Journal of Coastal Research	11	3	573-582	Fort Lauderdale, Florida	Summer 1995

Accelerated Sea Level Rise 2,000 Years BP in the Delaware Bay: Stratigraphic Evidence from the Leipsic River Valley, Delaware, U.S.A.

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ABSTRACT

JOHN, S.J. and PIZZUTO, J.E., 1995. Accelerated sea level rise 2,000 years BP in the Delaware Bay: Stratigraphic evidence from the Leipsic River Valley, Delaware, U.S.A. *Journal of Coastal Research*, 11(3), 573-582. Fort Lauderdale (Florida), ISSN 0749-0208.

Radiocarbon dating, diatom analyses, and lithologic data from over 50 cores are used to reconstruct the Holocene depositional history of the Leipsic River Valley. Facies sampled in the cores include sand and muddy sand, peat, and olive gray mud. These facies were deposited in river channels and floodplains, tidal wetlands, and broad tidal streams or estuaries. The Holocene estuarine environment of the Leipsic River Valley may have been similar to the modern estuarine environments of drowned tributary valleys of Delaware's Inland Bays.

An estuary or broad tidal stream occupied the valley of the Leipsic River 3620 years BP. By 2300 years BP, emergent tidal wetlands filled the valley. About 2000 years BP, an estuary (or broad tidal stream) once again occupied the valley, drowning the pre-existing emergent tidal wetlands. By 900 years BP, the valley of the Leipsic River was again filled with tidal wetland facies.

The dramatic transgression which drowned the Leipsic River Valley 2000 years BP has also been observed in two other valley fill deposits of the Delaware Bay. Because other factors are unlikely to have caused these widely separated but synchronous transgressive facies changes, the rate of local relative sea-level rise probably increased 2000 years ago in the Delaware Bay.

ADDITIONAL INDEX WORDS: *Holocene sediments, estuarine deposits, tidal wetlands, tidal stream, transgression.*

INTRODUCTION

Several Holocene sea-level curves from the U.S. Atlantic Coast document gradually decreasing rates of sea-level rise throughout the Holocene (Belknap and Kraft, 1977; Finkelstein and Ferland, 1987; Newman and Rusnak, 1965; Stuiver and Daddario, 1963; van de Plassche, 1990; van de Plassche *et al.*, 1989). Other, more recent studies indicate a more varied Holocene sea-level history which often includes dramatic fluctuations in the rate of Holocene sea-level rise. For example, Thomas and Varekamp (1991), Varekamp *et al.* (1992), and van de Plassche (1991) utilize a variety of techniques, including geochemical indicators, the distribution of fossil foraminifera, and stratigraphic data to postulate a punctuated sea-level history recorded in tidal wetland deposits of the Connecticut coast. In the southeastern U.S., a mid-Holocene high sea-level stand has been proposed by Colquhoun and Brooks (1986), Deprater and Howard (1981), and Gayes *et al.* (1992). Fletcher *et al.* (1993a) and Meyerson (1972) suggest fluctuations in the rate of sea-level rise based on studies of Holocene wetland deposits of Delaware Bay.

In this paper, we describe abrupt transgressive facies changes recorded in the tidal wetland deposits of the Leipsic River, a tributary of the Delaware Bay. Although such facies changes may be caused by many processes unrelated to regional sea-level changes, the discovery of temporally correlative transgressive facies changes at two other Delaware Bay marshes suggests that the rate of sea-level rise may have increased rapidly 2000 years ago in the Delaware Bay.

STUDY AREA

The study area is located along the Leipsic River and the Alston Branch in Kent County, Delaware in the Atlantic Coastal Plain and Continental Shelf Province (Figures 1 and 2) (Kraft *et al.*, 1976). Sediments of this region consist of a seaward thickening wedge of Cenozoic and Me-

94136 received and accepted in revision 13 July 1994.

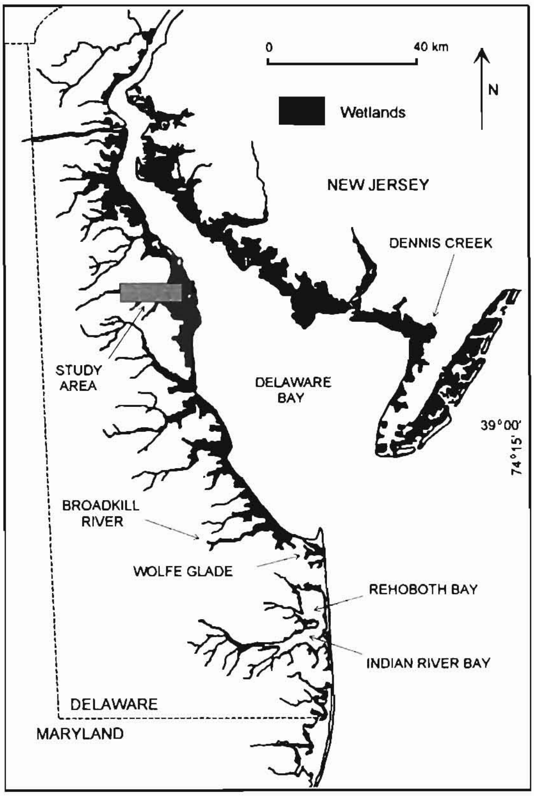

Figure 1. Location of the study area along the Leipsic River. Other areas mentioned in the text are also indicated.

sozoic deposits which are overlain by the Pleistocene Columbia Formation (PICKETT, 1976). Low stands of sea-level during the Quaternary Period caused coastal plain streams to erode into preexisting deposits, forming deeply incised valleys (BELKNAP and KRAFT, 1977; RICHTER, 1974). These valleys have been filled with sediment as sea-level has risen during the Holocene (FLETCHER *et al.*, 1990).

METHODS

In order to document the sedimentary record of the ongoing Holocene transgression into the coastal plain valleys of central Delaware, coring sites were selected along the valley of the Leipsic River and the Alston Branch (Figure 2). The modern environments sampled at these sites range from fluvial channels, floodplains, and backswamps at the uppermost transect of the Alston Branch to tidal streams and salt marshes in the lower reaches of the Leipsic River. Modern environments of the study area are discussed in detail by JOHN and PIZZUTO (1993). Transitional environments, such as brackish forested and emergent tidal wetlands, were sampled at intermediate positions within the valley. Thus, the coring locations were selected to represent the full range of modern sedimentary environments of the Leipsic River Valley and the Alston Branch. These modern environments provide models for inter-

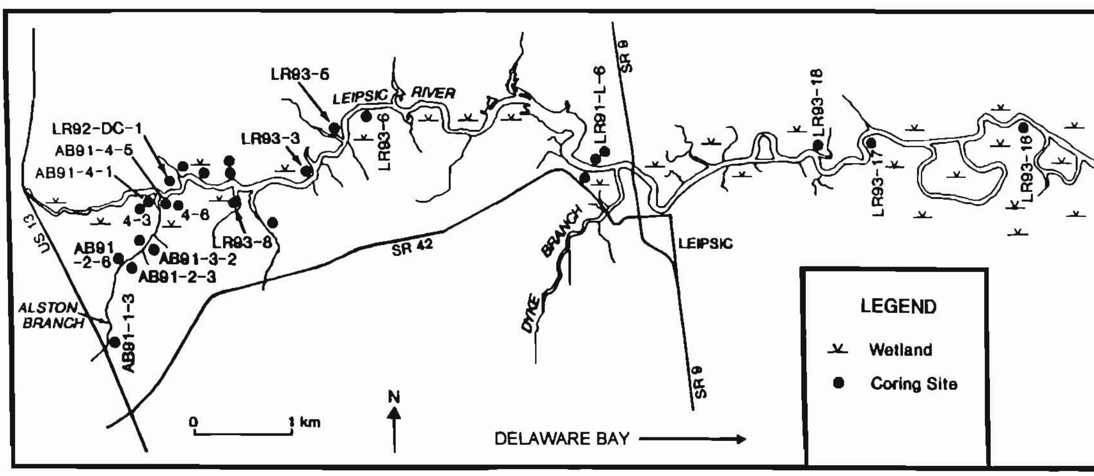

Figure 2. Detailed map of the study area showing the locations of cores discussed in the text. Some of the cores from the Alston Branch are not indicated here; locations for these cores are presented by JOHN and PIZZUTO (1993). The complete numbers for cores 4-3 and 4-6 are AB91-4-3 and AB91-4-6.

Table 1. *Radiocarbon dates from selected samples.*

Sample No.	C^{14} Age (years B.P.)	Calibrated Age[a] (sidereal year B.P.)
AB91-2-6-18-22	2370 ± 90	2368 (2333–2496)[b]
AB91-3-2-250-252	1880 ± 100	1838 (1720–1930)
AB91-4-1-405-409	2480 ± 80	2629 (2384–2470)
AB91-4-3-495-500	3490 ± 80	3764 (3669–3875)
AB91-4-6-202-208	880 ± 80	783 (712–916)
AB91-4-6-369-374	2010 ± 70	1969 (1891–2060)
LR91-L-6-78-85	2190 ± 80	2177 (2089–2329)
LR91-L-6-470-480	2260 ± 130	2324 (2119–2379)
LR91-L-6-795-800	3620 ± 100	3936 (3839–4099)

[a]Based on a 20-year atmospheric calibration curve (File 2—ATM20.14C of STUIVER and REIMER (1987)) and a 100 year sample age range

[b]One standard deviation range

preting Holocene sedimentary facies sampled in cores.

Fifty five cores were obtained using an Eijkelkamp gouge auger. The auger consists of a 1 meter long, half cylindrical blade with a diameter of 2.5 cm, along with 1 m long extension rods. The cores were initially described in the field. At selected locations, cores were taken again using a 5 cm diameter coring blade. These cores (in 1 m sections) were wrapped in plastic and aluminum foil, placed in split PVC pipe, and transported back to the laboratory for detailed description and sampling.

In describing sedimentary textures, we have followed the classification of FOLK (1974) for inorganic sediments. For organic sediments, terminology similar to that of KOSTERS (1989) was adopted. Thus, the term *true peat* is used for sediments with greater than 75% organic matter, while the term *peat* refers to sediments with greater than 35% organic matter but less than 75% organic matter. The colors of the various facies were defined using the GSA Rock Color Chart (GEOLOGICAL SOCIETY OF AMERICA, 1991).

Aerial photos were used to determine the locations of the coring sites. At the Alston Branch, the relative elevations of the cores at each cross-section of the valley were determined using a hand-level, stadia rod, and tape. The absolute elevations of these cores, relative to the National Geodetic Vertical Datum of 1929 (NGVD 1929), was determined using 1:600 scale topographic maps obtained from the Delaware Department of Transportation. The local relationships between NGVD 1929 and mean water level were obtained from the National Oceanic and Atmosperic Administration (NOAA, 1990). [These methods are discussed in greater detail by PIZZUTO and ROGERS (1992) and JOHN and PIZZUTO (1993)].

In the valley of the Leipsic River, the greater distances between cores and the lack of detailed topographic maps required a different method for determining the elevations of the coring sites. In brackish wetlands, the marsh surface was assumed to approximate mean high water (ODUM *et al.*, 1984). In salt marshes dominated by *Spartina alterniflora* the marsh surface was assumed to lie halfway between mean high water and mean sea level (NIERING and WARREN, 1980; VAN DE PLASSCHE, 1991). In the study area this corresponds to an elevation of 0.3 m above mean sea level (NOAA, 1990). Because the topography of salt marshes is irregular (OERTEL *et al.*, 1989), this method could cause errors of several decimeters in relating the elevation of a particular site to mean sea-level.

Selected samples of peat and wood fragments were sent to Beta Analytic Inc. for radiocarbon dates. All radiocarbon dates were converted to sidereal years using methods described by STUIVER and REIMER (1987) (calibration methods are discussed in Table 1). The carbon content of selected samples was approximated by loss-on-ignition (LOI) analysis (BALL, 1964). Diatoms were identified by the Philadelphia Academy of Natural Sciences (SHERMAN, unpublished data as presented by JOHN and PIZZUTO, 1993), using qualitative methods similar to those described by FLETCHER *et al.* (1993b).

RESULTS

The Holocene sediments of the study area consist of three major lithologic units: sand, peat, and mud (Figures 3 and 4). Holocene sediments are underlain by the Miocene Calvert Formation (PICKETT and BENSON, 1983), which consists of olive gray (5Y 4/1) to light bluish gray (5B 7/1) dense medium to coarse sand with scattered highly weathered pebbles and granules.

The basal unit of the the Holocene section consists of fluvial sand and muddy sand. Mud laminations are frequently encountered along with scattered wood fragments, granules and pebbles. In some cores, the fluvial sand and muddy sand is overlain by mud with root casts, scattered rust-colored mottles, and little preserved organic material. This mud is probably a fluvial overbank deposit (the stratigraphic occurrence of the fluvial overbank deposits, though not defined here, is

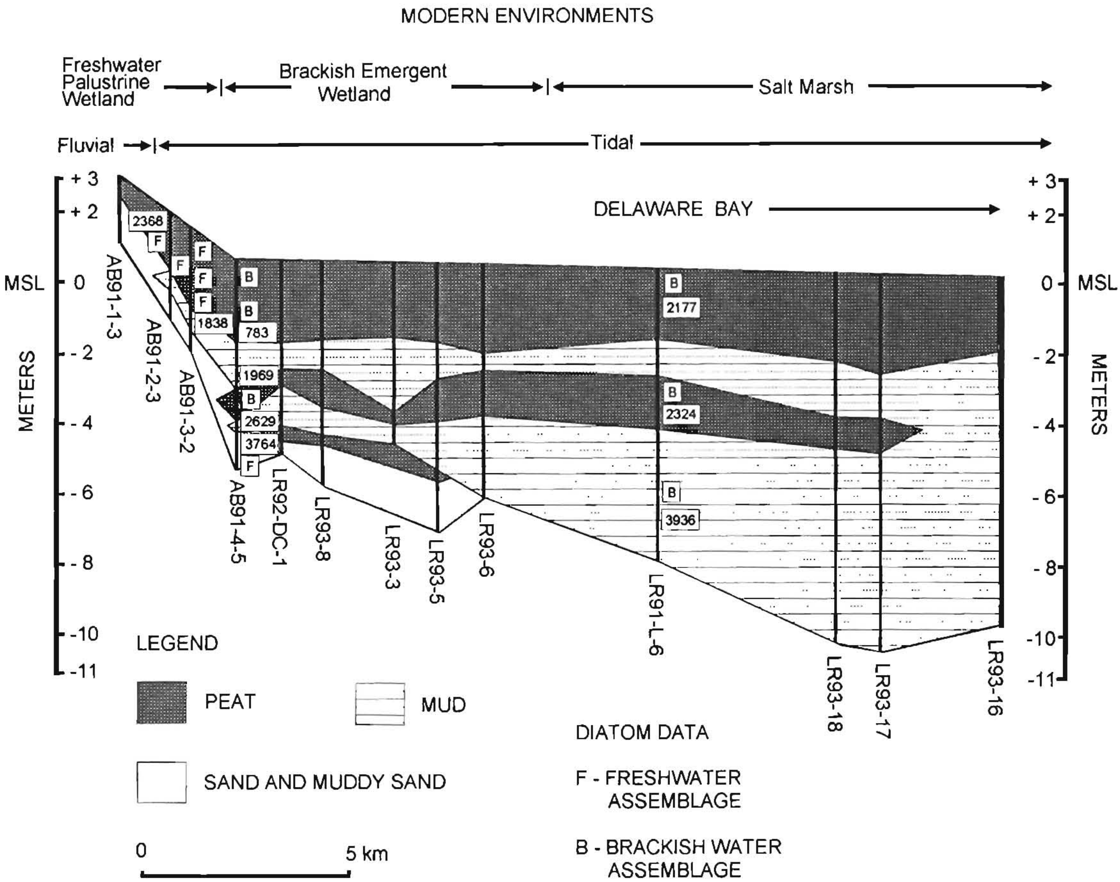

Figure 3. Longitudinal cross-section of the Alston Branch and the Leipsic River showing the distribution of Holocene deposits, diatom data, calibrated radiocarbon dates, and characteristics of the modern environments of the study area. The locations of the cores are presented in Figure 2. Modern environments were defined using field observations and maps of the National Wetlands Inventory (COWARDIN *et al.*, 1979; TINER, 1985).

discussed in greater detail by JOHN and PIZZUTO, 1993).

A peat facies is commonly found in a variety of stratigraphic settings overlying fluvial sands and muds. This facies is highly variable. It consists of partially decomposed roots, stems, leaves, wood fragments, and rhizomes mixed with varying amounts of inorganic matter. Locally the peat facies consists of true peat, while elsewhere it is an organic-rich mud. Colors commonly encountered include dusky yellowish brown (10YR 2/2), dark yellowish brown (10YR 4/2), olive gray (5Y 4/1) and black (N1). LOI values from the peat facies of the Alston Branch range from 30% to 84% with a mean value of 55%. Diatom analyses indicate that the peat facies of the Alston Branch was deposited in fresh to brackish water, with the freshwater deposits lying in stratigraphically lower and also more landward settings than the brackish deposits (Figure 3) (Table 2). In the Leipsic River Valley (core LR91-L-6, Figure 3), diatoms indicate a brackish depositional environment. The peat facies observed in the cores closer to the modern Delaware Bay (LR91-L-6, LR93-18, LR93-17, LR93-16) represent the modern *Spartina alterniflora* salt marsh.

An olive gray (5Y 4/1) mud facies underlies the modern wetland peat facies in most of the study area (Figures 3 and 4). The olive gray mud facies consists of a dense, often laminated or bedded

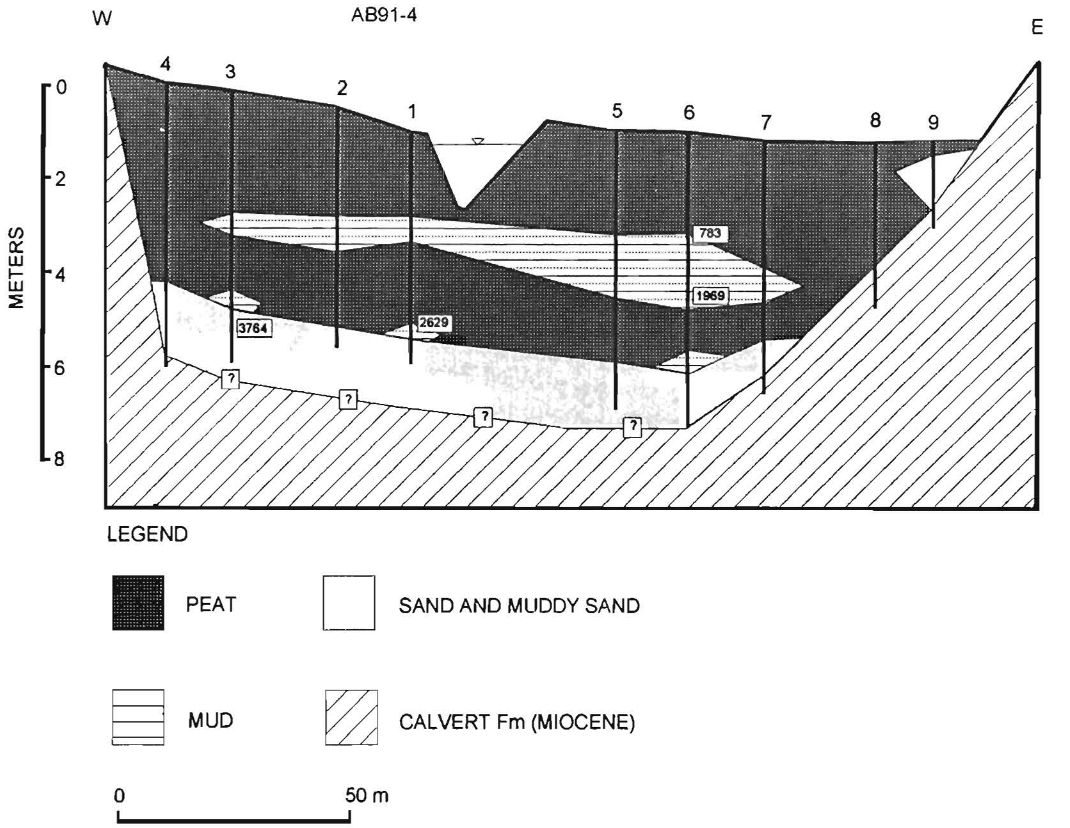

Figure 4. Cross-section of the mouth of the Alston Branch. The locations of cores AB91-4-3 and AB91-4-6 (indicated here simply as 3 and 6) are indicated in Figure 2.

mud with varying amounts of organic matter. LOI analyses indicate a drastic decrease in combustible organic matter as compared with the peat facies (Figure 5). Furthermore, fossil diatoms indicate that this olive gray mud was deposited in a brackish depositional environment (Figure 3) in most of the study area. In the Alston Branch, the most landward part of the olive gray mud facies was deposited in fresh water (Figure 3). Here, the olive gray mud facies directly overlies the fluvial sand and muddy sand facies.

Table 2. *Indicator diatoms identified in core samples (complete descriptions of the diatoms identified in each sample are presented by* JOHN *and* PIZZUTO *(1993)).*

Freshwater	Brackish Water
Fragilaria sp.	*Coscindiscus* sp.
Gomphonema sp.	*Rhopododia* sp.
Eunotia sp.	*Melosira* sp.
Amphora sp.	*Achnanthes* sp.
Cyclotella sp.	
Epithemia sp.	

In the lower Alston Branch and also in the Leipsic River valley, the olive gray mud facies is split into upper and lower units by a tongue of the peat facies. Near the town of Leipsic (cores LR93-5, LR93-6, LR91-L-6), the uppermost of the two mud units (Figures 2 and 3) increases slightly in organic content. The olive gray mud facies typically extends across most of the valley when viewed in cross-section (Figure 4).

The basal contact of the upper unit of the olive gray mud facies is important for interpreting both the depositional environment of this facies as well as the sea-level history which it implies. This contact is abrupt in places and gradational in others. However, vertical plant stems were observed in several cores, indicating that the basal contact is not erosional.

Radiocarbon Dates

The results of nine radiocarbon analyses from peat and mud samples are presented in Table 1. The calibrated ages range from 3936 to 783 sidereal years BP. Locations of the dated horizons and the corresponding ages are illustrated in Figures 3 and 4.

The radiocarbon dates indicate that the olive gray mud facies was being deposited at core LR91-L-6 by 3620 BP. By 2480 BP, this same facies was being deposited at the mouth of the Alston Branch. A regressive facies change is recorded by the expansion of the peat facies at 2260 BP (Figure 3). This regression, of course, need not be caused by a sea-level change, but could be related to a variety of other factors including an increase in sediment supply, a change in the hydrologic input from the upland, *etc.* Around 2000 years BP, a transgressive facies change occurred as the peat facies was buried by the renewed landward expansion of the olive gray mud facies. By 900 years BP, a regressive peat facies had again expanded seaward.

DISCUSSION

The data presented above indicate that a variety of environments have characterized the study area during the last 4000 years or so. The sand and muddy sand facies represents fluvial environments and the peat facies represent both freshwater and estuarine tidal wetland environments (Pizzuto and Rogers, 1992). The olive gray mud facies has been described elsewhere along the Delaware coast (Belknap and Kraft, 1977; Chrzastowski, 1986; Fletcher *et al.*, 1993b; Stedman, 1990; Yi, 1992). It has been interpreted as a subtidal facies representing deposition in a tidal stream, lagoon, or estuary. The lithology of the unit defined here, in addition to the presence of brackish diatoms, suggests that this interpretation is also a reasonable one for the olive gray mud facies of the Leipsic River Valley.

Figure 3 indicates that the olive gray mud facies may be divided into a lower part and an upper part. These parts are separated by a regressive peat deposit. Because we have collected detailed data from the upper part, we are able to interpret the geomorphic setting in which it was deposited in addition to potential changes in sea-level which it may represent.

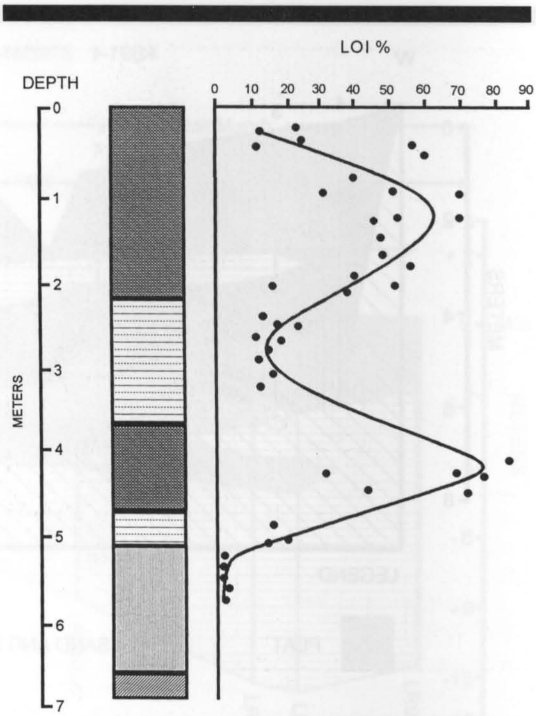

Figure 5. Loss-on-ignition (LOI) results for cores from the Alston Branch. The curve is fitted by eye. Definitions of lithologic symbols are presented in Figures 3 and 4. The core illustrated here is schematic; the data were actually obtained from several cores, all of which contained all of the stratigraphic units illustrated here. Because the thickness of each sedimentary unit varies from core to core, the sample locations plotted here were determined with reference to the thickness of the particular unit where the sample was obtained, rather than the distance from the top of the core.

The geomorphic setting in which the upper olive gray mud was deposited may be inferred from its environment of deposition, its geographic extent, and its conformable lower contact. The upper part of the olive gray mud extends across most of the valley of the Leipsic River and the Alston Branch. Because the lower contact of the unit is not erosional, it is unlikely that the preserved lateral extent of the olive gray mud facies is due to migrating tidal streams. This suggests that the olive gray mud was deposited in a wide tidal river or an arm of the Delaware Bay which once extended up into the valley of the Leipsic River. This interpretation is consistent with paleoenvironmental reconstructions proposed by Stedman (1990) for the Holocene valley fill of the Broadkill River (Figure 1).

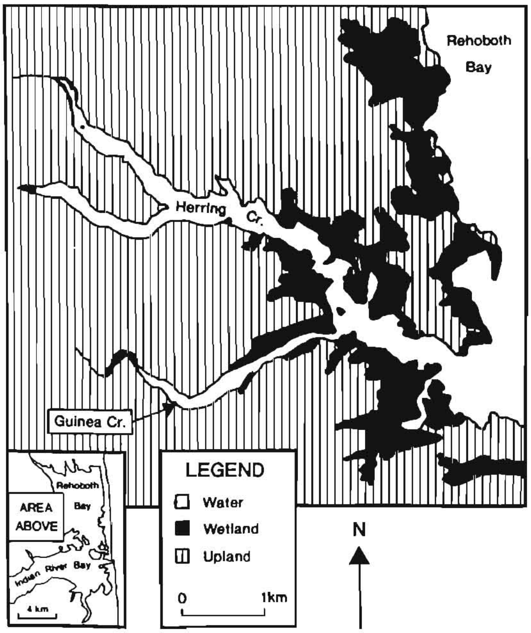

Figure 6. Modern environments of Herring and Guinea Creeks and part of Rehoboth Bay.

A potential modern geomorphic analogue for the depositional environment of the upper part of the olive gray mud facies may be found in the drowned tributary valleys of Indian River and Rehoboth Bays of the Delaware Atlantic Coast (Figure 6). These drowned tributary valleys are landward extensions of the Indian River and Rehoboth Bays (referred to below as the Inland Bays), and they represent small estuaries which broaden into the Inland Bays. Salt marshes and other emergent tidal wetlands often border these small estuaries (Figure 6). In the geologic record, deposits of these fringing wetlands are preserved as organic-rich muds or peats which encase the mud facies deposited in the axis of the valley (CHRZASTOWSKI, 1986; FLETCHER *et al.*, 1993b; STEDMAN, 1990), similar to the facies illustrated in the cross-section of Figure 4. The muds deposited in the center of these small estuaries are qualitatively similar to the olive gray mud facies of the Leipsic River, according to descriptions of many vibracores obtained by CHRZASTOWSKI (1986). Thus, when the upper olive gray mud facies was being deposited in the Leipsic River valley, the valley probably looked like the modern drowned tributary valleys of Delaware's Inland Bays.

Implications for Sea-level History

The peat facies that splits the olive gray mud facies into two parts represent a regressive phase in the history of the Leipsic River valley about 2300 years BP. Conversely, the burial of the peat deposits by the overlying muds represent a dramatic transgression which occurred about 2000 years BP.

Similar transgressions and regressions have been described from other valley fills of the Delaware Bay coast (ALLEN, 1978; FLETCHER *et al.*, 1993b; MEYERSON, 1972; YI, 1992). Furthermore, FLETCHER *et al.* (1993a) demonstrate that the transgressive facies transition represented by the base of the upper part of the olive gray mud facies is coeval with similar transgressions observed in deposits of Wolfe Glade (FLETCHER *et al.*, 1993b) and the Dennis Creek Marsh (Figure 1) (MEYERSON, 1972), both located nearly 100 km from the Leipsic River Valley. Thus, the transgression which drowned the Leipsic River Valley about 2000 years B.P. also drowned the valleys of Wolfe Glade and Dennis Creek.

Transgressive facies transitions in valley fill deposits may be caused by a variety of different processes including laterally migrating tidal stream channels, a decrease in sediment supply, autocompaction, short-term (10^2 yr) increases in the rate of regional subsidence, and increases in the rate of local relative sea-level rise. All of these factors should be explicitly considered when interpreting the synchronous transgressions observed in the valleys of Leipsic River, Wolfe Glade, and Dennis Creek.

Laterally migrating tidal streams could cause an apparent transgression by superimposing tidal channel facies over tidal wetland facies. However, such a facies change would be separated by an erosional contact. The contacts observed at the Leipsic River appear to be gradational, with preserved vertical stems and roots further suggesting a conformable contact. In addition, rates of lateral migration of modern (GAROFALO, 1980) and Holocene (CHRZASTOWSKI, 1986) tidal streams have been very low, and it is unlikely that such slowly migrating streams could have produced an extensive erosional surface. Finally, migrating tidal streams should not produce regionally synchronous facies boundaries.

A regional reduction in the sediment supply to the tidal system could cause a transgressive facies change. The marsh accretes vertically by storing peat and by capturing sediment transported during tidal inundation. Thus the long-term stability of the marsh system is determined by the relative rates of both sediment accretion and sea-level rise (MITSCH and GOSSELINK, 1986). In the event of a decrease in sediment supply, the marsh surface could be drowned by a steadily rising sea level. However, coastal plain tributaries to the Delaware Bay carry very little sediment (MANSUE and COMMINGS, 1974), and it is unlikely that changes in local sediment supply could create regionally synchronous abrupt transgressive facies changes. In addition, PHILLIPS (1991) argues that coastal plain estuaries are strongly insulated from changes in sediment yields in their watersheds because most sediment is trapped in the headwaters of the estuary. Thus, changes in regional sediment yield in the watershed of the Delaware River would probably not cause abrupt synchronous drowning of wetlands throughout the Delaware Bay.

Autocompaction (KAYE and BARGHOORN, 1964; BLOOM, 1964; ALLEN, 1978) and regional subsidence (DAVIS, 1987; FLETCHER, 1988) can certainly affect the local relative rates of sea-level rise and marsh accretion. However, it seems unlikely that the same rates of autocompaction would occur regionally, affecting sedimentary units of varying lithology and thickness in different tributaries at the same time. Regional subsidence can be discounted on the basis that it operates on longer time scales than those considered here.

Having shown other causes to be unlikely, the remaining explanation for the synchronous drowning of three river valleys of the Delaware Bay 2000 years ago is a regional increase in the rate of sea-level rise. The increase in the rate of sea-level rise may have been rather small; a change in the rate of sea-level rise of as little as a millimeter or two per year can determine if the marsh will survive or drown (MITSCH and GOSSELINK, 1986).

CONCLUSIONS

Deposits of the Leipsic River Valley consist of sand and muddy sand, peat, and olive gray mud. These facies were deposited in river channels and floodplains, tidal wetlands, and broad tidal streams or estuaries. The Holocene estuarine (or broad tidal stream) environment of the Leipsic River Valley may have been similar to the estuarine environments of drowned tributary valleys of Indian River and Rehoboth Bays.

Radiocarbon dates demonstrate that estuarine conditions prevailed in the Leipsic River Valley at 3620 years BP. A regression filled the valley with emergent tidal wetlands at 2300 years BP. At 2000 years BP, a dramatic transgression occurred, causing the pre-existing tidal wetlands to be drowned by an expanding estuary or broad tidal stream. By about 900 years BP, the valley of the Leipsic River was again filled with regressive tidal wetland facies.

Transgressions and regressions may be caused by many different factors, and, therefore, the repeated transgressions and regressions of the Leipsic River Valley cannot simply be interpreted in terms of sea-level history. However, the transgression that occurred 2000 years ago has also been noted in deposits of Wolfe Glade and the Dennis Creek Marsh, both located over 100 km from the Leipsic River. Because it is unlikely that other factors could have caused these synchronous transgressions, the rate of local relative sea-level rise probably increased 2000 years ago in the Delaware Bay.

ACKNOWLEDGEMENTS

The research described in this paper was partially supported by the University of Delaware Center for Archeological Research and the Delaware Department of Transportation. Financial arrangements were facilitated by Joseph Wutka, Kevin Cunningham, and Jay Custer. Monica Tsang and Axel Schwendt assisted in the field. We thank Johan C. Varekamp and two anonymous reviewers for their critical comments on the original manuscript.

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