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Paleo-Environmental Analyses of Marsh Sequences (Clinton, Connecticut): Evidence for Punctuated Rise in Relative Sealevel During the Latest Holocene

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ABSTRACT

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We developed an integrated chemical-faunal approach to paleo-environmental analysis of salt marsh sequences. Sediment cores from the Hammock River Marsh (Clinton, Connecticut, U.S.A.) were studied for benthic foraminiferal assemblages and sediment chemistry (Fe, Zn, Cu, S). Foraminiferal faunal assemblages, especially the relative abundance of the species *Trochammina macrescens*, as well as the abundance of Fe, Zn and S are reliable indicators for the flooding frequency of marsh sub-environments in the intertidal range. The faunal assemblages largely reflect the average exposure time to the atmosphere, and the sediment chemistry reflects the trapping of fine-grained particulate matter in the marsh, and thus reflects the complementary aspect, flooding frequency. Results from the chemical and faunal analyses are in close agreement, and indicate that the Hammock River Marsh underwent three relatively sudden periods of drowning over the last 1500 years, followed by marsh recovery. Much of the rise in relative sea level over the last 1500 years can be accounted for by these three periods of drowning of the marsh. We propose that these pulses might represent true eustatic accelerations with an estimated time span of several decades to some hundred years.

ADDITIONAL INDEX WORDS: *Climate change, marsh foraminifera, sea level rise, trace elements in marsh sediments.*

INTRODUCTION

Global sea level has been rising since the initiation of the last deglaciation about 15,000 years ago, predominantly because of melting of the polar ice sheets and continental glaciers (*e.g.*, WALCOTT, 1972; CLARK *et al.*, 1978; NIXON, 1982). This process will continue over the foreseeable future, and in macro- and micro-planning of society and economy one can not neglect the fact that shorelines will keep retreating in the future. Models for future sea level rise are based either on computational models that take the rising temperature caused by the atmospheric anthropogenic greenhouse effect into account, or extrapolate historic trends in relative sea level rise into the next century. Many of these models assume a smooth time-function for the change in sea level during the past and in the near future. Exceptions to this generalization are studies by FAIRBRIDGE (1961, 1981, 1987), MOERNER (1976, 1980, 1987), RAMPINO and SANDERS (1981), VAN DE PLASSCHE (1982), SCOTT and MEDIOLI (1986) and KRAFT *et al.* (1987), among others, who interpreted the available data for the last several thousands of years as indicative of a fluctuating pattern of sea level rise, with oscillations on the order of hundreds of years.

Most studies of sea level rise over the last few millennia document age-depth profiles in sediments from the intertidal range, based on sample intervals of several hundreds of years. The scattered data points are commonly connected through a least-squares regression analysis with a straight line or with a curve based on an exponential fitting routine (*e.g.*, PINTER and GARDNER, 1989). These studies assume that the scatter in data points is related to compaction,

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errors in ^{14}C dating (for instance, by mixing in of older, recycled peat material or younger roots penetrating the peat from above), and uncertainty with regard to the position of the dated material to sea level (*see* FIELD *et al.*, 1979, for a comparison of different sea level curves).

We carried out a detailed study of marsh sediment cores from the Hammock River Marshes (Clinton, Connecticut). The sediments in these cores (up to 2 m long) correspond to the last 1500–2000 (radiocarbon) years (VAN DE PLASSCHE *et al.*, 1989), and our sampling interval was on the order of 30 years or less. Paleoenvironmental analyses, based on sediment chemistry and variations in the faunal composition of benthic foraminifera, suggest that sea-level rise in the studied region was not a smooth function of time but occurred in several discrete pulses of several decades to hundreds of years duration. Thus we suggest that the observed scatter in data points of sea-level curves with an interval of several decades to several hundreds of years may be (at least partially) a true indication of fluctuations in the rate of relative sea level rise. If relative sea level rise over the last 2000 years has indeed been spasmodic, with recurrence intervals of several hundreds of years, the rationale for future sea level projections by linear or smooth function extrapolations becomes a doubtful undertaking.

PALEO-ENVIRONMENTAL ANALYSES OF MARSH SYSTEMS

The intertidal area with mudflats and marshes is an environment exposed to strong and rapid variations in physical and chemical depositional parameters. Marsh environments are commonly subdivided into low, middle and high marsh (*e.g.*, REDFIELD, 1972; LONG and MASON, 1983; see NIXON, 1982, for Connecticut marshes). The differences in the marsh sub-environments are best classified on the basis of the average percentage of time that the area is flooded, or the number of flooding events per year. The difference in elevation between the higher and lower of these three environments in the Clinton area of the Connecticut coastline is between 75 and 100 cm (tide-tables). Each sub-environment is characterized by a specific flora, although there are broad overlaps in the ranges of macrophytic species. The low marsh is generally characterized as the area between mean high water at neap tide and mean high water. This zone is vegetated largely by *Spartina alterniflora* in the study area (NIXON, 1982; VAN DE PLASSCHE, this volume). The middle marsh is the zone between mean high water and mean high water at spring tide; the vegetation is more diverse than in the low marsh. *Spartina patens* is common and may dominate the flora; other common halophytes are *Distichlis spicata, Juncus* spp., and *Salicornia* spp. The latter three taxa become more common in the high marsh, which is the area above mean high water at spring tide. This zone contains a mixture of halophytic and non-halophytic floral species, with common *Spartina patens* and other middle-marsh species as well as Cyperaceae. *Phragmites* species are common where fresh water enters the high marsh. The high marsh is only flooded by the highest tides, and extends up to the highest point of influence of the tidal waters (highest high water level: HHWL; in the Clinton area about 1 m above MSL). Seepage of groundwater and stream run-off cause on-average a low salinity in high marshes, although the salinity may be high during warm periods as a result of evaporation. A gradient in average salinity from mean sea level to HHWL was documented for Nova Scotia estuarine marshes (SCOTT and MEDIOLI, 1978; 1980).

The nutrient-rich marsh environment is host to large numbers of unicellular, benthic, heterotrophic eukaryotic organisms (foraminifera and thecamoebians), which form shells (called tests) by agglutinating small silt grains into a matrix of organic material. On the mudflats around MSL foraminifera with tests secreted of calcium carbonate (calcite) occur in addition to the agglutinated forms; these calcareous forms become more numerous (relative to agglutinated forms as well as absolute) below MSL. The few tests of calcareous specimens in the marsh environment are usually not preserved in peats because of calcite dissolution. Agglutinated tests (size range: 63 μm to several hundreds of μm), however, are preserved in the sediments in large numbers.

The position of foraminifera in food-chains has not been well-documented, but they obtain nutrients in many different ways: there are omnivores, carnivores, herbivores, detritivores, and some taxa are known to use extracellular metabolites of photosynthetic symbionts (*e.g.*, LEE, 1974; MURRAY, 1973; BOLTOVSKOY and WRIGHT, 1976). Foraminifera feed largely on minute organisms such as bacteria, diatoms, and nannoplankton (*e.g.*, LIPPS and VALENTINE, 1970). Several species use particulate and dissolved organic matter, which in salt marshes may be derived from the dense macrophyte growths and the bacteria living on these macrophytes. This abundant supply of organic matter supports large standing crops of foraminifera (LEE, 1974; PHLEGER and WALTON, 1950; SCOTT and MEDIOLI, 1980).

In marine marshes and estuaries organic material in the form of fine-grained detritus, bacteria and epiphytes is abundant, but many of the larger invertebrates cannot use such small food items, cannot directly assimilate the particulate or dissolved organic matter, or do not feed where the organic matter occurs. Thus foraminifera form a key link in the estuarine food chains, assimilating energy available from minute autotrophs, and retrieving energy available during the final stages of degradation of organic debris (LIPPS and VALENTINE, 1970; MURRAY, 1973).

Marsh microfaunal assemblages are of low diversity, usually containing 5 to 6 species only. Thecamoebians live almost exclusively in fresh water, foraminifera in brackish to salt water (*e.g.*, LEE, 1974). Various species and ecophenotypes are sensitive indicators of salinity, and the composition of the faunas at different levels in cores can be used to estimate paleo-salinities (*e.g.*, MURRAY, 1968; SCOTT, 1976; SCOTT and MEDIOLI, 1978, 1980; SCOTT *et al.*, 1987; ALLEN and RODA, 1977). Numerous studies on modern estuaries (mainly in the Nova Scotia area) indicate that different assemblages occupy well-defined vertical zones in relation to MSL, parallel to marsh floral zones (*e.g.*, SCOTT and MEDIOLI, 1980; SCOTT *et al.*, 1986; SCOTT and LECKIE, 1990). These faunal zones are narrow compared to floral zones and several zones can be distinguished between MSL and HHWL (Figure 1, after SCOTT and MEDIOLI, 1980). Foraminifera do not occur above the upper boundary of the high marsh (above HHWL). In the topmost 5–10 cm (vertical) of the high marsh, the fauna is essentially monospecific, consisting of *Trochammina macrescens* (faunal subzone IA in SCOTT and MEDIOLI, 1980). Thecamoebians (fresh-water forms) may co-occur in this zone. Below subzone IA the foraminifera increase in numbers and diversity: *Trochammina macrescens* is still a common faunal component, with the addition of the common species *Trochammina inflata* and *Tiphotrocha comprimata.* The latter species tends to be more common in dense vegetation stands, whereas the former is more common in areas with relatively high salinity and less dense vegetation, such as mixed stands of *Salicornia* species and thin *S. patens* (faunal subzone IB in SCOTT and MEDIOLI, 1980; see below). Additional species in this zone can be *Pseudothurammina limnetis* and *Polysaccamina ipohalina* (SCOTT *et al.*, 1981). In the inner reaches of estuaries where the salinities are lower *Haplophragmoides manilaensis* (*H. bonplandi* in SCOTT and MEDIOLI, 1980) may be common.

Trochammina macrescens strongly decreases in relative abundance or is absent in the middle and low marsh (faunal subzones IIA and IIB, SCOTT and MEDIOLI, 1980), where *Miliammina fusca* and *Arenoparrella mexicana* become much more common. Close to MSL, calcareous species such as *Helenina andersoni* and *Protelphidium orbiculare* occur, together with ostracodes, but these calcareous forms are not well-preserved in the peats.

Foraminifera are very common (usually several hundreds of specimens per cm^3 of peat) in samples deposited in the high marsh through low marsh, and on to the intertidal mudflats. Therefore we can trace paleo-environmental changes (especially changes in position relative to MSL) through studies of changes in species-composition of assemblages of agglutinated foraminifera and thecamoebians (*e.g.*, SCOTT and MEDIOLI, 1978, 1980, 1986; SCOTT *et al.*, 1987) in marsh sediment sequences. These faunal variations in marshes (as related to position relative to HHWL) are probably largely determined by the tolerance of the different species to atmospheric exposure.

A major difference between foraminiferal data and pollen data is that the pollen in the peat samples may have been transported from large distances, and the floral assemblage represents a mixture of pollen from a large region (*e.g.*, CLARK, 1986; CLARK and PATTERSON, 1985). Foraminifera, however, represent the local environment only. There may be some transport of material from the immediate environment, but agglutinated foraminiferal tests

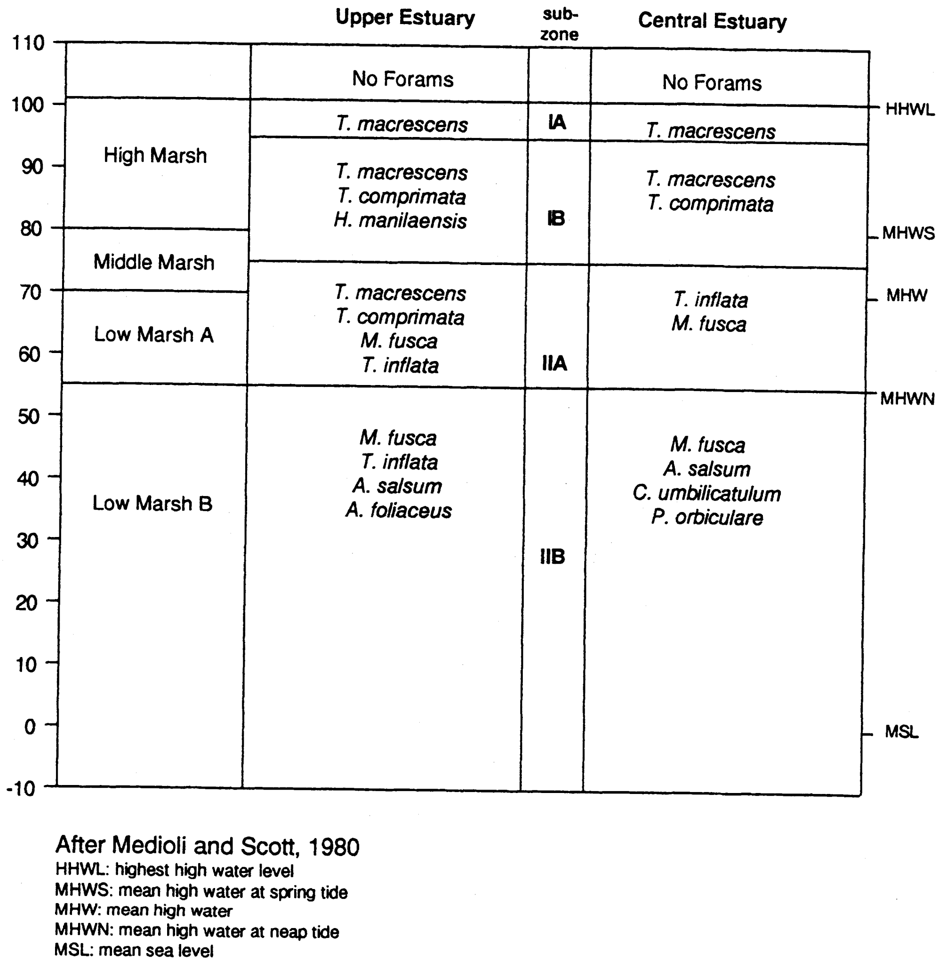

Figure 1. Marsh sub-environments with vertical distances from mean sea level (MSL) and foraminiferal assemblages (after SCOTT and MEDIOLI, 1980).

are prone to oxidation, and thus fall apart quickly during transport outside a small area.

Not only the foraminiferal faunas, but also the chemical environment in the transect between MSL and HHWL is strongly influenced by flooding frequency. Each flooding event carries fine-grained material into the marshes, which is trapped in the marsh flora. In paleoenvironmental analyses of marsh depositional systems one may therefore apply variations in the relative abundance of clay and organic matter as a crude distinction between upper high marsh versus low marsh environments. High marsh peats are dominated by organic matter, because the vigorous tidal currents that bring in seawater with its suspended clay load do not reach this zone often. Lower marsh environments are frequently covered by seawater and will trap clay as well as hydrous iron-oxide particles that commonly precipitate in estuarine mixing zones (*e.g.*, COONLEY *et al.*, 1971). Therefore we expect a higher clay content as well as higher iron concentrations in lower salt marshes compared to upper salt marsh environments.

A paleo-salinity indicator for sediments deposited in marsh environments is the Sedimentary Phosphate Method (NELSON, 1967). This method distinguishes fresh/brackish water environments from saline environments through comparison of the main cation in diagenetic phosphates: vivianite (Fe-phosphate) in upper marshes and apatite (Ca-phosphate) in lower marshes. This method of measuring cation abundance of diagenetic phosphates has been applied successfully in New Jersey marshes (MEYERSON, 1972), but shortcomings of the method (*e.g.*, as a result of the presence of detrital apatite or fish bones) were pointed out by GUBER (1969).

The salinity of the water covering the marsh surface affects diagenesis of marsh sediments, especially with regard to the formation of diagenetic sulfides. In a low-salinity environment the sulfur content of the sediment is relatively low (<1 wt. %), and the main source of sulfur is probably decaying organic matter (GIVEN, 1975). Sediments deposited under marine conditions are enriched in sulfur up to several weight percent, and as a first approximation their sulfur content may be used as a paleo-salinity indicator (*see e.g.*, RAISWELL and BERNER, 1985).

The formation of diagenetic sulfides has been the scope of extensive research (*e.g.*, BERNER, 1970, 1984, 1985; LORD and CHURCH, 1983). Three parameters may be limiting sulfur fixation during diagenesis of anoxic sediments: the abundance of dissolved sulfate in pore waters, the abundance of "labile" organic matter, and the abundance of reactive iron in the sediments (BERNER, 1985). The sulfate reduction rate in the pore fluids is largely a function of the availability of labile organic matter (BERNER, 1984), which may be the limiting factor in many marine environments. In fresh-water anoxic sediments the supply of dissolved sulfate may be limiting. The diffusion rate of sulfate into the sediment column is determined by the sulfate concentration gradient from the surface fluids to pore fluids at a given depth. The abundance of dissolved sulfate in surface waters of estuarine environments depends on the mixing ratio between fresh water (groundwater, rain water or river water) and sea water, and the evaporation rate, which depends among other things on the ambient temperature. Sulfide diagenesis in modern marsh environments is extremely complex and may involve, in addition to diffusion, transport in the unsaturated upper zones of the marsh sediment during dry periods as well as slow movement of the pore fluids (CASEY and LASAGA, 1987). In marsh environments sediments commonly contain more than 20 weight percent organic matter, and the sulfate reduction rate is probably not limited by the abundance of labile organic matter. The sulfate diffusion flux into sediments that are only sporadically flooded (upper marsh environments) may ultimately limit the amount of sulfate reduction (CASEY and LASAGA, 1987). Marsh sediments that were flooded but became emerged may loose their sulfides through oxidation processes (GIVEN, 1975).

Sulfate reduction rates may be high, but reduced sulfur becomes re-oxidized and H_2S will diffuse out of the sediment column into the atmosphere (HOWES *et al.*, 1984; LORD and CHURCH, 1983). The sulfur fixation rate is largely determined by the contents of reactive iron of the sediments. Iron is predominantly present in coastal sediments as fine-grained hydrous oxides (*e.g.*, ferrihydrite, goethite, hematite), which precipitated as fine-grained oxides in the estuarine mixing zone (COONLEY *et al.*, 1971). Ferric iron is reduced and the hydrous ferric oxides dissolve in the pore waters, possibly mediated by bacterial activity (CANFIELD, 1989). In saltmarsh sediments iron reacts with the reduced sulfur and iron sulfides precipitate. The dominant sulfide phase in marsh sediments is pyrite, which may be precipitated directly during diagenesis or through intermediary monosulfide formation (HOWARTH, 1979; LORD and CHURCH, 1983). In pore waters of saline marshes, the post-depositional mobility of iron and other chalcophilic metals is extremely small because of the limited solubility of their sulfides. In low-salinity coastal marshes iron may diffuse upwards, where it can form an Fe-enriched layer in the upper centimeters of the sediment column, which are oxygenated by the roots of *Spartina* macrophytes.

In conclusion, the abundances of iron and sulfur in anoxic sediments can be used as paleoenvironmental indicators **only** when diagenetic sulfur fixation is not primarily limited by the availability of labile organic matter. In most salt marsh environments, the abundance of reactive iron in the sediments will be the primary control on sulfur fixation in the sediments. If iron is brought into the marshes during flooding as particulate matter, the iron abundance in marsh sediments is proportional to the number of flooding events per time unit. The iron-rich sediments of the lower marshes will fix more reduced sulfur during diagenesis than the low-iron, upper marsh environments. The sulfate supply or the abundance of fine-grained iron oxides in the sediments may be limiting diagenetic sulfur fixation in the extreme upper marsh environments.

Trace elements enter the marsh with the particulate flux in sea water, especially hydrous iron oxides and particulate organic matter (LEE, 1975; MILLWARD and MOORE, 1982; VAREKAMP, this volume). We expect therefore a relatively high Zn and Cu content in iron-rich lower marsh environments. Salt marsh macrophytes may partly recycle these metals through uptake, leading to the high metal concentrations in *Spartina* spp. (WINDOM, 1975).

LOCATION, SAMPLING AND ANALYTICAL METHODS

Sampling Sites and Lithology

The Hammock River Marshes in Connecticut (BLOOM and STUIVER, 1963; BLOOM, 1964; VAN DE PLASSCHE *et al.*, 1989) are located to the southeast of the town of Clinton (Figure 2). The marshes consist of two "lobes," to the north and south of the village of Harbor View; Hammock River itself is in the northernmost of the two "lobes." We studied cores from both lobes: core F1 from the northern lobe, to the north of the Hammock River, and several cores (CY cores) from the southern lobe, just to the east of Route 145, the north-south road from Clinton to Kelsey Point. Initial chemical and faunal studies were done to investigate the several "black bands" in the peat sequences using samples from core CYX (40–135 cm depth; see VAN DE PLASSCHE, this volume). We collected additional CY cores (CYA and CYB) about 10 m south of the original sample location. Comparable intervals in lithology occur at slightly different depths in cores from the CYX and CYA-CYB localities (Figure 3). A complete chemical profile was established for core CYB (0–155 cm depth), whereas the faunal contents of the section 0–70 cm were studied in core CYA, taken close to core CYB. The lithology in cores CYA and CYB is the same: "black layers" (see below) occurred at exactly the same depths in both cores. In addition, we present faunal data from cores west of the CY location (cores KM), and from a core in the Indian River marsh, located to the east of the town center of Clinton (Core DMM; Figure 2). The lithology and floral contents of the cores are described by VAN DE PLASSCHE (this volume); our cores were selected from the core inventory of several hundreds of cores to represent areas typical for lithological development of the marsh in general, without evidence for the presence of erosional levels due to channel migration in the marsh.

Sediments consisted of peat,with varying amounts of terrigenous material (Figure 3). Different levels in the cores were dominated by different species of cord grasses, and dominant plant material in the peat was contributed by *Spartina patens, Spartina alterniflora,* and *Distichlis spicata.* Three black horizons were recognized in and correlated between many cores (Figure 3; see VAN DE PLASSCHE, this volume); the F core locality lacks the black bands in the sediments. The black layers are between 10–20 cm thick, and occur at slightly variable depths that approximate 40–60 cm, 70–100 cm, and 100–120 cm. A detailed description of the lithology and stratigraphy of the cores is presented by VAN DE PLASSCHE (this volume).

Cores (up to 2 m length) were collected with a steel handcorer coated with acrylic lacquer. The cores were wrapped in plastic foil in the field, and split and sampled upon arrival in the laboratory. The rhizomes and root systems were described, together with the color, estimated amount of clay, and macroscopic sediment characteristics. The cores were cut up in sample slices of a few centimeters thickness, and sample boundaries were chosen at lithological boundaries. Core-sections of constant lithology were cut into equal-length sections of at most 6 cm in the F and CY cores and up to 10 cm in the KMA core. The whole core length was sampled and all samples were analyzed, providing a continuous record.

Sample Preparation

For microfaunal analyses samples were immediately placed in an alcohol-water mixture to prevent oxidation of the foraminiferal tests, or kept frozen until processing (SCOTT and MEDIOLI, 1980). Samples were washed through

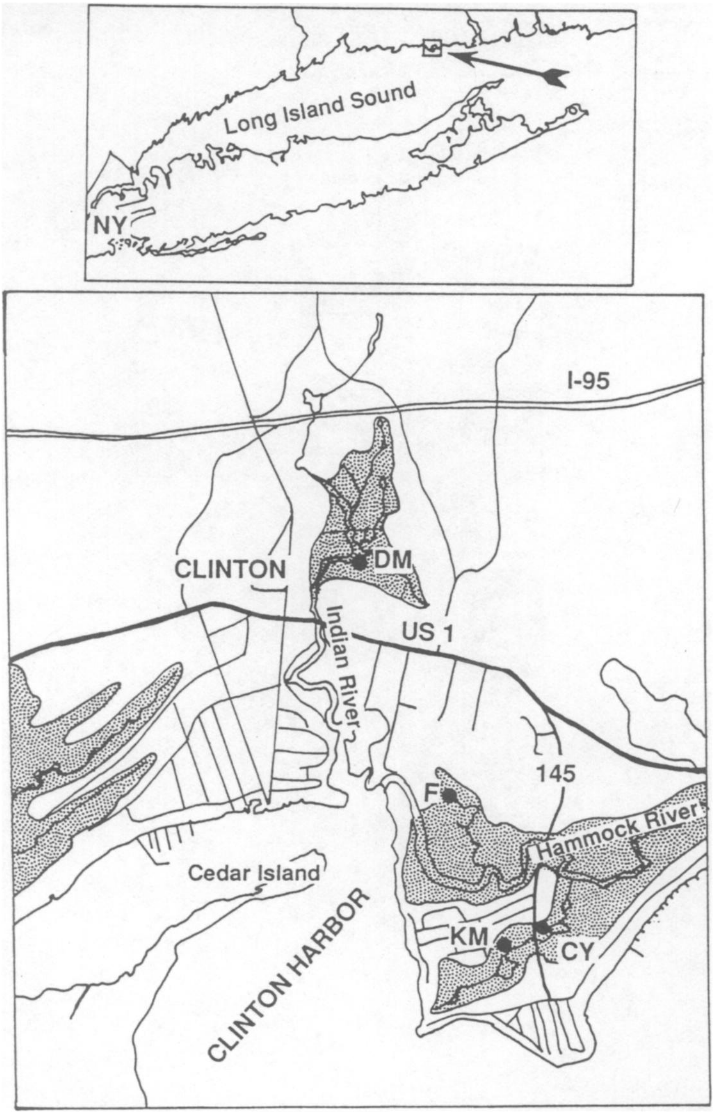

Figure 2. Location of the cores in the Hammock River Marshes (CY, F and KM) and Indian River marsh (DM).

two sieves (500 µm and 63 µm) and the large size fraction was dried and kept, but did not contain foraminifera. The size fraction smaller than 63 µm was discarded. The fraction between 500 µm and 63 µm was dried, weighed, and suspended in alcohol. Specimens were picked from the material after the alcohol had evaporated. For the first cores examined (cores CYX, DMM, KMB) we used a microsplitter to obtain a split of 0.1 gram, and all specimens were picked from that split. For the later cores a small split was obtained, containing so much material that a picking tray was thinly covered. Specimens were picked, and if less than 100 were present in the tray another split was made and picked, until at least 100 specimens were obtained. The material used to obtain the specimens was then weighed. If there were less than

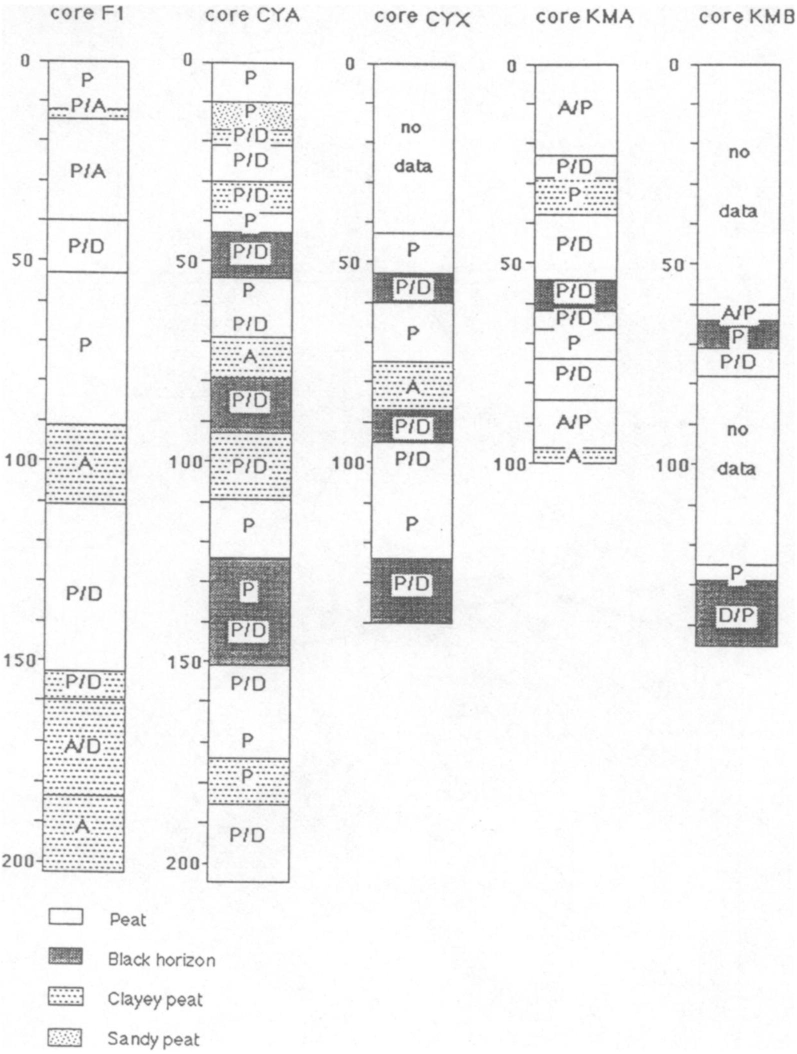

Figure 3. Lithology and rhizomes in the studied cores. Abbreviations in columns indicate rhizomes: A = *Spartina alterniflora*; P = *Spartina patens*, D = *Distichlis spicata*.

25 specimens in 5 trays of material, we stopped further picking of material and the data on these samples were not used. Such samples are labeled "not containing foraminifera" in this paper. The number of specimens was calculated per gram of dried sediment (in the size fraction between 500 μm and 63 μm). All counted specimens were picked and mounted in cardboard slides.

The samples for chemical analyses were air-dried and subsequently pulverized with a glass mortar and pestle, and sieved through a 180 μm stainless steel screen. The coarse fraction was commonly a small amount and consisted of dense wood and root pieces; it was not further considered.

Splits of 2–3 grams of the sieved sediment samples were leached with a solution made of 50 ml 8% HCl—18% HNO_3 to which 10 ml of 15% H_2O_2 was added. The samples were stirred at room temperature for 8 hours. This leaching procedure dissolves all iron oxides, takes metals from clay exchange sites, dissolves sulfides (including pyrite) and breaks down organic matter. Test-runs with finely ground pyrite showed total dissolution of the samples in 8 hours. The leachate solutions were filtered and brought up to a volume of 100 ml. The solutions were further diluted and analyzed for Fe, Cu, and Zn with a flame Atomic Absorption Spectroscope (AAS), Perkin and Elmer model 372. A split of the leachate solution was titrated with 10N NaOH until it had reached a pH of about 6–7, brought to a fixed volume, and filtered to remove the precipitated hydrous iron oxides. These solutions were further diluted and analyzed for sulfate with ion chromatography (Dionex, QIC model). Standards were prepared from Na_2SO_4 dissolved in sample matrices, neutralized and analyzed.

During the chromatography we observed a peak at the end of the spectrum with a retention time characteristic of oxalate or selenate, in addition to the peaks from the leachate solution and sulfate. Independent analyses of the sediments by Graphite Furnace AAS indicated that this signal must be largely ascribed to oxalate, and we assume that an organic precursor of oxalate in the samples is oxidized during the leaching process. The "oxalate contents" of samples from Core F1 are reported, but these values represent the relative amounts of the oxalate precursor in the sediment.

Organic carbon contents were not directly determined, but weight loss on ignition (LOI) was determined through burning of the samples in a furnace for 1 hour at 850°C. During this procedure, pyrite is oxidized to hematite, leading to a 33% weight loss of the pyrite fraction. The data have not been corrected for this effect, because the weight loss due to the release of water from clays also affects the results. The LOI values are representative of organic carbon contents, however. A subset of 5 samples was selected for analyses by Inductively Coupled Plasma Optical Emission Spectroscopy (ICP) for 23 elements in aqua regia leachates.

All analytical data were plotted versus depth as follows: a sample taken between 16 and 20 cm depth, for instance, was plotted as a bar between 16.5 and 19.5 cm. The next sample value (20–25 cm depth) was plotted over the interval 20.5 to 24.5 cm. This mode of plotting takes into account that the samples were homogenized over the sample width interval. The field collection of the cores, during which minor stretching may occur, and subsequent processing and sampling lead to a depth resolution of about 2–3 cm.

RESULTS

Faunal Studies

The faunal assemblages (Figures 4–7; Tables 1–3) strongly resemble those described from many Nova Scotia locations, and assemblages (subzones) representative of different levels between HHWL and MSL were recognized (SCOTT and MEDIOLI, 1980; 1986; SCOTT *et al.*, 1987; Figure 1). Detailed descriptions of distributions of recent marsh foraminiferal taxa in Connecticut are not available, and we compared our data with the Nova Scotia assemblages. Such comparison is feasible because marsh foraminiferal faunas are very similar in their component species over large distances (SCOTT *et al.*, in press). Foraminifera in Long Island Sound were described by PARKER (1952) and BUZAS (1965), but these authors concentrated on the faunas in the Sound itself, and included few data on marsh foraminifera. Foraminiferal assemblages in New England marshes were presented by PARKER and ATHEARN (Poponesset Bay, Massachusetts; 1959) and PHLEGER and WALTON (Barnstable Marsh, Massachusetts; 1950), but the authors presented no data on detailed depth-zonations. More recent studies on marsh foraminifera from Great Sippewisset Marsh (Falmouth, Massachusetts) also suggest that the zones recognized in Nova Scotia can be recognized over wider regions (SCOTT and LECKIE, 1990). Preliminary data on surface samples from the Hammock River marshes (Table 4) are in agreement with the Nova Scotia foraminiferal distributions described by SCOTT and MEDIOLI (1980, 1986).

The lower part of Core F1 (Figure 4; 203–149 cm) contains a fauna dominated by *T. comprimata* and *T. inflata*, with up to 25% *T. macrescens*, suggesting a depositional environment in the lower middle marsh (higher subzone IIA). Below 185 cm *T. comprimata* is more abundant than *T. inflata*, but the latter species becomes dominant at about 180 cm. From 149–139 cm foraminifera are absent, suggesting an environ-

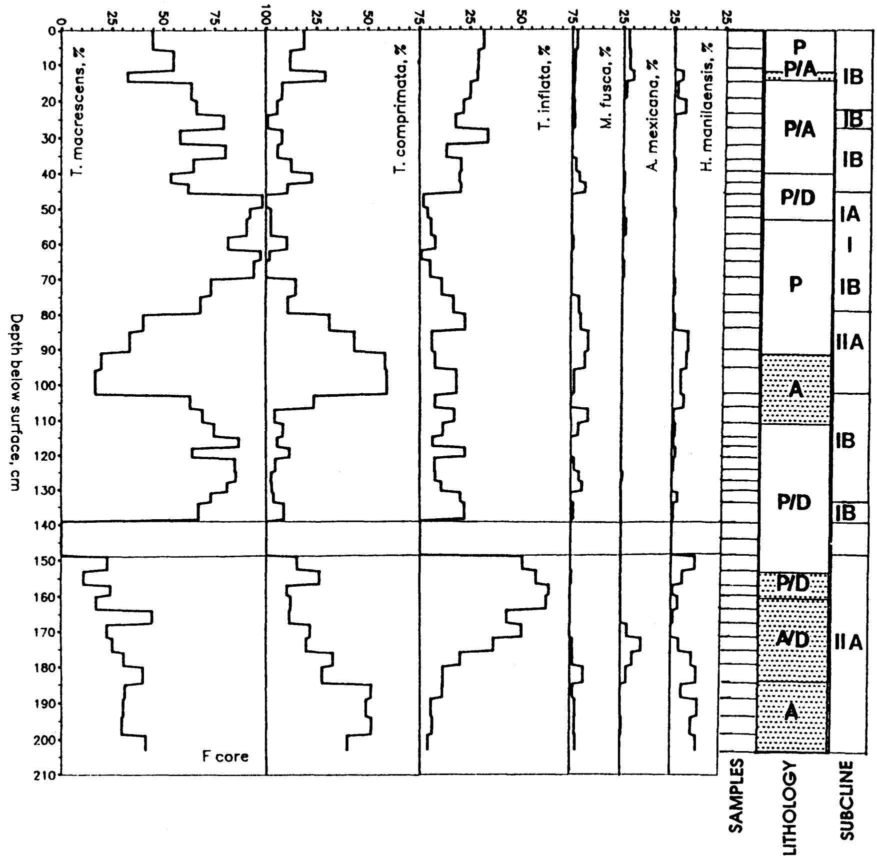

Figure 4. Relative abundances of the most common foraminiferal species in core F. Lithology as in Figure 3, faunal subzones after Scott and Medioli, 1980.

ment where foraminifera could not survive, possibly above HHWL. In the short interval from 131–139 cm the fauna is dominated by *T. macrescens*, with more than 25% *T. inflata* (lower subzone IB), and from 139 to 103 cm the fauna is strongly dominated by *T. macrescens* (upper subzone IB to lower IA). At 103 cm the fauna quickly changes to become dominated by *T. comprimata*. This species remains dominant from 103 through 80 cm, but *T. macrescens* slowly and gradually increases in relative abundance in the upper part of this interval (upper subzone IIA to lower subzone IB). The section from 80 through 46 cm is again strongly dominated by *T. macrescens* (subzone IA), but at 46 cm the relative abundance of this species decreases sharply. The interval from 46 through 28 cm contains a mixture of *T. macrescens*, *T. comprimata* and *T. inflata* (lower high marsh, IB). There is a short interval of increase in relative abundance of *T. macrescens* at 28–24 cm; then its relative abundance decreases to the present marsh surface.

For the section at CY we combined data from cores CYA and CYX (described above, Figures 5A, 5B). The lowermost interval of core CYX (133–140 cm) contains no foraminifera. A thin interval (129–133 cm) contains common *T. macrescens*, with *T. comprimata*, *T. inflata*, and up to 25% *M. fusca* (subzone IIA, upper low marsh to middle marsh). From 91 through 129 cm the fauna is dominated by *T. macrescens* (subzone IA to uppermost IB), with the exception of the interval between 99 and 103 cm which did not contain enough specimens for analysis (close to or just above HHWL). From 75

TABLE 1. *Counts of benthic foraminifera, Core Fl.*

Core	Depth (cm)	*M. fusca*	*H. manilaensis*	*T. comprimata*	*T. inflata*	*T. macrescens*	*T. ochracea*	*P. ipohalina*	*A. salsum*	*Thecamoebians*	*H. bradyi*	*A. mexicana*	*Calcareous*	nr/gr
F1	0- 6	6	0	46	78	110	0	0	0	0	0	7	0	1235
F1	6- 12	2	0	18	44	83	0	0	0	0	0	5	0	1855
F1	12- 15	3	11	78	77	87	0	0	0	0	0	14	0	3253
F1	15- 20	1	2	10	32	81	0	0	0	0	0	2	0	1620
F1	20- 24	5	26	26	100	303	0	0	0	0	0	0	0	2528
F1	24- 28	3	1	2	40	178	0	0	0	0	0	1	0	2344
F1	28- 32	0	0	10	43	74	0	1	0	0	0	0	0	1134
F1	32- 36	0	0	6	14	84	0	1	0	0	0	0	0	912
F1	36- 40	3	1	18	30	94	0	0	0	0	0	0	0	2863
F1	40- 43	4	0	24	21	57	0	0	0	0	0	1	0	1151
F1	43- 46	8	0	13	25	76	0	0	0	0	0	1	0	1821
F1	46- 50	0	0	0	2	98	0	0	0	0	0	0	0	1961
F1	50- 53	0	1	3	5	115	0	0	0	0	0	1	0	2119
F1	53- 58	0	0	3	7	111	0	0	0	0	0	2	0	1118
F1	58- 62	1	0	12	9	95	0	0	0	0	0	0	0	1522
F1	62- 65	0	0	2	1	103	0	0	0	0	0	0	0	2255
F1	65- 70	0	0	0	6	106	0	0	0	0	0	1	0	2093
F1	70- 75	0	1	16	12	80	0	1	0	0	0	0	0	1124
F1	75- 80	4	0	11	17	69	0	1	0	0	0	0	0	927
F1	80- 85	5	1	32	23	41	0	1	0	0	0	0	0	1759
F1	85- 91	11	10	56	8	43	0	1	0	0	0	0	0	1473
F1	91- 96	10	10	84	11	28	0	1	0	0	0	0	0	2043
F1	96-103	2	5	72	22	20	0	1	0	0	0	0	0	1017
F1	103-107	0	6	25	8	67	0	1	0	0	0	0	0	195
F1	107-111	10	1	5	20	81	0	1	0	0	0	0	0	1064
F1	111-115	5	2	11	15	98	0	1	0	0	0	0	0	1365
F1	115-118	0	1	7	8	109	0	1	0	0	0	0	0	1116
F1	118-121	0	2	13	25	72	0	1	0	0	0	0	0	780
F1	121-125	2	1	5	8	93	0	1	0	0	0	0	0	405
F1	125-128	5	0	3	9	102	0	0	0	0	0	1	0	484
F1	128-131	6	0	3	11	84	0	0	0	0	0	0	0	310
F1	131-134	0	4	5	27	99	0	1	0	0	0	0	0	531
F1	134-139	2	1	11	28	86	0	1	0	0	0	0	0	278
F1	139-145	0	0	0	0	3	0	0	0	0	0	0	0	24
F1	145-149	0	0	0	0	0	0	0	0	0	0	0	0	0
F1	149-153	0	14	18	60	27	0	1	0	0	0	0	0	763
F1	153-157	1	7	33	72	14	0	0	0	0	0	0	0	439
F1	157-160	0	1	11	68	26	0	1	0	0	1	0	0	161
F1	160-164	0	4	14	72	20	0	2	0	0	5	0	0	192
F1	164-168	0	1	11	41	43	0	0	0	0	1	0	0	247
F1	168-172	0	0	26	60	27	0	4	0	0	0	4	0	807
F1	172-176	2	6	29	53	37	0	6	0	0	0	15	0	576
F1	176-180	2	14	45	27	42	0	0	0	0	0	8	0	672
F1	180-185	9	17	37	15	54	0	0	0	2	0	4	0	2473
F1	185-189	2	7	66	14	40	0	0	0	0	0	0	0	1122
F1	189-194	3	15	55	6	34	0	0	0	1	0	0	0	807
F1	194-199	3	12	61	7	35	0	0	0	0	0	1	0	793
F1	199-203	4	17	53	5	55	0	0	0	0	0	0	0	1165

to 99 cm the fauna is dominated by *T. inflata* and *M. fusca*, with *T. comprimata* and *A. mexicana* (subzone IIA). Samples between 57 and 99 cm contain too few foraminifera for analysis, with the exception of the sample from 60–63 cm, which is dominated by *T. macrescens* (above highest high water to subzone IA). The fauna between 46 and 57 cm is dominated by *T.*

TABLE 2. *Counts of benthic foraminifera, CY cores.*

Core	Depth (cm)	*M. fusca*	*H. manilaensis*	*T. comprimata*	*T. inflata*	*T. macrescens*	*T. ochracea*	*P. ipohalina*	*A. salsum*	*Thecamoebians*	*H. bradyi*	*A. mexicana*	*Calcareous*	nr/gr
CYA	0- 5	20	1	17	106	45	0	0	0	2	0	6	0	7800
CYA	5- 10	11	5	11	97	16	0	0	0	0	0	6	0	1007
CYA	10- 13	5	28	10	58	29	0	0	0	0	0	5	0	189
CYA	13- 17	7	12	17	35	60	0	0	0	0	0	1	0	334
CYA	17- 21	6	0	29	2	83	0	0	0	1	0	0	0	264
CYA	21- 24	0	0	50	21	33	0	0	0	0	0	25	0	717
CYA	24- 27	9	1	42	25	25	0	0	0	0	0	14	0	318
CYA	27- 30	2	4	52	64	48	0	0	0	0	0	5	0	1167
CYA	30- 34	2	4	21	48	42	0	0	0	0	0	11	0	776
CYA	34- 38	0	0	25	48	28	0	0	0	0	0	8	0	325
CYA	38- 43	1	0	4	28	79	0	0	0	0	0	0	0	299
CYA	43- 45	2	0	3	18	94	0	0	0	1	0	1	0	315
CYA	45- 47	0	4	14	17	77	0	0	0	4	0	0	0	1493
CYA	47- 51	0	8	4	16	84	0	4	0	10	10	2	0	294
CYA	51- 54	0	0	2	3	10	0	3	0	5	13	0	0	63
CYA	54- 58	0	0	1	0	0	0	0	0	4	1	0	0	5
CYA	58- 62	0	2	1	3	0	0	1	0	6	0	2	0	26
CYA	62- 65	0	3	26	59	6	0	0	0	1	0	35	0	1290
CYA	65- 69	0	1	36	54	23	0	0	0	0	0	15	0	921
CYA	69- 71	0	0	25	59	10	0	0	0	0	0	19	0	628
CYX	43- 46	3	2	10	129	85	0	0	0	2	0	0	0	2310
CYX	46- 49	9	0	34	42	194	1	0	0	1	0	0	0	2810
CYX	49- 53	16	0	23	36	127	0	1	0	0	0	0	0	2030
CYX	53- 57	18	7	27	57	164	0	3	0	2	12	0	0	2900
CYX	57- 60	0	0	0	0	0	0	0	0	0	0	0	0	0
CYX	60- 63	0	1	0	2	19	0	2	1	0	0	0	0	25
CYX	63- 67	0	0	0	1	0	0	2	1	0	0	0	0	4
CYX	67- 71	0	0	0	0	0	0	0	1	0	0	0	0	1
CYX	71- 75	1	0	1	5	2	0	0	0	0	0	0	0	9
CYX	75- 79	25	0	41	96	39	0	0	0	0	0	8	0	2090
CYX	79- 83	72	0	35	56	49	0	1	0	0	0	27	0	2400
CYX	83- 87	29	2	29	83	65	0	0	0	0	2	19	0	2290
CYX	87- 91	8	0	10	163	68	0	0	0	1	0	6	0	2560
CYX	91- 95	7	2	2	1	114	0	0	0	2	0	1	0	1290
CYX	95- 99	3	4	2	2	91	0	0	0	0	0	3	0	1050
CYX	99-103	0	0	1	4	8	0	0	0	0	0	0	0	13
CYX	103-109	0	0	0	8	63	0	0	0	0	0	1	0	720
CYX	109-115	0	0	0	2	98	0	1	0	0	0	0	0	1010
CYX	115-120	3	0	2	0	104	0	0	0	0	0	0	0	1090
CYX	120-125	3	4	0	1	79	0	0	0	1	1	0	0	890
CYX	125-129	2	12	5	0	116	0	0	1	0	0	1	0	1370
CYX	129-133	43	20	17	15	95	1	0	0	2	15	0	0	2080
CYX	133-137	1	0	0	0	2	0	0	0	0	0	0	0	3
CYX	137-140	1	2	0	0	5	0	0	0	0	0	0	0	8

macrescens, with some *M. fusca, T. inflata*, and *T. comprimata* (upper subzone IB). In the uppermost sample from the core (43–46 cm) *T. inflata* is dominant, after a sharp drop in relative abundance of *T. macrescens* (lower subzone IB).

In core CYA (Figure 5B) the interval between 62 and 75 cm is dominated by *T. inflata* with common *T. comprimata*, and *A. mexicana* (subzone IIA). The interval between 54 and 62 cm does not contain foraminifera (above highest high water). From 38 to 54 cm the fauna is dominated by *T. macrescens* with some *T. comprimata* and *T. inflata* (upper subzone IB). There is

TABLE 3. *Counts of benthic foraminifera, cores KM and DMM*

Core	Depth (cm)	*M. fusca*	*H. manilaensis*	*T. comprimata*	*T. inflata*	*T. macrescens*	*T. ochracea*	*P. ipohalina*	*A. salsum*	*Thecamoebians*	*H. bradyi*	*A. mexicana*	*Calcareous*	nr/gr
KMA	0- 11	48	1	6	41	13	0	0	0	0	0	3	0	254
KMA	11- 23	8	0	4	67	41	0	0	0	0	0	0	0	412
KMA	23- 29	3	1	1	9	84	0	0	0	0	0	0	0	220
KMA	29- 38	1	0	10	30	63	0	0	0	0	0	0	0	471
KMA	38- 48	1	2	15	29	22	0	0	0	0	0	8	2	1338
KMA	48- 54	1	0	17	33	24	0	0	0	0	0	9	0	1617
KMA	54- 58	0	0	7	21	76	0	0	0	0	2	0	0	574
KMA	58- 62	1	0	5	3	62	0	0	0	0	3	1	0	1114
KMA	62- 66	1	1	1	7	20	0	0	0	0	2	0	0	275
KMA	66- 70	0	4	8	18	68	0	0	2	0	4	0	1	1500
KMA	70- 74	4	2	12	7	48	0	0	1	0	8	1	0	1386
KMA	74- 84	0	0	31	14	23	0	1	0	0	3	1	0	2250
KMA	84- 91	2	0	41	17	14	0	9	0	0	0	3	0	455
KMA	91- 96	0	0	58	23	10	0	0	0	0	0	2	0	3100
KMA	96-100	1	1	32	35	4	0	0	0	0	0	4	0	679
KMB	60- 64	5	4	12	108	76	2	0	0	2	0	6	0	2150
KMB	64- 67	1	2	5	46	63	0	4	0	5	0	0	0	1260
KMB	67- 71	0	0	0	0	4	0	0	0	2	0	0	0	6
KMB	71- 75	0	0	0	0	4	0	0	0	2	0	0	0	6
KMB	75- 78	0	1	0	0	1	0	1	0	5	0	0	0	8
KMB	115-119	1	6	68	144	30	3	1	0	3	0	8	0	2640
KMB	119-123	6	9	44	84	23	0	0	0	3	0	11	0	1800
KMB	123-127	14	10	32	7	49	3	1	0	1	0	0	0	1170
KMB	127-131	0	0	2	2	7	0	0	0	0	0	0	0	11
KMB	131-134	1	0	3	4	5	0	0	0	1	0	0	0	14
DMM4	150-155	4	12	3	2	90	0	0	0	0	0	0	0	1110
DMM4	155-160	1	33	10	0	68	0	0	0	0	0	0	0	1120
DMM4	160-164	3	71	25	17	54	0	0	0	0	0	0	0	1700
DMM4	164-172	0	55	24	4	52	0	0	0	0	0	0	0	1350
DMM4	172-180	0	0	0	0	0	0	0	0	0	0	0	0	0
DMM4	180-185	0	0	0	0	0	0	0	0	0	0	0	0	0
DMM4	185-190	0	0	0	0	0	0	0	0	0	0	0	0	0

TABLE 4. *Data on surface samples, CY core area. Data are on total (dead plus alive) foraminifera.*

	M. Fusca	*H. manilaensis*	*T. comprimata*	*T. inflata*	*T. macrescens*	*T. ochracea*	*P. ipohalina*	*A. salsum*	*H. bradyi*	*A. mexicana*	*Thecamoebians*	*Calcareous*
Surface 1	0	8	40	123	54	0	0	0	0	0	0	0
Surface 2	21	2	47	101	26	0	0	0	0	0	0	2
Surface 3	87	3	46	43	8	0	0	0	0	0	0	29

Surface 1: *S. patens* (thin stands) and *Salicornia*
Surface 2: *S. patens* (dense stands)
Surface 3: *S. alterniflora*

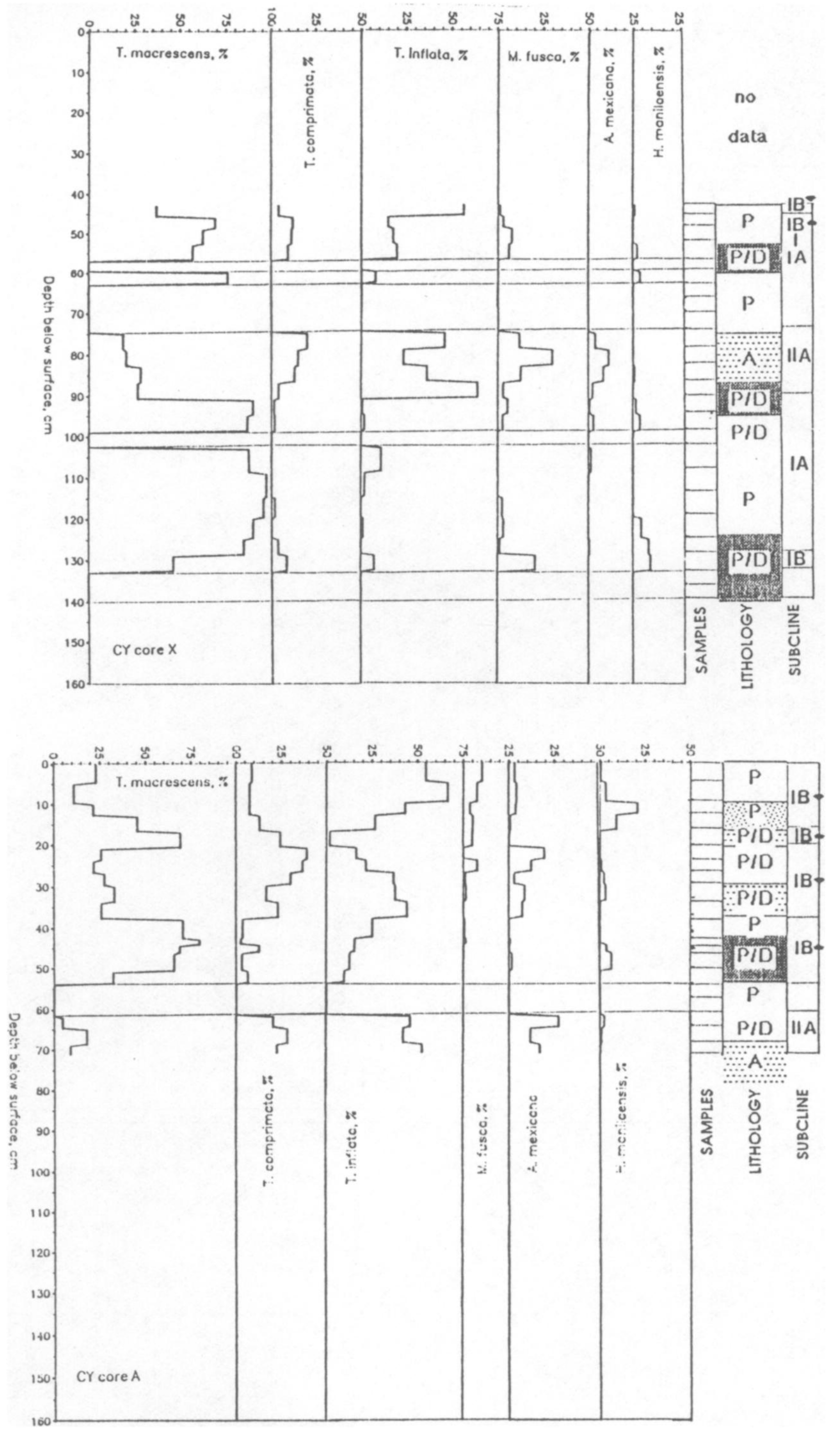

Figure 5. Relative abundances of the most common foraminiferal species in core CYX (Figure 5A) and core CYA (Figure 5B). Lithology as in Figure 3, faunal subzones after Scott and Medioli, 1980. Relative abundances of the most common foraminiferal species in core CYX (Figure 5A) and core CYA (Figure 5B). Lithology as in Figure 3, faunal subzones after Scotty and Medioli, 1980.

a sudden decrease in relative abundance of *T. macrescens* at 38 cm, and the section between 21 and 38 cm is dominated by a combination of *T. inflata, T. comprimata,* and *T. macrescens,* with *A. mexicana* and *M. fusca* (subzone IIA). One sample (17–21 cm) is again dominated by *T. macrescens* (lower subzone IA to upper IB), and then the relative abundance of this species decreases until the present marsh surface (subzone IB).

Faunal changes in the overlapping core sections of CYX and CYA were recognized in both cores, but at slightly different depths (distance between these cores about 10 m, see above). Correlations between the cores based on lithology, faunal fluctuations as well as sediment chemistry (discussed further on) show excellent agreement. A strong decrease in relative abundance of *T. macrescens* occurs just above the top black layer in both cores CYX (46 cm) and CYA (38 cm); this layer is somewhat higher in core CYA (43–54 cm) compared to core CYX (53–60 cm; Figure 3). The interval lacking foraminifera is thicker in core CYX than in CYA (57–75 cm versus 54–62 cm).

Faunal data on core KMA (Figure 6) are in excellent agreement with those in cores CY and KM, although faunal changes occur generally at slightly greater depths in core KMA (Table 3; Figure 6). *T. macrescens* is dominant from 54 to 74 cm in core KMA, versus 46–57 cm in core CYX, 38–54 cm in core CYA. A strong decrease in relative abundance of this species occurs at 54 cm, just above the upper boundary of the top black layer, just as in the CY cores. In the lower part of the black layer we observed the species *Hemisphaerammina bradyi* and several thecamoebians in cores CY and KMA; this is the only interval in all studied samples in which these two groups occur. The fauna in the interval between 29 and 54 cm in core KMA is dominated by *T. inflata,* with *T. comprimata, T. macrescens,* and *A. mexicana* (subzone IIA; correlates to the interval between 21 and 38 cm in core CYA). One sample (23–29 cm) is dominated by *T. macrescens* (upper subzone IB to lower IA), and then the relative abundance of this species decreases to the surface of the present day marsh. The uppermost sample of the core contains a higher relative abundance of *M. fusca* than the uppermost sample of core CYA, which reflects the position of the latter core at a slightly higher elevation in the recent marsh.

Two short sections across the top and middle black layers in the sediments were investigated in core KMB, taken close to core KMA (Table 3). The topmost section of core KMB corresponds closely to the section across the uppermost dark horizon in core KMA. The lower section in core KMB shows a similar faunal pattern as that across the middle dark layer in core CYX (Table 3): just below this dark layer and in its lowermost part there are no foraminifera; upwards we see an increase in number of foraminifera.

Black bands are also present in core DMM from the Indian River marsh (Figure 2), and there is a change from absence of fauna to presence of fauna across one of these dark layers (Figure 7). In the DMM core the most common additional species was *H. manilaenis,* which was much more abundant than in the F and CY cores. This species is more abundant in the inner reaches of estuaries (SCOTT and MEDIOLI, 1980); core DMM is indeed much further inland than cores CY, F and KMA (Figure 7).

Discussion of the Faunal Studies

There are considerable fluctuations in the faunal composition of benthic foraminifera in all studied cores. The faunal composition was not stable over time, and there is no simple trend in assemblages over the total studied interval in any of the cores. Intervals of strong and rapid increase and decrease in the relative abundance of *T. macrescens* occur in cores from different "lobes" of the marsh. These events (*i.e.,* relatively rapid changes in faunal composition) were labeled E1 through E8 (Figure 8; Table 5). The correlation between faunal events in the cores is demonstrated in a combined plot of the relative abundances of "other species" (*i.e.,* 100 minus the relative abundance of *T. macrescens*) for the different cores (Figure 8). Note that event E4 is gradual over about 10 cm in cores F and KMA, but sudden in the CY cores, suggesting the presence of an erosional surface in the latter cores.

The relative abundance of *T. macrescens* reflects the vertical distance of the environment of deposition of a sample from HHWL (Figure 1; SCOTT and MEDIOLI, 1980): from 100% close to HHWL, to almost absent in the low marsh. The abrupt changes in abundance of *T. macrescens* in all studied cores indicate sudden shifts, rel-

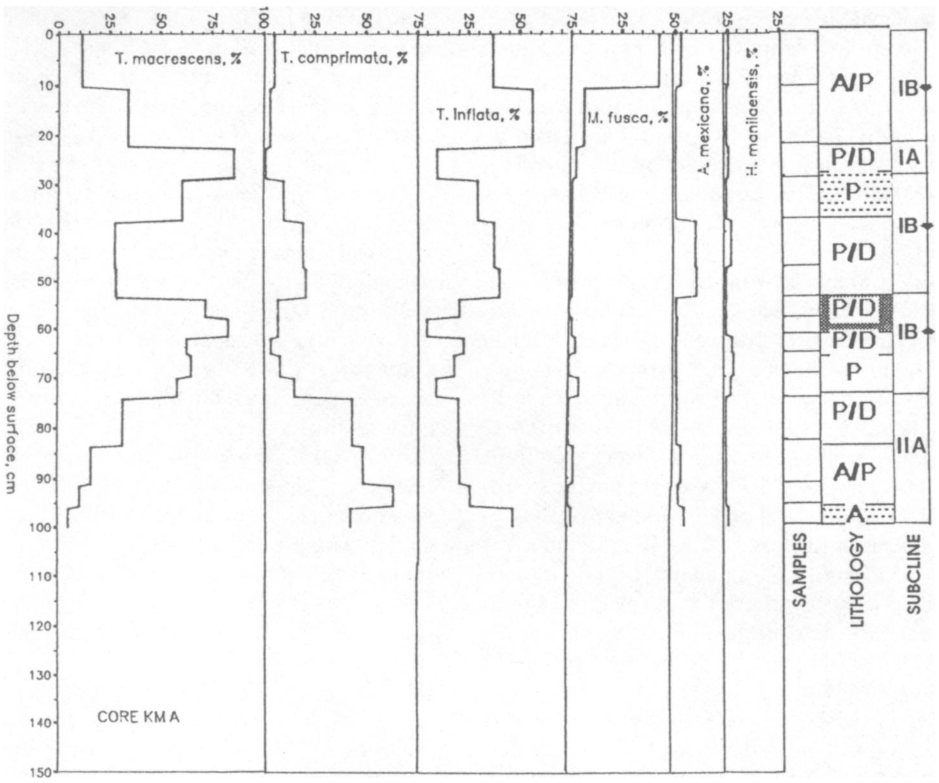

Figure 6. Relative abundances of the most common foraminiferal species in core KMA. Lithology as in Figure 3, faunal subzones after SCOTT and MEDIOLI, 1980.

ative deepening and shallowing, in depositional environments. These shifts represent periods during which the marsh growth remained behind the rise in relative sea level (deepening), or in which marsh accretion was faster than the rise in relative sea level (shallowing). We cannot state unequivocally that these faunal and environmental changes occurred at the same time at all locations because it is impossible to obtain ages of the sediments at such precision. It seems probable, however, that the faunal changes can be correlated in time from core to core: the **sequence** of events is the same in all cores (Table 5, Figure 8), although the exact environment of deposition is not the same for each core site. The interval between events E3 and E4, for instance, is characterized by deposition high in zone IB and in IA at cores F and KM, in zone IA (and above HHW) in cores CY (where the situation may be complicated by some erosion, see above). The correlation based on faunal events corresponds closely to the correlation between the cores based on lithology (VAN DE PLASSCHE, this volume), and the cores used in this study were selected from the large core inventory studied by that author to represent locations outside areas of active channel motion.

We used the data from foraminiferal assemblages to construct a "marsh paleo-environmental curve" (MPE curve), which portrays the position of the samples with respect to their vertical distance from HHWL during deposition. Our MPE curve shows the approximate location of all samples with regard to MSL versus depth in the core, assuming a distance between HHWL and MSL of 1 meter (the present distance between these two levels, Figure 8). The sections of the core where the MPE curve is vertical represent time intervals where

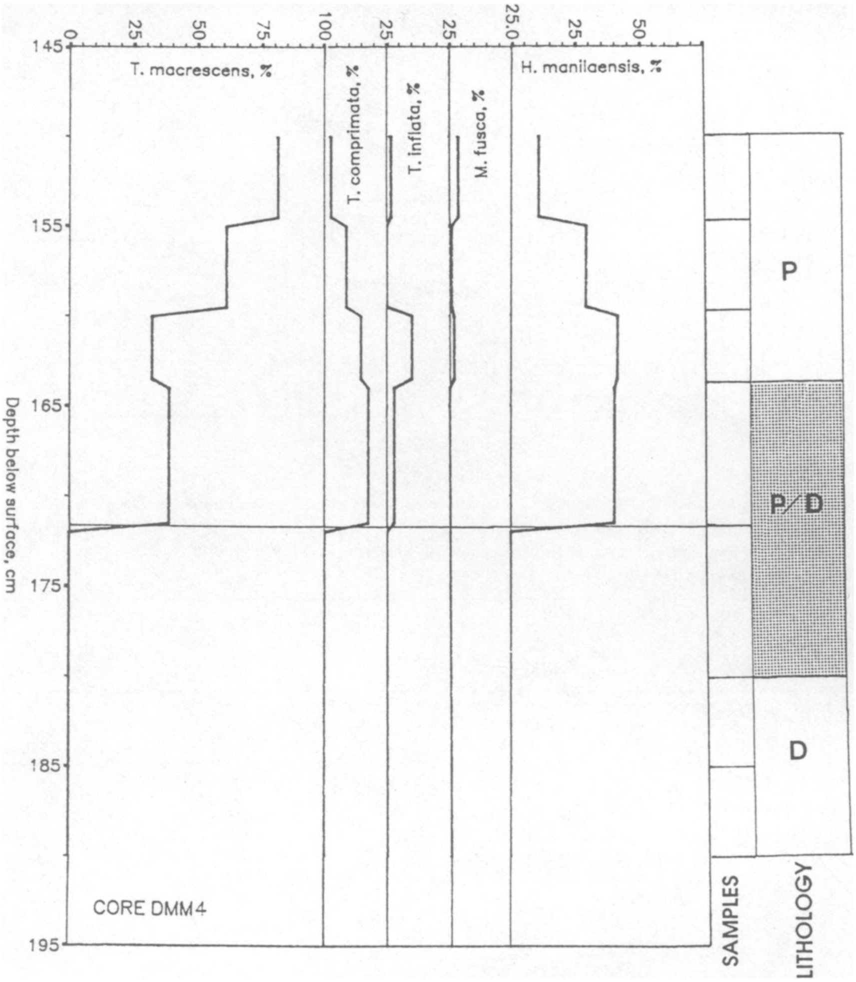

Figure 7. Relative abundances of the most common foraminiferal species in core DMM.

marsh growth kept up with relative sea level rise. Core sections where the MPE curve swings to the right (towards MSL) represent periods of drowning (indicated in the figure with D1-D3), whereas shifts to the left represent relative emergence. The curve was mainly constructed from data of core F1, our most complete record, but MPE curves derived from other cores are parallel: at all sites deepening-shallowing occurred at similar levels (Table 5).

At the time of deposition of the bottom layers of core F, deposition occurred in the middle marsh environment. At faunal event E8 the marsh environment changed suddenly to high marsh or even above HHWL. This period of shallowing ended suddenly by drowning, with an approximate change in elevation of about 20 cm. This drowning event (D-1) was shortlived, the marsh recovered, and for some time (between events E6 and E5) marsh accretion kept pace with relative sea level rise. A new drowning (D-2) was the cause of faunal event E5, with a relative lowering of the depositional site of about 30 cm with respect to HHWL. This second drowning event was longer-lived and a more gradual recovery of the marsh occurred, with a small jump at faunal event E4. The marsh accretion then kept up with relative sea level rise and even outpaced sea level rise.

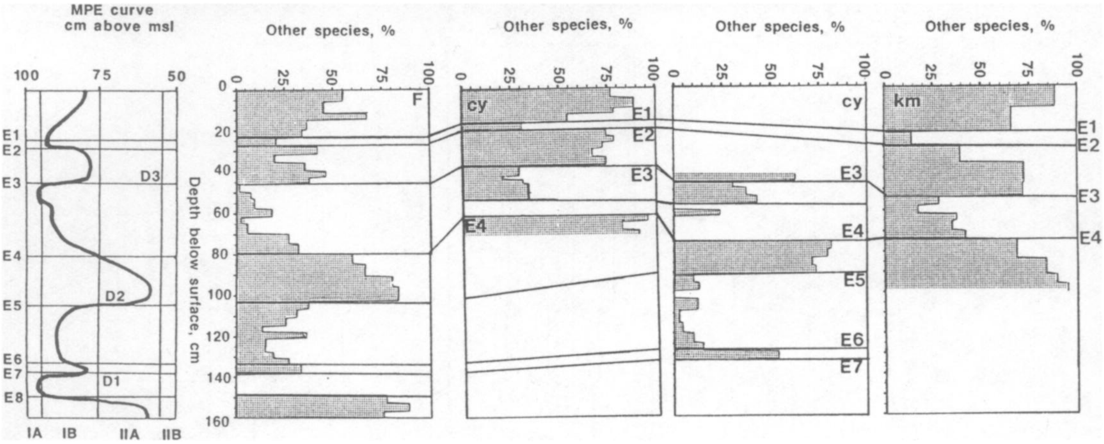

Figure 8. Relative abundances of "other species," *i.e.*, 100 minus the relative abundance of *Trochammina macrescens*, for all studied cores. Correlation lines connect corresponding events in the different cores. The Marsh PaleoEnvironment (MPE) curve was constructed from the location of faunal subzones according to SCOTT and MEDIOLI (1980). Faunal events are indicated by E1 through E8, drowning events by D1 through D3.

TABLE 5. *Foraminiferal faunal events and depths in core.*

		Depth in core, (cm)				
Event	Interpretation	CYA	CYX	F1	KMA	Lithology
E1	flooding	17	—	24	23	
E2	emergence	21	—	28	29	
E3	flooding	38	—	46	54	top black layer
E3B	slight flooding	55	57	nr	nr	
E4	emergence	62	75	80	74	
E5	strong flooding	—	91	103	—	black layer
E6	gradual emergence	—	129	131	—	
E7	flooding	—	133	139	—	black layer
E8	strong emergence	—	—	149	—	

nr: not recognized in the core
— : interval not recovered in core

Event E3 represents the third drowning of the marsh (D-3), which is suddenly terminated (E2) and followed by a period of more gradual submergence, lasting until the present day.

The most pronounced interval of deposition in middle marsh environments in all cores (relatively speaking, the zone with the most marine influence) is present between about 75 and 100 cm (after D-2, between events E4 and E5, Figure 8), and corresponds to sediments in the upper part of, and just above, the middle "black layer" in the sediments. The other two "black layers" (Figure 3) correspond to the other periods of drowning (D1 and D3).

Chemical Results

Depth profiles of concentrations of the elements Fe, Zn, Cu and S as well as Loss-on-Ignition (LOI) values for cores F, CYB and CYX are shown in Figures 9 and 10 (Tables 6 and 7). The CY cores show strong Fe and S enrichments in and just above the "black bands." The F core does not contain "black bands" (Figure 3), but shows dramatic peaks in the concentrations of Fe, Zn and S at similar depth intervals, *e.g.*, a main peak at 80–110 cm depth. A smaller peak in the concentrations of Zn and Fe occurs at 125–133 cm depth in core F (Figure 9), and

TABLE 6. *Chemical data, Core F1.*

Core	Depth (cm)	LOI (%)	S (ppm)	Fe (ppm)	Cu (ppm)	Zn (ppm)
F1	0- 6	43.8	17300	17000	34.0	54.0
F1	6- 12	32.9	20700	16000	47.0	43.0
F1	12- 15	29.0	23100	35400	44.0	47.0
F1	15- 20	31.6	16600	22000	35.0	53.0
F1	20- 24	25.7		27000	23.0	57.0
F1	24- 28	24.9	8300	15400	11.0	29.0
F1	28- 32	30.9		18000	28.0	16.0
F1	32- 36	35.5	15000	13000	12.0	25.0
F1	36- 40	30.9	8900	8200	20.0	14.0
F1	40- 43	36.2	11300	15300	23.0	26.0
F1	43- 46	31.1		11700	42.0	39.0
F1	46- 50	38.2	15300	11300	24.0	21.0
F1	50- 53	56.0	14000	8800	11.0	20.0
F1	53- 58	45.9		4000	26.0	17.0
F1	58- 62	58.1	14400	13000	10.0	19.0
F1	62- 65	48.7		4900	10.0	17.0
F1	65- 70	40.1	18100	6300	18.0	19.0
F1	70- 75	55.0	17900	6100	15.0	17.0
F1	75- 80	41.3	14800	7200	14.0	20.0
F1	80- 85	52.5	21700	11000	14.0	23.0
F1	85- 91	41.2	31800	17600	14.0	40.0
F1	91- 96	42.6	26300	25900	14.0	32.0
F1	96-103	47.7	30900	23300	14.0	34.0
F1	103-107	27.9	12300	12500	18.0	42.0
F1	107-111	32.0		13500	10.0	26.0
F1	111-115	21.4	11400	4800	8.0	22.0
F1	115-118	33.5	13200	5700	8.0	24.0
F1	118-121	42.1	16400	4800	11.0	21.0
F1	121-125	37.4	13800	5800	10.0	18.0
F1	125-128	34.4	13400	8700	14.0	19.0
F1	128-131			18700	20.0	48.0
F1	134-139	47.0	14500	2900	12.0	13.0
F1	139-145	44.5	14600	5800	14.0	17.0
F1	145-149	42.3	14700	6600	14.0	20.0
F1	153-157	30.0	20400	16700	22.0	47.0
F1	157-160	30.0	20300	18700	26.0	48.0
F1	160-164		16200	18200	22.0	43.0
F1	164-168	18.3	25900	21300	21.0	37.0
F1	168-172	18.3	14900	21700	22.0	49.0
F1	176-180	18.9	20800	26000	34.0	68.0
F1	180-185	12.0	20900	29300	20.0	70.0
F1	185-189	19.2		42300	18.0	49.0
F1	189-194	31.8	12400	6100	18.0	35.0
F1	194-199	14.8	15000	12900	18.0	37.0
F1	199-203	14.8	16100	12900	18.0	30.0

small positive Fe anomalies occur at 60 cm and at 40–55 cm, the latter correlated with a Zn anomaly and a small S anomaly. The clay-rich bottom part of the F-core is relatively rich in Fe, Zn and S. An interval with gradually increasing amounts of S, Fe, and Zn occurs from 30 cm upwards, culminating in an enriched level at about 10–20 cm. The top 10 cm of the core is less rich in Fe, whereas Zn and S concentrations remain high. The lowest concentrations of Fe and Zn occur between 135 and 149 cm depth and at 55 and 65 cm depth. The positive Fe anomalies have been labeled A-F from top to bottom (Figure 9). The "oxalate" profile for core F shows a broad positive anomaly in the middle of the core and no significant correlation with other chemical parameters.

Core CYB (Figure 10A) contains several positive Fe anomalies, notably at 135–155, 115–125, 65–105, 45–55 and 5–15 cm depth, labeled in the same way as the peaks in core F as peaks A to F. The small Fe peak in core F1 (peak C)

TABLE 7. *Chemical data, CY cores.*

Core	Depth (cm)	LOI (%)	S (ppm)	Fe (ppm)	Cu (ppm)	Zn (ppm)
CYX	43- 46			16611		
CYX	46- 49	37.48	0	15643	18.8	24. 4
CYX	49- 53	48.24	0	11397	36.0	48. 6
CYX	53- 57			11009		
CYX	57- 60	42.66	0	9745	80.5	9. 6
CYX	60- 63	41.29	0	8456	9.7	8. 9
CYX	67- 71	48.87	0	7395	14.6	11. 6
CYX	71- 75	50.09	677	10045		23. 5
CYX	75- 79	43.01	10577	17650		49. 4
CYX	79- 83	36.20	9207	18714	24.1	61. 8
CYX	83- 87	36.65		20981		40. 3
CYX	87- 91	35.99	13524	31274	14.9	45. 7
CYX	91- 95	46.28		9643		14. 8
CYX	99-103	45.14		8649	24.0	15. 3
CYX	103-109			6390		
CYX	109-115			4637		
CYX	115-120			24121		
CYB	0- 5	20.46	3400	18200	57.78	71.89
CYB	5- 10	13.29	2800	26100	61.91	55.67
CYB	10- 15	15.96	3800	22700	51.56	74.77
CYB	15- 20	16.74	16800	14200	34.79	56.39
CYB	20- 25	17.39	14400	14700		
CYB	25- 30	17.44	5900	13300	24.71	43.05
CYB	30- 35	12.38	3500	14300	18.64	38.70
CYB	35- 40	21.32	6000	10900	17.81	16.84
CYB	40- 45	30.05	7400	10500	20.91	11.05
CYB	45- 50	30.42	12200	11100	24.16	6.52
CYB	50- 55	20.98	13800	13000	12.89	4.73
CYB	55- 60	20.76	8800	8200	20.91	4.10
CYB	60- 65	20.81	13300	15300	24.16	20.44
CYB	65- 70	18.80	18700	25000	12.89	39.60
CYB	70- 75	17.12	15400	23700	20.98	47.92
CYB	75- 80	18.02	21400	26700	24.96	37.04
CYB	80- 85	19.90	18400	24500	25.69	41.49
CYB	85- 90	25.92	20800	23900	24.52	30.72
CYB	90- 95	31.49	34400	33500	12.22	40.43
CYB	95-100	32.38	23700	25000	16.12	16.64
CYB	100-105	32.47	15000	12700	11.26	10.39
CYB	105-110	46.78	10500	5200	1.25	10.48
CYB	110-115	48.88	14800	6600	0.00	30.66
CYB	115-120	50.11	21800	11500	0.00	26.76
CYB	120-125	52.80	30300	20400	0.00	21.64
CYB	125-130	58.26	16000	4500	0.00	0.11
CYB	130-135	55.76	15800	5600	0.00	11.12
CYB	135-140	42.28	17000	11000	7.90	17.22
CYB	140-145	35.49	16900	11800	2.09	16.48
CYB	145-150	28.90	11000	9600	6.29	16.74
CYB	150-155	30.38	15000	11300	3.94	24.72
Ditch		19.86	18500	29300	26.35	78.04

was not detected in the CYB core. The Fe peaks correlate well with the Zn peaks, except for the B peak. There is no clear correlation between the concentrations of Fe and Cu. The sulfur profile shows a strong correlation with the Fe profile, whereas the LOI is not significantly correlated to other chemical parameters. The less detailed CYX data show a good agreement for Fe, S and Zn for the D peak and possibly the E peak. These peaks correlate well with those in core CYB (Figures 10A, 10B).

Four samples were selected for ICP analyses for a spectrum of elements, two in the D peak and two in the low Fe interval between peaks C

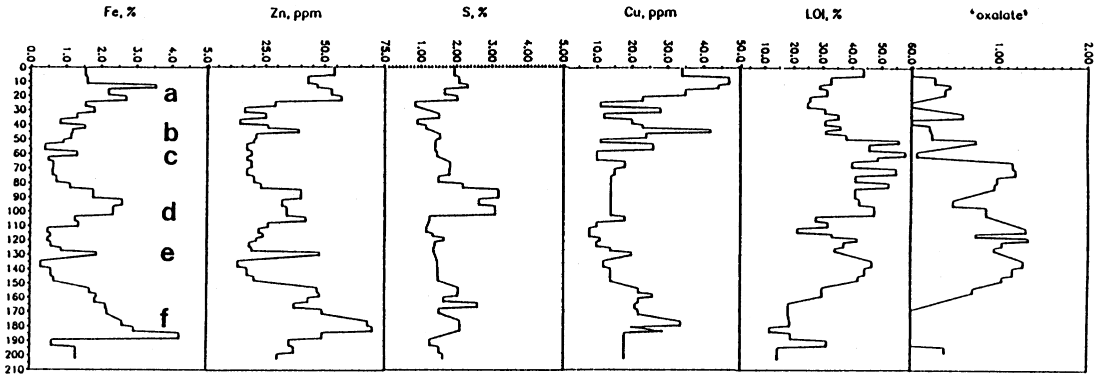

Figure 9. Concentrations of Fe, Zn, Cu, and S as well as LOI values versus depth for core F; "virtual oxalate" contents are discussed in the text; positive elemental anomalies are indicated with A-F.

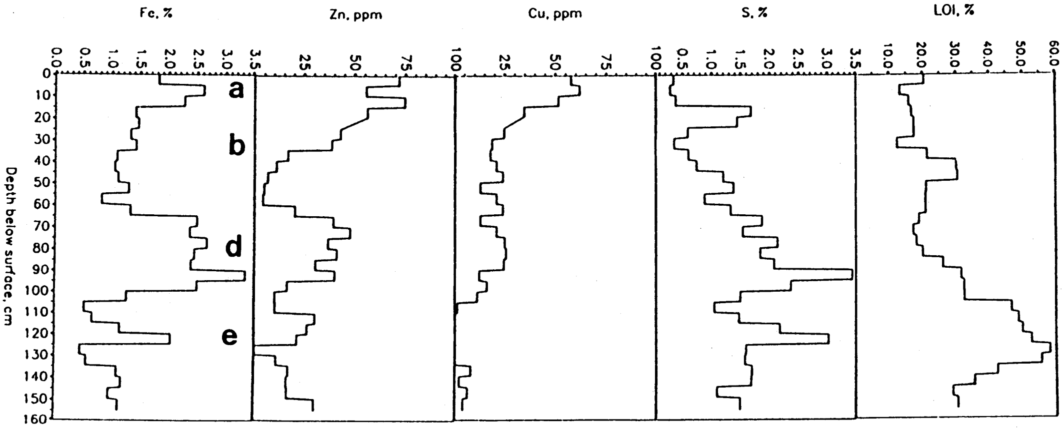

Figure 10A. Core CYB. Concentrations of Fe, Zn, Cu and S versus depth for the CY cores, together with LOI values.

and D of core F (Table 8). The Cu and Zn values show reasonable agreement with our AAS data. The high Fe-samples are characterized by relatively high levels of Zn, Se, B, V, Co, Zr, Ni and Mo, whereas Sn, Pb, Ba, Li, Sc, Cr, Cu, As, Sr and Y did not show significant differences between samples with high and lower Fe-contents. The strongest enrichments in the high-Fe samples as compared with the low-Fe samples were found for Zn (factor 2) and Mo (factor 2.5).

Discussion of the Sediment Chemistry

The depths of intervals with high values of Fe and Zn in the CY cores correlate very well with the depths of similar anomalies in core F. Within the resolution of our studies (3–4 cm), we can correlate most of the peaks labeled A to F between the two cores. The interval of overlap between the CYX and CYB cores shows slight differences in element profiles, but the profiles

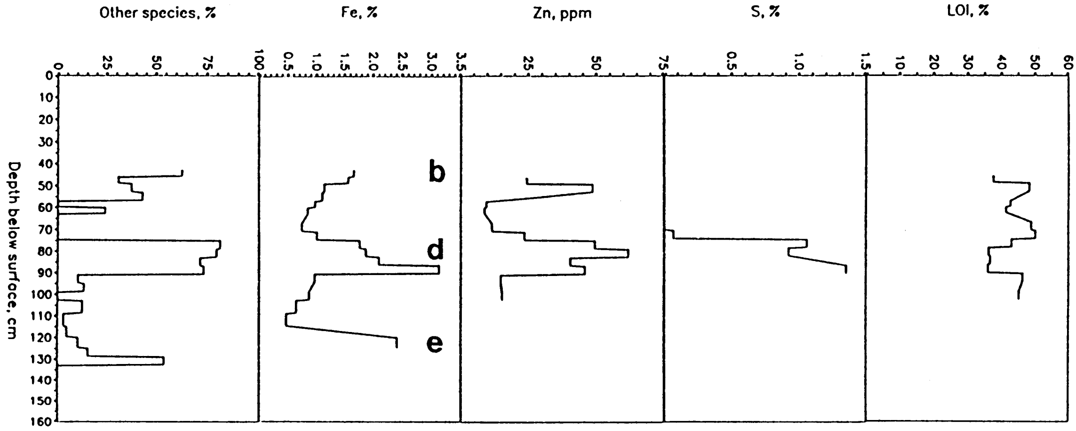

Figure 10B. Core CYX.

TABLE 8. *Chemical data, core DMM.*

Core	Depth (cm)	LOI (%)	S (ppm)	Fe (ppm)	Cu (ppm)	Zn (ppm)
DMM4	150-155	30.44	11440	20928	24.7	81.8
DMM4	155-160	34.43	10804	21230	31.6	45.0
DMM4	160-164	37.13	13424	21103	10.2	53.0
DMM4	164-172	65.75	17065	41217	20.8	22.2
DMM4	172-180	80.64	17198	32039	48.5	9.2
DMM4	180-185	88.31	16425	18921		5.3
DMM4	185-190	88.87	9567	7148	15.0	4.7

TABLE 9. *Results of analyses of 4 samples, core F1.*

Sample	Li	B	Sc	V	Cr	Co	Ni	Cu	Zn	As	Sr	Y	Zr	Mo	Sn	Ba
065–070	11	49	1.4	19.8	18	4	7	14.5	20.0	8	85.4	3.7	2.5	8	24	11
075–080	16	45	1.5	22.6	20	4	9	10.2	23.2	9	76.6	4.4	2.5	9	28	13
091–096	17	62	1.3	27.0	23	8	18	13.1	41.3	11	74.7	5.3	3.7	23	26	15
096–103	19	61	1.5	29.8	24	6	15	13.1	42.8	10	65.0	5.4	3.7	22	16	19

Sample	Pb	Se	S, %	Fe, %	S/Se (wt.)
065–070	5	3.0	1.8	0.63	0.60×10^4
070–075	9	2.8	1.5	0.72	0.54×10^4
091–096	4	4.2	2.6	2.59	0.62×10^4
096–103	8	4.5	3.1	2.33	0.69×10^4

can be correlated straightforwardly, with peaks at slightly different depths. Correlation between cores according to lithology and fauna agrees with the correlation using chemical data.

At both core-sites we observed a trend of Cu and Zn enrichment from about 40 cm upwards, with superimposed anomalies (Figures 9, 10). This enrichment in the topmost levels of the cores is most likely related to anthropogenic pollution (*e.g.*, McCaffrey and Thomson, 1980; Varekamp, this volume) and should be interpreted carefully with regard to paleo-environmental analyses. Therefore we consider in the following discussion only data for the "unpolluted" core section, with samples from depths

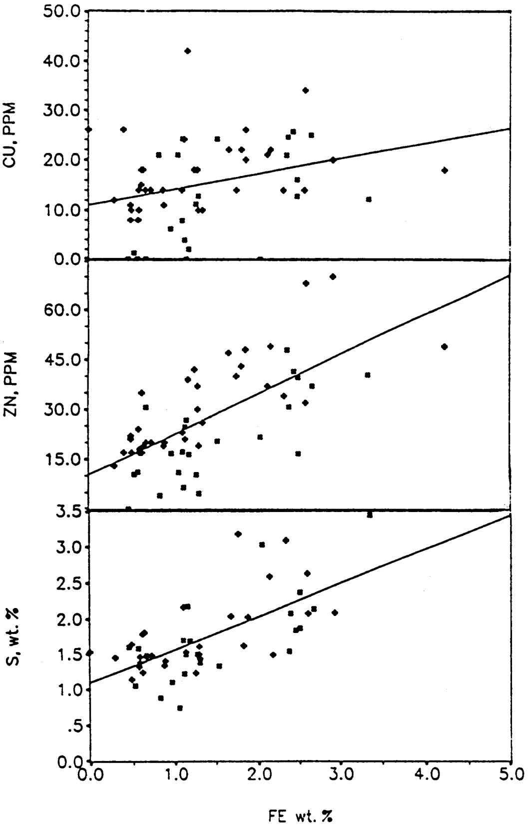

Figure 11. Correlations of Cu, Zn and S with Fe for samples from the CYB and F cores with a depth greater than 40 cm.

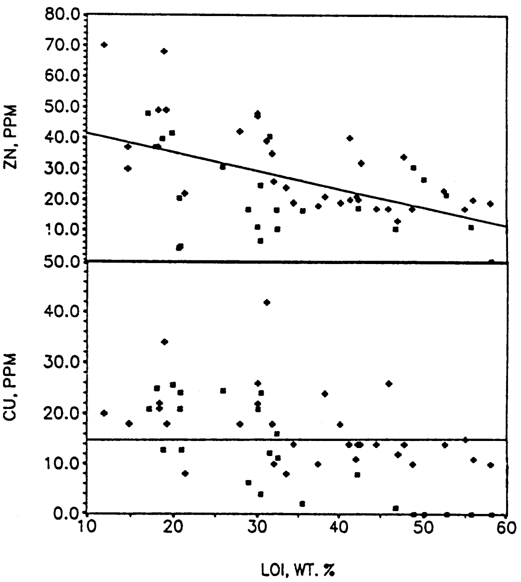

Figure 12. Correlation diagrams for Zn and Cu with LOI values for samples from CY and F cores with depth greater than 40 cm.

greater than 40 cm (*i.e.*, pre-dating anthropogenic influences; see VAREKAMP, this volume).

The concentration of Fe shows a significant positive correlation with that of Zn (R = 0.68) and S (R = 0.67), but a poor correlation with that of Cu (R = 0.3; Figure 11). The Zn concentration shows a significant negative correlation with LOI (R = 0.52) and a weak positive correlation with S (R = 0.42) (Figure 12). The concentration of Cu is not significantly correlated with either S or LOI (Figure 12).

The lack of correlation between S and LOI in the marsh peats suggests that the amount of organic matter was not the limiting variable for S fixation during diagenesis. The amount of non-pyrite-bound iron (NP-Fe), calculated from molar iron minus 0.5 molar sulfur (Figure 13), shows a strong positive correlation with total Fe (R = 0.78). The low-Fe samples contain excess sulfur (negative NP-Fe values), possibly in the form of native sulfur or organically-bound sulfur, whereas the high-Fe samples contain excess Fe with respect to pyrite. In the low-Fe samples, all reactive Fe has been consumed during diagenetic pyrite formation. In combination with the positive correlation of total Fe with S, this is strong evidence for Fe-control on pyrite formation.

The inorganic chemistry of the peats is largely determined by the input of fine-grained suspended matter during flooding of the marsh. Low marsh sections, with a higher flooding frequency, will trap more fine-grained matter (clay, silt, hydrous iron oxides) than the upper marshes, which have a lower flooding frequency. The chemistry of the peats is probably very sensitive to the trapping efficiency of the marsh flora for the different grain size fractions, the distance from tidal gullies and maximum depth of water during flooding. Measurement of a parameter indicative for clay contents (*e.g.*, Al or Rb) may provide a better estimate of clay contents than LOI values and could serve as a rough environmental indicator.

We assume that frequently flooded marsh areas trap more fine-grained, Fe-rich suspended material than the upper marsh realm.

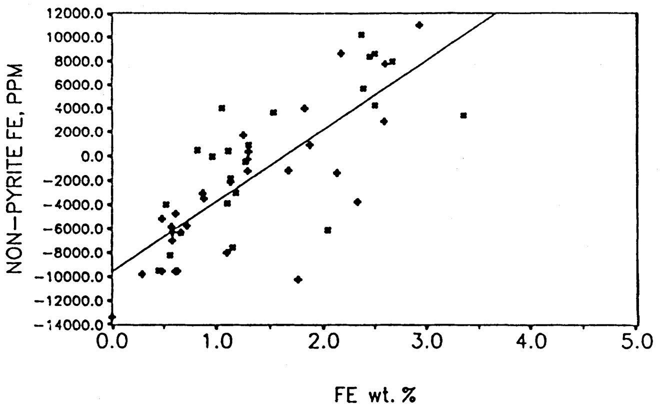

Figure 13. Correlation diagram of Non-Pyrite iron (NP-Fe) versus total Fe. NP-Fe calculated according to Fe (moles/gram)—0.5 S (moles/gram) under the assumption that pyrite is the only iron sulfide present. The Pearson correlation coefficient is 0.78; significant at >99%. Negative NP-Fe values indicate the presence of native sulfur and/or organically bound sulfur.

We do not think it probable that this change in trace element chemistry resulted from the shifting of the location of a marsh-channel, because at our core locations there are no indications from the lithology that the marsh channels shifted. In addition, the black horizons can be recognized over a very large part of the whole marsh, and thus are not likely the result of the shifting of one local channel (VAN DE PLASSCHE, this volume). The Fe-rich bands in the cores are therefore interpreted as the result of relatively sudden shifts from upper high marsh to middle marsh environments. Deposition of the Fe-rich bands occurred in an environment that was more frequently flooded than the adjacent core sections. The suspended sediment fraction in sea water carries adsorbed Zn, Se, Mo and possibly Cu with it, leading to trace metal enrichments in the Fe-peak anomalies. The sediment layers then become enriched in S during diagenesis, and the more Fe-rich sediments fix more S in pyrite than Fe-poor peats. In addition, more frequent flooding provides a larger potential sulfur flux, although it is unlikely that sulfur fixation is limited by the availability of sulfate.

The chemistry of Cu in the peats is enigmatic: there is no significant correlation between Cu concentration and that of any other element. Possibly, Cu was relatively mobile during diagenesis in polysulfide complexes, which are common sulfur species in marsh pore fluids (LUTHER *et al.*, 1986), but we cannot assess that for our samples. A similar poor correlation between Cu and other elements was found for the mudflats in the Connecticut River estuary (VAREKAMP, this volume).

Our chemical data from surface sediments in the CY location (Table 7) show high levels of Fe, Zn and S (comparable to that of the peak levels in the core samples) in muds from mosquito ditches. To some degree, the mosquito ditches represent a physical environment similar to that envisioned to occur during the sudden drowning events: a more pronounced marine invasion during high water stands. The strong Fe enrichments in the muds of these ditches may result from a more ample supply of Fe-rich suspended matter, which is trapped in the slimey, cyanobacteria-rich bottom muds of the ditches. The strong Zn enrichments are thought to be related to the particulate Fe-influx.

Our metal data agree with data from other marshes (WINDOM, 1975; MCCAFFREY and THOMSON, 1980). Iron and Zn contents of sediments from the Farmington marsh (Branford, Connecticut) are higher, but these values were reported on an "ashed basis" (MCCAFFREY and THOMSON, 1980). Their Zn profile below 40 cm depth resembles ours, with a low-Zn section between 50 and 70 cm depth. The authors do not present an Fe profile over the full length of the core, but the "clay abundance" data show peaks that as a first approximation agree with our major Fe-anomaly at about 80–100 cm. It is commonly accepted (McCaffrey and Thomson, 1980; Varekamp, this volume) that the trace metal enrichment in the upper part of the core resulted from anthropogenic activity. Our data indicate that the trace-metal flux in the pre-pollution period was associated with iron oxide particles trapped in the marsh during flooding. McCaffrey and Thomson (1980) argued that the anthropogenic input is largely derived from the atmosphere. In how far the suspended particle derived metal flux is important in the total metal budget of the upper 40 cm in the cores is unclear. Supply of metals from settling of suspended hydrous iron oxides was hypothesized for the mudflat sediments from the Connecticut River estuary (Varekamp, this volume).

Comparison of Faunal and Chemical Data

A comparison of faunal and chemical data shows a strong correlation between the faunal composition of a sample and the concentrations of Fe, Zn, and S (Figure 14, 15). High relative abundances of "other species" (all non-*T. macrescens* specimens) occur in samples with high concentrations of Fe and Zn. The lowest concentrations of Fe and Zn occur in samples labeled "no foraminifera" (above HHWL) or with low foraminiferal counts dominated by *T. macrescens* (subzone IA, just below HHWL). Even small anomalies consisting of a single sample show coincidence of high Fe and high percentage of "other species" (*e.g.*, 60 cm depth interval in core F, Figure 14). The correlation between the Zn concentration and the relative abundance of "other species" breaks down in the upper 40 cm of the cores, where there is probably a strong anthropogenic metal input (McCaffrey and Thomson, 1980; Varekamp, this volume). The concentrations of Fe and Zn are significantly correlated with the relative abundance of "other species" for samples below 40 cm ($R_{Fe} = 0.63$; $R_{Zn} = 0.68$; Figure 16).

Faunal contents and sediment chemistry reflect changes in depositional environments over time. The faunal composition, especially the relative abundance of *T. macrescens*, largely reflects the average time of exposure of the marsh surface, and the metal concentrations are proportional to the flooding frequency and sediment trapping efficiency of the marsh.

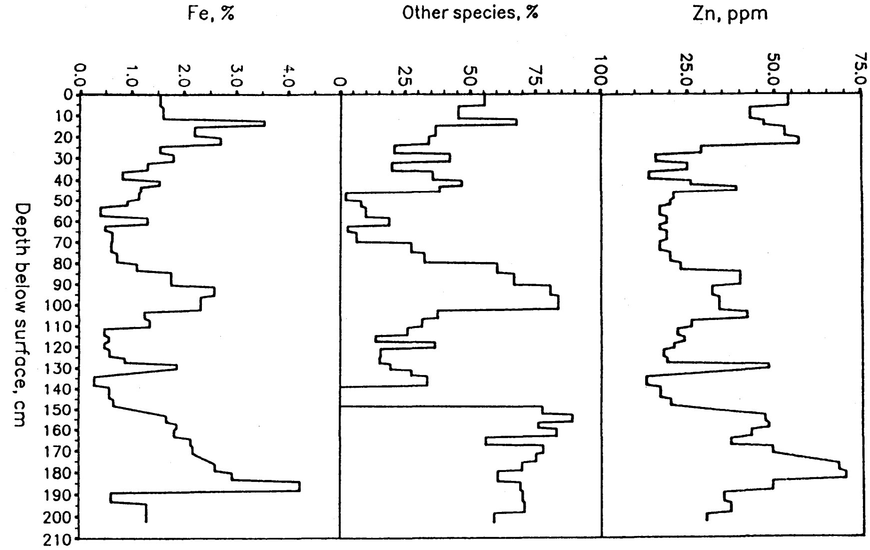

Figure 14. Comparison of Fe and Zn contents with percentage of other species in core F. "Other species" values is equal to 100 minus the relative abundance of *T. macrescens*. The increase in Zn concentration from 40 cm depth upwards is an anthropogenic pollution effect, whereas the increase of Fe and percentage of other species are related to the changing environment of deposition as discussed in the text.

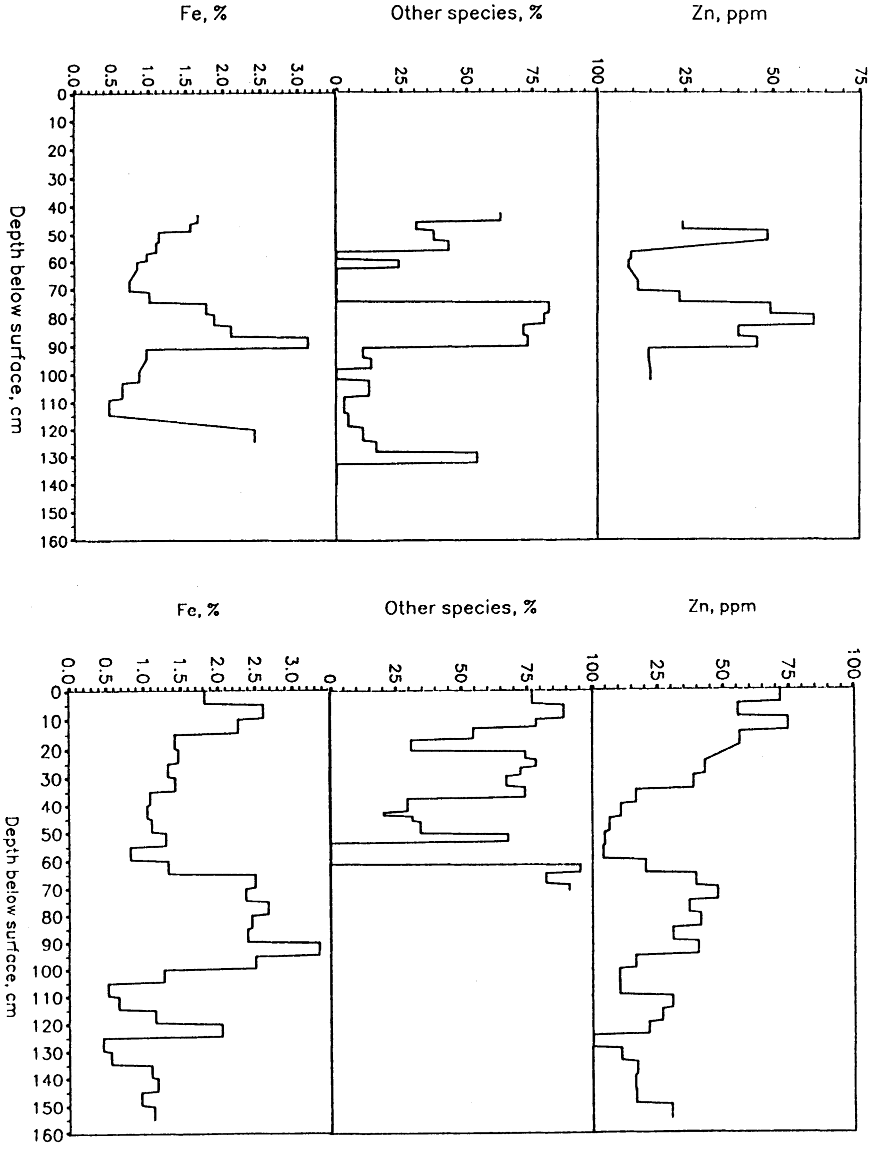

Figure 15. Comparison of Fe and Zn contents with percentage "other species" for cores CYX (Figure 15A) and CYB (Figure 15B). "Other species" value is equal to 100 minus the relative abundance of *T. macrescens*. The increase in Zn concentration from 40 cm depth upwards is an anthropogenic pollution effect, whereas the increase of Fe and percentage of other species are related to the changing environment of deposition as discussed in the text. Comparison of Fe and Zn contents with percentage "other species" for cores CYX (Figure 15A) and CYB (Figure 15B). "Other species" value is equal to 100 minus the relative abundance of *T. macrescens*. The increase in Zn concentration from 40 cm depth upwards is an anthropogenic pollution effect, whereas the increase of Fe and percentage of other species are related to the changing environment of deposition as discussed in the text.

The Fe abundance in the sediments is likely a primary feature of the peats, whereas the S abundance is a diagenetic feature, partly influenced by the Fe abundance. The agreement between faunal and Fe abundances confirms that this chemical signature (Fe-abundance)

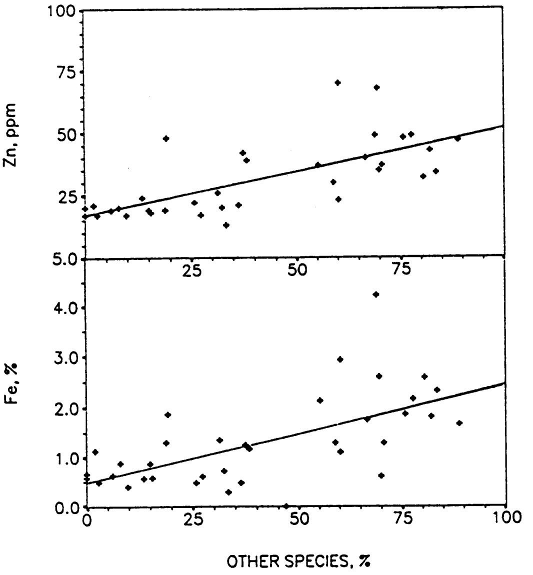

Figure 16. Correlation of percentage of other species with Fe and Zn contents in core F; samples from greater than 40 cm depth. "Other species" value is equal to 100 minus the relative abundance of *T. macrescens*. Both correlations are significant (>99%) with Pearson correlation coefficients of 0.68 (Zn) and 0.63 (Fe).

reflects the conditions of deposition of the sediments at the time when the faunas were living, rather than diagenesis.

These two different data sets lead us to a similar paleo-environmental reconstruction of the marshes through time. Both lines of evidence indicate the occurrence of three periods during which the marsh drowned: sea level rise was faster than marsh accretion (Figure 8). These periods of drowning of the marsh are reflected in the lithology of some cores (CY, KM, but not F) by "black bands," which can be traced throughout a large part of the Hammock River marsh (VAN DE PLASSCHE, this volume). The black color is most likely caused by the presence of finely divided Fe-sulfides. The vertical extent of the Fe-rich bands indicates that for some time the rate of relative sea level rise exceeded the marsh accretion rate. After some time, marsh accretion caught up with relative sea level rise and from then on the accretion rate equaled the rate of relative sea level rise, or in some instances exceeded the rate of relative sea level rise, which led to emergence (Figure 8).

The cause of the drowning of the marsh can as yet not be ascertained: it might have been an increase in the rate of true sea-level rise (eustatic rise), a tectonic lowering of the land area (during seismic events), or a change in the tidal range in the marsh, which would change our reference level of HHWL. The latter might be caused by morphological changes in the marsh and river mouth, or be related to a regional change in tidal range, but these factors are difficult to evaluate.

A tectonic lowering of the land may cause a local apparent rise in sea level. NELSON and coworkers applied the marsh foraminiferal technique to distinguish between the different salt marsh sub-environments along the west coast of the U.S.A. (Oregon) and found evidence for sudden apparent sea level jumps. They explained those data as indicative of major earthquakes (*e.g.*, NELSON and JENNINGS, 1988). We do not think that seismic events are a probable cause for all the flooding events of the Hammock River Marshes because tectonic events are expected to be sudden, whereas the drowning started gradually during the youngest and middle event. In addition, the start of the youngest drowning pulse must have occurred approximately in the late part of the last century, and no major earthquakes are known to have occurred in Connecticut during that period.

If the periods of drowning can be recognized over a larger area along the northeastern U.S. seaboard, and are coeval over that area, a change in the rate of true sea level rise is the more probable explanation. A comparison of our data with studies from the New Jersey coast (MEYERSON, 1972) and Barnstable marsh (MA, *fide* MEYERSON, 1972) suggests that in all three areas surges were observed in submergence-rates. MCCAFFREY and THOMSON (1980) indicated a period of rapid relative sea level rise from about 1900 till recent, preceded by more gradual relative sea level rise. PATTON and HORNE (this volume) found a steepening in their sea level curve around (or postdating) 1670 AD. Tide gauge data from New York harbor also indicate an elevated rate of relative sea level rise over the last 80 years compared to average sea level rise over the last 1500 years (VAN DE PLASSCHE *et al.*, 1989). Comparable results were obtained from England by ALLEN and RAE (1987; 1988). The increased metal contents in the top of our sediment cores probably represent an anthropogenic metal input, and we can date the level of metal increase at approximately 1850 (± 40 years) AD (VAREKAMP, this volume). The increased rates of sea level rise reported by the work cited above all started around that period. Thus we suggest that fluctuations in the rate of true sea level rise (eustatic acceleration) are a likely explanation for the last drowning period and possibly for all three periods of drowning in the Clinton marshes.

CONCLUSIONS

Marsh foraminiferal assemblages and sediment chemistry from coastal marshes provide reliable information on the environment of deposition of marsh peats through time. Building largely on the work of SCOTT and MEDIOLI (1980) for faunal information, we have developed a combined chemical-faunal method of paleo-environmental reconstruction of coastal salt marsh sequences. The chemical signatures as well as the relative abundance of foraminiferal species are largely related to flooding frequency. Low relative abundances of the species *T. macrescens* and high relative abundances of the species *T. comprimata, T. inflata*, and especially of *M. fusca* and *A. mexicana* occur in samples with high concentrations of Fe, Zn, and S, and probably indicate a depositional zone in the middle marsh environment. High relative abundances of *T. macrescens* occur in samples with low concentrations of Fe, Zn and S, which are likely deposited close to HHWL. The construction of paleo-environments curves from faunal data enabled us to reconstruct jumps in relative sea level rise over time.

Marsh sediment chemistry is largely determined by the relative strength of sediment and vegetational input terms. The fixation of sulfur during diagenesis is largely limited by the abundance of Fe and not by the availability of organic matter or sulfate. The Zn contents of marsh sediments that predate anthropogenic pollution correlate strongly with Fe abundances, and are therefore thought to relate to the same process: trapping of fine, Fe-rich suspended matter with adsorbed Zn in the marsh during flooding. Thus construction of profiles of foraminiferal faunal assemblages and concentrations of the elements Fe, Zn and S versus depth-in-core will enable the reconstuction of the paleo-environments of the marsh, and will allow the identification of periods during which the marsh accretion kept up with, exceeded, or fell behind relative sea level rise. This technique may be applied towards detailed sea level rise studies as well as towards paleo-seismic investigations and studies of marsh-configuration.

Data from the Hammock River Marshes (Clinton, Connecticut) provide evidence that marsh accretion during the last 1500–2000 years did not occur smoothly and evenly. We recognize three major periods of marsh drowning with characteristic chemical and faunal signatures. The oldest event was the most sudden, progressing from partial emergence to sudden drowning, whereas the middle and youngest events were somewhat more gradual. During these three periods, marsh accretion fell markedly behind the rate of relative sea level rise. The explanation of this change in relative rates of sea level rise and marsh accretion can not yet be fully ascertained, but the periods of drowning of the marshes may be related to periods with an increased rate of true sea level rise. These events may also have been recognized in marsh sequences from New Jersey and Massachusetts; the youngest event seems to be recognizable at several locations worldwide. Much of the sea level rise (about 40%) over the last 1500 years may have occurred during the three relatively short pulses, whereas there was only a small increase in mean sea level in the intervening periods. Obviously, extrapolation of **average** relative sea level rise over the last 1500 years to make predictions for sea level in the next century could be severely in error. Our MPE graph (Figure 8) indicates that we have entered a period of a gradual increase in the rate of relative sea level rise during this century. The occurrence of several periods in the last 1500 years with increased rates of apparent sea level rise may suggest that the current, relatively rapid rate of relative sea level is not necessarily related to an anthropogenic greenhouse effect. The relevance of the drowning pulses and correlation with global climatic changes are discussed elsewhere (VAN DE PLASSCHE *et al.*, in press).

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SYSTEMATIC TAXONOMY

All specimens studied were picked and placed in cardboard slides. Taxonomy follows SCOTT and MEDIOLI (1980), except where emended in SCOTT and MEDIOLI (1986), and where indicated.

Ammotium salsum (CUSHMAN and BROENNIMANN).

Ammobaculites salsus CUSHMAN and BROENNIMANN, 1948, Some new species and genera of Foraminifera from brackish water of Trinidad: *Cushman Laboratory for Foraminiferal Research Contributions,* 24, 16, pl. 3, Figures 7–9.

Ammotium salsum (CUSHMAN and BROENNIMANN), PARKER and ATHEARN, 1959, Ecology of Marsh Foraminifera in Poponosset Bay, Massachusetts: *Journal of Paleontology,* 33, 340, pl. 50, Figures 6, 13.

Ammotium salsum (CUSHMAN and BROENNIMANN). SCOTT and MEDIOLI, 1980, Quantitative studies of marsh foraminiferal distributions in Nova Scotia: implications for sea level studies. *Cushman Foundation for Foraminiferal Research, Special Publication,* 17, 35, pl. 1, Figures 11–13.

This species occurs as a few single specimens in few samples only.

Arenoparella mexicana (KORNFELD)

Trochammina inflata (MONTAGUE) var. *mexicana* KORNFELD, 1931, Recent littoral Foraminifera from Texas and Louisiana: *Stanford University, Department of Geology, Contributions,* 1, 86, pl. 13, Figure 5.

Arenoparrella mexicana (KORNFELD), PARKER and ATHEARN, 1959, Ecology of Marsh Foraminifera in Poponosset Bay, Massachusetts: *Journal of Paleontology,* 33, 340, pl. 50, Figures 6, 13.

Arenoparrella mexicana (KORNFELD) SCOTT and MEDIOLI, 1980, Quantitative studies of marsh foraminiferal distributions in Nova Scotia: implications for sea level studies. *Cushman Foundation for Foraminiferal Research, Special Publication,* 17, 35, pl. 4, Figures 8–11.

The species is absent to rare in samples from the highest marsh, is absent in samples from the inner estuarine area (Core DMM), and comprises up to 25% of the fauna in subzone IIA (subzone name after SCOTT and MEDIOLI, 1980).

Haplophragmoides manilaensis ANDERSEN

Haplophragmoides manilaenis ANDERSEN 1953, Two new species of Haplophragmoides from the louisiana Coast. *Cushman Foundation for Foraminiferal Research Contributions,* 4, 22, pl. 4, Figures 8a, b.

Haplophragmoides hancocki CUSHMAN and McCULLOCH, PARKER and ATHEARN 1959, Ecology of Marsh Foraminifera in Poponosset Bay, Massachusetts: *Journal of Paleontology,* 33, 339, pl. 50, Figures 2, 3.

Haplophragmoides bonplandi TODD and BROENNIMANN, SCOTT and MEDIOLI, 1980, Quantitative studies of marsh foraminiferal distributions in Nova Scotia: implications for sea level studies. *Cushman Foundation for Foraminiferal Research, Special Publication,* 17, 35, pl. 4, Figures 8–11.

The species in our samples is clearly the same as that figured in SCOTT and MEDIOLI (1980). SCOTT, however, studied type material of several species of *Haplophragmoides* and now considers *H. bonplandi* TODD and BROENNIMANN 1957 to be conspecific with *H. manilaensis* ANDERSEN 1953 (written comm., 1988). The species is usually present at less than 10% of the assemblage, with the exception of the samples from the inner reaches of the marshes (core DMM) where it reaches up to 50%.

Helenina anderseni (Warren)

t*Valvulineria* sp., Phleger and Walton, 1950, Ecology of marsh and bay foraminifera, Barnstable, Mass., *American Journal of Science,* 248, pl. 2, Figures 22a, b.

Pseudoeponides anderseni Warren, 1957, Foraminifera of the Buras-ScoeFIELD Bayou region, southeast Louisiana: *Cushman Foundation for Foraminiferal Research Contributions,* 8(1), p. 39, pl. 4, Figures 12–15.

Helenina andersoni (Warren) Scott and Medioli, 1980, Quantitative studies of marsh foraminiferal distributions in Nova Scotia: implications for sea level studies. *Cushman Foundation for Foraminiferal Research, Special Publication,* 17, 40, pl. 5, Figures 10, 11.

This calcareous species is absent in almost all samples with the exception of a few samples (subzone IIA) in core KMA, and in surface samples from the *Spartina alterniflora* zone or lower.

Hemisphaerammina bradyi Loeblich and Tappan

Hemisphaerammina bradyi Loeblich and Tappan, 1957 in: Loeblich, A.R., Tappan, H., Beckmann, J.P., Bolli, H.M., Gallitlelli, E.M., and Troelsen, J.C., Studies in Foraminifera; *U.S. National Museum Bulletin* 215, 224, pl. 72, Figure 2.

Hemisphaerammina bradyi Loeblich and Tappan, Scott and Medioli, 1980, Quantitative studies of marsh foraminiferal distributions in Nova Scotia: implications for sea level studies. *Cushman Foundation for Foraminiferal Research, Special Publication,* 17, 40, pl. 1, Figures 4, 5.

This species is absent in most samples, or occurs as rare, single specimens; it is more common, however, in a few samples in the lower part of, and just below, the middle "black layer" in the sediment in the CY and KM cores.

Miliammina fusca (Brady)

Quinqueloculina fusca Brady, 1870, in: Brady, G.S., and Robertson, D., The ostracoda and foraminifera of tidal rivers. With analysis and description of Foraminifera by H.B. Brady, part II: *Annual Magazine of Natural History,* series 4, 6, 47, pl. 11, Figures 2, 3.

Miliammina fusca (Brady), Phleger and Walton, 1950, Ecology of marsh and bay foraminifera, Barnstable, Mass., *American Journal of Science,* 248, 280, pl. 1, Figures 19a, b.

Miliammina fusca (Brady) Parker and Athearn, 1959, Ecology of Marsh Foraminifera in Poponosset Bay, Massachusetts: *Journal of Paleontology,* 33, 340–341, pl. 50, Figures 11, 12.

Miliammina fusca (Brady) Scott and Medioli, 1980, Quantitative studies of marsh foraminiferal distributions in Nova Scotia: implications for sea level studies. *Cushman Foundation for Foraminiferal Research, Special Publication,* 17, 40, pl. 2, Figures 1–3.

The species is absent in samples from higher marsh areas, common (10–40%) in samples from subzone IIA.

Polysaccamina ipohalina Scott

Polysaccamina ipohalina Scott, 1976, Brackish-water foraminifera from southern California and description of *Polysaccamina ipohalina,* n. gen., n. sp., *Journal of Foraminiferal Research,* 6, 318, pl. 2, Figures 1–4, text Figures 4a–c.

Polysaccamina ipohalina Scott, Scott and Medioli, 1980, Quantitative studies of marsh foraminiferal distributions in Nova Scotia: implications for sea level studies. *Cushman Foundation for Foraminiferal Research, Special Publication,* 17, 43, pl. 2, Figures 8–11.

The species is commonly present as rare specimens or fragments.

Protelphidium orbiculare (Brady)

Nonionina orbiculare Brady, 1881, On some Arctic Foraminifera from soundings obtained on the Austro-Hungarian North Polar Expedition of 1872–76: *Annual Magazine of Natural History,* 8, 415, pl. 21, Figure 5.

Protelphidium orbiculare (Brady) Scott and Medioli, 1980, Quantitative studies of marsh foraminiferal distributions in Nova Scotia: implications for sea level studies. *Cushman Foundation for Foraminiferal Research, Special Publication,* 17, 43, pl. 5, Figure 7.

Haynesia orbiculare (Brady) Scott, Schafer, and Medioli, 1980, Eastern Canadian estuarine foraminifera: a framework for comparison. *Journal of Foraminiferal Research,* 10, 205–234 (in footnote).

This calcareous species is absent in almost all samples with the exception of a few samples (subzone IIA) in core KMA, and in surface samples from the *Spartina alterniflora* zone or lower.

Pseudothurammina limnetis (SCOTT and MEDIOLI

Thurammina(?) limnetis SCOTT and MEDIOLI, 1980, Quantitative studies of marsh foraminiferal distributions in Nova Scotia: implications for sea level studies. *Cushman Foundation for Foraminiferal Research, Special Publication,* 17, 43, pl. 1, Figures 1-3.

Pseudothurammina limnetis (SCOTT and MEDIOLI), SCOTT, WILLIAMSON and DUFFETT, 1981, Marsh Foraminifera from Prince Edward Island: their recent distribution and application for former sea level studies. *Maritime sediments and Atlantic Geology,* 17, 126.

The species is rare, usually present as rare single specimens or fragments. More common (up to a few percent) in samples from the lower part of, and just below, the "black layer" in cores CY and KM.

Tiphotrocha comprimata (CUSHMAN and BROENNIMANN)

Trochammina comprimata CUSHMAN and BROENNIMANN, 1948, Additional new species of arenaceous Foraminifera from the shallow waters of Trinidad: *Cushman Laboratory for Foraminiferal Research Contributions,* 24, 41, pl. 8, Figures 1–3.

Tiphotrocha comprimata (CUSHMAN and BROENNIMANN), PARKER and ATHEARN, 1959, Ecology of Marsh Foraminifera in Poponosset Bay, Massachusetts: *Journal of Paleontology,* 33, 341, pl. 50, Figures 14–17.

Tiphotrocha comprimata (CUSHMAN and BROENNIMANN) SCOTT and MEDIOLI, 1980, Quantitative studies of marsh foraminiferal distributions in Nova Scotia: implications for sea level studies. *Cushman Foundation for Foraminiferal Research, Special Publication,* 17, 44, pl. 5, Figures 1–3.

A common species in many samples (up to 65%), with the exception of those from the highest marsh areas. In surface samples the species is more common in densely vegetated zones of *S. patens,* less common in less dense stands and in areas of common *Salicornia* growth.

Trochammina inflata (MONTAGU)

Nautilus inflatus MONTAGU, 1808, *Testacea Brittanica,* supplement, Exeter, England, S. Woolmer, pl. 18, Figure 3.

Trochammina inflata (MONTAGU), PHLEGER and WALTON, 1950, Ecology of marsh and bay foraminifera, Barnstable, Mass., *American Journal of Science,* 248, 280, pl. 2, Figures 1–3.

Trochammina inflata (MONTAGU), PARKER and ATHEARN, 1959, Ecology of Marsh Foraminifera in Poponosset Bay, Massachusetts: *Journal of Paleontology,* 33, 341, pl. 50, Figures 18–20.

Trochammina inflata (MONTAGU) SCOTT and MEDIOLI, 1980, Quantitative studies of marsh foraminiferal distributions in Nova Scotia: implications for sea level studies. *Cushman Foundation for Foraminiferal Research, Special Publication,* 17, 44, pl. 3, Figures 12–14, pl. 4, Figures 1–3.

Trochammina macrescens BRADY

Trochammina inflata (MONTAGU) var. *macrescens* BRADY, 1870, p. 290, pl. 11, Figures 5a–c.

Trochammina macrescens BRADY, PHLEGER and WALTON, 1950, Ecology of marsh and bay foraminifera, Barnstable, Mass., *American Journal of Science,* 248, 281, pl. 2, Figures 6–9.

Trochammina macrescens BRADY, PARKER and ATHEARN, 1959, Ecology of Marsh Foraminifera in Poponosset Bay, Massachusetts: *Journal of Paleontology,* 33, 341, pl. 50, Figures 23–25.

Jadammina polystoma Bartenstein and Brand, PARKER and ATHEARN, 1959, Ecology of Marsh Foraminifera in Poponosset Bay, Massachusetts: *Journal of Paleontology,* 33, 381, pl. 50, Figures 21, 22, 27.

Trochammina inflata BRADY, SCOTT and MEDIOLI, 1980, Quantitative studies of marsh foraminiferal distributions in Nova Scotia: implications for sea level studies. *Cushman Foundation for Foraminiferal Research, Special Publication,* 17, 44–45, pl. 3, Figures 1–8.

Present in most samples, dominant in samples from the highest marsh (subzone IA). The variant *T. polystoma* was not observed.

Trochammina ochracea (WILLIAMSON)

Rotalina ochracea WILLIAMSON, 1858, *On Recent Foraminifera of Great Britain,* Royal Society (London) Publication, 55, pl. 4, Figure 113.

Trochammina ochracea (WILLIAMSON), SCOTT and MEDIOLI, 1980, Quantitative studies of marsh foraminiferal distributions in Nova Scotia: implications for sea level studies. *Cushman Foundation for Foraminiferal Research, Special Publication,* 17, 45, pl. 4, Figures 4, 5.

Occurs as a few specimens in a few samples only.