8 mm in diameter, and a shallow adventitious root system. The rhizome of *S. robustus* forms tubers. *Panicum virgatum* has an erect culm with narrow leaves, a solid rhizome 4-8 mm in diameter, and a shallow but dense adventitious root system. The dicots *Hibiscus* and *Kosteletzkya* have similar morphologies. Both have tough stems 1-2 cm in diameter, and a well-developed root system that extends at least 30 cm into the sediment. The plants

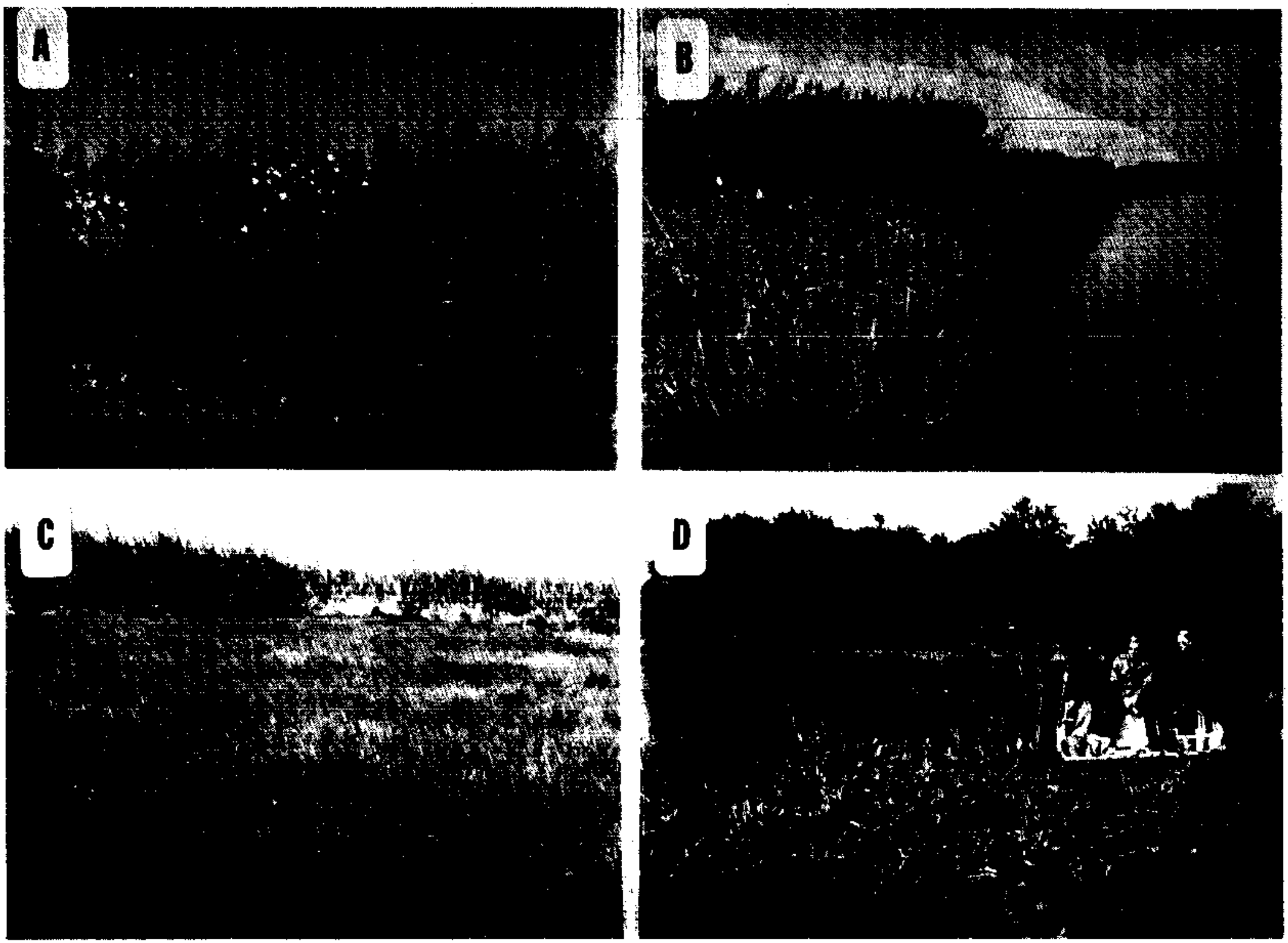
Figure 41. Vegetation and environments of the brackish marsh.

A. Photograph of bank and levee vegetation on the Smyrna River, a major tidal river along Delaware Bay. The low marsh on the river bank is populated by *S. alterniflora*. The vegetation on the higher levee consists of *H. palustris*, *K. virginica* and *S. cynosuroides*.

B. Photograph of bank and levee vegetation along the Smyrna River. *S. alterniflora* populates the lower bank environment and *H. palustris*, *B. halimifolia*, and *P. communis* populate the river levee here.

C. Photograph of the back-levee marsh populated by *S. patens* in the foreground and a pure stand of *S. cynosuroides* in the background. The Smyrna River is to the right of the photograph.

D. Photograph of a *Peltandra* sp. community along the upper reaches of the Smyrna River.


A
B
C
D

stand about one meter tall. *S. cynosuroides* has the same dimensions as *P. communis*. The culm and rhizome have hollow centers (8-20 mm dia.) and large and small roots which extend 30-60 cm into the sediment. *Polygonum* is 30 to 100 cm tall with a very fine, hairlike root system. *Atriplex* is an annual herb, 25-100 cm tall, with a short root system. It is a minor component in coastal marshes. *Typha* has similar dimensions to those of *P. communis* and *S. cynosuroides*. It has a solid stem and adventitious root system. *Juncus* is up to 150 cm tall and wiry. The leaf sheath extends about one-third the way along the rigid stem and the leaf blade is stiff. The underground portion consists of slender, hollow center, elongate rhizomes and fibrous roots.

Figures 42-49 illustrate some of the anatomical features of these brackish-marsh plants in both modern and sediment thin sections. These figures will be referred to in the following discussion.

A. Salt-marsh and brackish-marsh transitional subfacies

Megascopic characterisitics. Transitional sediments are fibrous and have intermediate fiber contents. Remains of *S. patens*, *D. spicata*, *S. alterniflora*, and *Scirpus* may be identified. Salt-marsh fragments are usually tan; *Scirpus* fragments are usually red brown to black. The triangular culm of *Scirpus* and the rhizome tuber of *S. robustus* are easy to recognize.

Microscopic characteristics. Roots, rhizomes, and leaf sheaths are common to abundant in thin section. Roots of the sedge, Scirpus are easily distinguished from grass roots (Figure 44). Leaves are more common than in salt-marsh sediments. Larger Juncus fragments may be present. Fusinite is common locally. Some horizons show evidence of high decay, and fungal remains are present. Large fecal pellets are common.

Depositional environment. Spartina-Distichlis marshes with minor amounts of the typical brackish-marsh plants such as Scirpus and Typha are common along the Delaware Bay coast. These plant associations may be seasonal (occurring late in the growing season) or may vary from year to year. Salinities recorded in this study vary from 8-15 $^{o}/_{oo}$ with most frequent values at 11 $^{o}/_{oo}$. This transitional marsh may be located in a band landward of the back-barrier Phragmites marsh or it may cover a large expanse of marsh.

B. Tidal-river levee subfacies

Megascopic characteristics. Tidal-river levee sediments are coarsely fibrous, loosely bound, and usually sandy. Fiber contents are low to intermediate. Sediments are light to dark brown depending upon the sand content and both dark-colored and orange mottles may be present. Culms of Scirpus, tap roots, and grass roots can be recognized.

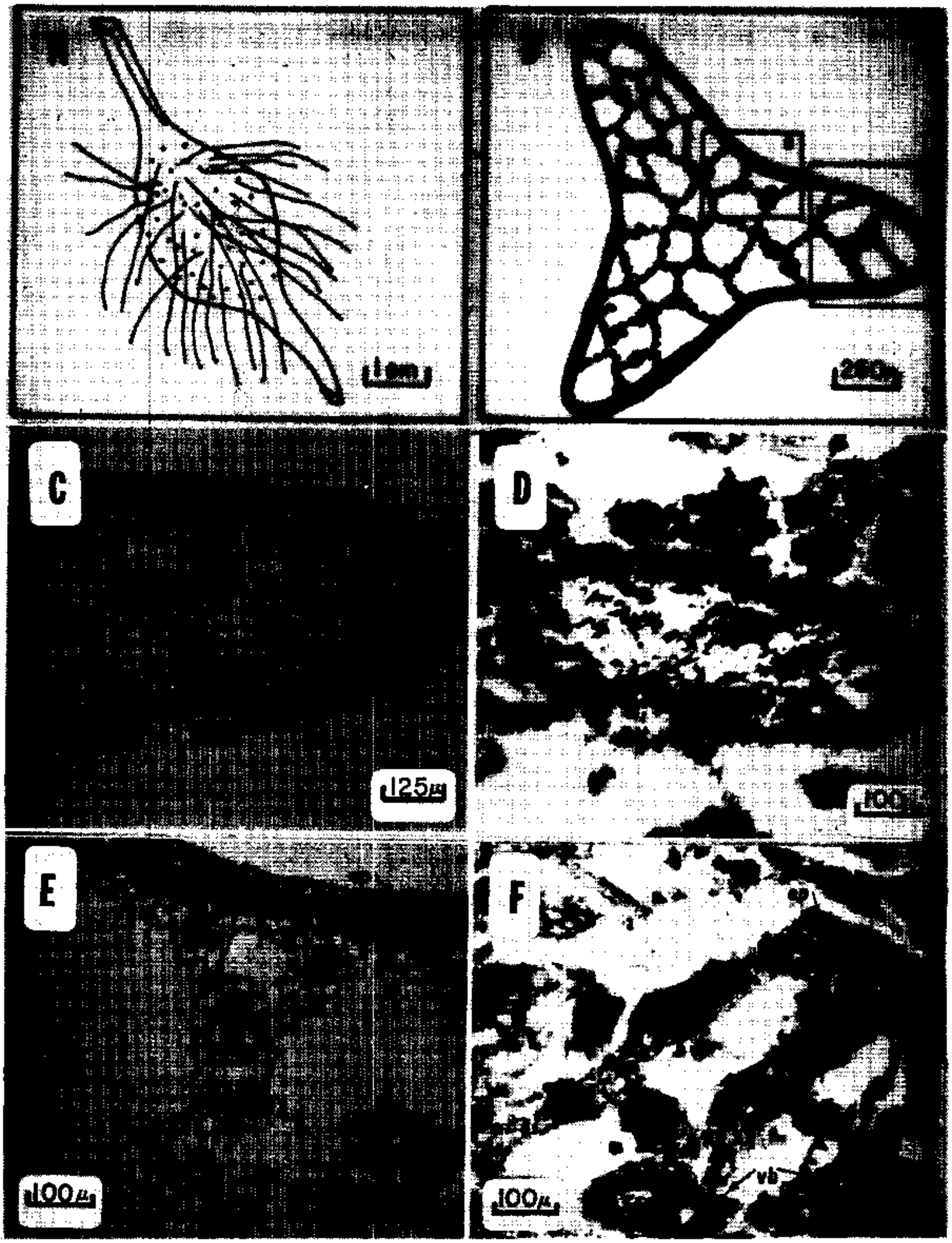

C
125μ
D
100
E
100μ
F
100μ
vb

Figure 42. Tuber and stems of Scirpus spp.

A. Line drawing of a Scirpus robustus tuber.

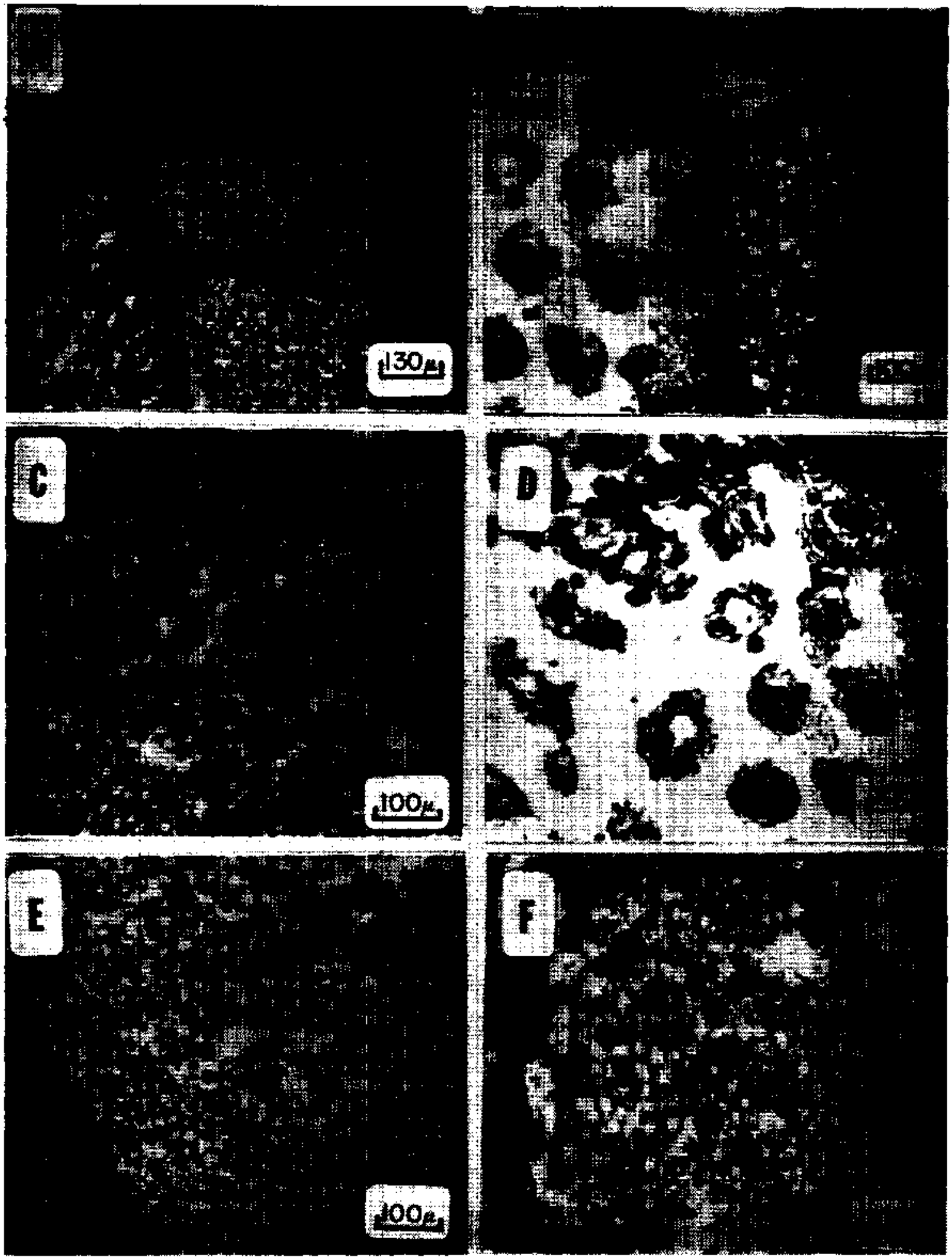
B. Line drawing of a Scirpus sp. stem. The common name, "three square" refers to the triangular shape of the stem. Relative locations of photographs C and E are indicated on the drawing.

C. Photomicrograph of a portion of a modern Scirpus americanus stem. General location of section is noted in the line drawing in B.

D. Photomicrograph of a portion of a fusinized Scirpus sp. stem in the sediment. The large intercellular spaces and open network of cells are apparent. Compare this with the modern section in C.

E. Photomicrograph of a portion of a modern S. americanus stem (epidermis, ep; vascular bundle, vb). General location of section is noted in the line drawing in B.

F. Photomicrograph of a portion of a Scirpus sp. stem in the sediment. Note the same open network of cells and positioning of vascular bundles as seen in modern section in E (epidermis, ep; vascular bundle, vb;).



130μ
C
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D
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Figure 43. Rhizomes, vascular bundles, and cortex of Scirpus spp.

A. Photomicrograph of a modern S. americanus rhizome (cortex, co; stele, st).

B. Photomicrograph of a Scirpus sp. rhizome in the sediment (cortex, co; stele, st). Compare this with the modern section in A.

C. Detail of the vascular bundles in the stele of modern S. americanus.

D. Detail of the vascular bundles in the stele of Scirpus sp. in the sediment. The multi-layered bundle sheaths are distinctive and appear to be more resistant to decay than other portions of the stele. Compare this with the modern section in C.

E. Detail of the cortex of modern S. americanus.

F. Detail of the cortex of Scirpus sp. in the sediment. Note the presence of dark-colored (red) cell fillings in both modern section (E) and sediment section.

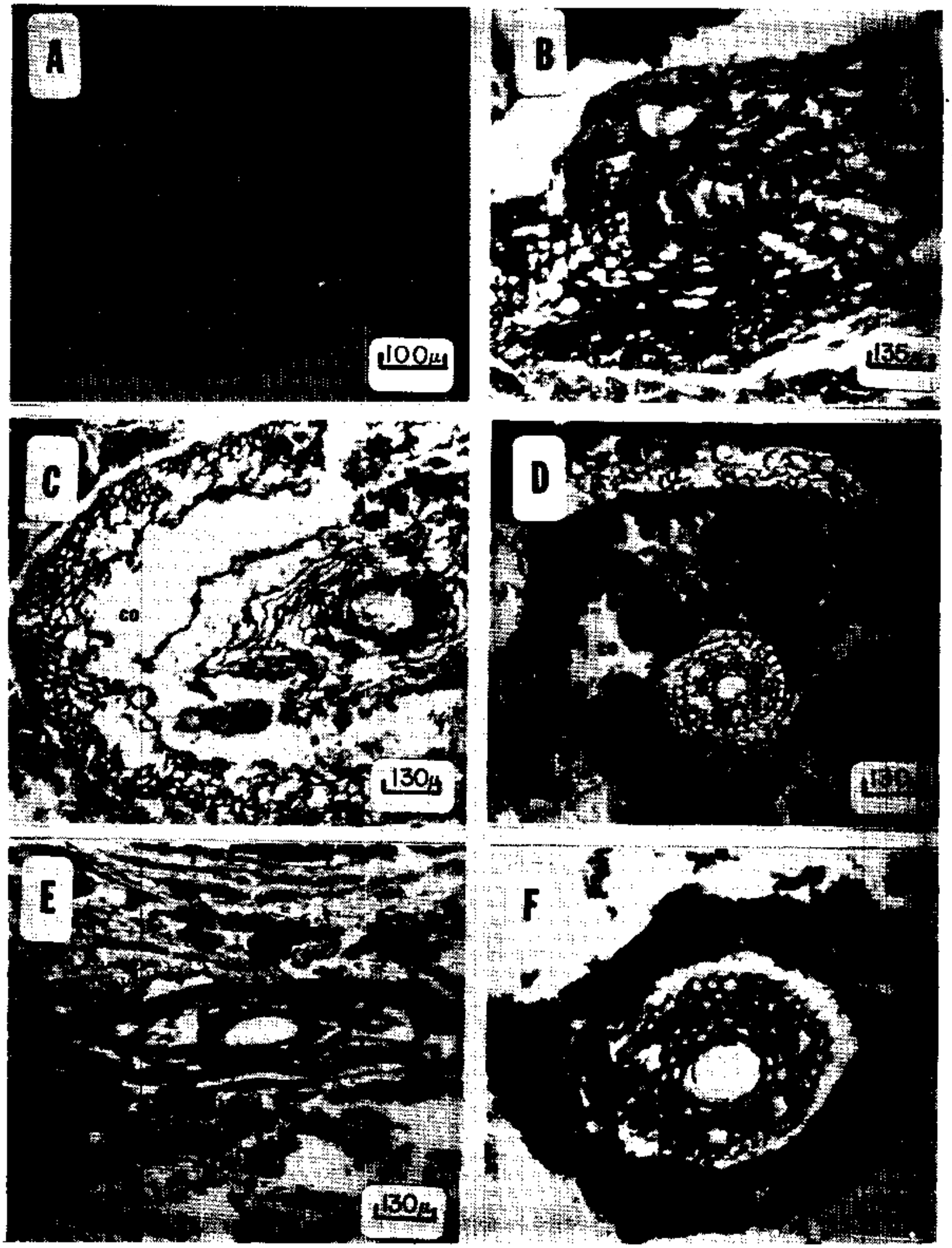

A
100μ
B
135μ
C
co
130μ
D
E
130μ
F

Figure 44. Roots of Scirpus spp.

A. Photomicrograph of a modern S. americanus root (co, cortex). Note the single central lacuna. The dark band of the stele is usually retained in roots found in the sediment.

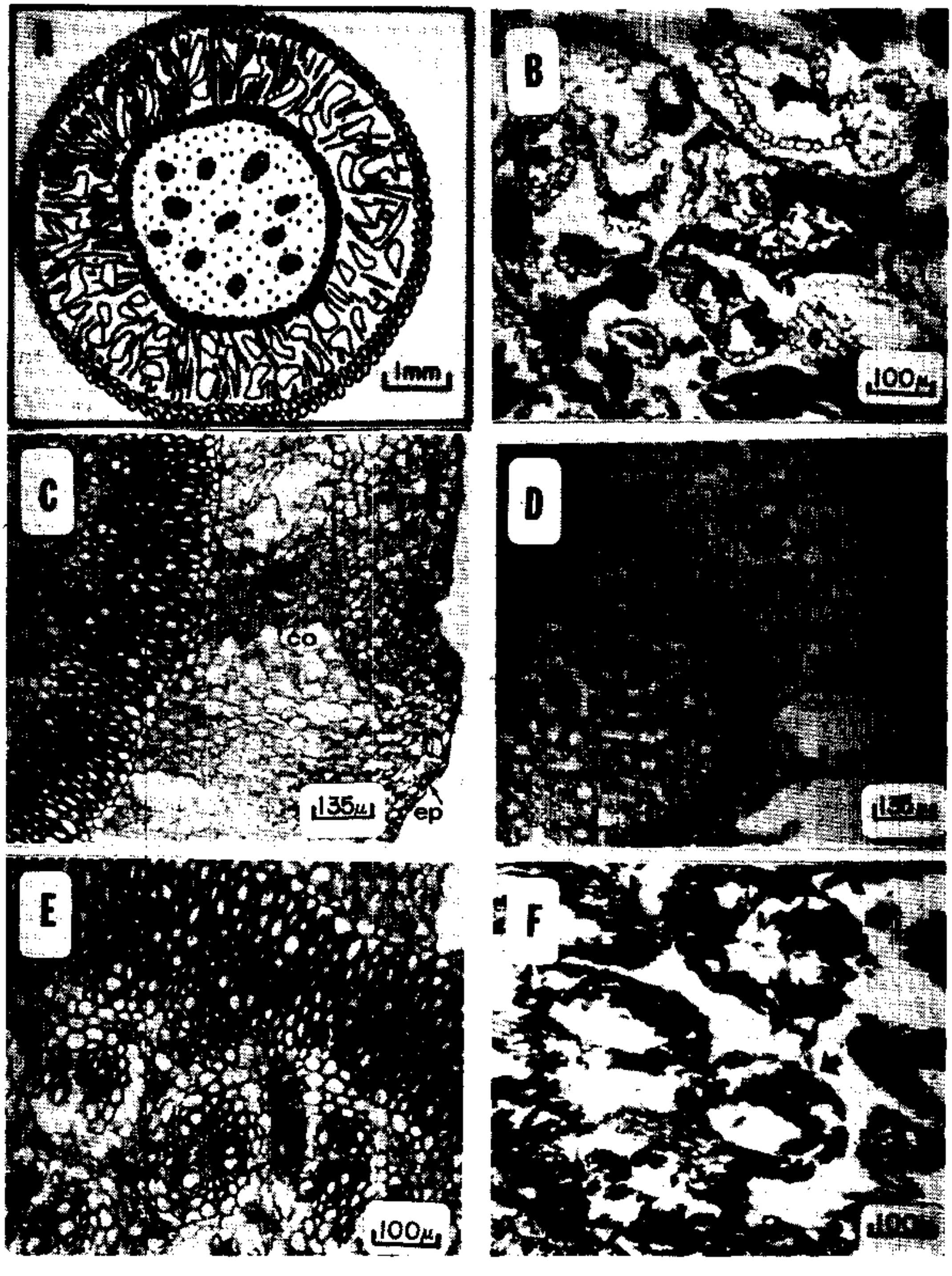
B. Photomicrograph of Scirpus sp. root in the sediment. Most of the features of the modern root (A) are preserved.

C. Photomicrograph of a Scirpus sp. root in the sediment. The cortex (co) has decayed but the dark band of the stele is well defined. Compare this with the modern section in A.

D. Photomicrograph of a Scirpus sp. root in the sediment. The cortex (co) is entirely removed and replaced with sediment. The stele and hypodermis appear "bleached". Compare this with the modern section in A.

E. Photomicrograph of a compressed Scirpus sp. root in the sediment. Most of the stele has been removed but the dark band is well defined. Compare this with the modern section in A.

F. Close up photomicrograph of an isolated stele of a Scirpus sp. root in the sediment. Compare this with the modern section in A.


1mm
B
100μ
C
co
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ep
D
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E
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F
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Figure 45. Stems and roots of _Panicum virgatum_.

A. Line drawing of a _P. virgatum_ stem.

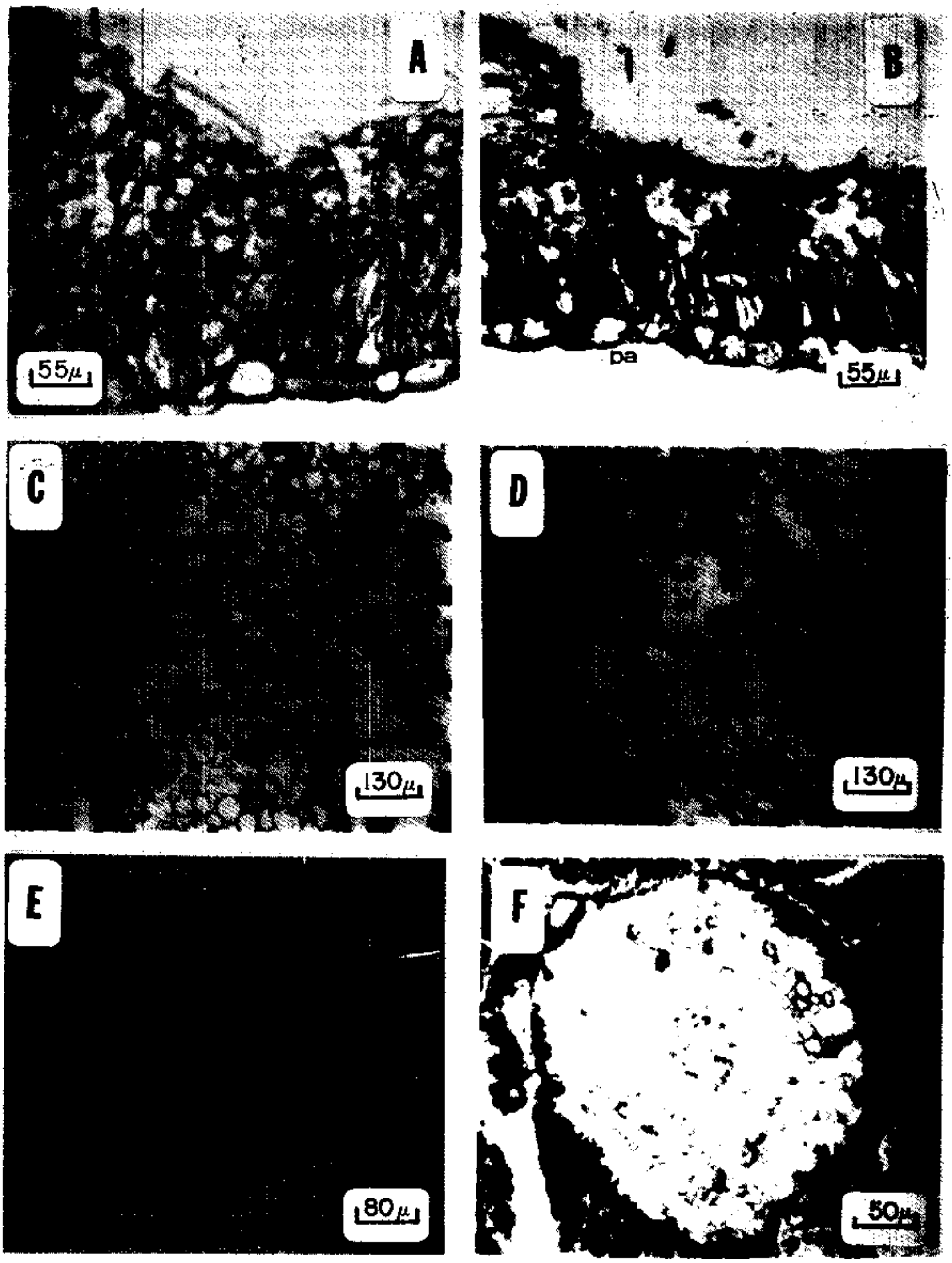
B. Photomicrograph of the dense interlocking network of _P. virgatum_ roots in sediment thin section.

C. Photomicrograph of a portion of a modern _P. virgatum_ rhizome in cross-section (epidermis, ep; hypodermis, hy; cortex, co; mechanical tissue, mt; stele, st). Close up shown in E.

D. Photomicrograph of a portion of a _P. virgatum_ stem in the sediment (hypodermis, hy; cortex, co; mechanical tissue, mt; stele, st). Compare this with the modern section in C.

E. Close up of modern _P. virgatum_ vascular bundles. Arrow points to the series of sheaths around the bundles.

F. Close up of a _P. virgatum_ vascular bundle in the sediment. Xylem and phloem tissues are removed; the arrow points to the series of sheaths around the bundles. These sheaths are now dark bands. Compare this with the modern section in E.


A
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55µ
C
130µ
D
130µ
E
80µ
F
50µ

Figure 46. Leaves, stems, and roots of Hibiscus palustris.

A. Photomicrograph of a modern H. Palustris leaf (palisade layer, pa).

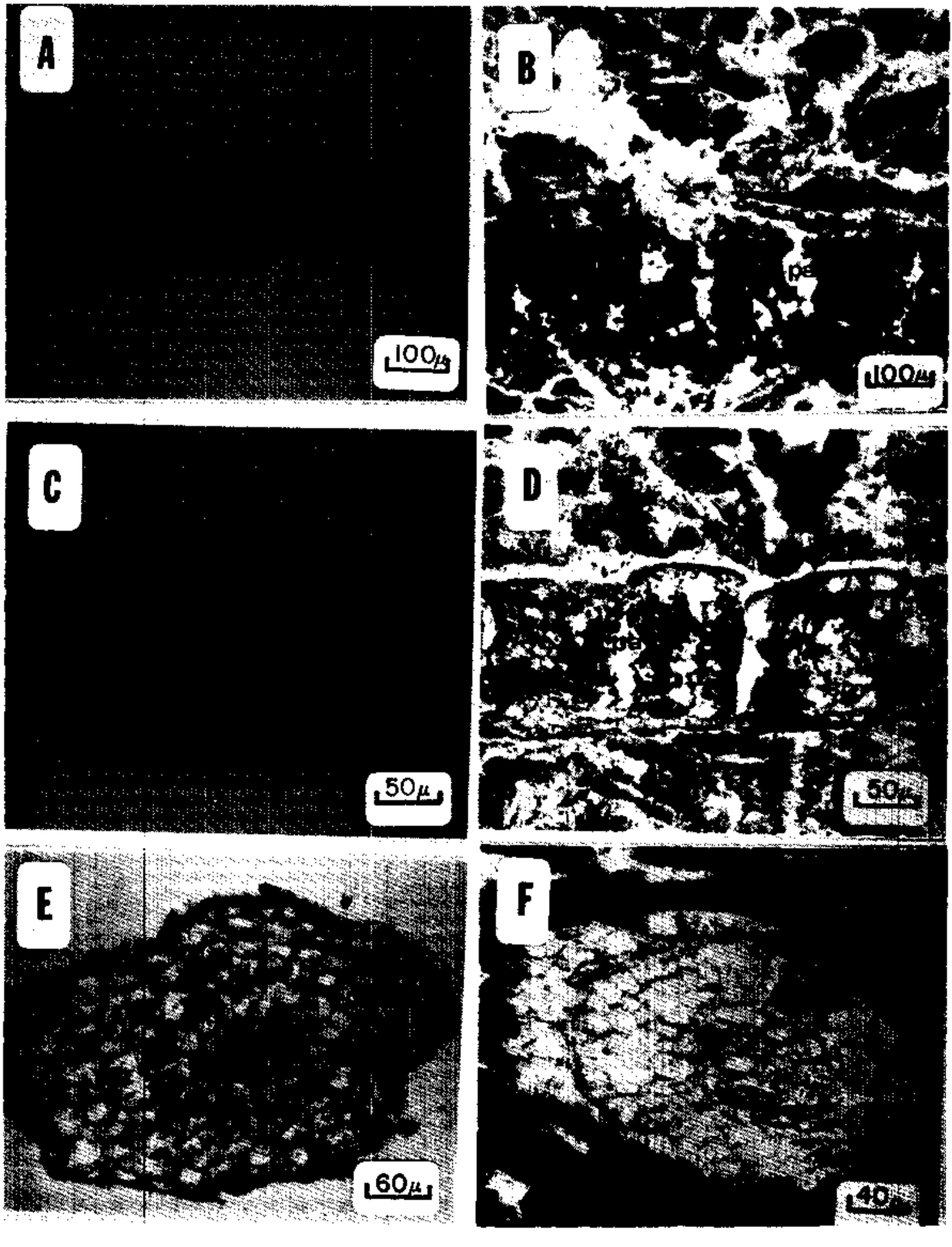
B. Photomicrograph of a H. palustris leaf in the sediment (palisade layer, pa). Compare this with the modern section in A.

C. Photomicrograph of a modern cross section of the pith of a H. palustris stem (pith, pi; stele, st).

D. Photomicrograph of the pith of a H. palustris stem in the sediment. Compare the cell pattern with that in C (pith, pi; stele, st).

E. Photomicrograph of a modern H. palustris root.

F. Photomicrograph of a H. palustris root in the sediment. Compare this with the modern section in E.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40μ

Figure 47. Leaves and roots of Kosteletzkya virginica.

A. Photomicrograph of a modern K. virginica leaf in cross-section (epidermis, ep; palisade layer, pa; vascular bundle, vb).

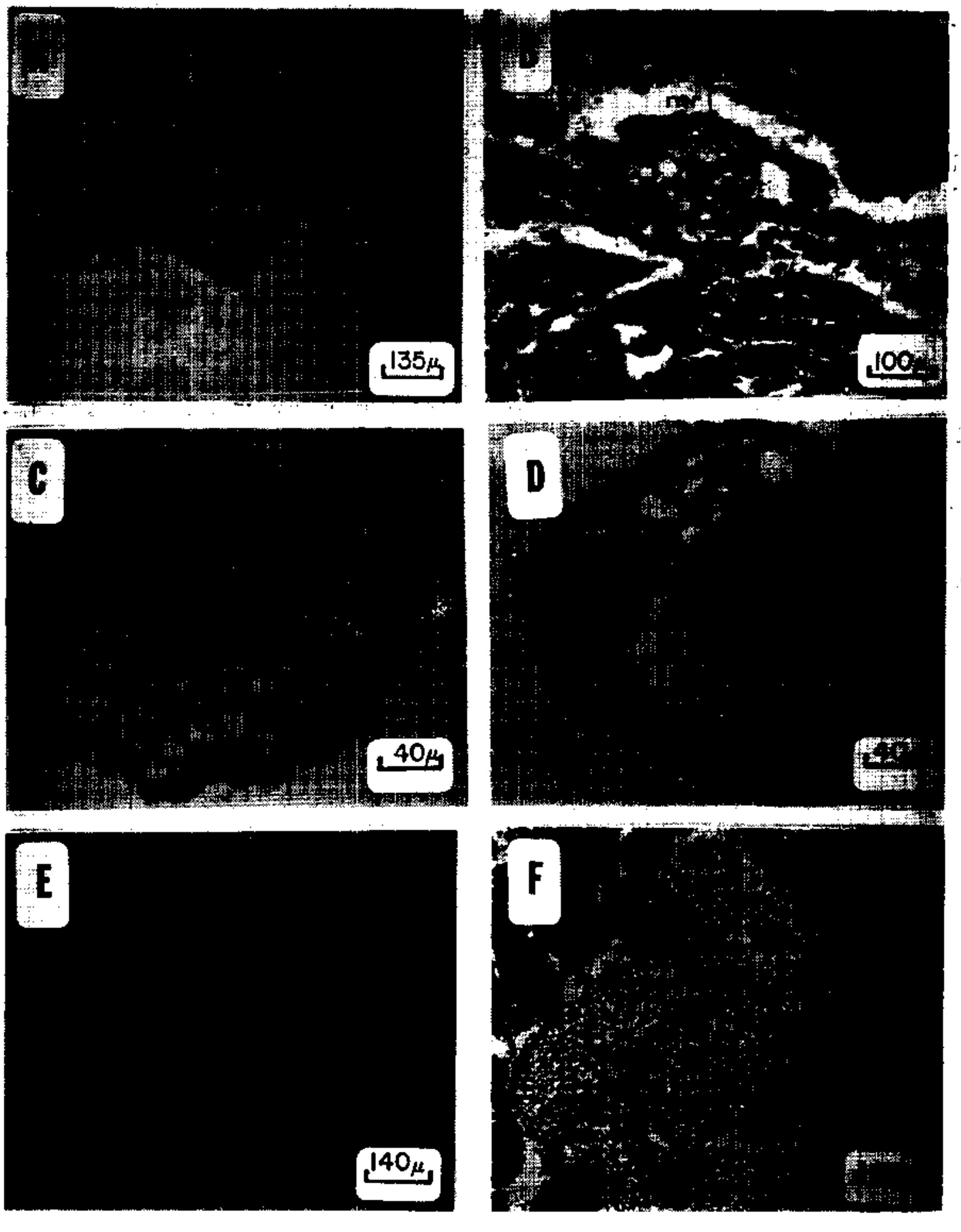
B. Photomicrograph of a fusinized K. virginica leaf in the sediment (palisade layer, pa). Note the vascular bundle on the left-hand portion of the leaf (white arrow). Compare this with the modern section in A.

C. Close up of a modern K. virginica leaf showing detail of the epidermis (ep), palisade layer (pa) and spongy mesophyll (sm).

D. Photomicrograph of a K. virginica leaf in the sediment (epidermis, ep; palisade layer, pa; spongy mesophyll, sm). Compare this with the modern section in C.

E. Photomicrograph of a modern K. virginica root.

F. Photomicrograph of a K. virginica root in the sediment. Compare this with the modern section in E.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D
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F

Figure 48. Leaves and roots of *Polygonum punctatum* and stems of *Atriplex patula*.

A. Photomicrograph of the midrib section (mr) of a modern *P. punctatum* leaf.

B. Photomicrograph of the midrib section (mr) of a *P. punctatum* leaf in the sediment. The leaf tissue has shrunk considerably. Compare this with the modern section in A.

C. Photomicrograph of a modern *P. punctatum* root.

D. Photomicrograph of *P. punctatum* root in the sediment. Compare this with the modern section in C.

E. Photomicrograph of a portion of a modern *A. patula* stem.

F. Photomicrograph of a portion of an *A. patula* stem in the sediment. Compare this with the modern section in E.

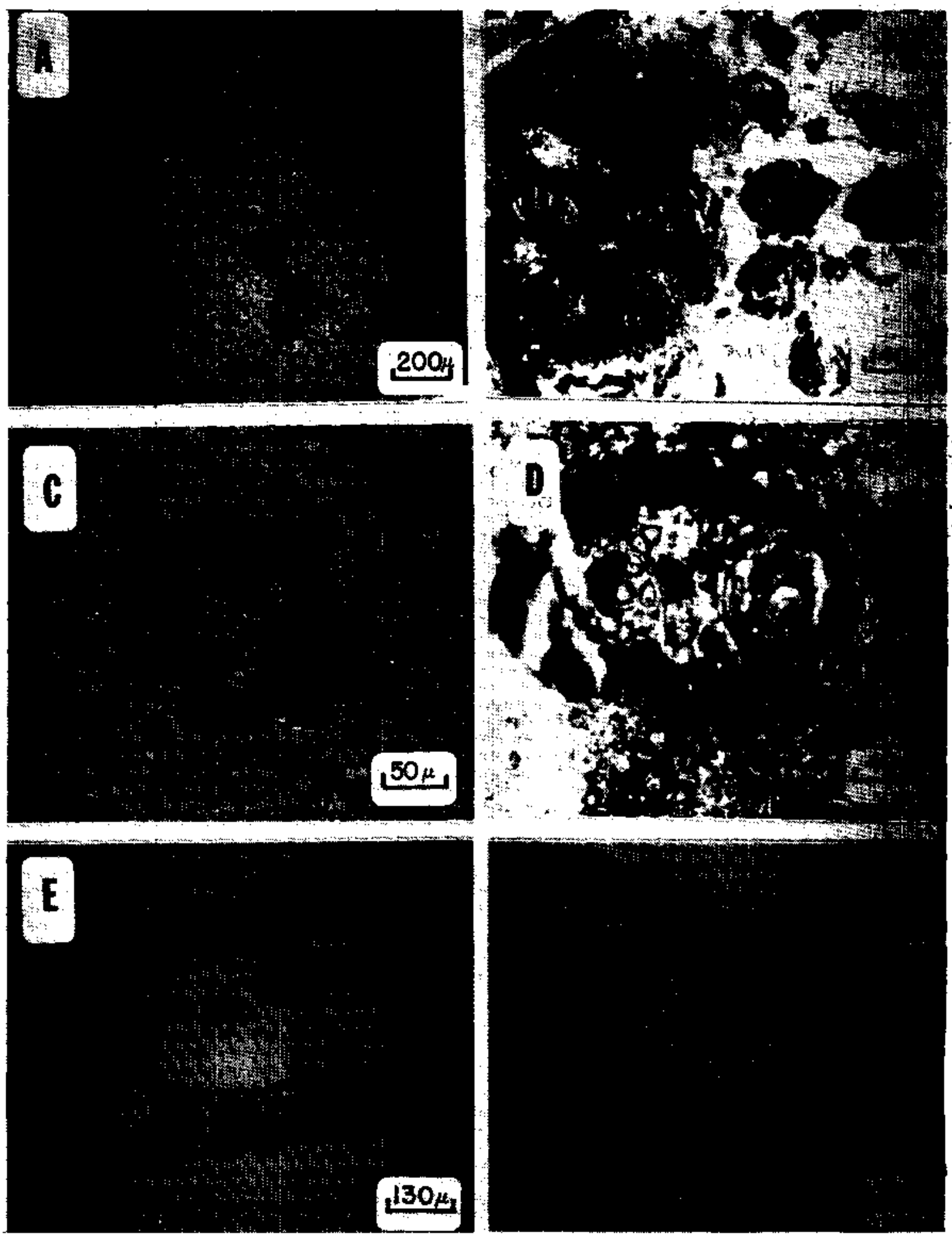

A
200μ
C
D
50μ
E
130μ

Figure 49. Leaves of *Juncus* sp. and *Typha* sp.

A. Photomicrograph of a portion of a modern *Juncus* sp. leaf (epidermis, ep; vascular bundle, vb).

B. Photomicrograph of a portion of a *Juncus* sp. leaf in the sediment (epidermis, ep; vascular bundle, vb). Compare this with the modern section in A.

C. Close-up of a vascular bundle in a modern *Juncus* sp. leaf.

D. Close-up of a vascular bundle from the *Juncus* sp. leaf in the sediment shown in B. Compare this with the modern bundle in C.

E. Photomicrograph of a modern *Typha* sp. leaf.

F. Photomicrograph of *Typha* sp. leaf in the sediment. Compare this with the modern section in E.

Large diameter (10-18 mm) stems may be *Phragmites* or *S. cynosuroides*. Plant tissues are pale yellow, tan, reddish brown, and black. These sediments contain a much greater variety of fragments which have a greater range in sizes than previous sediments discussed.

Microscopic characteristics. Roots and rhizomes are common. Surface litter components are usually rare.

Matrix color is medium to dark red brown reflecting high decay. Fine granular debris and cells and tissue fragments are abundant. The high permeability of the sandy sediment results in significant degradation beneath the sediment surface. The presence of common fungal remains confirms this.

Species identified include *K. virginica*, *H. palustris*, *S. alterniflora*, *S. cynosuroides*(?), *Scirpus*, *S. patens*, *Polygonum* and *Atriplex* (Figures 42-49). Yet plant remains are often so highly degraded that identifications cannot be made always.

Depositional environment. Tidal-river levees are exposed to constant wave and tidal action. They are built and maintained during high energy conditions. These high energy conditions tend to sweep away any surface litter accumulation. They also contribute sand and pebble-size material to the sediment. The plants on the levee trap sediment in the waters and bind it with their root systems.

Salinities vary from the mouth of the river to the head, within one tidal cycle, seasonally and yearly. Salinities recorded in the Smyrna River ranged from 8 $^{o}/_{oo}$ at the mouth to 2 $^{o}/_{oo}$ upstream.

C. Back-levee brackish-marsh subfacies

Megascopic characteristics. These sediments are finely- to coarsely-fibrous and rarely contain sand. Texture is very similar to that of S. alterniflora sediments, although there is usually a greater range in sizes of fragments in back-levee deposits. Sediments are light to medium brown with occasional orange mottles. Species identified include S. patens, D. spicata and Scirpus. P. communis and/or S. cynosuroides may also be present. Plant fragments are pale yellow, tan, or black.

Microscopic characteristics. Roots, rhizomes, and leaf sheaths form the framework composition of these sediments. Occasionally, leaves are present. Large grass roots, attributed to S. cynosuroides, occur. Other species identified include S. patens, D. spicata, Scirpus, Hibiscus, and Typha (Figures 42, 43, 44, and 49). Some sediments are highly degraded, others are well preserved.
Cells and tissue fragments are abundant and fine granular debris is variable. Cell fillings are present, sometimes common.

Depositional environment. This environment supports a wide variety of brackish-marsh vegetation in both pure and mixed stands. Inorganic sedimentation is low except when the levee is breached. The marsh surface is more variable in elevation than most salt marshes. Some depressions may contain stands of *Typha*. This environment is characterized by its complexity in vegetation patterns. A pure stand of *S. patens* may be adjacent to a mixed stand of *Scirpus*, *S. cynosuroides* and *S. patens* with no apparent difference in physical conditions. Surface litter accumulations are common.

D. Brackish-marsh surface-litter subfacies

Megascopic characteristics. Surface litter sediments tend to part along planes or fall apart when handled. Roots are rare. Short cylindrical fragments are abundant and interpreted as culms. *Scirpus* culms are triangular and usually black in color. Broad sheets, identified as leaf sheaths in thin section, are common. Rhizomes are rare and can be distinguished from culms by the presence of roots at nodes on rhizomes. Inorganic sediment is low.

Microscopic characteristics. Framework composition contains stems, leaves, leaf sheaths, and a few roots. *Panicum* and *Scirpus* fragments dominate the deposit (Figures 42, 43, 44, and 45). Some fragments are well preserved, others are highly decayed. Many fragments are compressed and show microbedding similar to that of high-marsh cowlick sediments.

Matrix color varies from medium to dark red and suggests a high rate of decomposition of fragments into fine granular debris. Fungal remains are common. Cell fillings are more common than in salt-marsh sediments. Also, fecal pellets are common.

Other plant species identified include: Hibiscus, Kosteletzkya, Polygonum, S. cynosuroides, and Atriplex (Figures 46, 47 and 48).

Two subtypes of surface-litter sediments are recognized:

1. High-decay surface litter: low F/M ratio. Matrix consists of fine granular debris, cells and tissue fragments, cell fillings, fungal remains and fecal pellets. Large fragments are highly decomposed. Micrinite is common to abundant and fusinite is variable.
2. Low-decay surface litter: high F/M ratio. Large fragments are well preserved, and matrix components are similar to those described above.

Depositional environment. This environment is covered only by spring high tides. Inorganic sedimentation is low and surface litter is exposed to aerobic oxidizing conditions during most of the tidal cycle. The high-decay surface litter sediment probably develops when sedimentation is very low, conditions are dry (water table is low) and oxidation, therefore, is very high. The low-decay surface litter sediment develops when the rate of accumulation of plant matter and/or inorganic sediments is high enough that surface litter is buried before it is highly decomposed. The marsh surface is highly irregular and contains small pools (20-30 cm dia) of standing water. Organic matter in these depressions may undergo less decay than matter on slightly higher ground.

E. Brackish-marsh root subfacies

Megascopic characteristics. Brackish-marsh root sediments are finely fibrous with high to very high fiber contents. *Panicum* roots form a very dense root mat with little inorganic sediment. *Scirpus* roots are not as densely bound and are associated with lenses or pods of inorganic sediment and finely-fragmented organic debris. Sediment color is light to medium brown with dark or orange mottles. Plant fragments may be tan, black (mostly *Scirpus*) or orange.

Microscopic characteristics. Framework composition consists of roots and rhizomes of *Scirpus* and *Panicum*, almost to the exclusion of other species (Figures 42, 43, 44, and 45). These roots and rhizomes are well preserved and F/M ratios are usually high.

Matrix is light to medium brown and contains fine granular debris, cells and tissue fragments, cell fillings, and foraminifers. Fecal pellets, especially small ones in plant tissues, are present.

Other species identified include: *D. spicata*, *S. patens*, *S. cynosuroides*, *Hibiscus*, *Kosteletzkya*, *Polygonum*, and *Baccharis* (Figures 46, 47 and 48).

Degradation. *Scirpus* and *Panicum* are the most common brackish-marsh species identified in sediments, so discussion of degradation will be restricted to them. Types of degradation are described in captions for Figures 42-45.

Cortical cells in *Scirpus* rhizomes are usually well preserved. As degradation proceeds, dark amorphous patches representing decay of small groups of cells appear. The epidermal cells decay early forming a dark red band. Vascular bundles in the stele seem to be more resistant to decay than fundamental tissue. They rarely contain cell fillings such as those present in *D. spicata* and *S. patens*. Bundle sheaths are particularly resistant to decay. *Scirpus* roots show decay patterns similar to those of grass roots. Generally, cortical cells are weaker than hypodermal and stele cells and may be removed. Sometimes cortical cells decay in place and the cortex is filled with dark-red to brown amorphous material. A band of cells in the stele usually turns dark brown. In late stages of decay, the internal portion of the stele and the cortex may be lost, leaving encircling rings of dark material representing the remains of the stele band and hypodermis.

Cortical cells of *Panicum* stems decay into lateral rays of cells and cell fragments similar to the pattern observed in *D. spicata*. The band of mechanical tissue darkens early. Two major degradation patterns are observed for vascular bundles. In one case, the bundle may be removed entirely. In the other case, the internal portion of the bundle and external fundamental cells of the stele may be removed, but the bundle sheaths remain. Usually, cell structure in the bundle sheaths is lost. Roots appear to be highly susceptible to decay and often consist only of hypodermal layers with unfilled cavities in the center portion.

Depositional environment. Although the surficial environment consists of a great variety of vegetation including *Hibiscus*, *Kosteletzkya*, *S. patens*, *D. spicata*, *Polygonum*, *Scirpus*, *S. cynosuroides*, *Panicum* and others, the sediment consists almost entirely of *Panicum* and *Scirpus* roots and rhizomes. These two species tend to mask the remains of other plants which populate brackish marshes. Many of the other species may contribute fine granular debris and unidentifiable cells and tissue fragments to the sediment through decomposition.

These sediments are quite different from salt-marsh sediments. They have much higher F/M ratios, lower percentages of pyrite, and a greater diversity of species. These deposits are probably very similar to the "sedge peats" described by Bloom (1964) in Connecticut marshes.

VI. Fresh-Water Marsh Facies

Fresh- and slightly brackish-water marshes examined in this study are populated by *Peltandra* and *Pontederia* (Figure 41D). Both plants have stout stems, thick leaves and thick, short roots.

Megascopic characteristics. These sediments are granular in texture although some have a slightly fibrous texture. Color is dark brown with brown to red mottles. Inorganic composition is variable and sizes range from clay to pebbles.

Some sediments appear to contain very thin roots. Large plant fragments are rare. No species can be identified. Plant fragments are dark brown to black.

Microscopic characteristics (Figure 50). Framework components are rare and consist of an occasional *Peltandra*, *Scirpus*, *Pontederia* or fern (?) root or leaf fragment. Large fragments are highly decayed.

Matrix color is medium- to dark-red brown and components consist of fine granular debris, highly-decayed cells and tissue fragments, fern spores, seeds, diatom hash, pyrite, cell fillings, and fern annuli.

Depositional environment. *Peltandra* and *Pontederia*

Figure 50. Stems and leaves of _Pontederia_ sp.

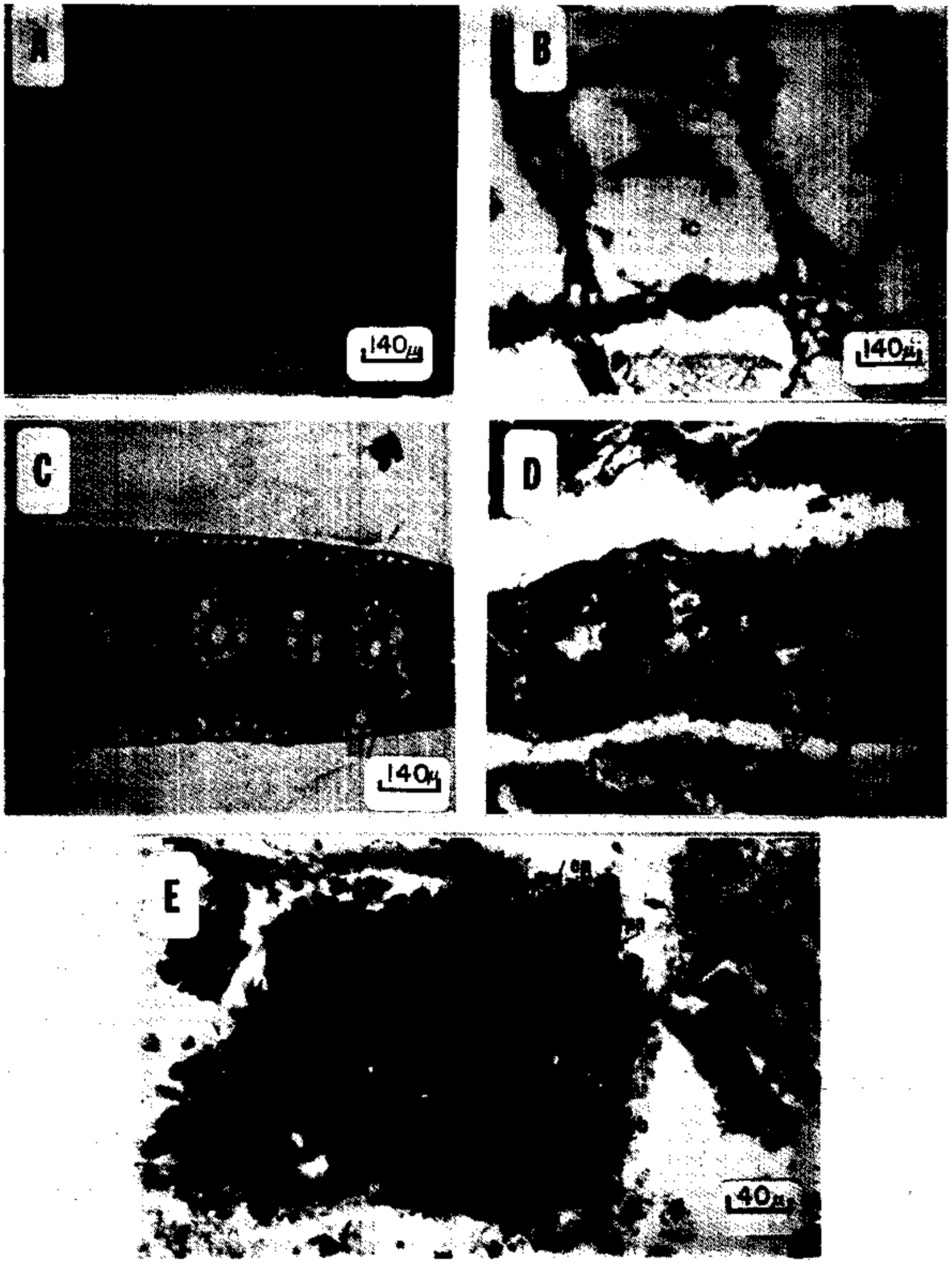
A. Photomicrograph of a portion of a modern _Pontederia_ sp. stem (large intercellular spaces, ic; vascular bundles, vb).

B. Photomicrograph of a portion of a _Pontederia_ sp. stem in the sediment (large intercellular spaces, ic; vascular bundles, vb). Compare this with the modern section in A.

C. Photomicrograph of a portion of a modern _Pontederia_ sp. leaf. The elongate cell fillings (cf) are characteristic of this species.

D. Photomicrograph of a portion of a _Pontederia_ sp. leaf in the sediment. Note the dark (red), elongate cell fillings (cf) comparable to those seen in modern section in C.

E. Photomicrograph of a fusinized _Pontederia_ sp. leaf fragment in the sediment. Note preservation of epidermal cells (ep), palisade layer (pa), and vascular bundles (vb). Compare this with the modern section in C.


A
140μ
B
140μ
C
140μ
D
E
40μ

communities along the bank in the upper reaches of tidal rivers are submerged during a large portion of the tidal cycle. Yet, they are highly decomposed. Probably this is due to the perishable nature of the plants. They are delicate herbs with high water contents and short, adventitous root systems, none of which tends to be preserved. The inorganic sediments in these deposits are very poorly sorted. The water is not necessarily fresh although salinities were not recorded above 3 $^{o}/_{oo}$.

Surface environments containing ferns were not studied although fern remains were identified in core samples. Ferns grow in fresh-water areas that are shaded. While Pontederia and Peltandra may withstand slightly saline conditions, ferns are a definite indicator of fresh-water conditions.

VII. Detrital-Organic Facies

Megascopic characteristics. These sediments are well sorted and have a granular texture. This type of deposit is often described as "coffee grounds" (Coleman and others; 1969). The structure is laminated to, at times, imbricated, and color is highly variable, from light brown to black within one deposit. Inorganic content appears to be low, but actually, there is a significant sand component. Plant fragments are 1-10 mm long (or longer) and rarely can be identified to species. Organs such as stems, leaf sheaths and occasionally leaves, can be recognized. The deposit appears to contain a great variety of plant species. Shell fragments, including those of horseshoe crabs, are common. Cohen (1970) noted similar deposits on beaches in southwestern Florida.

Microscopic characteristics. These sediments consist almost entirely of framework components. Stems, rhizomes, leaf sheaths, leaves, and roots are present in varying degrees of decomposition. Microbedding is evident. Plants identified include: *S. patens*, *D. spicata*, *S. alterniflora*, *Baccharis*, *Iva*, *Hibiscus*, *Phragmites*, *Polygonum* and dicots. Fusinized fragments are present and often slightly rounded, suggesting abrasion during transport. Fragments of large fecal pellets and pyrite associated with tissue fragments are common. The presence of roots indicates that some components were eroded at their source.

Depositional environment. Detrital sediments are located on tidal flats, beaches, washover fans, and on back-barrier marshes. Deposits reach thicknesses of 50 cm. Frequently, detrital organics are washed onto and across sandy barriers after storms, although they may be deposited under normal conditions. Sources of these organics include tidal-flat exposures and subtidal subcrops of *in situ* marsh sediments, and sediments carried to the littoral transport system by tidal rivers. Tidal rivers and creeks carry surface litter washed off the marsh surface and organics eroded along banks into Delaware Bay.

These sediments are well sorted by wave action, and deposits with distinct size ranges can be distinguished suggesting deposition under different energy conditions. Deposits on the marsh surface are reworked slightly by burrowing organisms and root penetration as fine-grained sedimentation and vegetation growth continues. Those deposits buried by sands are less disturbed.

Discussion

Observations on the modern depositional environment, the megascopic features of the sediment, and the microscopic features of the sediment, all contribute to characterization of marsh environmental facies.

Environmental parameters provide qualitative information for interpreting the depositional conditions of the marsh subfacies. Knowledge of factors such as drainage, density of vegetation, and energy conditions helps to explain the distribution of components in sediments.

Megascopic observations provide a great amount of information once a thorough microscopic examination has been made to determine the range and variety of sediments under study. When this has been done and when the morphological and anatomical features of the possible plant contributors are understood, informative megascopic descriptions can be made. Table 2 presents the most important plant contributors

SPECIES	DIAMETER (mm) Rhizomes	DIAMETER (mm) Lg. roots	DISTINGUISHING CHARACTERISTICS	POSSIBLE MISIDENTIFICATIONS
Spartina alterniflora	2.5-10.0	1.0-1.5	1. Center of rhizome (stem) is hollow, often collapsed. 2. Leaf sheaths are common in the sediment. 3. There is orange mottling of the sediment around roots, especially around small roots. 4. Fragments are frequently light tan, although they may also be black or orange.	1. Rhizome (stem) anatomy is similar to that of S. patens and P. communis. Difficult to distinguish megascopically when size approaches that of two species; eg, small S. alterniflora and large S. patens or large S. alterniflora and small P. communis.
Distichlis spicata	1.5- 4.0	1.0	1. Rhizome is knobby with distinct leaf scales. 2. Rhizome has solid center. 3. Leaf sheaths are common in the sediment. 4a. Dense interlocking network of roots and rhizomes or b. Loosely bound sediment with laminations containing few roots and abundant stems.	1. Rhizome (stem) anatomy is similar to that of Typha sp, but D. spicata is much smaller and there is little chance of misidentification.
Spartina patens	1.0- 3.0	1.0	1. Rhizome is slender and straight and has a hollow center. 2. Produces similar deposits (4a. and b.) to D. spicata: species are often intermixed.	1. See S. alterniflora.
Phragmites communis	8.0-20.0	1.0-2.0	1. Stem has a hollow center and is rigid; often filled with mud or sand. 2. Leaf sheaths are common in the sediment. 3. Deposit often contains sand. 4. Deposit generally monospecific, but may contain minor amounts of marsh fringe plants such as Baccharis and Iva.	1. See S. alterniflora. 2. Stems are the same size as S. cynosuroides. Could be misidentified megascopically, but not microscopically.
Scirpus sp.	4.0- 8.0	1.0	1. Rhizome has solid center and fragments are frequently black or dark orange. 2. Root is very distinctive in thin section. 3. S. robustus rhizome possesses a tuber. 4. Culm is triangular in some species.	1. Rhizomes may be confused with those of P. virgatum megascopically.
Panicum virgatum	4.0- 8.0	1.0	1. Rhizome has solid center. 2. Roots form a tightly bound, fibrous network with very little inorganic sediment.	1. See Scirpus sp.

Table 2. Distinguishing megascopic characteristics of some of the more important plants contributing to coastal-marsh sediments in Delaware.

to coastal-marsh sediments in Delaware with their distinguishing megascopic characteristics. It should be noted that some sediment components are larger than the width of the thin section (1 cm) and can only be studied megascopically.

Microscopic observations provide the greatest amount and variety of information and usually are essential in identifying marsh subfacies. Some of the more important microscopic observations provide information on:

1. Plant species composition.
2. The distribution of components that can be viewed only under magnification such as foraminifers, diatoms, and sponge spicules.
3. Characteristics of the depositional environment such as degree of sediment oxidation (matrix color) including fires (fusinite) and degree of bioturbation (fecal pellets).
4. Degradation patterns in plant organs.
5. The development of coal macerals and comparative information for use in understanding geochemical changes in sediments.

A summary of the important characteristics of each marsh subfacies or facies and its depositional environment is provided in Table 3. Some of the major points of this table are discussed below:

1. Low-marsh facies (IA, IB, IC, ID) have low F/M ratios and high percentages of inorganic sediments. Plant organs are usually well preserved and consist of S. alterniflora roots, rhizomes, and leaf sheaths, almost to the exclusion of other species. Subfacies IC and ID usually lack *in situ* plant remains.
2. High-marsh facies (IIA, IIB, IIC) have higher carbon values than low-marsh facies. Vegetation density is higher and surface litter is less likely to be washed away by tides in high-marsh environments. F/M ratios also tend to be higher than those in low-marsh environments. Yet, surface oxidation may be great enough to reduce organs to finely fragmented debris, thus lowering the F/M ratio. High-marsh subfacies IID, rotten spots, have highly decayed tissue remains, low to intermediate F/M ratios, and are microbedded due to intercalations of fine granular debris (possibly remains of blue-green algae) and diatom-rich zones.
3. Marsh-pond facies III are characterized by detrital organics which are usually highly decayed, suggesting desiccation. F/M ratios are low to intermediate.

		I A. *S. ALTERNIFLORA* LOW-MARSH SUBFACIES	I B. *S. ALTERNIFLORA* CREEK-BANK SUBFACIES	I C. UNVEGETATED CREEK-BANK SUBFACIES	I D. TIDAL-CREEK SUBFACIES
	SALINITY	Intermediate to high	Low to high	Low to high	Low to high
	EXPOSURE INDEX	Low	Low to intermediate	Low to intermediate	Very low
	DRAINAGE WHEN EXPOSED	Poor to good	Good to excellent	Good to excellent	Poor
	SUBSTRATE CONSISTENCY	Very soft to moderately firm	Very soft to moderately firm	Very soft to moderately firm	Very soft to soft
	GRAIN SIZE	Clay, silt; sand	Clay, silt; sand	Clay, silt; sand	Clay, silt; sand
	VEGETATION DENSITY	Intermediate	Low to intermediate	None	None
	ENERGY CONDITIONS	Low to intermediate	High	High	High
MEGASCOPIC CHARACTERISTICS	PLANT ORGAN COMPOSITION	Roots, A; rhizomes, C; leaf sheaths, P-C	Roots, C; rhizomes P-C; leaf sheaths, C-A	Detrital organics, roots, R	Detrital organics roots, R
	TEXTURE	Finely fibrous; FC-intermediate to high	Finely fibrous; FC-low to intermediate	Parallel to subparallel orientation of fragments	Parallel to subparallel orientation of fragments
	STRUCTURE	Massive; sand, mud lenses	Massive; sand, mud lenses	Laminated to massive; sand lenses	Laminated to massive; sand lenses
	COLOR	Brown; orange mottles	Lt to dk brown; orange mottles	Lt to med brown, dark mottles	Lt to dk brown, dark mottles
	% CARBON	Low (6-10)	Low (4-6)	Very low (3-5)	Very low (3-5)
MICROSCOPIC CHARACTERISTICS	SPECIES	*S. alterniflora; occas. S. patens, D. spicata*	*S. alterniflora*	Highly variable	Highly variable
	F/M RATIO (%)	Low to intermediate (10-34)	Low to intermediate (5-19)	Very low to low (0-14)	Very low (0-4)
	COMPACTION OF ORGANS	P	R	N	N
	FRAMEWORK: PLANT ORGAN COMPOSITION	Roots, A; rhizomes C; leaf sheaths, P-C; leaves, N-R	Roots, C; rhizomes, P; leaf sheaths, C-A; leaves, N-R	Tissue fragments, P-C; leaf sheaths, C-A; leaves, N-R	Tissue fragments, P-C; leaf sheaths, C; roots, R-P
	STRUCTURE	Massive	Massive	Microbedded	Microbedded
	% FUSINITE	N-A (0-12)	N-P (0-2)	N-P (0-2)	N (0)
	MATRIX: MISCELLANEOUS COMPONENTS	Diatom frag, C; forams, C; tissue, cell frag, R-P	Diatom frag, C; forams, C; tissue, cell frag, C-A; fine granular debris, C-A	Fine granular debris, A; diatom, foram frag, A; cell fillings, P	Fine granular debris A; diatom, foram A
	FECAL PELLETS	C-A	A (medium size)	A (medium size)	C-A (all sizes)
	COLOR	Lt to med brown	Lt to med brown	Lt to med brown	Lt to med brown
	% MICRINITE	R-P (3-12)	R-P (4-14)	P-C (4-18)	P-C (10-20)
	% PYRITE	N-A (0-8)	N-A (0-13)	N-C (0-6)	N-C (0-6)
	%OTHER MINERALS	C-A (5-12)	C-A (5-10)	C-A (7-11)	A (8-12)

Table 3. Summary of the microscopic characteristics, megascopic characteristics, and depositional environments of the 17 marsh facies and subfacies. Explanation: A, abundant; C, common; P, present; R, rare; N, not present; FC, fiber content.

(continued on pp. 188a and 188b) ➤

		II A. LOW MARSH-HIGH MARSH TRANSITIONAL SUBFACIES	II B. HIGH-MARSH COWLICK SUBFACIES	II C. HIGH-MARSH ROOT SUBFACIES	II D. ROTTEN-SPOT SUBFACIES	III. MARSH-POND FACIES	V C. BACK-LEVEE BRACKISH MARSH SUBFACIES
	SALINITY	Intermediate to high	Intermediate to high	Intermediate to high	High to very high	Low; variable	Low
	EXPOSURE INDEX	Intermediate	High	High	High	Low	Intermediate to high
	DRAINAGE WHEN EXPOSED	Poor to good	Good to excellent	Good to excellent	Poor to fair	None	Poor to good
	SUBSTRATE CONSISTENCY	Moderately soft to firm	Firm to very firm	Firm to very firm	Firm	Very soft to moderately firm	Soft to firm
	GRAIN SIZE	Clay, silt; sand	Clay, silt; sand	Clay, silt; sand	Clay, silt; sand	Clay, silt; sand	Clay and silt
	VEGETATION DENSITY	Intermediate to high	High	High	None	None to low	Intermediate to high
	ENERGY CONDITIONS	Low to intermediate	Low	Low	Low	Low	Low
MEGASCOPIC CHARACTERISTICS	PLANT ORGAN COMPOSITION	Roots, C-A; rhizomes, P-A; leaf sheaths, C-A	Roots, R-P; rhizomes, R-P; culms,A; leaf sheaths, A	Roots, A; rhizomes, A; leaf sheaths, A	Blue-green algae, detrital organics	Detrital organics	Roots, A; rhizomes, A; leaf sheaths, C
	TEXTURE	Finely fibrous; FC-intermediate to high	Parallel to subparallel orientation of fragments	Finely fibrous; FC-high	Parallel to subparallel orientation of fragments	Parallel to subparallel orientation of fragments	Fibrous; FC-intermediate to high
	STRUCTURE	Massive; sand, mud lenses	Laminated to massive	Massive	Laminated	Laminated	Massive; sand. mud lenses
	COLOR	Brown	Brown to dk brown; occas. dk mottles	Brown to dk brown; occas. dk mottles	Lt to dk brown; orange mottles	Dk brown to black	Lt to med brown; orange mottles
	% CARBON	Low (5-10)	Intermediate (7-11)	Intermediate (7-11)	Low (6-8)	Low to high (6-20)	Inter. to high (9-20)
	SPECIES	S. alterniflora, S patens, D. spicata others minor	S. patens, D. spicata	S. patens, D. spicata	Variable, algae	H. palustris, P. communis, D. spicata	Scirpus, Spartina, P. communis, highly variable
	F/M RATIO (%)	Intermediate (10-24)	Low to high (5-60)	Intermediate to high (25-60)	Low to intermediate (6-19)	Low to intermediate (5-24)	Low to high (9-35)
	COMPACTION OF ORGANS	R-P	C-A	P-C	N	R	P
	FRAMEWORK: PLANT ORGAN COMPOSITION	Roots, C-A; rhizomes, P-A; leaf sheaths, C-A	Roots, R-P; stems, A; leaf sheaths, A; leaves, R	Roots, A; rhizomes, A; leaf sheaths, A	Tissue fragments, P-C	Stems, A; leaf sheaths, C, leaves, roots, R-P	Roots, A; rhizomes, A; leaf sheaths, A; leaves, P
MICROSCOPIC CHARACTERISTICS	STRUCTURE	Massive	Microbedded	Massive	Microbedded	Microbedded	Massive
	% FUSINITE	R-P (2-3)	P-C (2-7)	N-P (0-3)	P-C (3-7)	N-C (0-4)	P-C (2-6)
	MATRIX: MISCELLANEOUS COMPONENTS	Diatoms, forams, C;	Fungal hyphae, A; forams, diatoms, C; tissue, cell frag, C-A; cell fillings, P	Fungal hyphae, C; forams, diatoms, C; tissue, cell frag, R-P;cell fillings,P	Diatoms, A; tissue, cell frag, C-A; plant fibers C; cell fillings P-C	Fine granular debris C-A; tissue, cell frag, A; fungi, P-A	Fine granular debris P-A; fungi,C;tissue, cell frag, A
	FECAL PELLETS	C-A	C	C	C	P	C-A
	COLOR	Lt to med brown	Lt to dk red brown	Lt to dk brown	Lt to med brown	Med to dk brown	Med to dk red brown
	% MICRINITE	P (8-12)	P-A (8-34)	N-A (3-29)	P-C (4-15)	C-A (0-40)	P-C (12-22)
	% PYRITE	R-C (1-6)	N-C (0-6)	N-C (0-6)	P-C (1-3)	N (0)	N-C (0-5)
	%OTHER MINERALS	C-A (4-13)	R-A (1-13)	R-A (1-13)	C-A (6-12)	N-C (0-6)	C-A (6-14)

(continued) ▼

		V D. BRACKISH MARSH SURFACE LITTER SUBFACIES	V E. BRACKISH MARSH ROOT SUBFACIES	IV. *P. COMMUNIS* FACIES	V A. SALT-BRACKISH MARSH TRANSITIONAL SUBFACIES	V B. TIDAL-RIVER LEVEE SUBFACIES	VI. FRESH-WATER MARSH FACIES	VII. DETRITAL-ORGANIC FACIES
	SALINITY	Low	Low	Low to high	Low to intermediate	Low to intermediate	None	Low to high
	EXPOSURE INDEX	High	High	High	Intermediate to high	High	Low	Usually high
	DRAINAGE WHEN EXPOSED	Poor to good	Poor to good	Good	Poor to good	Excellent	Poor	Poor to excellent
	SUBSTRATE CONSISTENCY	Soft to very firm	Soft to very firm	Firm	Soft to firm	Firm	Very soft	Soft
	GRAIN SIZE	Clay and silt	Clay and silt	Sand, silt; clay	Clay, silt; sand	Clay, silt; sand	Clay to pebbles	Highly variable
	VEGETATION DENSITY	Intermediate to high	Intermediate to high	High	Intermediate	Intermediate	Low to high	None
	ENERGY CONDITIONS	Low	Low	High	Low	Intermediate to high	Low to high	Very high
MEGASCOPIC CHARACTERISTICS	PLANT ORGAN COMPOSITION	Stems, A; leaves, C	Roots, A; rhizomes, C-A	Roots, A; rhizomes, A; leaf sheaths, A	Roots,A;rhizomes,C-A,leaf sheaths,C;leaves,R-P	Roots, A; rhizomes, P-C	Roots, C; fragments, A	Highly variable
	TEXTURE	Parallel to subparallel orientation of fragments	Fibrous; FC-high to very high	Coarsely fibrous; FC-low to high	Fibrous; FC-intermediate	Fibrous; FC-low to intermediate	Granular	"Coffee grounds," well sorted, granular
	STRUCTURE	Laminated	Massive	Massive	Massive	Massive sand, mud lenses	Massive to laminated, sand, clay lenses	Laminated to imbricated
	COLOR	Med to dk brown, orange mottles	Brown; orange and dark mottles	Brown; orange and dark mottles	Brown	Lt to dk brown; dk, orange mottles	Dk brown; br to red mottles	Lt brown to black
	% CARBON	Inter. to high (11-35)	Inter. to high (11-17)	Low to high (5-26)	Low to high (3-20)	Low (5-9)	Highly variable	High to v. high (25-30)
MICROSCOPIC CHARACTERISTICS	SPECIES	*Scirpus*, *P. virgatum*; *others often common*	*Scirpus*, *P. virgatum*, *others often common*	*P. communis*	*S. alterniflora*,*S. patens* *D. spicata*, *Scirpus*, *Juncus*	*H.palustris*,*K. virginica*, *S. alterniflora*, *highly variable*	*Peltandra*, *Pontederia* *Scirpus*, ferns	Salt marsh to upland species
	F/M RATIO (%)	Intermediate to high (25-60)	Intermediate to high (10-38)	Low to high (10-34)	Low to intermediate (4-24)	Low (10-14)	Low	Very high
	COMPACTION OF ORGANS	C-A	C	P-C	P	R	N	C
	FRAMEWORK: PLANT ORGAN COMPOSITION	Stems, A; leaves, C; roots, P; leaf sheaths, C	Roots, A; rhizomes, C-A	Roots, A; rhizomes, A; leaf sheaths, A	Roots, A; rhizomes, C; leaf sheaths, C; leaves, P	Roots, A; rhizomes, P-C; leaves, R-P	Roots, C; leaves, P-C	All plant organs
	STRUCTURE	Microbedded	Massive	Massive	Massive	Massive	Massive to microbedded	Microbedded
	% FUSINITE	N-P (0-2)	R (1)	P-C (2-14)	R-A (1-9)	P (2-4)	P-C	P
	MATRIX: MISCELLANEOUS COMPONENTS	Fine granular debris C-A;fungi,C; tissue, cell frag, A; cell fillings, C	Fine granular debris, P-C; tissue, cell frag,C;cell fillings C; forams, C	Cell fillings, C-A; plant fibers, C; tissue, cell frag,A; fungi, C	Diatoms, forams, C; tissue, cell frag, C	Fine granular debris, C-A; fungi,C;tissue, cell frag, A	Fine granular debris, C; cell fillings,C, spores,A; annulus,C; seeds,C; cell frag,A	None to very few
	FECAL PELLETS	C (small)	R-C	P-C (large)	C	C	P-C	N
	COLOR	Med to dk red brown	Lt to med brown	Lt to dk red brown	Lt to med brown	Med to dk red brown	Med to dk red brown	
	% MICRINITE	P-A (10-33)	P (10-14)	P-C (5-14)	P-A (10-36)	P-C (7-20)	A	R
	% PYRITE	N-P (0-3)	N-C (0-5)	N-A (0-24)	P-A (3-9)	P-C (3-5)	P	P-A
	% OTHER MINERALS	R-P (1-6)	P-C (4-6)	A (10-14)	C (7-8)	A (8-12)	P-A	R-C

4. _P. communis_ facies IV show significant variation in texture and structure. Some sediments have a high percentage of mineral grains which are usually poorly sorted. F/M ratios tend to be low. Other sediments have high organic contents dominated either by roots and rhizomes (high F/M ratio) or by finely-fragmented debris (low F/M ratio). Most sediments are mottled.

5. Brackish-marsh subfacies (VA, VB, VC, VD, VE) contain tissue fragments of a much greater variety of plant species than other facies or subfacies. F/M ratios are low in subfacies VB because tides carry surface litter off the marsh and deposit inorganic sediments. The other subfacies contain high percentages of organics, of which surface litter makes a major contribution.

6. The fresh-water marsh facies VI contains remains of _Peltandra_, _Pontederia_, _Scirpus_, and ferns. F/M ratios are usually low, plant fragments are usually highly decomposed, and inorganic sediments are poorly sorted. Structure may be massive or microbedded.

7. The detrital-organics facies VII is well sorted with laminated to imbricated structure. F/M ratios are very high. Organ and plant species composition

is very diverse due to the variety of possible sources of eroded organics. Organic carbon values are high, but there is a significant sand component in the deposit.

Some geologists refer to coastal marsh deposits as salt-marsh peats. The AGI definition of peat, which is roughly equivalent to those used by coal geologists, requires a 60% carbon content of the sediment (Gary and others, 1972). The highest percent carbon of the sediments described in this study, which are light weight and do look like peats, is only 30%. In fact, it appears from literature descriptions (see especially Chapman, 1974) and my field observations that very few temperate-zone coastal-marsh (particularly salt-marsh) deposits along the Atlantic coast and in other parts of the world are true peats. For example, Kaye and Barghoorn (1964) state:

> The writers found that a dried sample of seemingly slightly silty Spartina alterniflora peat from 3 feet below the surface in the large marsh south of Lynn, Massachusetts, was 74.4 percent by weight mineral matter.

I suggest dropping the use, even informal use, of the term "salt-marsh peat" unless the deposit has greater than 60 percent carbon. Instead, "salt-marsh deposit", "coastal-marsh sediment", and "organic-rich sediment" are suggestions to replace it.

HOLOCENE STRATIGRAPHY AND PALEOGEOGRAPHY ALONG THE WESTERN SHORE OF DELAWARE BAY

Introduction

The preceding identification of 17 coastal-marsh facies provides the framework for a discussion of Holocene stratigraphy of coastal-marsh deposits. This section discusses the nature of the contacts of marsh sediments with Pleistocene deposits and Holocene sandy barriers along the western shore of Delaware Bay. Patterns in marsh-facies distribution can be related to sea-level change, sediment supply, compaction, shoreline configuration, slope of the pre-Holocene surface, and drainage. Three typical vertical sequences representing the evolution of coastal-marsh deposits along this transgressive coast are constructed from facies analyses of cores (Appendix 1) and outcrop samples.

Holocene-Pleistocene Boundary

Holocene marsh sediments usually are underlain by Pleistocene sediments along the Delaware coast (Kraft 1971a, b). Although pre-Pleistocene sediments occasionally are encountered directly beneath Holocene marsh deposits along the northern part of the shoreline (Kraft and John, 1976), they were not encountered in this study.

Recognition of the boundary. Pleistocene deposits underlying Holocene marsh sediments typically contain one or more of the following kinds of sediments:

1. Firm sand or pebbly sand, usually white or orange (Fowler Beach core 1, page 284; Primehook core 2, page 286).
2. Firm clay that is usually light brown with orange- and/or green-colored mottles (Primehook core 1, page 285).
3. Reworked (during Holocene Epoch) sands and gravels with orange mottles that are poorly-consolidated firm sands and gravels (South Bowers cores 2 and 4, pages 277 and 279).

These sediments have the same characteristics as some of those of the Pleistocene Columbia formation (Jordan, 1964). The contact between the firm Pleistocene or pre-Holocene sediments and the overlying poorly consolidated Holocene marsh sediments has been traced in the subsurface to surface exposures by Kraft and his colleagues (see especially Kraft and John, 1976).

Basal marsh sediments. Basal marsh sediments containing fresh- or brackish-water plant remains and resting on sands and gravels have been noted by many researchers on the New England coast (Davis, 1910; Johnson and Raup, 1947; Deevey, 1948; Bloom, 1964; and others). These basal sediments usually are overlain by brackish-marsh sediments and/or salt-marsh sediments.

Basal fresh- and brackish-marsh sediments are found along the Delaware coast, but several other variations also exist (Figure 51). Basal brackish-marsh sediments are found in South Bowers core 2 (page 277) and consist of abundant Scirpus remains with S. alterniflora and D. spicata. Yet, low-marsh sediments are found at the contact in South Bowers core 4 (page 279) and Fowler Beach core 1 (page 284). A mixed zone of high-marsh and brackish-marsh sediments is found at the contact in Primehook core 2 (page 286). In Primehook core 1 (page 285), marsh pond or pan sediments rest on the unconformity.

These variations in sedimentary environment suggest that several factors control the initial type of sediment deposited on the unconformity at the leading edge of the transgression. One is distance from shoreline at point of initial deposition. If tidal waters extend far inland and are diluted by fresh water, then deposits along this longitudinal section will consist of brackish and fresh-

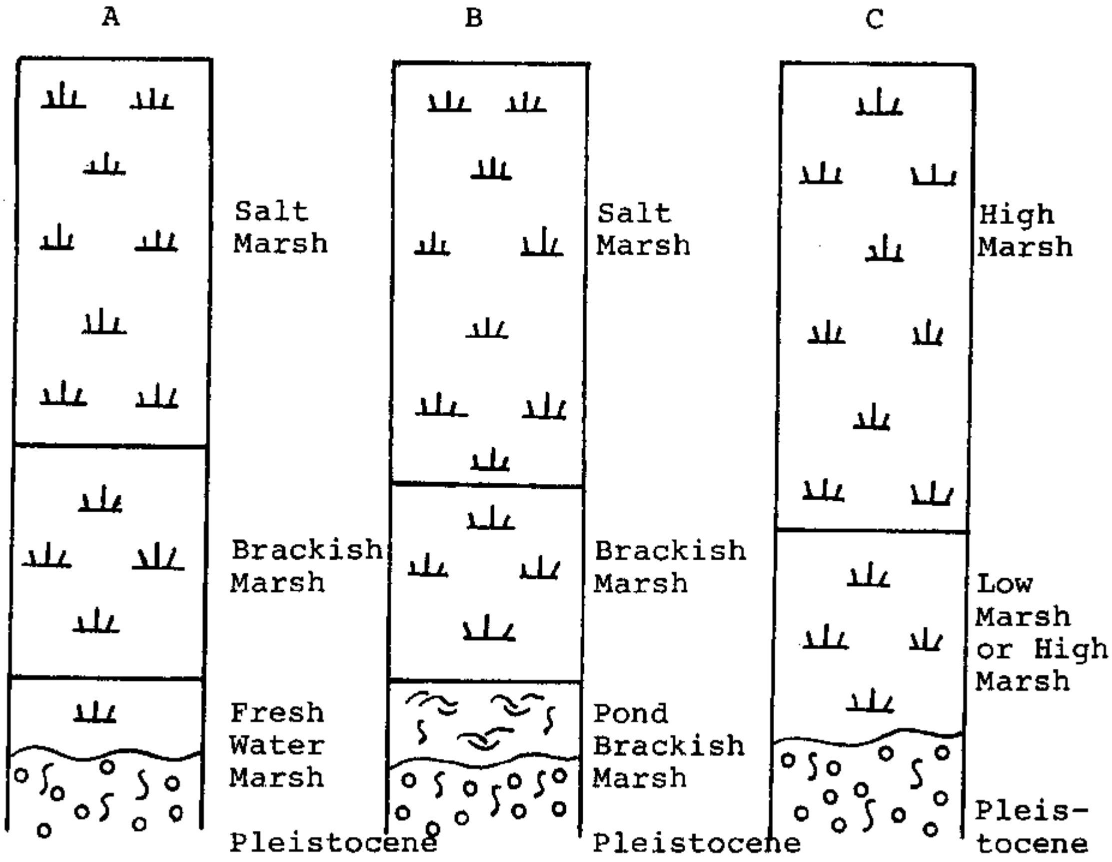


Figure 51. Principal kinds of basal marsh sediments along the western Delaware Bay shoreline. Scale is not shown because it is highly variable. Sequence A: Transgressive sequence of fresh-water marshes to brackish-water marshes to salt marshes. Also well documented on the New England coast. Sequence B: Brackish-marsh sediments (sometimes indicating poorly-drained conditions) forming on the Pleistocene contact. Sequence C: Salt-marsh sediments (indicating a well-drained marsh) forming on the Pleistocene contact.

water sediments. When the distance between the active shoreline and the pre-Holocene upland is short and the back-barrier marsh is well-drained, high-marsh or low-marsh environments form a sharp contact with the upland surface. There is insignificant development of brackish-water vegetation. Basal marsh sediments at this type of contact contain S. patens-D. spicata and/or S. alterniflora remains. When the back-barrier marsh is poorly-drained, marsh pans may form on the unconformity. Not only are these pans or ponds identified in core section, but they are seen forming at the landward edge of the marsh at Primehook.

Another variable controlling the type of environment formed at the leading edge of the transgression includes the rate of inundation of the pre-Holocene surface, which depends on the rate of sea-level rise, on the slope of the pre-Holocene surface, and on supply of sediments. Sea-level rise restricts the opportunity for brackish-marsh development if these marshes are rapidly flooded by marine waters Barghoorn (1949b). Slope in part controls the breadth of the active shoreline, causing narrow marshes to develop where the pre-Holocene surface slopes steeply and broad marshes to develop where the slope is shallow. Sediment supply also is a controlling factor on width of marsh development. High rates of deposition favor establishment and maintenance of broad marshes regardless of slope.

Root penetration. Pleistocene sediments underlying marsh sediments contain fine roots which extend the length of the core section (rarely more than 50 cm) and appear to decrease in number with increasing depth (South Bowers cores 2 and 4, pages 277 and 279; Fowler Beach core 1, page 284; Primehook cores 1 and 2, pages 285 and 286). There are two probable explanations for the presence of these roots:

1. These roots originate from upland vegetation present before the surface was covered by coastal marshes. Sand and/or clay sediments and roots are part of a soil zone.
2. These roots belong to marsh plants. Roots of marsh plants are known to extend their roots to depths of one meter (Pomeroy and others, 1970, cited in Frey, 1976).

In order to test these hypotheses, surficial Pleistocene sediments supporting woody and herbaceous vegetation were augered or dug up at Primehook and Woodland Beach. Similar stratigraphic sections are found in each case and no roots penetrate Pleistocene sediments (Figure 52).

In all cases (5 cores) when marsh sediments overlie Pleistocene sediments, the Pleistocene sediments contain fine roots extending to the end of the core (up to 50 cm).

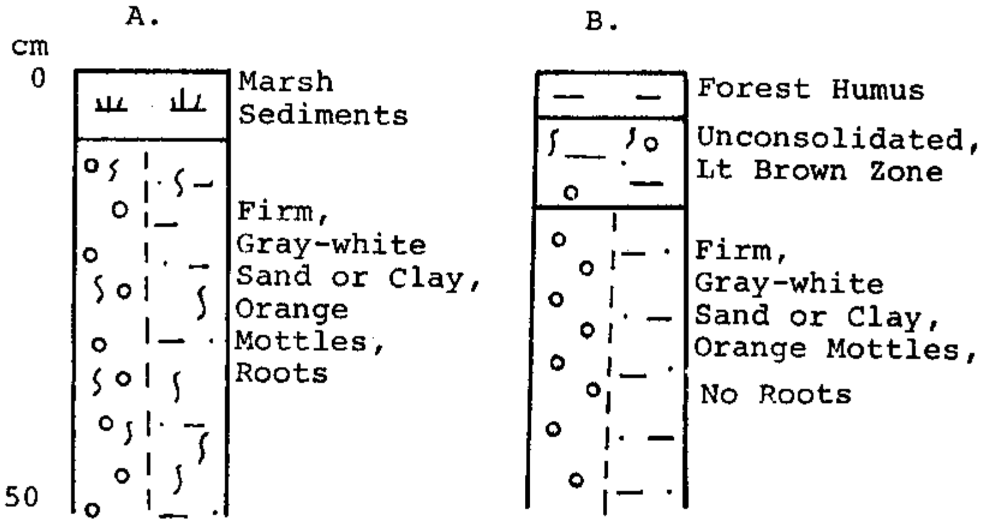


Figure 52. Abundance of roots in Pleistocene sediments. A. Pleistocene sediments buried by Holocene coastal sediments. B. Pleistocene sediments of a well-drained upland surface supporting tree and herbaceous vegetation.

Also, in all cases (4 auger holes and pits) when upland vegetation forms on the pre-Holocene surface, the sediments show development of a brown organic zone of forest humus, and roots are shallow and do not penetrate the pre-Holocene sediments beyond 10-15 cm.

Therefore,it seems likely that roots from upland vegetation are oxidized very rapidly in well-drained sandy sediments and in at least some clay sediments but that the organic-rich reducing marsh sediments provide a protective seal against oxidation of marsh roots in the sediments.

Yet, it also is possible that roots preserved from upland vegetation might be unrecognizably mixed with marsh sediments but obscured by marsh sediment development. The available evidence, however, indicates that roots penetrating Pleistocene sediments to depths of 50 cm from the interface originate from marsh plants at the basal contact.

Relict-Marsh Tidal Flats

Broad tidal flats formed of *in situ* marsh deposits are common along the shoreline (Figure 3B). Tidal-flat sediments were studied in detail at Pickering Beach, Kitts Hummock,and South Bowers. Marsh sediments representing a wide range of environments are present,but the most frequent environments encountered are those of *Phragmites* and the high-marsh *Baccharis*-*Iva* fringe. These two environments form in a back-barrier position and are the first environments to be covered by the sandy washover barrier as the shoreline migrates landward. Exposed on the tidal flat, these marsh sediments undergo considerable erosion and are probably the major source of detrital organics along the shore of Delaware Bay.

As the characteristically thin deposits of *Phragmites* and/or *Baccharis*-*Iva* marshes are eroded and reworked, the high-marsh sediments, stratigraphically below the back-barrier fringing vegetation, are exposed and in turn eroded. In many cases, it is possible for living marshes to be exposed on the tidal flat the following year.

The sedimentological characteristics of these deposits are altered by continuous exposure to saline waters. Pyrite is more abundant in these sediments than in the same environment landward of the barrier. Evidence of decay is uniformly high which suggests that at least part of it is due to exposure. Stratigraphic sections representing the interface between the back-barrier fringing vegetation, sandy washover barrier, and tidal flat are presented in Figure 53.

Washover Sequences

The landward movement of coarse-grained sediments from the beach and nearshore area on to back-barrier marshes as washover fans raises the level of the marsh. Subsurface evidence indicates that this deposition can raise low-marsh

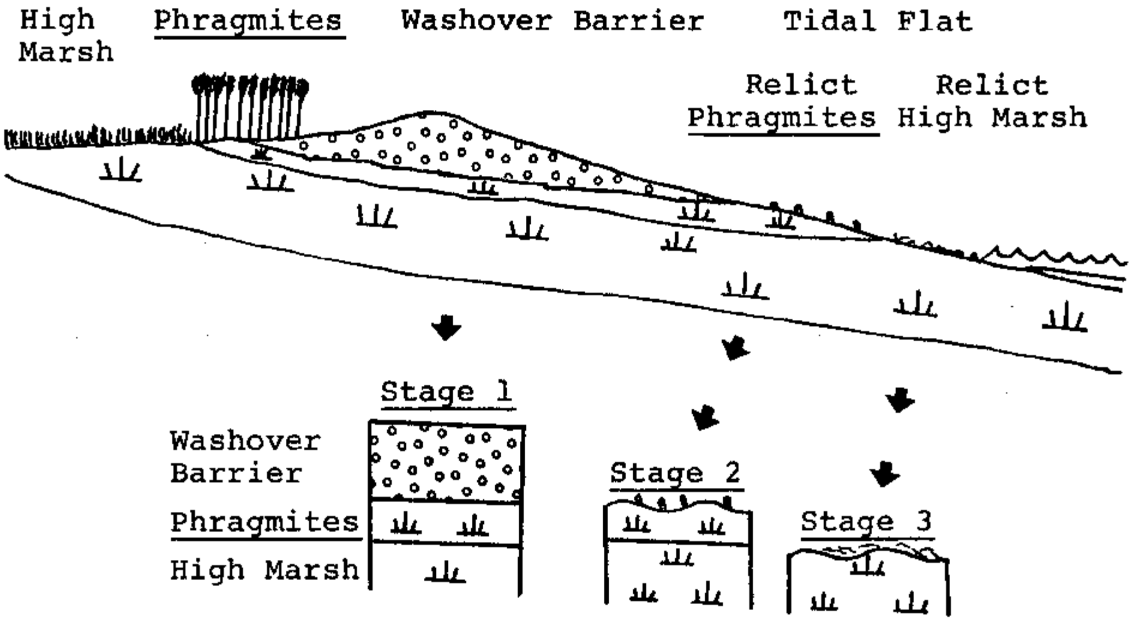


Figure 53. Cross-section and stratigraphic columns showing environmental facies beneath the back-barrier fringing vegetation, sandy washover barrier, and tidal flat. Stage 1 shows the stratigraphic section beneath the washover barrier. Stage 2 shows the stratigraphic section beneath the tidal flat at a time of initial exposure and erosion. Stage 3 shows the stratigraphic section beneath the lower tidal flat which is subjected to more extensive erosion.

levels to high-marsh levels (Woodland Beach core 1, page 274). Another common washover sequence along Delaware Bay consists of high-marsh sediments interlayered with washover sands and detrital organics. After deposition of washover sands, marsh is re-established on the fans by extension of rhizomes from living plants on adjacent marsh. The rate of recolonization is rapid and, depending upon the size of the fan, the surface can be revegetated by plants in one to several seasons (Maurmeyer and others, 1976). The effective height of the high marsh is raised with each event, so that the surface adjusts to sea-level rise. Stratigraphic sections from Kitts Hummock and Woodland Beach illustrating representative washover sequences are shown in Figure 54.

Overwash deposition is a significant process contributing sediment, predominantly coarse-grained, to the marsh system. The areal extent of these deposits may be great (on the order of several sq. km) during major overwash events such as the 1962 storm (a "100 year" storm). For example, south of Primehook the length of fans (each 20-40 m wide) was at least 80 m after the 1962 storm. More frequent overwash events that occur during spring high tides and strong onshore-wind conditions or during northeast storms contribute sediment to a relatively small marsh area (one to several hundred sq. m). In stratigraphic section, though, these minor washover advances are significant and

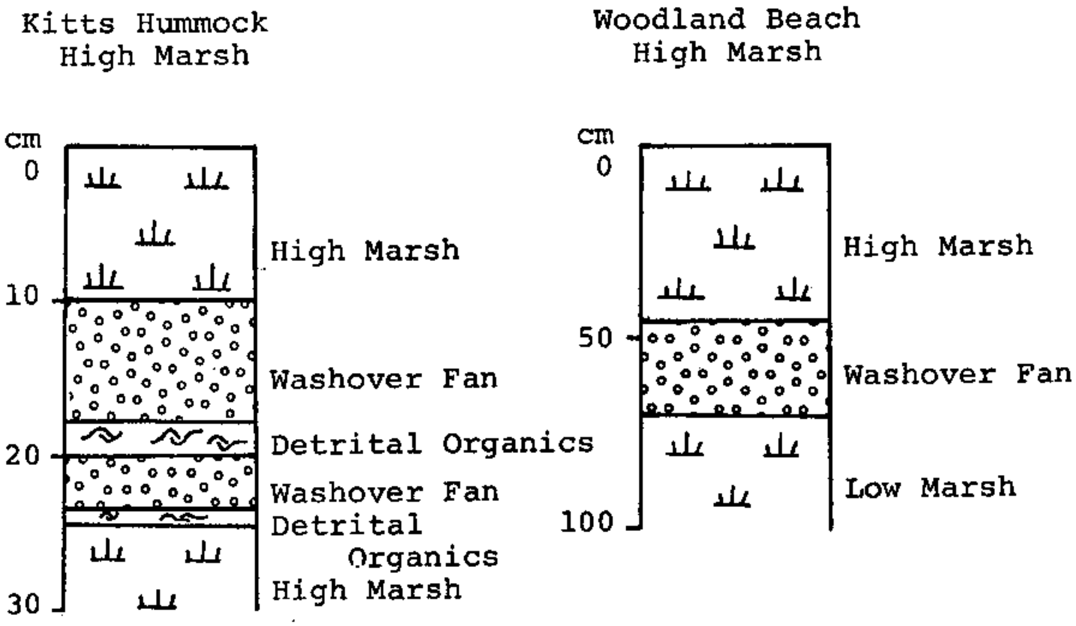


Figure 54. Interlayered coastal-marsh and washover-fan sediments. Such interlayering is typically found beneath the boundary between washover fans and tidal marshes. Note the different scales.

represent the lateral and vertical migration of coastal environments.

Tidal Channels

Surface observations. In contrast to fluvial systems, most meandering tidal channels in mature marshes do not appear to have migrated in historic time (Campbell, 1927; Goldthwait, 1936; Elliott, 1972; Redfield, 1972; and Frey, 1976). Goldthwait (1936) suggests that the bidirectional flow of tidal currents inhibits the migration of channels. One possible evidence of historic channel migration in mature tidal marshes comes from San Francisco Bay where studies of Coast and Geodetic Survey maps equivocally suggest minor changes between 1853 and 1963 (Pestrong, 1965; B. Atwater, written communication, 1977). Evidence of meandering has been noted in sandy tidal channels in marshes in Georgia (Land and Hoyt, 1966) and in South Carolina (L. Ward, oral communication, 1977). Extension of channels by headward erosion has been observed by Chapman (1974) and others.

Initial entrenchment of creeks is controlled by the developing marsh. In young marshes which contain hummocks of vegetation on broad mud flats, channels are ill-defined and shift frequently (Yapp and others, 1917; and Johnson and Raup, 1947). As vegetation spreads laterally and vertically, creeks begin to stabilize. Chapman (1974) identifies three phases of tidal-creek development on muddy marshes:

1. An active youthful phase which occurs during rapid accretion of the marsh. Creeks deepen and headward erosion may occur at rates of 3 m/yr.
2. A mature phase in which slumping, some accretion, and lateral erosion occur.
3. A senile phase in which vegetation dominates the system. Drainage is no longer effective and may be limited to an underground channel. Pans may also develop.

It appears that vegetation limits the migration of mature channels by stabilizing their banks. Yet such stabilization would be less effective in drainage systems with large volumes of water, high current velocities, sandy sediments, and plants having scanty root systems. Therefore, considerable variation in the effectiveness of vegetation in stabilizing channels might be expected in different marsh systems.

Stratigraphic record. In contrast to the lack of surface evidence for tidal-creek meanders, stratigraphic evidence of tidal-creek meanders is more common (McCormick, 1969; Greensmith and Tucker, 1973). In Delaware, there is stratigraphic evidence of both meandering of creeks in mature marshes and youthful development of stable creek systems.

Cores taken in creeks and on adjacent creek banks at Augustine Beach and along the St. Jones River suggest relatively recent development of stable creek systems (Figure 55). The presence of *in situ* fine roots in sediments below the tidal creeks, and the similarity of these sediments with those beneath the creek bank at the same horizon suggest a youthful marsh developing on muddy tidal flats which lack a stable drainage system. Subsequently, creek banks developed with denser vegetation, and more stable creek systems were established.

In South Bowers marshes, the stratigraphic record is much different. Here the sediments beneath the tidal channel are high-marsh sediments, suggesting that the creek may have been incised into the marsh by headward erosion as described by Chapman (1974).

Tidal-channel fill and potential for preservation. Tidal-channel sequences can contain active fill or abandoned fill (Figure 56). Active-fill sequences consist of mud and detrital-organic laminations. Only the top portion of the fill contains abundant roots representing marsh plant colonization as the creek meanders or aggrades. This type of fill may be the response of tidal creeks to continuing sea-level rise. As sea level rises, the marsh surface rises

TYPICAL CROSS SECTION OF A YOUTHFUL TIDAL CHANNEL

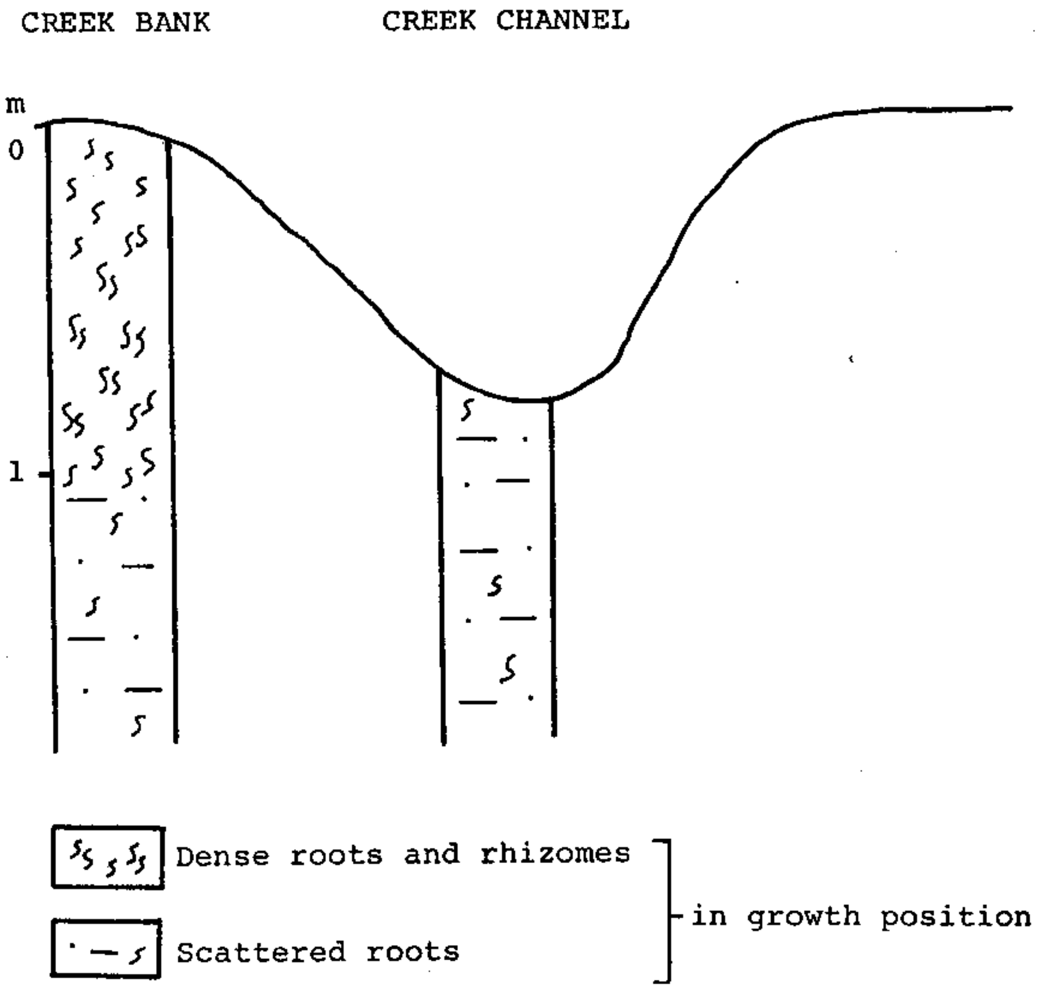


Figure 55. Typical cross section of tidal creeks at Augustine Beach and along the St. Jones River. The restriction of dense roots and rhizomes to the top meter beneath the creek bank suggests recent development of a stable creek and vegetated bank.

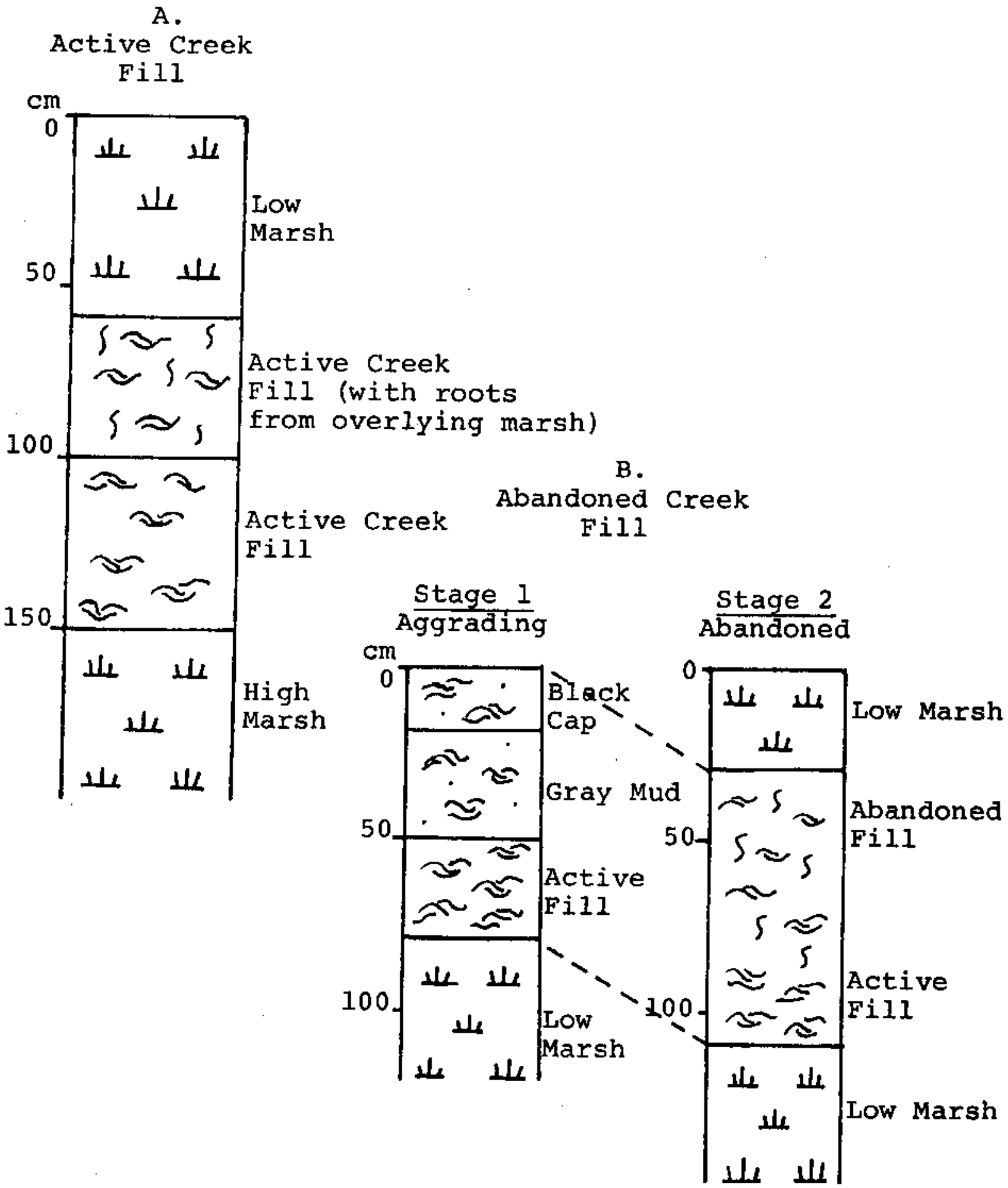


Figure 56. Generalized sedimentary records of the filling of active (A) and abandoned (B) tidal creeks.

and the floor of the creek also rises adjusting to a change in base level. Thus tidal-creek dimensions essentially are maintained. These detrital-organic sequences, interpreted as representing active tidal-creek deposition, range in thickness from 20-50 cm (South Bowers cores 3, 5 and 6; pages 279, 280 and 281).

Aggrading tidal creeks, or those representing abandoned fill, were encountered commonly on the surface. A typical stratigraphic section is presented in Figure 56B. The active-fill stage is represented by a gray to dark gray mud with detrital organics. The abandoned fill is represented by black sediments with a strong rotten egg odor suggesting the presence of hydrogen sulfide gas and iron sulfides (see Berner, 1971). These sediments contain some detrital organics. There is a thin oxidized zone at the surface which is light brown and shiny suggesting abundant diatoms.

As the tidal creeks become abandoned and are vegetated by _Spartina alterniflora_, the dark anaerobic muds with detrital organics are partly oxidized. Most of the black color is lost during conversion of metastable iron sulfides to pyrite (Berner, 1971). Thus, the stratigraphic evidence of tidal creeks consists of dark gray muds with detrital organics representing active channel fill, alteration of the black cap representing abandoned fill to dark gray muds, and a gradual increase in the density of roots until the next environment is reached. Abandoned-fill sequences cannot easily be distinguished from active-fill sequences according to these observations.

Paleographic Reconstructions

Introduction. The application of marsh facies analyses to paleoenvironmental reconstructions can provide detailed information on the nature of coastal change that cannot be determined from general facies studies. Primehook marsh and the Slaughter Beach-Cedar Creek area are particularly suited for this detailed study.

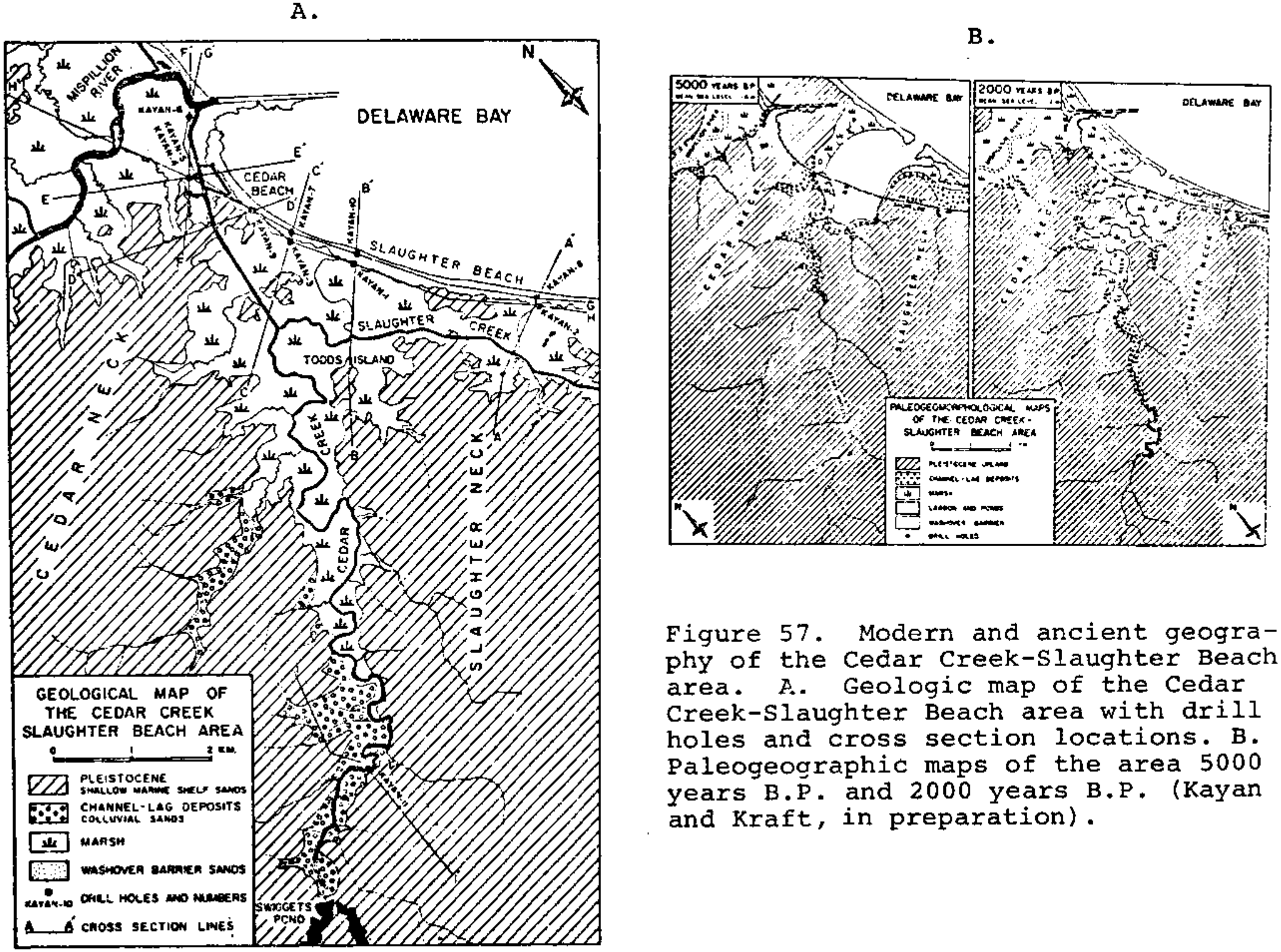
Primehook marsh. Primehook marsh is a poorly drained, brackish- to fresh-water marsh (salinity 2 $^{o}/_{oo}$) containing large marsh ponds or pans (Figure 3A). The area is presently under mosquito-control management to prevent salt-water intrusion (F.J. Murphy, oral communication, 1977), but topographic maps indicate the presence of these ponds as early as 1917.

Five cores taken in this marsh indicate that this area once supported high-marsh vegetation characteristic of a well-drained marsh (see Primehook core 2, page 286 for a representative example). Basal marsh sediments contain brackish-marsh vegetation. Salt-marsh vegetation is dominant in the middle and upper section of the core until there is a sharp break in section where detrital organics representing marsh-pond sediments are encountered.

The cause of this major change in the marsh system may be related to geomorphic changes occurring in the Cape Henlopen system in the early 1900's. In 1882 Primehook Creek emptied directly into Delaware Bay (Maurmeyer, 1974) and probably provided an effective drainage system for the Primehook marsh. However, by 1917 Primehook Creek had been cut off by northward spit extension of the wide sandy barrier at Broadkill located immediately south of Primehook (Maurmeyer, 1974). The presence of this wide sandy barrier without local inlet development severely reduced drainage on the marsh. Marsh ponds developed as a result and continue to dominate the marsh system today.

<u>Slaughter Beach</u>. A paleoenvironmental study in the Slaughter Beach area by Kayan and Kraft (in preparation) (Figure 57) provides the opportunity to correlate information from marsh facies analyses with standard approaches to paleoenvironmental reconstructions. Five thousand years B.P. a lagoon and fringing marsh existed behind the sandy barrier at Slaughter Beach (Kayan, oral communication; Figure 57B). By 2,000 years B.P., marshes covered much of the former lagoon. Microtome sections of marsh sediments from 4 core samples were prepared to determine marsh facies within this depositional framework.

Marsh sediments directly beneath barrier sands


A.

B.

Figure 57. Modern and ancient geography of the Cedar Creek-Slaughter Beach area. A. Geologic map of the Cedar Creek-Slaughter Beach area with drill holes and cross section locations. B. Paleogeographic maps of the area 5000 years B.P. and 2000 years B.P. (Kayan and Kraft, in preparation).

contain *Phragmites* remains. *Phragmites* back-barrier marshes are the first marshes to be covered by the landward-migrating washover barrier and logically would appear at this horizon. Marsh sediments located at depths of 5.0 m and 2.5 m (below MSL) in cores 6 and 7 (Figure 57A) contain remains of high-marsh plants, *D. spicata* and *S. patens.* Further analyses indicate that the marshes adjacent to the Mispillion River were more saline than those behind the Slaughter Beach sandy barrier. This suggests that tidal flow within the lagoon was present, but limited. Five thousand years B.P. the marshes bordering this lagoon were brackish to fresh, suggesting deposition along the upper reaches of the ancient Cedar Creek.

Surface and Subsurface Marsh Patterns

Introduction. Historic changes in marsh environments have been recorded by many investigators, notably Yapp (1922), Richards (1934), Bourn and Cottam (1950) and Redfield (1972). The rapid response of vegetation to changing physical conditions is well known, and major changes in vegetation patterns can occur within one growing season. Subsurface sediments may document these vegetation changes in time.

Redfield and Rubin (1962) suggest that salt-marsh accretion is controlled largely by sediment supply in lower marsh environments and sea-level rise in higher marsh environments. Sufficient sediment supply raises low-marsh environments to high-marsh environments. If the rate of sediment supply and relative sea-level rise are in balance, high-marsh environments are maintained.

Sedimentation rates are not uniform across the marsh. Accretion is typically more rapid at lower marsh elevations than at higher marsh elevations (Richards, 1934; Pestrong, 1965; Chapman, 1974 and others). Sedimentation rate is related to several other variables including distance of marsh from both major and minor drainage systems, surface slope, and particular plant characteristics and habits (Richards, 1934). Low-marsh environments located a considerable distance from a creek system will not always have high sedimentation rates. Vegetation environments change over a shorter distance on steep slopes than on shallow slopes. This factor is locally important where marsh forms along topographic highs of the pre-Holocene surface. Plants have different morphologic features that make them more or less suited to conditions, such as trapping sediment or contributing organics to the sediment. They also have different amplitudes of vertical range and different responses to competition from other species. One consequence of this diversity is that even seemingly level marsh surfaces are characterized by numerous vegetation zones.

Factors. Local relative sea-level change is the single most important factor affecting marsh systems along the Delaware Bay coast. This factor controls to some degree most other factors. Changes in shoreline configuration affect marsh systems by changing inlet locations and modifying drainage patterns. Sediment sources and volumes can be altered. Subsidence due to compaction is a very significant factor when great thicknesses of marsh sediments or other compressible sediments underlie living marshes. Thus,some marshes may have high sedimentation rates but show very little change in elevation or vegetation distribution because of subsidence due to compaction of underlying sediments. "Events" such as fires and storm erosion or deposition also produce major changes in vegetation patterns. This summary of factors stresses the importance of local conditions in controlling the distribution of marsh environments.

Delaware examples-surficial patterns. An excellent example of historic change in vegetation patterns, in part affected by man's activity, is recorded in Delaware marshes along the Mispillion River. Observations on vegetation patterns were made by Bourn and Cottam (1950) from the mid-1930's to the mid-1940's before and after the Mispillion marshes were ditched as part of a mosquito-control effort. Before ditching, 90% of the vegetation consisted of

S. alterniflora with the remaining percentage composed of *D. spicata* and *S. patens*.

Within one growing season after ditching, the greater percentage of *S. alterniflora* died and was replaced by *Pluchea*, *Iva*, *Baccharis* and other vegetation transitional to the upland.

In 1946, 10 years after ditching, *Baccharis* dominated the marsh and *S. alterniflora* occupied only lower areas in the center of the marsh. Ditching lowered the water table and increased drainage, effectively raising the marsh surface and providing an environment more suitable to high-marsh fringing vegetation. Yet at present, this area is again dominated by *S. alterniflora* and the ditches are no longer maintained (F.J. Murphy, 1977, oral communication). It is likely that the second major change in vegetation is caused by the effective lowering of the marsh surface due to the combined effects of: a.) relative sea-level rise; b.) compaction of underlying thick sequence of fine-grained sediments; and c.) reduced drainage due to partial filling of ditches.

Drainage reduction or impounding of marshes, whether natural or man-induced, can change low marshes and high marshes into brackish marshes, ponds, and open water marshes populated by widgeon grass (*Ruppia maritima* L.). Natural or man-made barriers restrict salt-water flow and upland drainage becomes dominant. These changes in vegetation in Delaware marshes due mostly to man's design or activity are recorded by Florschutz (1959), Tindall (1961), and Smith (1968).

Delaware examples-subsurface patterns. Several distinct patterns of marsh facies distribution are identified in the core sequences (Appendix 1). Abbreviations used during this discussion include the following: Fresh-water marsh, FM; brackish marsh, BM; salt marsh, SM; high marsh, HM; low marsh, LM; detrital organic layers, DO.

A. FM-BM-SM sequence. Variations: BM-SM, FM-SM sequences. Examples: Appoquinimink core 1, page 272; Bethany Beach core 1, page 287; Woodland Beach core 2, page 275; and Primehook core 2, page 286.

This sequence reflects the overall response of vegetation to sea-level rise. It is represented in long cores and in short cores. The sequence may be preserved in short cores located along the leading edge of the transgression where vegetation changes are more rapid along the steeper slope. Primehook core 2 reflects the response of vegetation to sea-level rise in the lower and middle sections and the importance of shoreline configuration altering drainage in the upper core section.

B. HM-LM-HM-LM repetitive sequence. Variations: HM-DO-LM and LM-DO-LM sequences. Examples: South Bowers cores 1, 2, 3, 5, 6, pages 276, 277, 278, 280, and 281.

HM-DO-LM or LM-DO-LM. Some detrital-organic layers may represent surface-marsh erosion and storm deposition of detrital organics. This might effectively lower surface elevation and favor growth of low-marsh *S. alterniflora*. Another possible explanation is that detrital organics represent tidal-creek fill. Creek meanders and headward erosion cut through both high-marsh and low-marsh sediments. After detrital organics representing creek fill are deposited, creeks may continue to meander or may become abandoned. In either case,the low elevation favors the growth of *S. alterniflora*. This tidal creek explanation is favored. For instance, the South Bowers core 6 sequence suggests meandering of tidal creeks through a stable low-marsh system.

HM-Fusinite layer-LM. The presence of a fusinite layer suggests burning of the marsh which contributes to lowering of the marsh surface level so that low-marsh vegetation replaces high-marsh vegetation. This sequence is represented in South Bowers core 3 (page 278); the fusinite band is located at 150 cm.

HM-LM. This pattern indicates that the subsidence rate due to compaction of underlying sediments and/or relative sea-level rise is greater than the sedimentation rate. Low-marsh vegetation gradually replaces high-marsh vegetation.

LM-HM. This change occurs when the surface level of the marsh is elevated. This can be caused by overwash deposition such as in Woodland Beach core 1 (page 274); by increased drainage, either natural or man-made, such as in the Mispillion marshes (Bourn and Cottam, 1950); or simply by a high sedimentation rate (portions of South Bowers cores). It seems possible that deposition of a detrital-organic layer on the low marsh could raise elevation so that high marsh was established; yet this pattern was not observed in core sequences.

These alternating patterns of high-marsh and low-marsh sediments are characteristic of core sequences at South Bowers. South Bowers sediments extend to depths of nearly 30 m (Kraft and others, 1976) and subsidence due to compaction is significant. Belknap (1975) determined the amount of compaction on some South Bowers sediments to be 8% in 1000 years and 21% in 6000 years. Subsidence due to compaction and sea-level rise certainly accounts for many of the changes. Yet there also seems to be a balancing effect between these two environments. It may be possible that one environment develops to the point where it can no longer maintain itself and favors development of the other environment.

For instance, high-marsh environments generally receive less sediment than low-marsh environments. Sedimentation may be reduced to the point where sea-level rise lowers marsh elevation without a change in sedimentation patterns. This favors the growth of low marsh _S. alterniflora_. With time,the drainage system may also respond to this change. The alteration of low-marsh to high-marsh environments is well documented. The high inorganic sedimentation rate in low marshes builds them into high marshes within historic periods of time.

It is suggested that subsidence due to compaction is the single most important factor controlling marsh sediment patterns at South Bowers. Important secondary effects are due to the interrelationship of relative sea-level change and sedimentation patterns.

C. _Single facies sequences_. Examples: Blackbird Creek core 2, page 273; Fowler Beach core 1, page 284; and South Bowers core 4, page 279.

These sequences are common in, but not restricted to, relatively short cores. They indicate that depositional conditions are in equilibrium with relative sea-level change. Thus,only a single marsh environment is represented in each core.

D. _Developing marsh sequences_. Examples: Augustine Beach cores 1 and 2, pages 270 and 271; Bennetts Pier cores 1 and 3, pages 282 and 283.

Changes in marsh environments in these cores can be directly related to high sedimentation rates. The evolution of tidal creeks into creek banks, creek banks into low marsh and low marsh into high marsh may occur within short periods of time.

Conclusion. Changes in marsh systems along the Delaware Bay shoreline are related to many factors. One factor may be dominant under certain conditions, yet nearly insignificant under others. Four major patterns are identified:

1. The overall factor controlling marsh deposition is sea-level rise. This produces a transgressive sequence of fresh-water to brackish- to salt-marsh sediments.
2. In deep sections, compaction is important. Repetitive sequences are produced reflecting the interaction of sea-level change, compaction, and sedimentation patterns. These sections show some of the subtle variations in marsh environments such as tidal-creek meanders which may not be recorded in shorter sections.
3. Single facies sequences indicate that there is a balance between depositional conditions and relative sea-level change.

4. The evolution from one marsh environment to another with a slightly higher elevation commonly, but not necessarily, occurs in young or developing marshes and can be attributed to characteristic high sedimentation rates of low marshes.

Typical Vertical Sequences

A block diagram and 3 vertical sequences representing coastal-marsh evolution along the Delaware Bay coast are constructed based on the preceding analyses (Figure 58). These sequences show the considerable variation and complexity of coastal-marsh environments in stratigraphic section. Yet within this complexity lies a sensitive record of coastal change.

In the washover barrier-broad marsh sequence, high- and low-marsh environments are the most important sediment producers. Brackish-marsh environments may contribute a significant amount to the sediments, but fresh-water marsh sediments are a minor component. In the tidal-river sequence, brackish-marsh environments are the most important sediment producers. Fresh-water marshes and high-low marshes probably contribute significant and relatively equal amounts to the sediment.

Stratigraphy of these organic coastal deposits indicates that it is extremely important to know the

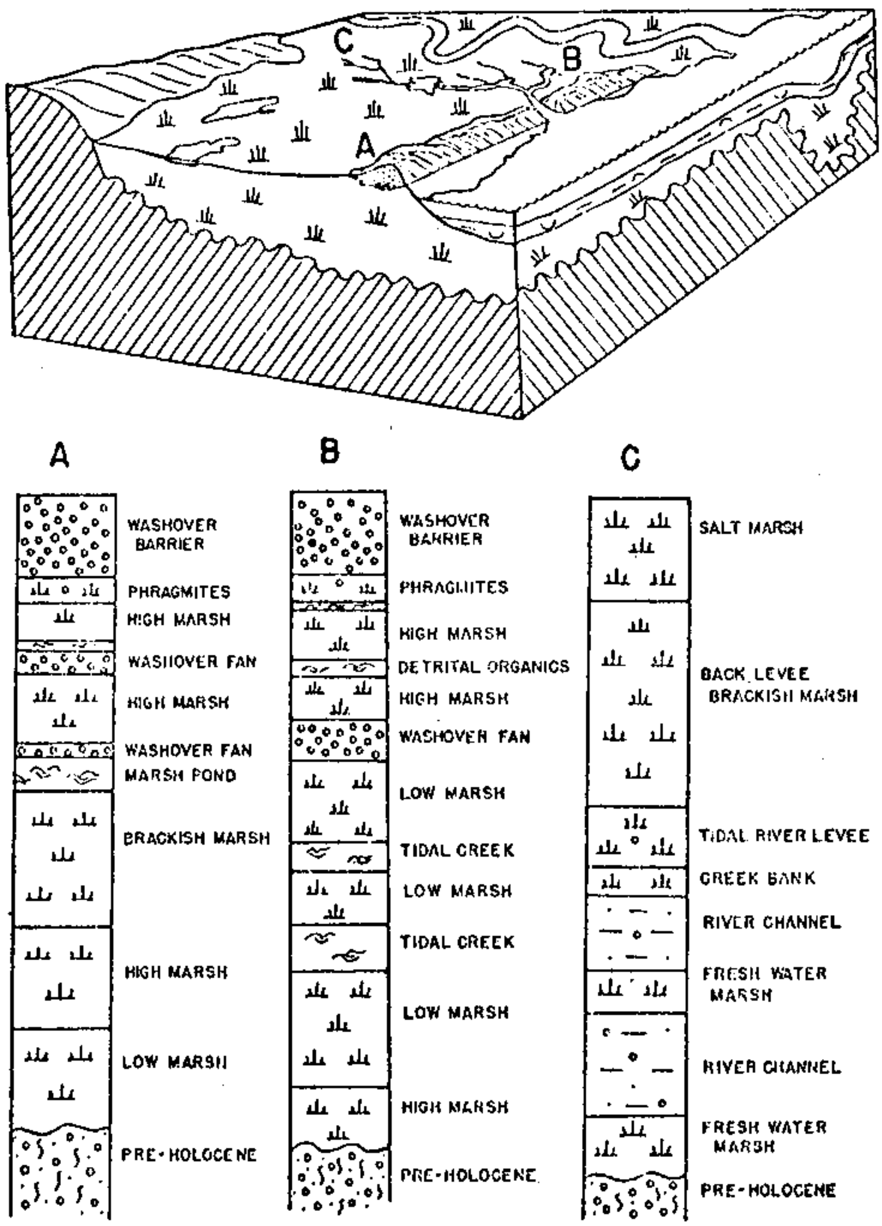


Figure 58. Typical vertical sequences of coastal-marsh sediments and associated environments along the western Delaware Bay shoreline. Sequence A is a section in a poorly-drained marsh with a broad, continuous barrier. Sequence B is in a well-drained marsh with a discontinuous barrier. Sequence C is a section along the tidal river.

characteristics of basal marsh deposits if the material is to be radiocarbon dated and used for construction of sea-level curves. For instance, some basal organic-rich sediments had the fibrous texture of S. alterniflora; yet in microtome section consisted entirely of ferns and fern debris (Figure 58C). Time framework between deposition of the fresh-water ferns and the overlying estuarine sediments may be only a couple hundred years; yet, it also could be on the order of a thousand years and have nothing to do with sea-level change.

ANALOGIES BETWEEN HOLOCENE COASTAL-MARSH DEPOSITS AND PRE-QUATERNARY COALS AND SHALES

Introduction

The theory of Uniformitarianism assumes that physical processes in modern marsh environments are the same as those in the past. However, because of evolution, there is some question whether modern marsh plant communities can be used as models for their ancient analogs. Studies by Cohen (1968, 1969, 1974) of modern sub-tropical coal-forming environments indicate that organic constituents are related as much to major differences in physical parameters (e.g., moisture) as they are to particular species. Moreover, Frey (1976) observed that "reed molds" found in Cretaceous deltaic and barrier-island facies probably occupy the same ecological position as modern marsh plants. These studies and others indicate that knowledge of modern marsh environments is essential to an understanding of pre-Quaternary carbonaceous shale and coal depositional environments.

In this study, three approaches are taken to relate Holocene coastal-marsh deposits in Delaware to pre-Quaternary coal and carbonaceous shale deposits. First, marsh facies are described by maceral composition rather than plant species distribution which was emphasized in previous discussions. Using this method, general marsh facies can be compared with carbonaceous deposits of any age. Second, the abundances of particular sediment components in 10 cores are plotted against depth to determine if distributions of components are related to depositional setting or depth of burial. Finally, from observations of the areal dimensions and internal variability of marsh deposits along western Delaware Bay, a model is constructed to predict similar features in ancient analogs and the preservation potential of marsh sediments.

Maceral Composition

Organic sediments can be discussed in terms of their maceral components since macerals are the organic equivalents of minerals and can be used to describe and identify constituents in carbonaceous sediments, especially peats and brown coals. Coal facies are identified most commonly by maceral constituents, mineral content, and texture (Stach and others, 1975). Carbonaceous shale facies should be subject to similar identification.

Maceral composition in lithified sediments is controlled by the original structure of the plant material, the initial decomposition of plants at the surface and immediately after burial, and degree of coalification (Stach and others, 1975). There are three major maceral groups which include: vitrinites, exinites and inertinites (following the classification of Stach and others, 1975).

Vitrinite includes cell-wall tissue and cell debris; it originates primarily from lignin and cellulose of cell walls. Inertinite includes fusinite, sclerotinite (fungal remains) and micrinite. These components have a characteristically high carbon content and low hydrogen content, and their formation is attributed primarily to decompositional processes rather than to original plant material. Exinite includes spores, pollen, cutins, resins (resinite), and waxes. These components originate from hydrogen-rich plant remains.

In this study, general observations have been made concerning the maceral composition of coastal-marsh sediments (Table 4). In related research, Cohen (1973) observed in the Okefenokee Swamp of southern Georgia that herbaceous peats have low amounts of pre-resinites, pre-sclerotinites, and fusinite and high amounts of pre-micrinites (fine granular debris). He suggested that these sediments would produce a massive, dull coal. Peats composed of woody vegetation remains contained higher amounts of pre-resinites, pre-sclerotinites, and fusinites, and lower amounts of pre-micrinites. These peats will produce a brighter, laminated coal.

Since the organic sediments of the coastal marshes of Delaware are composed of remains of herbaceous plants, they all contain similar characteristics to the herbaceous

PERCENT MACERAL COMPOSITION

	LOW-MARSH SEDIMENTS	HIGH-MARSH SEDIMENTS	BRACKISH-MARSH SEDIMENTS
PRE-VITRINITE	10-15	20-30	40-50
PRE-SCLEROTINITE	0.1	0.2-0.4	0.4
FUSINITE	0-4	3-10	2-6
PRE-MICRINITE	5-20	15-30	15-40
PRE-RESINITE	.5	1	2-4

Table 4. Percent maceral composition for some commonly occurring macerals in low-marsh, high-marsh, and brackish-marsh sediments.

peats described by Cohen (1973). Highly-decayed sediments contain abundant pre-micrinite macerals and are found commonly in high-marsh, brackish-marsh, and fresh-water marsh sediments. Abundances of fusinite are usually higher in these sediments than in Cohen's herbaceous peats. Pre-vitrinitic macerals are more abundant in brackish-marsh and high-marsh sediments than in low-marsh sediments. However, most values are significantly lower than those found by Cohen in Okefenokee herbaceous peats. Pre-sclerotinitic macerals are more abundant in high- and brackish-marsh sediments than in low-marsh deposits, whereas pre-exinites are represented poorly in all marsh facies. This can be due to the fragile nature of some pollen and also, much pollen decomposes in the surface environment. For instance, Juncus pollen grains have very thin exines and are extremely rare in sediments (Erdtman, 1943). In general, grasses and sedges produce small amounts of pollen. Stach and others (1975) note that Phragmites, Typha, and Scirpus have relatively high wax contents, and wax resinite is abundant, especially in some Tertiary coals, possibly due to the presence of these plants or similar species. The presence of common to abundant cell fillings (pre-resinites) in Delaware brackish-marsh sediments is consistent with this observation. Other sediments did not contain appreciable amounts of pre-resinites.

Thus, the maceral composition of the coastal-marsh sub-environments of Delaware are unique and readily recognizable. This permits their recognition in older Holocene and pre-Quaternary marsh deposits.

Distribution of Components

The sediment components chosen in this study appear to reflect particular depositional environments rather than changes that occur with depth of burial. To verify this, abundances of some of the more common and more variable components were plotted against depth for 10 cores (Figures 59-67). Depositional environments are presented also so that a cross-check can be made to determine whether distributions of components are related to depth or to depositional environment.

There is no indication that percent carbon values are dependent upon depth in these shallow cores, even upon changes in depth within the same environment. Carbon content is uniformly low in low-marsh, creek-bank, and tidal-creek sediments. It is slightly higher in *S. alterniflora* low-marsh sediments, significantly higher in high-marsh sediments, and even higher in brackish-marsh sediments.

Although matrix color is variable, it can be related roughly to depositional environment. Moreover, it does not show any pattern of change with depth of burial.

Framework/matrix (F/M) ratios are lowest in tidal-

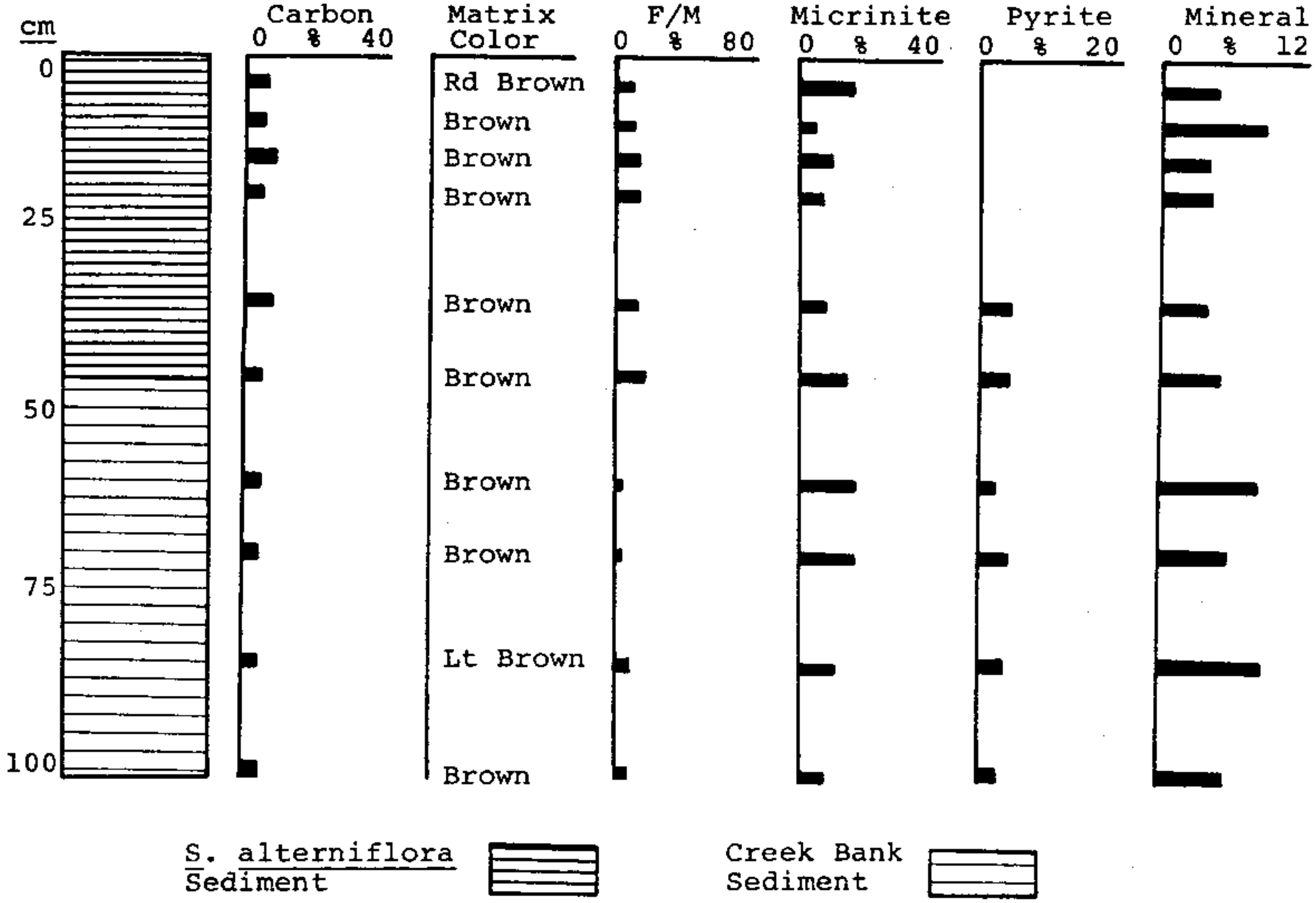


Figure 59. Selected constituents and properties of coastal-marsh sediments from core 1 at Augustine Beach.

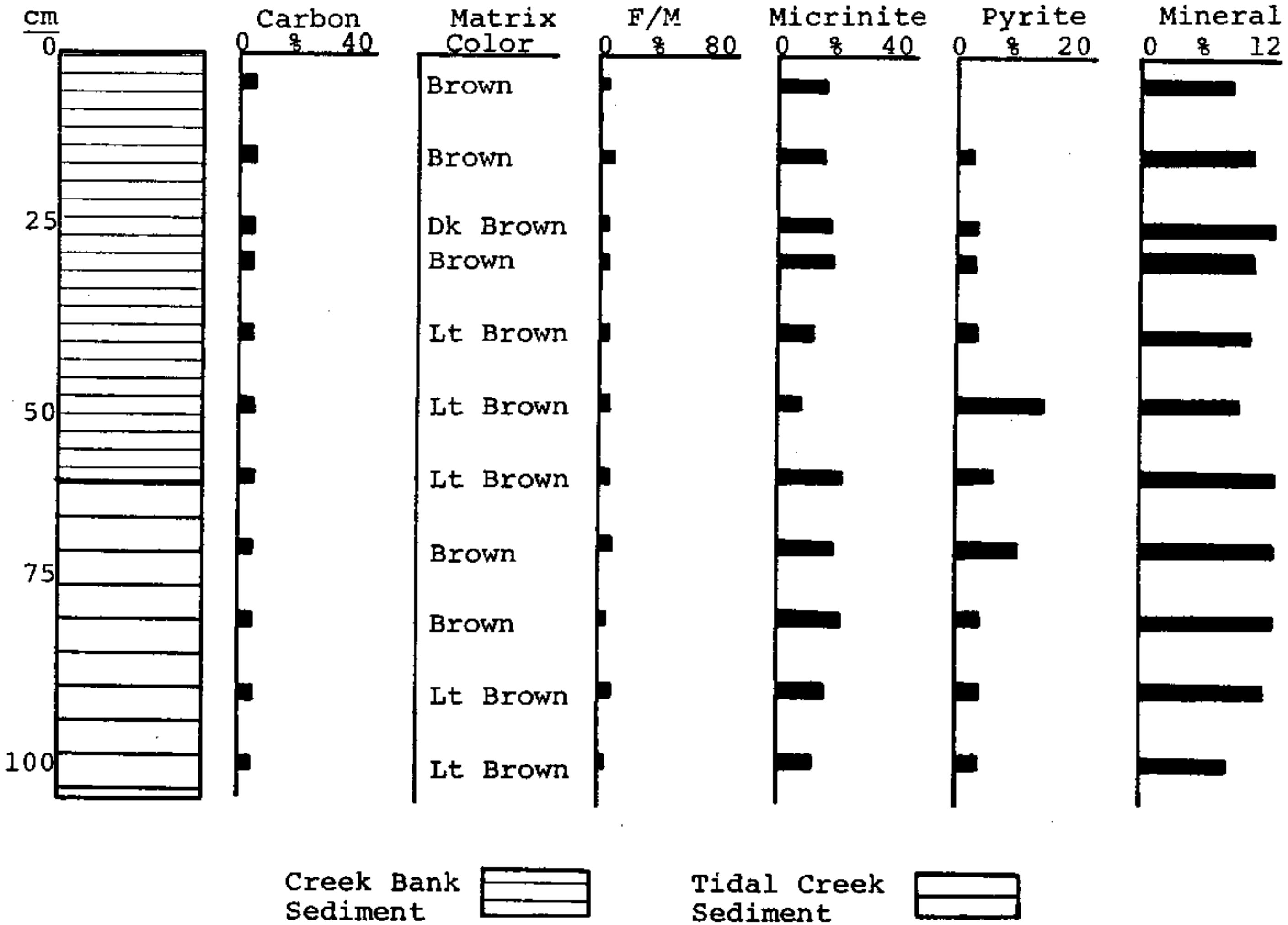


Figure 60. Selected constituents and properties of coastal-marsh sediments from core 2 at Augustine Beach.

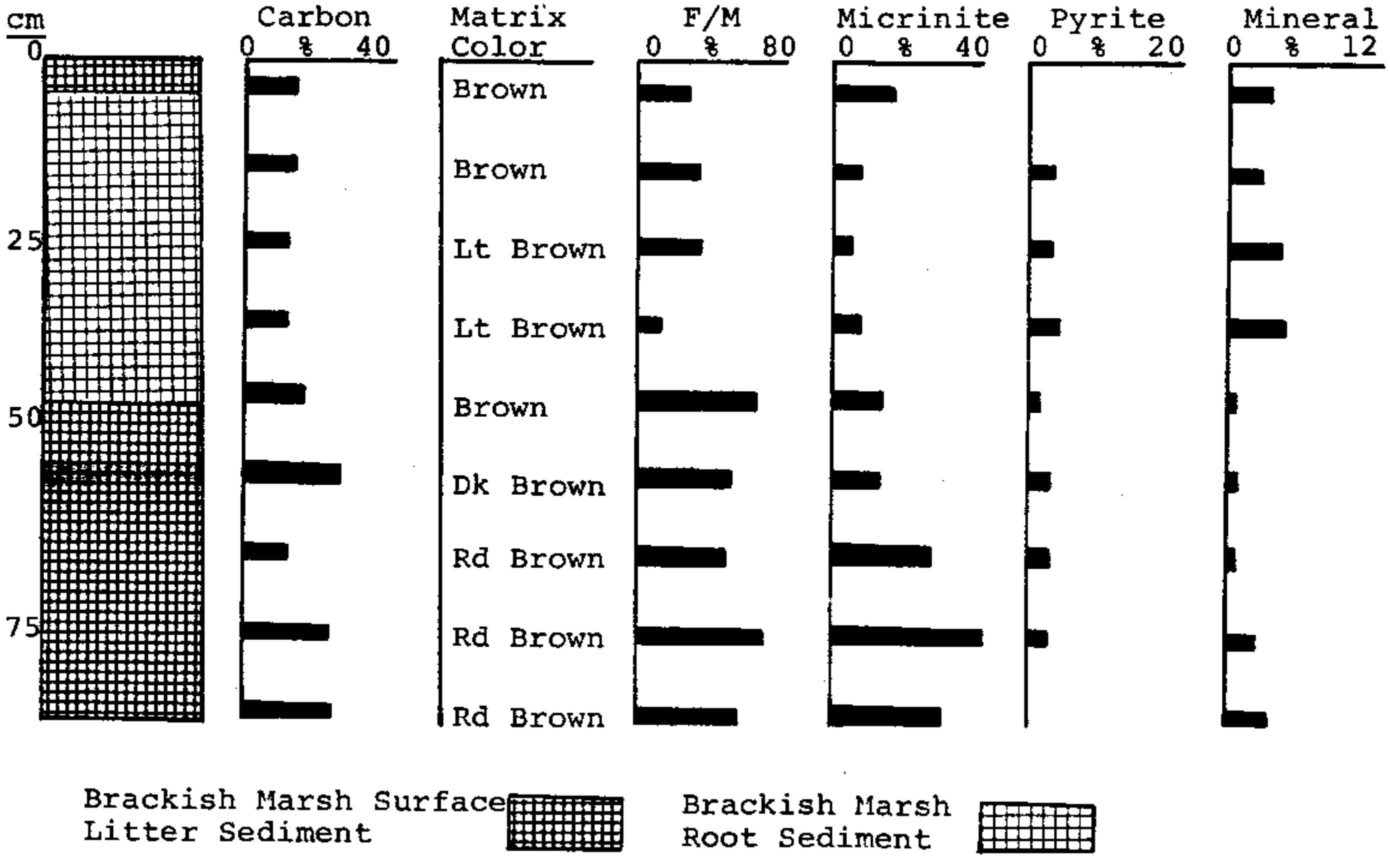


Figure 61. Selected constituents and properties of coastal-marsh sediments from core 2 at Blackbird Creek.

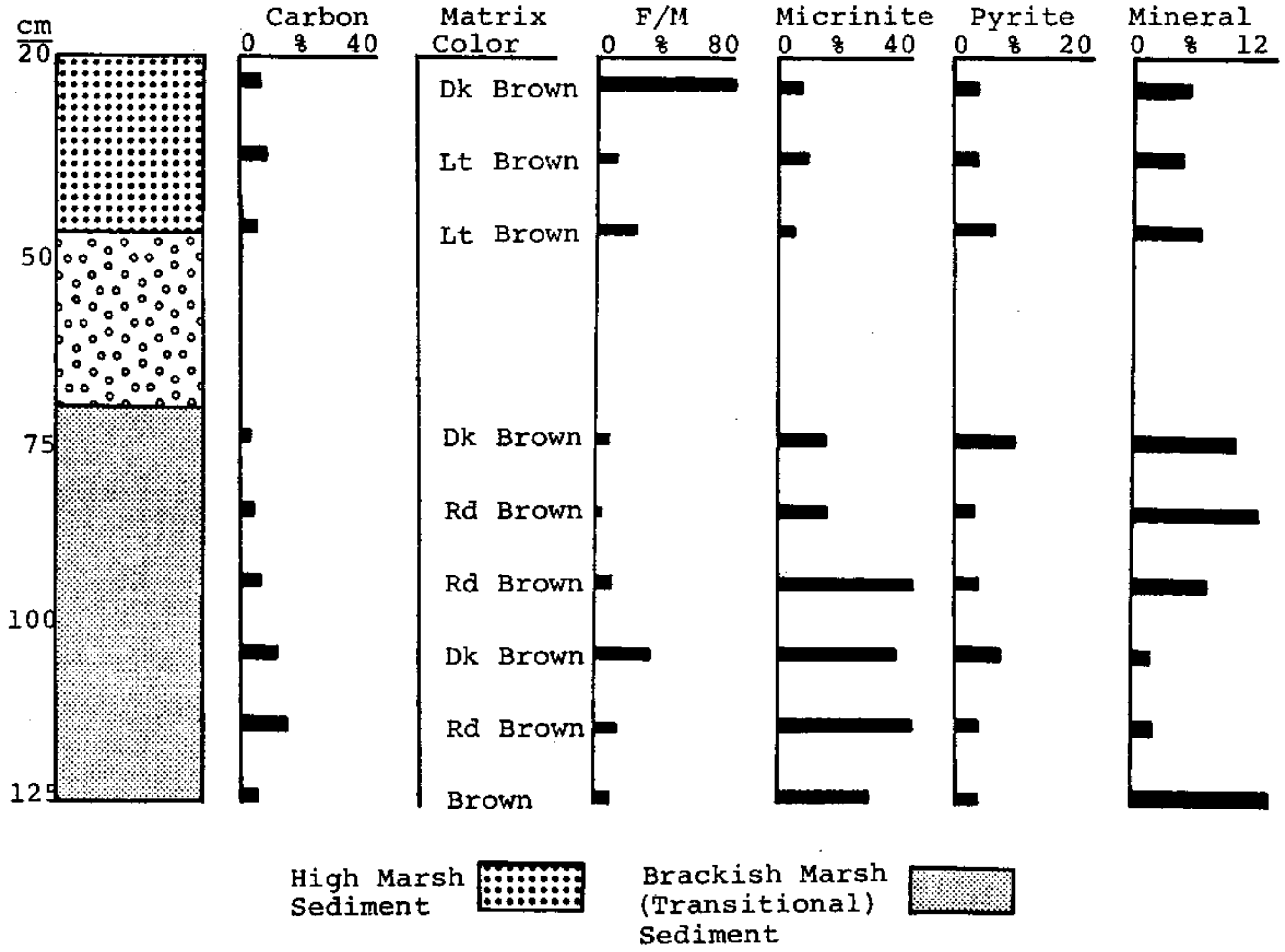


Figure 62. Selected constituents and properties of coastal-marsh sediments from core 1 at Woodland Beach.

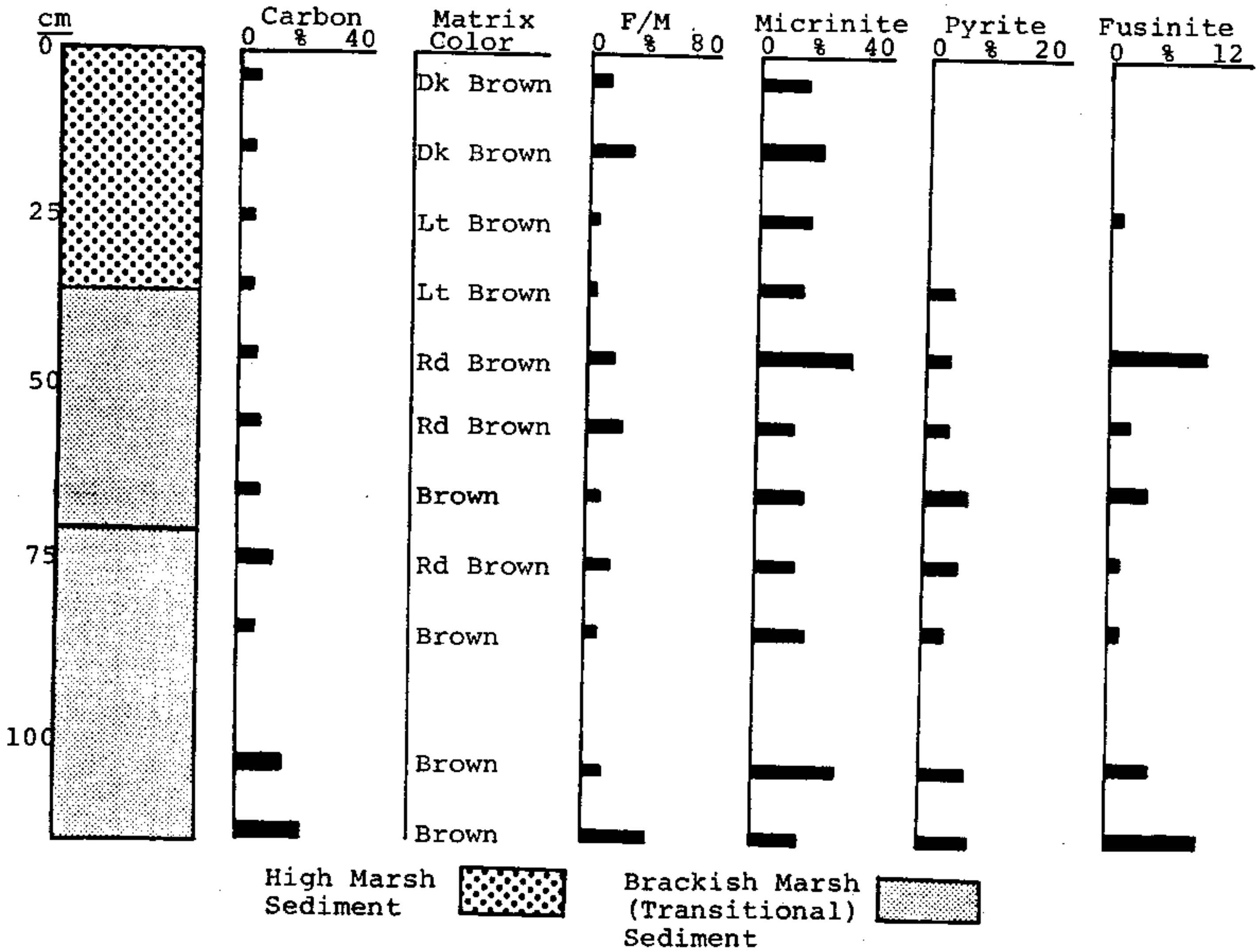


Figure 63. Selected constituents and properties of coastal-marsh sediments from core 2 at Woodland Beach.

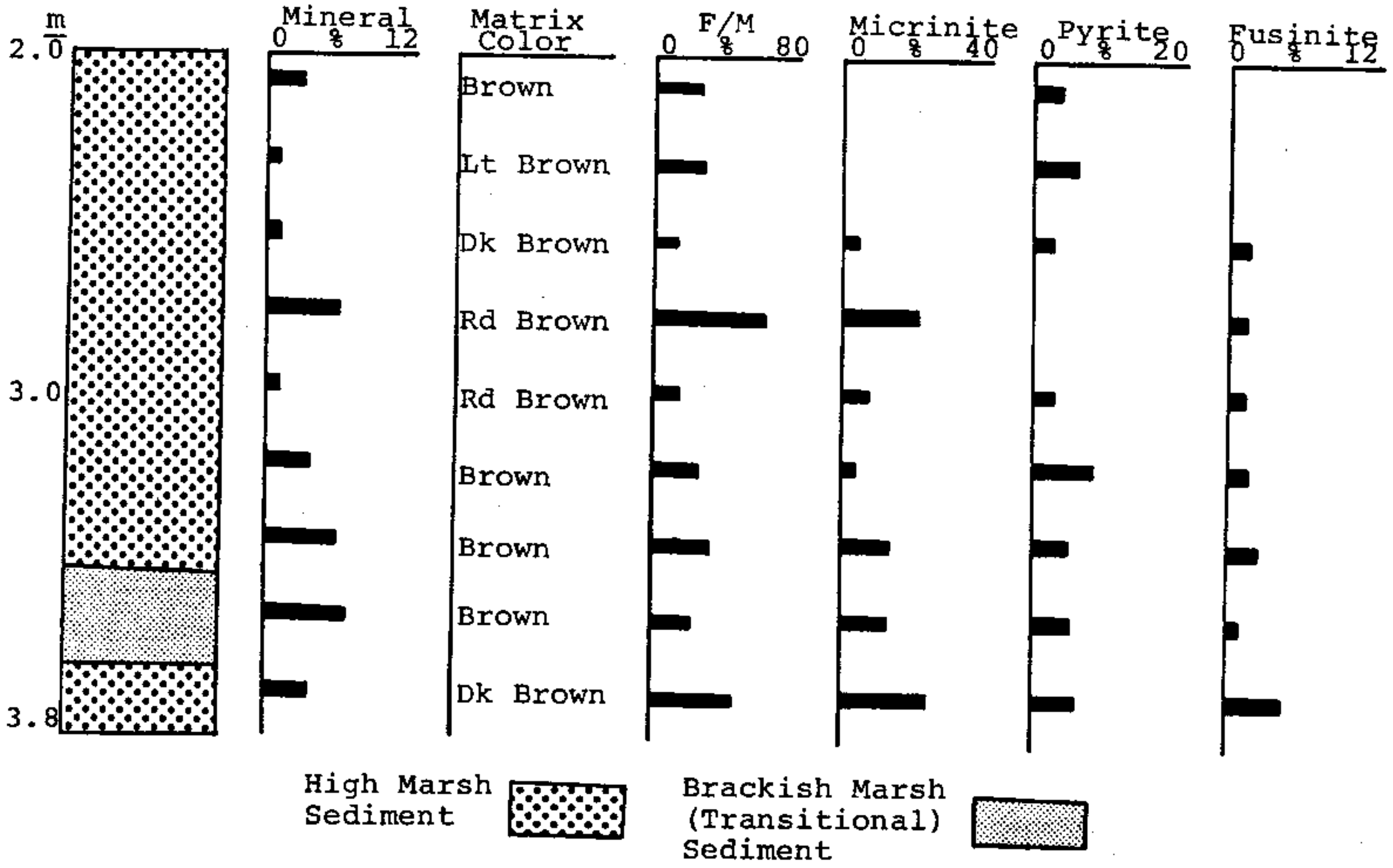


Figure 64. Selected constituents and properties of coastal-marsh sediments from core 3 at South Bowers.

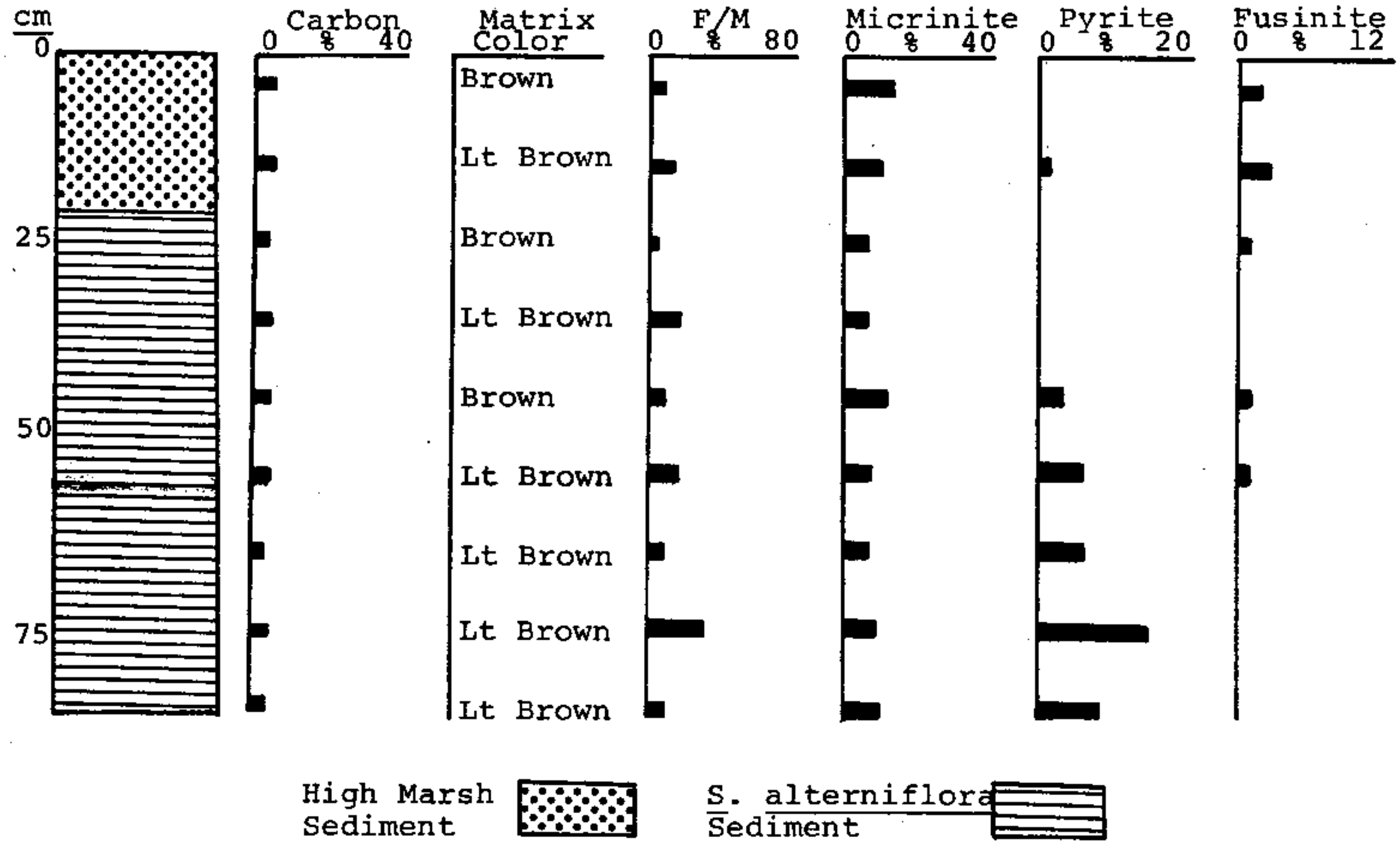


Figure 65. Selected constituents and properties of coastal-marsh sediments from core 1 at Bennetts Pier.

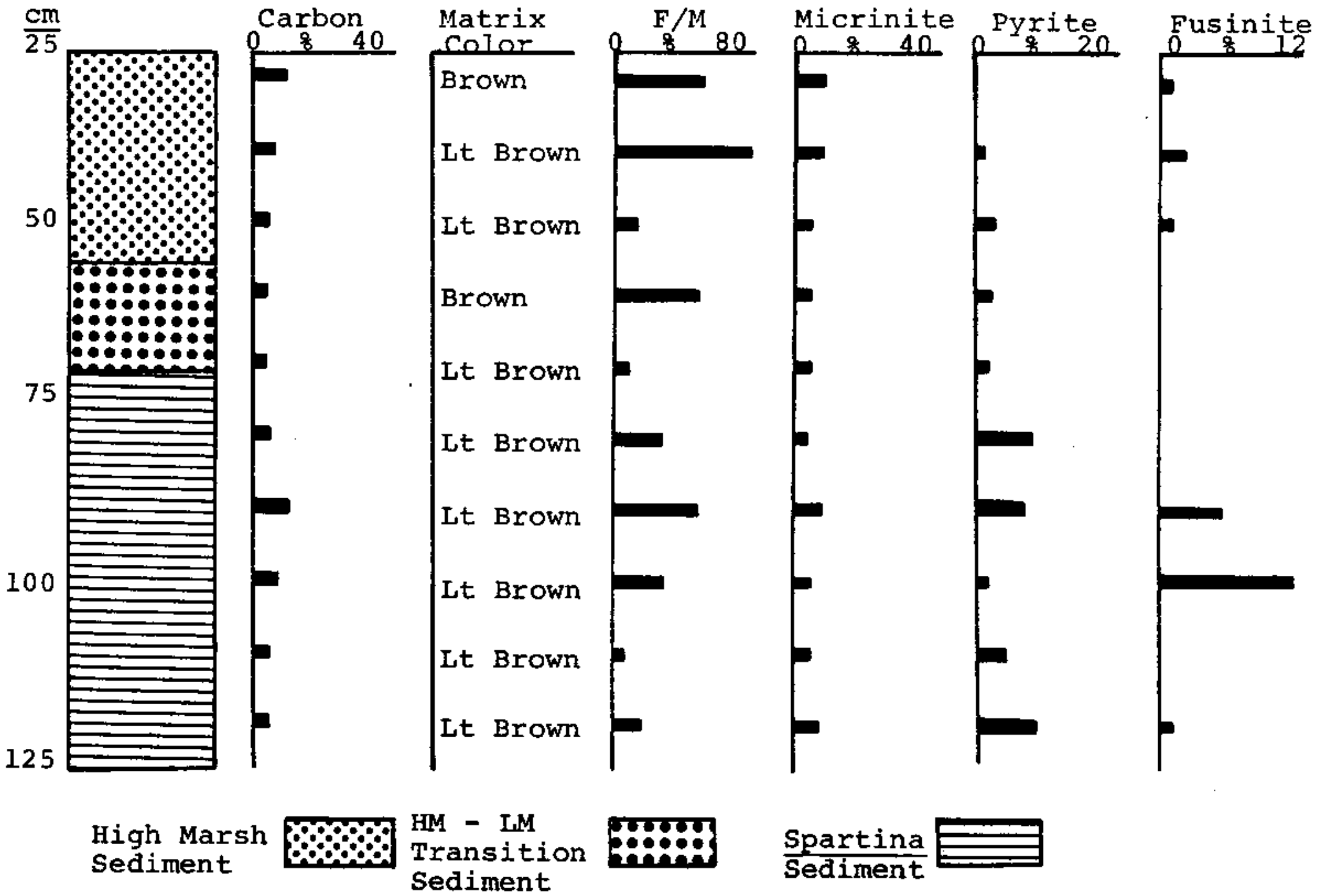


Figure 66. Selected constituents and properties of coastal-marsh sediments from core 3 at Bennetts Pier.

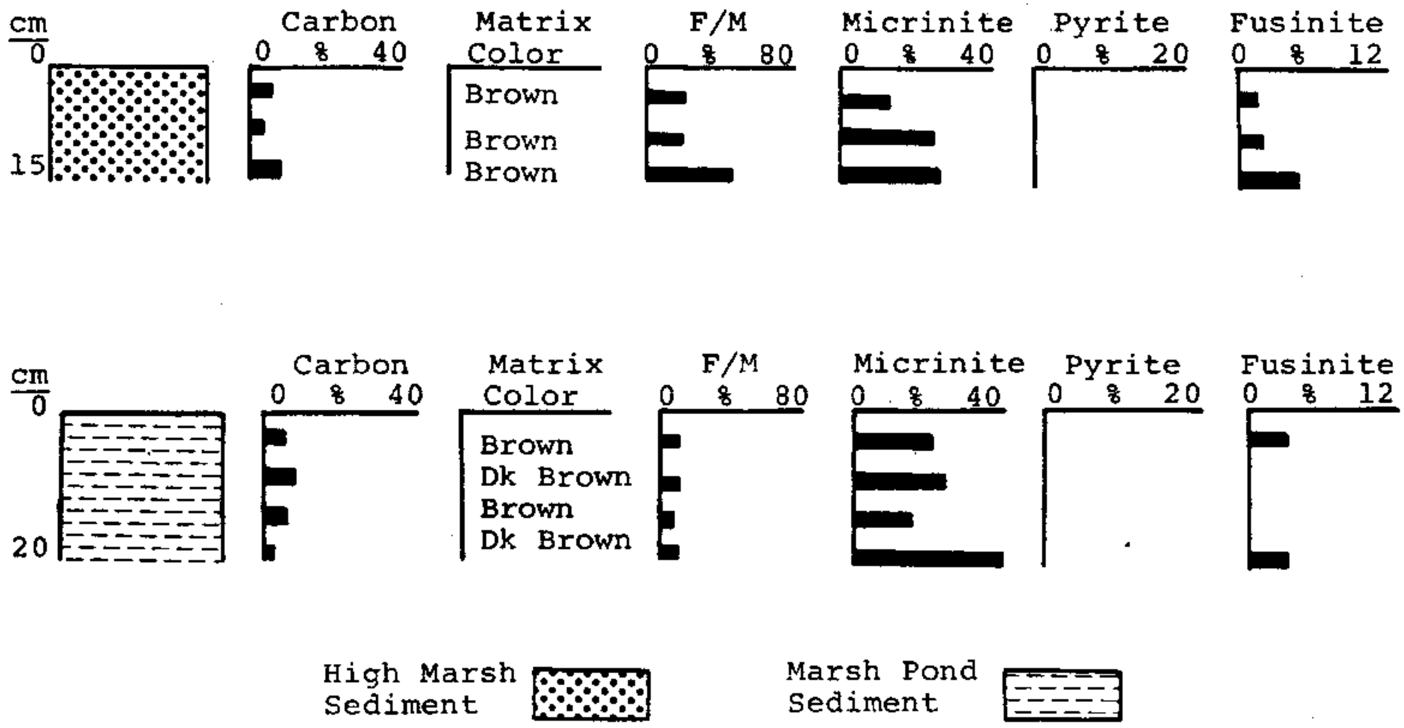


Figure 67. Selected constituents and properties of coastal-marsh sediments from core 1 at Fowler Beach (top) and core 1 at Primehook (bottom).

creek and creek-bank sediments. Higher values occur in S. alterniflora low-marsh sediments, and usually, but not always are higher still in high-marsh sediments. Brackish-marsh sediments contain consistently high F/M ratios. The F/M ratios do not decrease with depth, indicating that larger plant fragments do not break down to finer-grained material within the core depth range of 1-6 m.

The abundance of micrinite in the marsh sediments is slightly more variable but again is related to changes in environment rather than changes with depth of burial. This indicates that microbial activity within this depth range of the cores is not sufficient to effectively alter the color and texture of the sediment.

By contrast, the abundance of pyrite is related to depth of burial since pyrite is not found in the top 15 cm of any core (see discussion of pyrite on p. 75). Burrowing activity and living-root penetration may oxidize the top 15-30 cm of sediments sufficiently to prevent formation of pyrite, or iron sulfides may be present in the metastable forms of mackinawite and gregite rather than as pyrite (Berner, 1971). Pyrite distribution is quite variable beneath this top zone and, to a limited extent, can be related to marsh facies. Observations in this study support the concepts of others that framboidal pyrite is more abundant in sediments exposed to higher salinities than in sediments exposed to lower salinities. Brackish-marsh sediments contain less pyrite than salt-marsh sediments, and pyrite contents in fresh-water to slightly brackish-water sediments (not shown in these cores) are low. Pyrite may form initially in these depositional environments or secondarily after burial by overlying tidal river muds (Appoquinimink core 1, page 272; Bethany Beach core 1, page 287). In addition, relict-marsh sediments exposed to continuous salt-water conditions on tidal flats characteristically have higher values than sediments of the same environments landward of sandy washover barriers. This further suggests that pyrite increases in abundance because of exposure to salt water.

Fusinitic contents are not related to depth of burial. This component can be correlated to particular conditions (fires or highly-oxidizing conditions) that are observed more frequently on high dry marshes but also can occur in any marsh environment. In addition, some fusinite may be detrital.

As expected, mineral content does not show any change with depth of burial and, therefore, is related to depositional setting.

Predicted Rock Record of Delaware's Coastal-Marsh Sediments

Introduction. The detail recorded along the

Delaware Bay shoreline by more than 10 years of research by Kraft and his colleagues provides an opportunity to construct the three-dimensional features of this shoreline and to predict its potential for preservation.

Most of the early studies of sedimentary rocks relied heavily on the 19th century "layer cake" model of William Smith,which is based on the premise that sedimentary rocks occur as more or less tabular units that essentially are concordant. More recently, knowledge of modern coastal processes and the internal morphology of deposits has been used to construct depositional models for predicting and identifying various facies in the sedimentary rock record. These models stress the time-transgressive nature of the sedimentary units in contrast to previous models calling for erosional surfaces of regional extent, broad shallow seas, and frequent sea-level changes (Briggs, 1974).

In the pre-Quaternary rock record, there are numerous studies of both transgressive and regressive sequences in which carbonaceous shales have been interpreted as marshes. Examples of such studies on the Carboniferous strata of eastern United States include: Ferm (1974), Hobday (1974), Horne and others (1974), Horne and others (1976), Horne and Ferm (1976) and Horne and others (unpublished manuscript). Studies of the Cretaceous and Tertiary strata of the Western Interior, Plains, and Southwestern United States include:

Sears and others(1941), Fisher and others (1960), Campbell (1971), Land (1972), Weimer and Land (1976), and Gopinath and Martin (1975). Bridges (1976) recognizes transgressive barrier island-lagoonal sequences in the Lower Silurian of southwest Wales.

Western Delaware Bay Shoreline

Dimensions and external form. The present shoreline is approximately 150 km in length. Surface widths vary from several hundred meters to 8 km,but most commonly,the widths are 2-4 km (Figure 68). The landward edge of the deposit is highly irregular,while the shoreline edge is relatively straight. Marsh deposits reach maximum thicknesses of 30 m, but most common thicknesses vary between 5-15 m (Kraft and John, 1976). The dimensions of this deposit as well as many of the internal variations are strongly controlled by the highly-incised pre-Holocene surface. This marsh sequence represents deposition on a low- to moderate-energy shoreline. In the rock record, these sediments will produce strata consisting predominantly of carbonaceous shales and siltstones with shales and minor sandstones.

Internal variation (Figure 68). Bodies of silts and muds are surrounded by organic-rich sediments in the base of the section, particularly in the southern part of the shoreline. These silts and muds represent lagoons formed behind the sandy barrier and appear as lenses

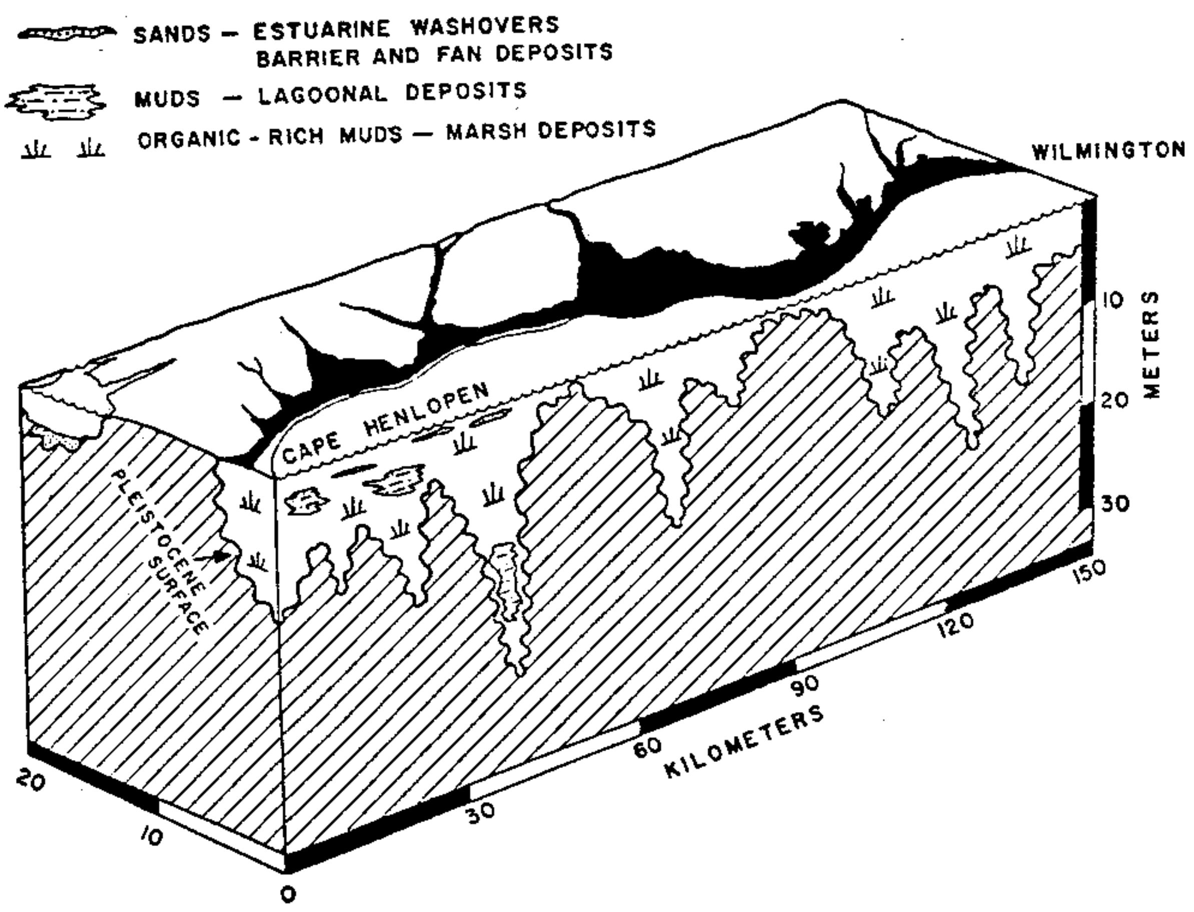


Figure 68. Block diagram of the western Delaware Bay shoreline showing the internal variability of sediments and aerial dimensions of the Holocene deposit. Note the vertical exaggeration. Marshes are shown in black.

"floating" in the more organic-rich sediments. These lagoonal silts and muds are seldom encountered in the top of the section. Instead, this portion of the section consists of a continuous sequence of organic muds and silts representing coastal-marsh deposition. These organic deposits are elongate both perpendicular (tidal river marshes) and parallel (broad marshes) to the shoreline. Sandy washover barriers and fans are represented as discontinuous lenses of sand. Their distribution is random and they are limited in size.

The abundance of pyrite will be low in the lower portion of the section along the pre-Holocene contact if the overlying sediments shield the fresh-water marshes from marine to brackish waters. Pyrite is higher in organic sediments beneath porous sand lenses representing washover barriers and fans, and exceptionally high in sediments exposed bayward of the barrier.

Transgressive phase. During the present transgressive phase, deposition has continued along the shoreline, increasing the thickness of the sedimentary wedge. However, the width of the shore zone has decreased due to erosion of marshes exposed bayward of the barrier. The lengths and widths of surface marshes appear to be maintained,although location is shifted to the northwest (Kraft, oral communication, 1977). Marsh sediments can also be lost during shoreline erosion along the Atlantic coast as sea-level rises and the Cape Henlopen-Atlantic shoreline migrates to the northwest.

If the rate of sea-level rise is relatively high, a large portion of the stratigraphic section may be preserved (Fischer, 1961; Kraft, 1971a; Kraft and others, 1973). The deeper portions of the section, especially those in the drowned river valleys, have greater potential for preservation, but they also will show the greatest variation in geometry and coastal facies and may be difficult to interpret.

Regressive phase. During a regressive phase caused by a lowering of sea level, these sediments will be exposed to subaerial weathering. Oxidation of these sediments will cause alteration of depositional characteristics, and erosion will remove some parts of the deposit entirely. The duration and extent of weathering and erosion during the regressive phase compared to the thickness of the sedimentary section determines the potential for preservation of the section. A thick sedimentary sequence exposed to a short period of subaerial erosion has high potential for preservation.

During a regressive phase caused by increased sedimentation, this coastal deposit will be buried and thus will have a greater opportunity for preservation.

SUMMARY AND CONCLUSIONS

Coastal marshes are dynamic systems which respond quickly to changes in sediment supply, tidal flow, and shoreline configuration. They are excellent indicators of coastal change, and are expecially useful in determining shoreline change in deposits where barrier sands are not preserved.

Seventeen coastal-marsh facies and subfacies can be distinguished along the western shore of Delaware Bay. These include: I. low-marsh facies (A. S. alterniflora low-marsh, B. S. alterniflora creek-bank, C. unvegetated creek-bank, D. tidal-creek subfacies); II. high-marsh facies (A. low-marsh and high-marsh transitional, B. high-marsh cowlick, C. high-marsh root, D. rotten-spot subfacies); III. marsh-pond facies; IV. Phragmites facies; V. brackish-marsh facies (A. salt marsh-brackish marsh transitional, B. tidal-river levee marsh, C. back-levee brackish-marsh, D. brackish-marsh surface litter, E. brackish-marsh root subfacies); VI. fresh-water marsh facies; and VII. detrital-organic facies. Each facies or subfacies is defined by a set of microscopic and megascopic constituents that can be related to the corresponding depositional environment. Microscopic constituents of coastal-marsh sediments provide a wide range of information on sediment component distributions that can be used to study degradation, maceral composition, and depositional history. Megascopic characteristics of coastal-marsh sediments also have interpretive value, but confident interpretation requires knowledge of the structure and morphology of the potential plant contributors to the sediment.

Specific conclusions and observations made during this study include the following:

1. Species composition is the single most important determinant of marsh facies.
2. Marsh subfacies are distinguished by organ composition (e.g. high-marsh root subfacies vs. high-marsh cowlick subfacies), or a combination of characteristics such as texture, matrix color, and mineral content.
3. The nonvascular tissue of the stele and hypodermal regions of roots and stems (culms and rhizomes) are usually better preserved than cortical regions. Vascular tissue and leaf sheaths are usually highly decayed.
4. Percent carbon values are highest in the detrital-organic facies, high in brackish-marsh facies, variable

in high-marsh facies, and low in low-marsh facies. The highest values are only 30 percent carbon which is significantly lower than the 60 percent carbon required to meet the AGI definition of peat. Few coastal-marsh sediments in temperate zones appear to meet this requirement. Therefore, the term peat should be dropped and replaced with terms such as salt-marsh deposit, coastal-marsh sediment, and organic-rich sediment.

5. Framework/matrix ratios are useful in characterizing facies. Low F/M ratios indicate a lack of large organ fragments. Matrix material may be dominated by highly decomposed organic material indicating dry, oxidizing conditions at the surface, or it may be dominated by mineral grains indicating high sedimentation rates. High F/M ratios indicate that plant organs are being incorporated in the sediment and are not being washed away by tides or decomposed on the marsh surface.

6. Miscellaneous components such as diatoms, foraminifers, cell fillings, and sponge spicules can be diagnostic for a particular subfacies or particular surface conditions. For example, masses of pennate diatoms characterize rotten-spot subfacies. Also, certain cell fillings, when abundant, strongly suggest <u>Phragmites</u> facies. The presence of abundant fibers (resistant plant material) indicates oxidizing surface

conditions.

7. The lack of pyrite in the top 15-30 cm of the sediment is attributed to oxidizing conditions created by living roots and burrowing organisms. The percentages of pyrite are higher in salt- and brackish-marsh sediments than in fresh-water marsh sediments. Highest percentages were recorded in outcrop exposures of marsh sediments on tidal flats regardless of original depositional environment. This suggest that exposure to saline waters increases pyrite content in sediments.

8. Roots in Pleistocene sediments underlying Holocene marsh deposits originated from marsh plants at the contact. Roots of upland herbaceous and woody vegetation do not appear to have been preserved, and it is suggested that the anaerobic marsh sediments provide a protective seal against oxidation of roots in the Pleistocene deposits.

9. Analyses of basal marsh sediments indicate that a variety of marsh sediments form at the leading edge of the transgression, depending upon local conditions. Brackish- to slightly fresh-water marshes form where tidal waters extend inland and mix with fresh waters. Brackish marshes form along the middle reaches of the tidal river, in poorly-drained areas, and where marshes are broad. Salt marshes form when drainage is

excellent and the distance between the active shoreline and the pre-Holocene surface is short.

10. Washover sequences contain intercalations of sand and both *in situ* and detrital marsh sediment. This depositional package allows the marsh surface to be maintained as relative sea level rises.

11. Relict-marsh sediments form broad tidal flats along the western Delaware Bay shoreline. Back-barrier marshes of *Phragmites*, *Baccharis* and *Iva* may be overwashed by barrier sands and exposed on the tidal flat within one year. As these sediments are eroded, the high-marsh sediments underlying the back-barrier sediments are exposed and eroded.

12. Tidal-channel sediments are represented in stratigraphic sections by detrital organic layers of high-marsh and low-marsh plants. Both abandoned and active creek fill sequences occur, but they cannot be distinguished at depth because of post-depositional alterations of the abandoned fill sequence.

13. These marsh sediment analyses provide detailed information on changes within marsh environments at depth that can refine interpretations of paleoenvironments. For instance, shoreline changes such as the opening and closing of inlets can be inferred from the succession of marsh environments.

14. Stratigraphic sections show repetitive sequences of marsh environments. These patterns can be related to the interaction of factors such as sediment supply, sea-level change, and compaction. Also, these patterns reflect the importance of local conditions such as shoreline configuration,and short-term conditions such as seasonal or yearly climatic change in controlling the distribution of marsh environments.

15. The distribution of marsh facies along the western Delaware Bay shoreline can be represented in three idealized vertical sequences. The broad marsh and continuous sandy barrier sequence contains brackish-marsh and salt-marsh sediments. A thick sequence of brackish-marsh sediments suggests poor drainage resulting from the presence of a wide, thick sandy barrier lacking inlets. Fresh-water marsh deposits are rare. The broad marsh and discontinuous sandy barrier sequence also contains brackish- and salt-marsh sediments. Salt-marsh sediments dominate the sequence because drainage is usually excellent. The complete tidal-river sequence contains mostly brackish-marsh sediments with relatively equal amounts of fresh-water marsh sediments at the base and salt-marsh sediments at the top.

16. General marsh facies can be defined by maceral composition. Low-marsh facies have lower pre-vitrinites,

pre-sclerotinites, fusinites, pre-micrinites, and pre-resinites than both high-marsh and brackish-marsh sediments. High-marsh sediments contain the highest fusinitic compositions, and brackish-marsh sediments contain significantly higher pre-resinitic and pre-vitrinitic compositions than both low-marsh and high-marsh sediment.

17. Sediment characteristics such as micrinite content, mineral content, and F/M ratios are related to changes in depositional environment rather than changes that occur at depth (1-6 m).

18. The coastal deposit along the western shore of Delaware Bay can be used as a model for interpreting transgressive coastal marsh sequences in the rock record. The sediments would produce carbonaceous shales and siltstones with minor sandstone bodies at irregular intervals. The deposit would trend both parallel (broad-marsh and barrier sequence) and perpendicular (tidal-river marsh sequence) to the paleoshoreline. Deposits in deep river valleys have the greatest potential for preservation.

19. Undoubtedly, future research in other temperate-zone marshes will reveal other marsh facies. Comparisons of marsh facies analyses from other marsh systems with the Delaware marsh deposits could prove quite valuable.

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APPENDIX I - CORE LOGS*

EXPLANATION

LM	LOW MARSH
HM	HIGH MARSH
SM	SALT MARSH
BMT	BRACKISH MARSH TRANSITION
BM	BRACKISH MARSH
SL	SURFACE LITTER
FM	FRESH MARSH
DO	DETRITAL ORGANICS
TC	TIDAL CREEK
CB	CREEK BANK
MP	MARSH POND
PH	PRE-HOLOCENE - HOLOCENE CONTACT
WA	WASHOVER

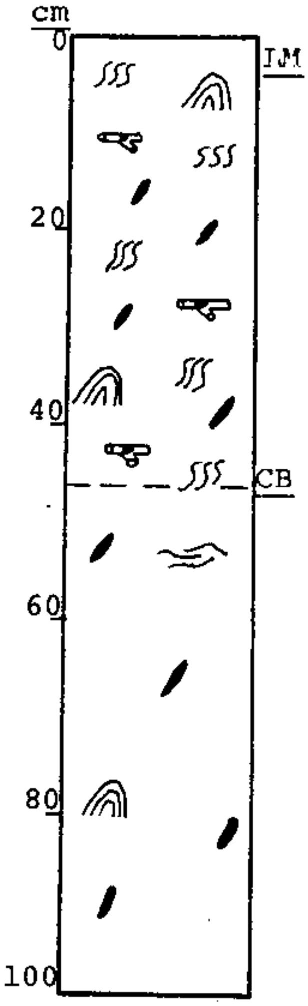
▬	MUD LENSES
⬭	SAND LENSES
▨	SAND
▩	PEBBLES, GRAVEL
— · —	MUD

⥼	RHIZOMES
⌒	LEAF SHEATHS
⸙	LEAVES
ʃʃʃʃ	DENSE ROOTS
ʃ ʃʃ	SPARCE ROOTS
●	S. ROBUSTUS TUBER
≈	DETRITAL ORGANICS
⊖	BRACKISH MARSH SURFACE LITTER
⊖	HIGH MARSH COWLICK
|/	UNDIFFERENTIATED ORGANIC SEDIMENT
●	FECAL PELLETS
∿	SHELLS

— —	MARSH ENVIRONMENT CHANGE
——	LITHOLOGIC CHANGE

*The marsh surface is considered zero depth. No attempt was made to adjust variations in marsh surface heights to a datum.

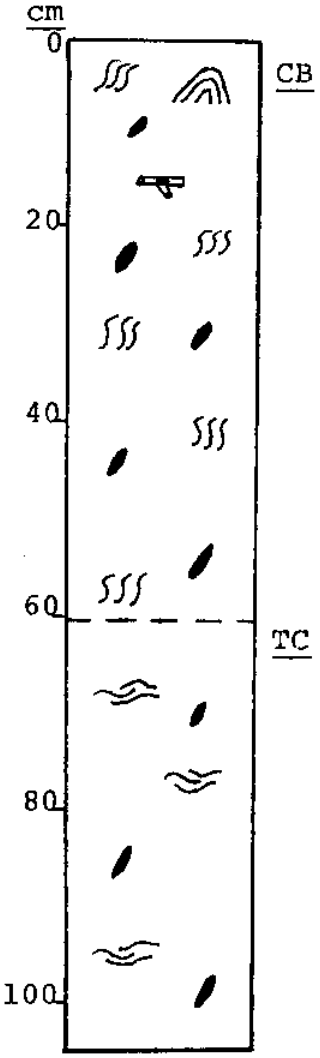
Augustine Beach core 1*



Characteristics Megascopic	 Microscopic
Orange mottling, Roots	Roots, leaf sheaths
S.alterniflora	S.alterniflora
Black leaf sheaths	Roots, fecal pellets
Same as above	.
Collapsed leaf sheaths	.
Large roots	.
Rhizome decay - yellow-orange	. S.alterniflora rhizome
Roots - lt tan, transparent	Fecal pellets, roots
Occas. blue-black mottling	Detrital organics
	Cell fragments
Rhizomes rare, some roots	Fecal pellets
Organics decrease with depth	Detrital organics
	Fecal pellets, few roots

*Core location: latitude 39° 39.58'
longitude 75° 35.16'

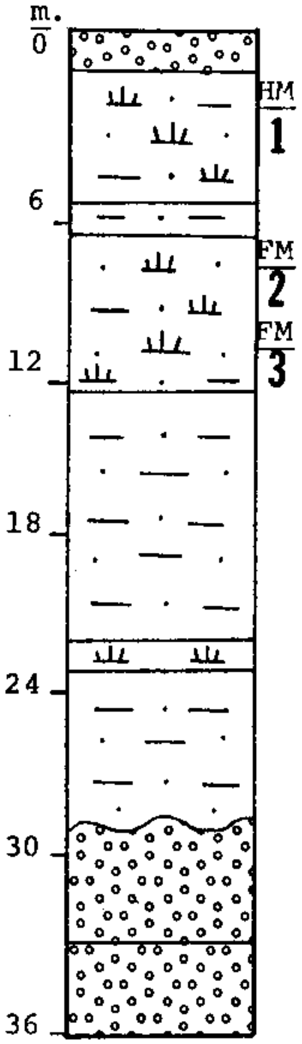
Augustine Beach core 2*



Characteristics	
Megascopic	Microscopic
Orange mottling S.alterniflora	Roots, fecal pellets Tissue,cell frag.
Leaf sheaths	.
V. few roots, no rhizomes, ?bedding planes	.
	Fecal Pellets
Blue-black mottling occas. in core	.
	S.alterniflora Fecal pellets
Few organics	Tissue,cell frag.
Partings along possible bedding planes	Occas. root, fecal pellets
	Detrital organics
	Occas. tissue, cell frag.

*Core location: latitude 39° 39.58'
longitude 75° 35.17'

Appoquinimink Drill Hole 1*

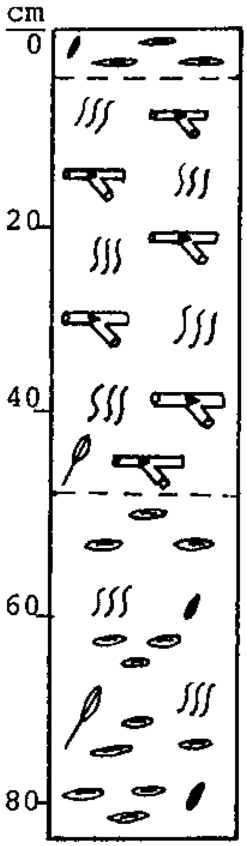


Characteristics

Megascopic	Microscopic
Fill	**1** 4 meter depth D. spicata roots, rhizomes
Phragmites? Spartina?	
Brown, high organics	**2** 9 meter depth Fern annulus, spores and debris Pontederia leaf Pyrite
Gray mud with bluish cast, a few organics	**3** 12 meter depth Fern roots? and debris Pontederia root Scirpus roots Seeds, diatoms-hash and whole
Brown organic debris	
Gray mud	
Glauconite (Eocene?)	
Hard-packed	

*Logged by D.F. Belknap, 1974
Core location: latitude 39° 27.76'
longitude 75° 37.05'

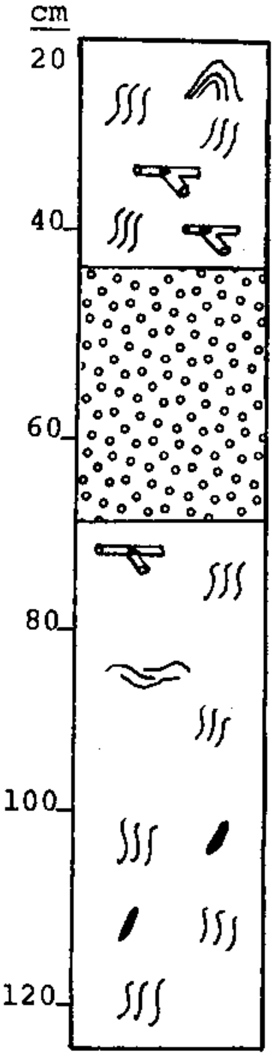
Blackbird Creek core 2*



	Characteristics Megascopic	 Microscopic
SL	Stems, no roots	Stems, fecal pellets compaction
BM	Very small roots *Scirpus* roots - reddish color	Roots, rhizomes *Hibiscus*, *Scirpus*, *Panicum*, *S.cynosuroides*
	Dense root network - *Panicum*	
		Occas. leaf Occas. *S.patens*
	Panicum? roots *S.cynosuroides*? roots	Mostly *Scirpus* and *Panicum*
	Scirpus? roots	Occas. *D.spicata*
SL	Stems, leaf sheaths	Plant fragments, high decay
	.	Fecal pellets
	.	Occas. roots Alternating layers of high and low decay
	.	
	S.cynosuroides	*Scirpus*, *Panicum* dom.

*Located at Stave's Landing
Core location: latitude 39° 25.88'
longitude 75° 36.09'

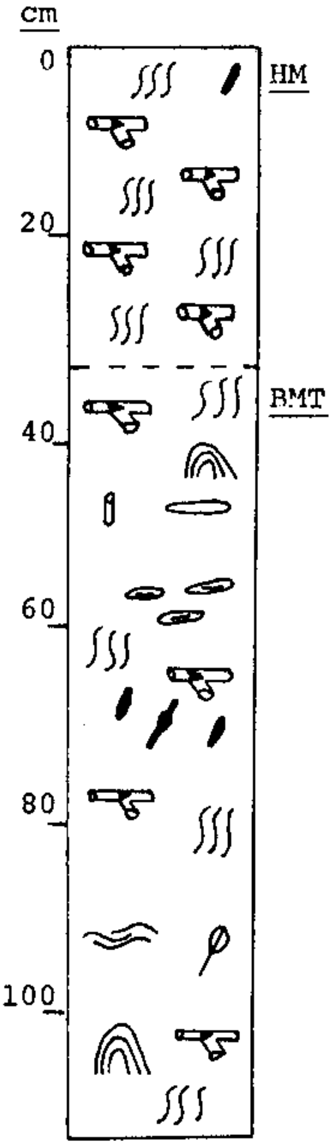
Woodland Beach core 1*



	Characteristics Megascopic	Characteristics Microscopic
HM	*D. spicata* *S.alterniflora* *S. patens*	*D. spicata* *S. alterniflora* *D. spicata*, *S. patens*
	S. alterniflora	*D. spicata*, *S.alterniflora* leaf sheaths
WA	Medium sand, well sorted	
	Fine sand with clay and silt	
BMT	Fine roots, Black mottling-fusinite?	*S. alterniflora*
		High decay, tissue fragments, detrital
	Few small roots, detrital organics	*Scirpus* roots, grass roots Fecal pellets
		Tissue fragments
		Scirpus roots

*Core location: latitude 39° 19.77'
longitude 75° 28.23'

Woodland Beach core 2*

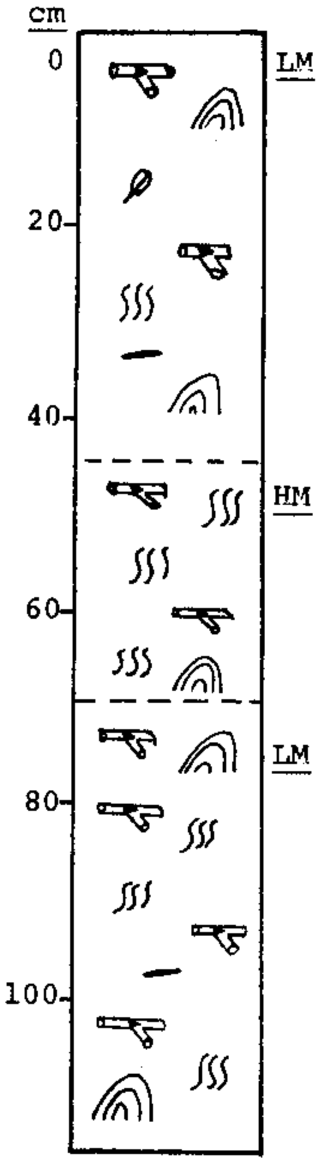


Characteristics

Megascopic	Microscopic
Orange,blue-black mottling D. spicata	Fecal pellets S. patens,D. spicata Baccharis
•	•
•	•
S. alterniflora rhizomes,leaf sheaths	S. patens Leaf sheaths-S.alterniflora Roots
Sand lenses, Phragmites stem	Scirpus root,high decay, surface litter
S. robustus tuber	Scirpus, Hibiscus stem
Scirpus Orange, blue-black mottling	D. spicata surface litter,compaction
Detrital	Scirpus,D.spicata S.patens, D.spicata
D. spicata	Leaf sheaths

*Core location: latitude 39° 19.75'
longitude 75° 28.26'

South Bowers core 1*



Megascopic Characteristics

S. alterniflora

Dicot leaf

S. alterniflora
S. patens (minor)
Scirpus (minor)
D. spicata (minor)

S. alterniflora dominant

D. spicata

S. alterniflora

S. alterniflora
P. communis?

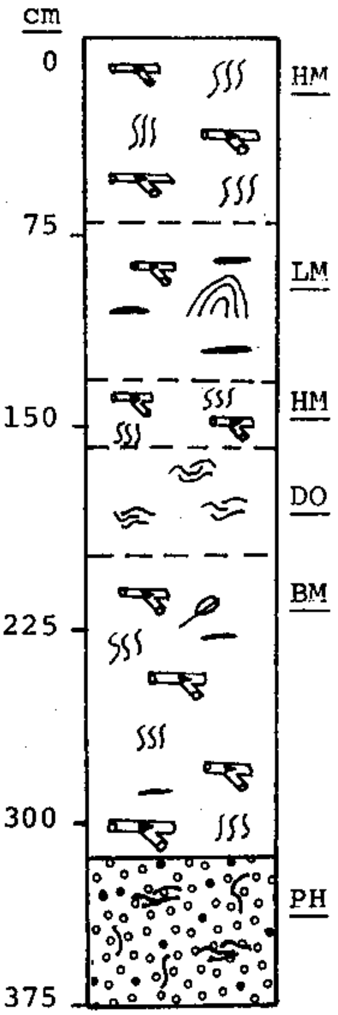
Very large roots

P. communis or *S. alterniflora* ?

Same as above

*Core location: latitude 39° 2.66'
longitude 75° 23.37'

South Bowers core 2*



Megascopic Characteristics

D. spicata, *S. patens*
S. alterniflora (minor)
S. patens dominant

S. alterniflora
Mud lenses
Very few roots

S. patens
S. alterniflora (minor)

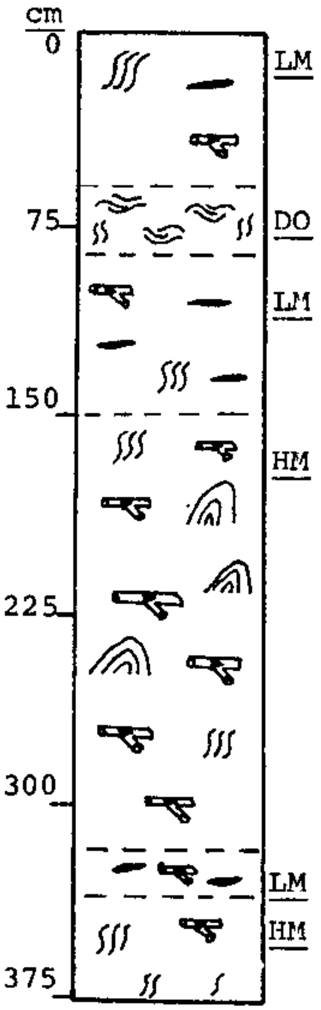
Same

S. alterniflora
Scirpus
Dicot leaf
Very large roots, *P. communis*?
S. patens abundant
Fusinite?
Scirpus, *S.alterniflora*,*D.spicata*

Sand with pebbles, roots extending from above, detrital organics
White and orange colors

*Core location: latitude 39° 2.80'
longitude 75° 23.33'

South Bowers core 3*



Megascopic Characteristics

D. spicata
Orange mottling, S.alterniflora dominant

S.alterniflora, S.patens (minor)

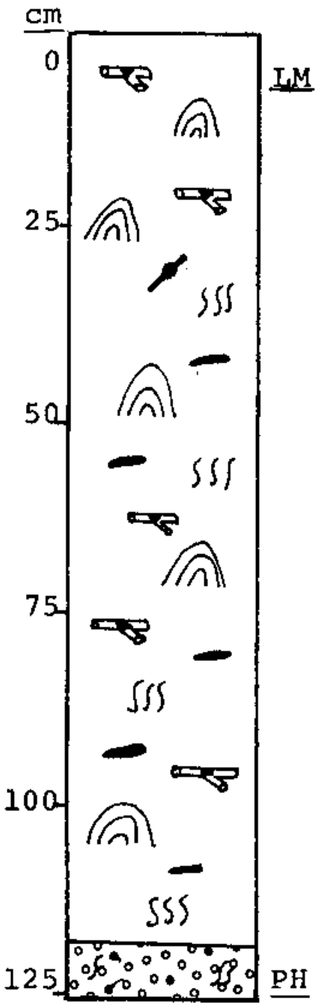
S. alterniflora, mud lenses
D.spicata, S.patens (minor)

Fusinite
D. spicata, S. patens
Dense fibrous root system

Megascopic	Microscopic
S. alterniflora (minor)	S. patens S.alterniflora (minor) Leaf sheaths D. spicata S. alterniflora
S. alterniflora	P. communis S. alterniflora
S. patens, D.spicata Muddy sand, grass roots	S. patens, D. spicata

*Core location: latitude 39° 2.88'
longitude 75° 23.33'

South Bowers core 4*



Megascopic Characteristics

S. alterniflora

S. robustus tuber

D. spicata

S. alterniflora

S. alterniflora?, very large roots, maybe *P. communis*

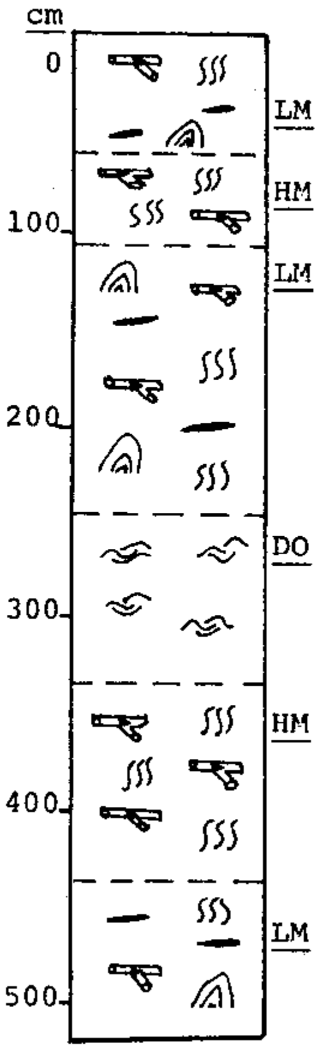
Brackish plants?

S. alterniflora

Muddy sand with pebbles, roots from above

*Core location: latitude 39° 2.66'
longitude 75° 23.47'

South Bowers core 5*



Megascopic Characteristics

S. alterniflora

Baccharis or Iva
S. patens, D. spicata

S. alterniflora
Mud lenses

S. patens (minor)

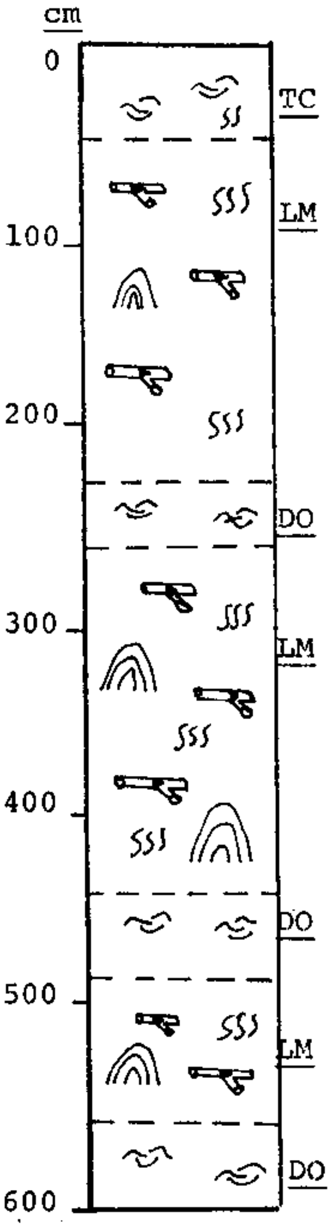
Fragments on bedding planes
S. alterniflora (dominant)
S. patens

D. spicata
S. patens
S. alterniflora (minor)

S. alterniflora
S. patens (minor)

*Core location: latitude 39° 2.96'
longitude 75° 23.55'

South Bowers core 6*



Megascopic Characteristics

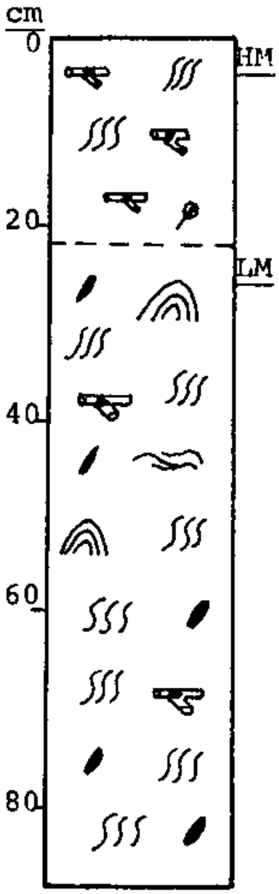
Black mud, detrital organics
Gray mud, detrital organics

S. alterniflora

D. spicata, S. patens (minor)

*Core location: latitude 39° 2.98'
longitude 75° 23.48'

Bennetts Pier core 1*

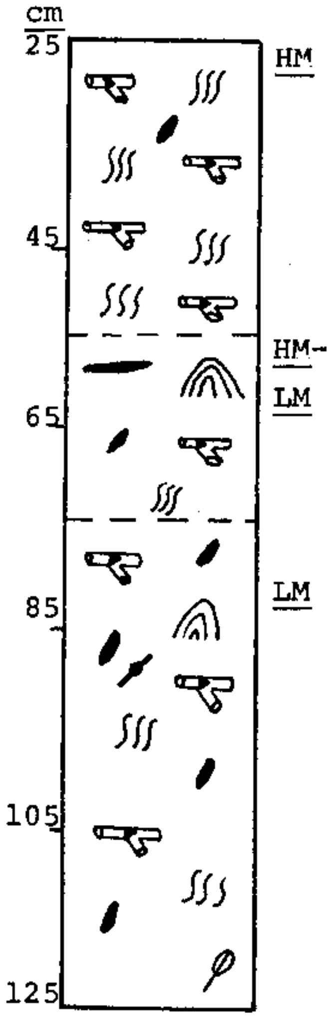


Characteristics

Megascopic	Microscopic
S.alterniflora rhizome S.patens dominant Roots	Small roots S.patens S.alterniflora Rhizomes S.patens leaf Fecal pellets Roots
S.alterniflora abundant Some S.patens Roots abundant	Leaf sheaths, high inorganic Fecal pellets Leaf sheaths abundant S.alterniflora throughout core Isolated vascular bundles-S.alter. Some detrital organics-bedding planes Roots, rhizomes Fecal pellets
Roots common, lower amount of organics	Detrital? High decay

*Core location: latitude 39° 2.42'
longitude 75° 22.20'

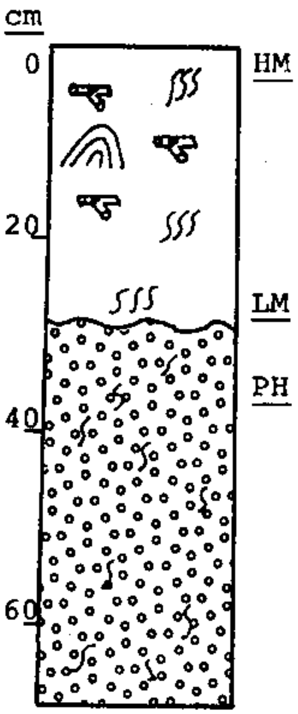
Bennetts Pier core 3*



Characteristics Megascopic	Characteristics Microscopic
D. spicata rhizomes	D.spicata rhizome, fecal pellets
.	.
.	.
.	.
.	Some S.patens
Mud lenses	
Small S.alterniflora	S.alterniflora leaf sheaths
	D.spicata,S.patens
S.alterniflora dominant,some S. patens	S.alterniflora,fecal pellets
Detrital S.robustus tuber	.
No roots	.
S. patens	.
S. alterniflora	.
D. spicata	D.spicata,leaf sheaths
S. patens	Panicum
	Baccharis leaf

*Core location: latitude 39° 2.39'
longitude 75° 22.18'

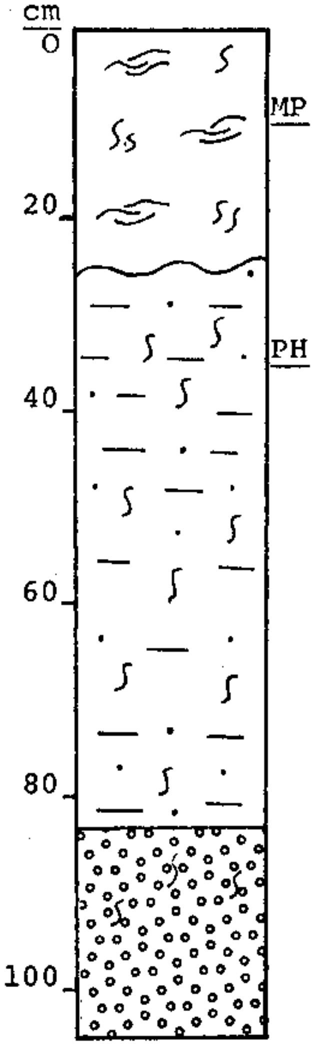
Fowler Beach core 1*



Characteristics	
Megascopic	Microscopic
S. alterniflora *D. spicata* dominant Sandy	*S. alterniflora* *D. spicata* dominant
S. alterniflora	
Hard-packed sand, fine roots extend to bottom of core	
Orange mottling	

*Core location: latitude 38° 52.68'
longitude 75° 16.53'

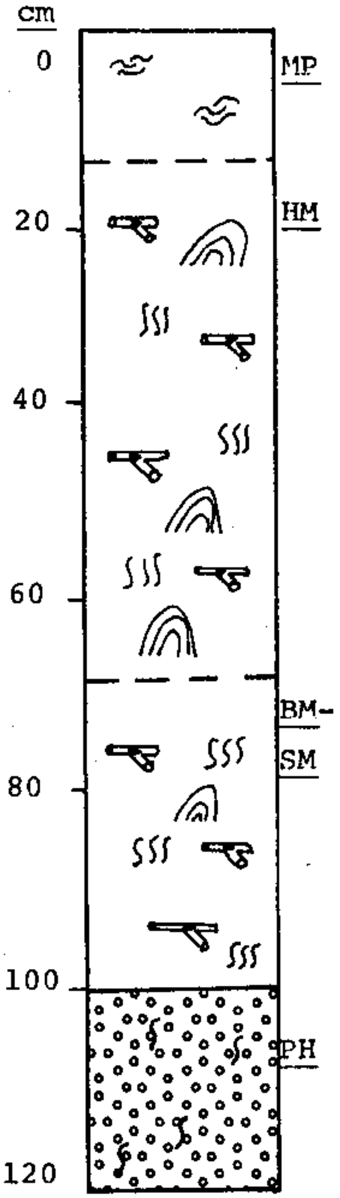
Primehook core 1*



Characteristics	
Megascopic	Microscopic
Highly decayed fragments Small roots Bedding planes?	Tissue and cell fragments, highly decayed Some fine roots Fecal pellets *D. spicata?*
Firm silt and clay with some sand, orange brown	
Fine roots extend through out the core, decrease with depth	
Firm sand	

*Core location: latitude 38° 51.17'
longitude 75° 15.25'

Primehook core 2*



Megascopic Characteristics

Detrital organics, lt to dk brown, possibly desiccated

D. spicata, S. patens
S. alterniflora (minor)

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.
.

Occasional Scirpus culm

D. spicata, S. patens, Scirpus (increases with depth)

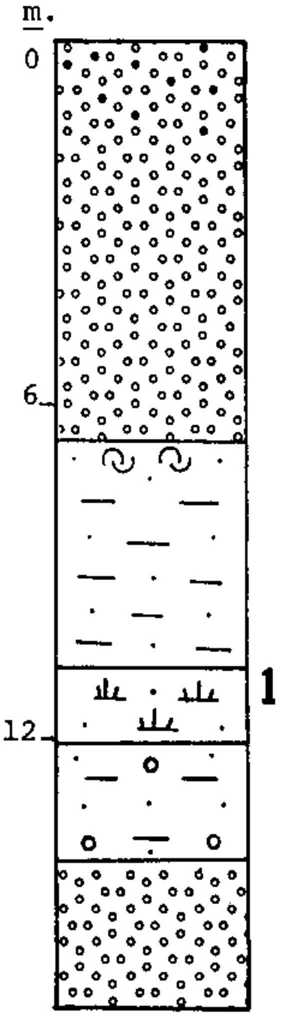
.
.

Sandy zone

Gray, firm slightly oxidized sand with fine roots from above

*Core location: latitude 38° 51.30'
longitude 75° 16.03'

Bethany Beach Drill Hole 1*



Characteristics	
Megascopic	Microscopic
Gravelly sand	**1** 12 meter depth
Fine sand,white-gray	Fern debris, Highly decayed
Fine sand,orange brown	
Silty fine sand, orange brown	
Mud - sand, orange oxidized burrows	
Shell fragments	
Oysters, articulated	
Dark gray mud, some organics	
Organic rich sediment ➡	Granular, dark brown-black with red mottling; clay lenses
Sandy mud	
Muddy sand	
Fine-medium sand, lt. blue-gray	

*Logged by C.L. Shields, 1973
Core location: latitude 38° 32.80'
longitude 75° 5.00'