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The Holocene History and Stratigraphy of Palustrine and Estuarine Wetland Deposits of Central Delaware

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ABSTRACT

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Unsaturated floodplains and riverine, estuarine, and palustrine wetlands of coastal plain river valleys of central Delaware have mean loss-on-ignition (LOI) values of 2–9%, 9–13%, 17–21%, and 43–46%, respectively. These distinctive LOI signatures are used in conjunction with radiocarbon dates and Delaware's local relative sea-level curve to reconstruct the Holocene history of the valleys of the study area. During the early Holocene, the sediment yield of the Delaware coastal plain was too low for rivers to build extensive subaerially exposed floodplains. Instead, organic-rich muds and peat accumulated in perennially inundated, non-tidal palustrine wetlands. These environments existed as long ago as 11,000 YBP, well before any possible influence of sea-level rise. The elevation of these deposits and Delaware's sea-level history suggest that tidal influence began 1,000–2,000 years ago. The transition from fluvial to estuarine conditions occurs without any lithologic change or discontinuity near the top of a uniform palustrine peat. Therefore, the base of the Holocene transgressive sequence is conformable in these valleys, except where lateral migration by tidal streams has subsequently removed the conformable transition. Outside of the valleys, however, the base of the transgressive sequence is a major unconformity. Thus, the transgressive sequence preserved landward of the Delaware Bay coast is bounded at its base by a complex stratigraphic surface which is primarily conformable in valley fills but which is unconformable on paleointerfluves.

ADDITIONAL INDEX WORDS: *Transgressive sedimentary sequences, tidal wetlands, river deposits, coastal stratigraphy, tidal rivers, peat.*

INTRODUCTION

Models of transgressive coastal sedimentary sequences have generally emphasized the deposits of barrier islands, lagoons, and other environments located relatively near the shoreline (KRAFT and CHRZASTOWSKI, 1985; KRAFT *et al.*, 1987). The influence of rising sea level, however, extends from the marine realm to the head of tide in the fluvial system. In many areas, the head of tide is located far from the open coast (ASHLEY and RENWICK, 1983; GIBBS, 1977; HORNE and PATTON, 1989; NICHOLS and BIGGS, 1985). Thus, a transgression is not only recorded in coastal sedimentary environments, but also in deposits of freshwater and brackish tidal rivers (DEMAREST and KRAFT, 1987; KEARNEY and WARD, 1986; STEVENSON *et al.*, 1985). Because tidal rivers deposit sediment near the base of a transgressive sedimentary sequence, these deposits have a high preservation potential (BELKNAP and KRAFT, 1981, 1985; CHRZASTOWSKI, 1986). Thus, the deposits of tidal rivers should be well represented in the geologic record, and they should also preserve a detailed history of changes in sea level.

In this paper, we describe the deposits of four tidal rivers of the Delaware Coastal Plain. Because our study area is located near the head of tide, these deposits record the onset of the Holocene transgression. As a result, we are able to present a detailed stratigraphic model of the transgressive inundation of a coastal plain river valley.

STUDY AREA

Sites were selected along four meandering tidal rivers and one sinuous non-tidal river (Figures 1–4). These rivers flow eastward from central Delaware to Delaware Bay through valleys incised into Tertiary and Pleistocene clastic sediments of the Delaware Coastal Plain. The age of incision of these valleys cannot be determined precisely. However, valley incision must have occurred when tributaries eroded downward to the lowered base level provided by an ancestral Delaware River flowing out onto the continental shelf during one (or more) of the Pleistocene low sea-level stands

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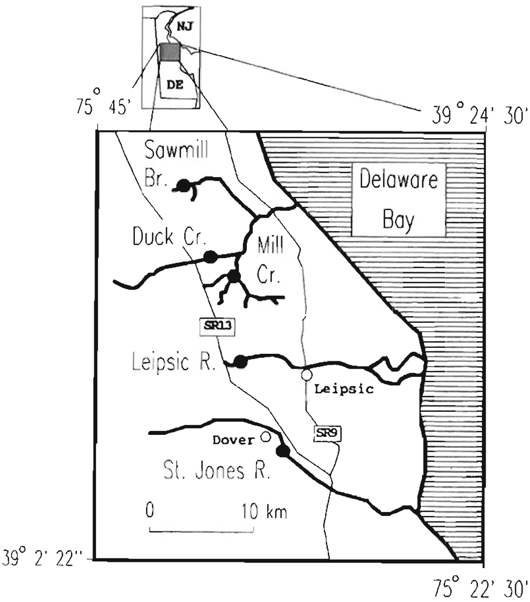

Figure 1. Locations of the five study sites (filled circles).

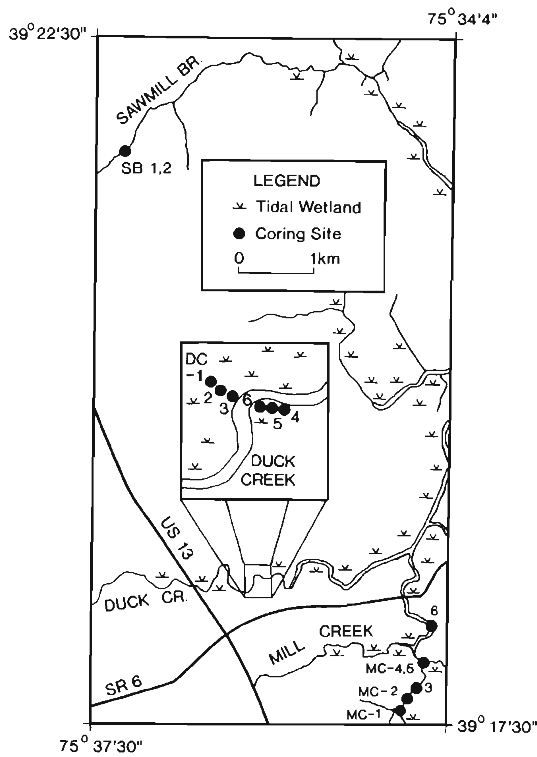

Figure 2. Locations of coring sites along Duck Creek, Mill Creek, and Sawmill Branch.

(FLETCHER *et al.*, 1990; KNEBEL *et al.*, 1988; SHERIDAN *et al.*, 1974).

According to the National Wetlands Inventory (NWI) (COWARDIN *et al.*, 1979; TINER, 1985), the environments of the study area include river channels (termed riverine wetlands by the NWI) and estuarine and palustrine wetlands. Estuarine wetlands of the study area are oligohaline tidal wetlands; they are found at Duck Creek and also at Mill Creek (Figures 1–2). Palustrine wetlands of the study area are freshwater tidal and non-tidal wetlands marginal to river channels. Tidal palustrine wetlands are found at the Leipsic River, the St. Jones River, and at Mill Creek (Figures 1–4). Non-tidal palustrine wetlands are found marginal to the channel of Sawmill Branch (Figure 2). Field surveys indicate that the wetlands of Sawmill Branch are only seasonally or temporarily flooded; thus, these wetlands could also be described as a typical floodplain environment.

Most of the modern and ancient environments described in this paper are saturated tidal or non-tidal wetlands for which the National Wetlands Inventory provides a useful environmental classification scheme. However, the National Wetlands Inventory does not provide a simple means for distinguishing between rarely saturated freshwater wetlands (such as those at Sawmill Branch) and frequently saturated freshwater wetlands. In this paper, freshwater environments marginal to river channels which are occasionally saturated or flooded are referred to as *floodplains,* while the corresponding environments which are frequently or permanently saturated are referred to as *palustrine wetlands.*

The wetland flora of the study area are extremely diverse. Although floral remains are not used here explicitly as stratigraphic tools, typical dominant flora of the palustrine and estuarine wetlands of the study area are presented in Table 1. More complete listings are provided by DAIBER (1976) and TINER (1985).

METHODS

Twenty-eight vibracores were obtained using methods of HOYT and DEMAREST (1981) at Mill Creek (Figures 1 and 2), Duck Creek (Figure 2), the Leipsic River (Figure 3) and the St. Jones River (Figure 4). At Mill Creek, vibracores were supplemented by six piston cores 1 m long and

Table 1. *Dominant wetland flora identified in the study area.*

Wetland Type	Dominant Flora
Non-tidal Palustrine Forested Wetland	*Acer rubrum*
	Fraxinus pennsylvanica
	Alnus serrulata
	Symptocarpus foetidus
Tidal Palustrine Wetland	*Fraxinus pennsylvanica*
	Peltrandra virginica
	Viburnum dentatum
	Alnus serrulata
	Phragmites australis
	Typha sp.
	Amaranthus cannabinus
Tidal Estuarine (oligohaline) Wetland	*Phragmites australis*
	Amaranthus cannabinus
	Scirpus robustus
	Hibiscus moschentos
	Typha sp.
	Peltrandra virginica

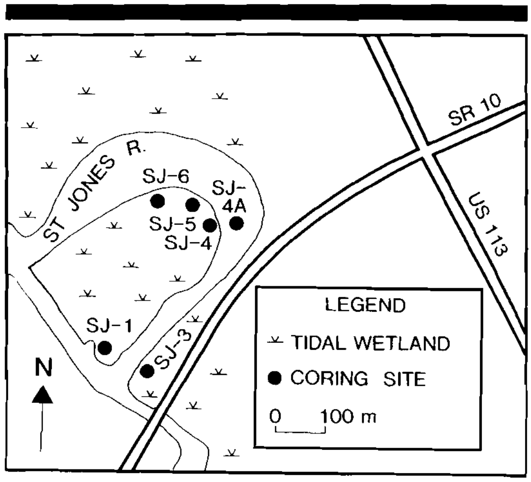

Figure 4. Locations of coring sites along the St. Jones River.

10 cm in diameter. At Duck Creek, 50 surface samples were obtained to characterize the sediment of the modern tidal river channel.

At the Sawmill Branch and the Leipsic River, additional cores were obtained using a hand driven auger. The auger samples 1 m lengths of sediment; each 1 m length was wrapped in plastic and aluminum foil, placed in a 1.2 m length of 5 cm I.D. plastic pipe, and transported to the laboratory for storage and analysis.

The goals of the sampling program differed at different sites. At Duck Creek and the Leipsic River, cores were located to obtain a cross-section of the river valley, and an effort was made to penetrate the complete Holocene section (Figures 2 and 3). Sampling at these sites was designed to elucidate the Holocene history and stratigraphy of transgressive valley fills of the study area.

At Mill Creek, the St. Jones River, and Sawmill Branch, cores were located primarily to sample specific modern depositional environments (Figures 2 and 4). Thus, these cores are shallower than those obtained at Duck Creek and the Leipsic River, and they cannot be used to create complete cross-sections of the Holocene valley fills at these sites.

As a consequence of this sampling scheme, the results presented below primarily focus on the Holocene histories of Duck Creek and the Leipsic River. Data from the other sites are used extensively to better understand modern wetland and floodplain sedimentary facies.

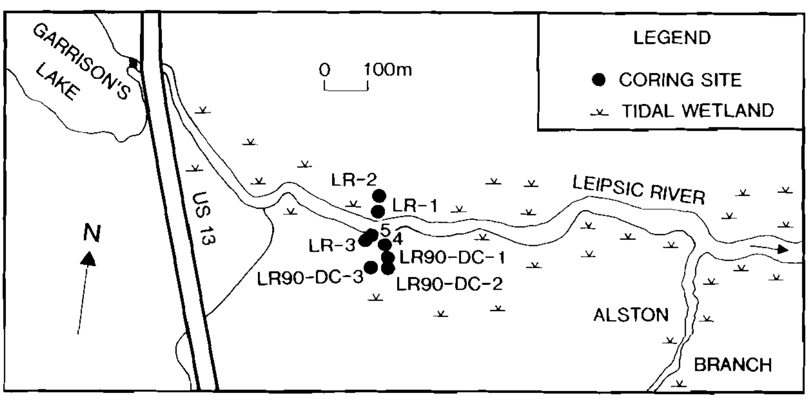

Figure 3. Locations of coring sites along the Leipsic River.

Coring sites were located in the field using 1:600 scale topographic maps (obtained from the Delaware Department of Transportation), aerial photographs, and 1:24,000 scale topographic maps. Because of the difficulty of surveying in these wetland environments, the elevations of coring sites were not determined directly. However, 1:600 scale topographic maps with a 30 m (1 foot) contour interval are available for sites at Duck Creek, the Leipsic River, and the St. Jones River. These topographic maps also present surveyed elevations in the wetlands to within 3 cm (0.1 foot). According to these maps, the wetland surface varies in elevation from 0.30 m to about 0.90 m (Natural Geodetic Vertical Datum, 1929). The nearest tide gauge, located at the town of Leipsic just downstream of the Leipsic River site (Figure 1), has a mean tidal range of 1.1 m (NOAA, 1990), and the mean water level is equivalent to 0.01 m (National Geodetic Vertical Datum, 1929). Thus, the marsh surface varies from about 0.35 m above mean high water (at the town of Leipsic) to about 0.25 m below mean high water. Accordingly, we have assumed that the elevations of coring sites on the marsh surface are approximately equal to mean high water. Mean low water is assumed to lie approximately 1.1 m below the marsh surface. This approach is consistent with results presented in other studies of brackish tidal wetlands (ODUM *et al.*, 1984).

Hand-driven cores were described in the field, and then another core was immediately obtained at the same site and preserved for laboratory analyses as described above. Vibracores and piston cores were returned to the laboratory, split, described, and photographed. Selected samples of peat and some wood fragments were sent to Beta Analytic, Inc. for radiocarbon dates. All dates were calibrated using methods described by STUIVER and REIMER (1987) and PEARSON *et al.* (1986). The carbon content of the sediments was approximated by the results of over 500 loss-on-ignition (LOI) analyses BALL (1964). To determine the LOI, samples were dried overnight at 100 °C, and subsequently ashed at 375 °C for 16–24 hours. Complete pollen analyses of several cores were completed by BRUSH (1989). Only sedimentation rates reported by BRUSH (1989) are included here because the full pollen data were not useful in identifying local sedimentary environments.

The sediments of the study area consist of mixtures of gravel, sand, mud, and organic material. Because terms for describing these mixtures have not been standardized, a classification scheme was developed for this study by combining the classification of FOLK (1974) for mixtures of sand and mud with an additional classification for organic-rich sediment. FOLK's (1974) terms are used for mixtures of sand and mud, while sediments with organic contents greater than 18% are termed *peat*. This usage of the term peat coincides with the term 'organic-rich soil' defined by the U.S. SOIL CONSERVATION SERVICE (1975). Thus, the peats described below are not typical 'true peats' as defined, for example, by KOSTERS (1989), but are sediments with considerably lower organic contents than 'true peats'.

We did not actually measure the percentage of organic carbon when classifying sediments. Rather, we measured the LOI. Because BALL (1964) suggests LOI values are typically two times higher than the percentage of organic carbon, the boundary between peat and clastic sediments suggested by our classification corresponds to a LOI value of about 35%.

DETERMINATION OF PALEOENVIRONMENTS

Qualitative observations of the cores did not provide an adequate means for distinguishing wetland environments because the lithologies in each environment are not unique and also because diagnostic sedimentary structures are often not present. However, LOI analyses from modern floodplain, riverine, estuarine, and palustrine environments, although individually highly variable, apparently tend to cluster into distinct groups (Figure 5). Sediments from floodplains tend to have the lowest LOI values, while mean LOI values apparently increase as one samples riverine, estuarine, and palustrine wetlands (Figure 5). These results initially suggested to us that LOI analyses could provide a useful stratigraphic tool for identifying paleoenvironments in cores (similar methods have also been used by JONES and CAMERON (1988) and WHIGHAM and SIMPSON (1976) to discriminate between high and low salt marshes).

The qualitative impressions presented above regarding the environmental groupings of LOI values require verification using statistical methods because of the high variability of LOI values within any particular environment and also because of the substantial overlap in LOI values between environments. Analysis of Variance

(ANOVA) was used to perform these statistical tests. However, the appropriate methods for applying ANOVA to the data illustrated in Figure 5 are not immediately obvious. ANOVA formally requires all populations to be normally distributed with equal variance; these conditions clearly do not precisely apply to the LOI distributions of Figure 5.

We adopted the following approach to circumvent these problems. We first applied ANOVA to the distributions without transformation (*i.e.*, as they are illustrated in Figure 5). Because it is necessary to be able to distinguish each population from all other populations, the populations were tested in pairs (for example, ANOVA was applied to determine if the population of floodplain LOI values was statistically distinct from the riverine LOI values. Then, another test was conducted to determine if the floodplain LOI values were statistically distinct from the estuarine LOI values, and so on). The four environments produce six independent pairs, each of which was tested using ANOVA.

Because the approach described above does not fully satisfy the assumptions formally required by the ANOVA method, we also analyzed the data in three additional ways. First, we repeated the method described above using log-transformed LOI values. This approach tended to normalize the skewed floodplain, riverine, and estuarine populations, thereby better satisfying the requirement of a normal distribution. Second, we also used a non-parametric test, the Mann-Whitney test, which requires no assumptions about the shapes of the distributions (although it does require that the distributions be of approximately the same form) (RYAN *et al.*, 1985). The Mann-Whitney test was applied to both the linear and the log-transformed data. Finally, ANOVA was also applied to all populations simultaneously. This method indicated that at least one of the LOI populations was different from the others. Then, Fisher's Least Significant Difference test (DOWDY and WEARDEN, 1983) was used to determine which, if any, of the population means were statistically distinct. This approach was also applied to both the linear and the log-transformed data.

Fortunately, all of these different methods yielded identical results: the mean LOI values for the four environments are statistically distinct (at the 95% confidence level). These results are summarized in the ANOVA table for log-transformed

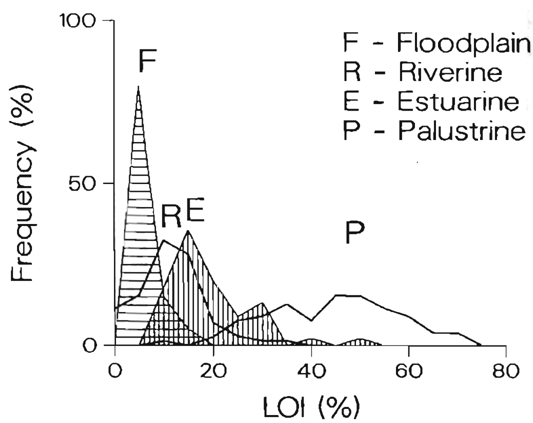

Figure 5. Distributions of LOI values from modern floodplain, riverine, estuarine, and palustrine environments.

data presented in Table 2, and, perhaps more concretely, by the 95% confidence intervals for the mean LOI values presented in Table 3 (the latter are for non-transformed data). These statistical tests demonstrate that LOI values may be used to distinguish between floodplain, riverine, estuarine, and palustrine environments (at least in the study area).

The results presented above were used to determine the paleoenvironments of Duck Creek and the Leipsic River in the following way. First, each core was divided into distinctive lithologic units. Then, these units were correlated between the cores to create lithologic cross-sections of the valley. Finally, LOI analyses were used to assign paleoenvironments to each lithologic unit by comparing LOI values for subsurface units with the LOI values of modern wetland environments. These comparisons were made using simple ANOVA. The environment of deposition of a subsurface unit was determined when its mean LOI value was statistically indistinguishable (at the 95% level) from the mean LOI value of a particular modern environment.

The method described above was applied to all the lithologic units sampled in the cores except for basal sand deposits which underlie peat. These basal sands have very low organic contents and several analyses confirmed that they also have very low LOI values. Furthermore, evidence presented below will demonstrate that the overlying peats were deposited in non-tidal freshwater wetlands. Because of their texture and stratigraphic

Table 2. *ANOVA table for log-transformed LOI data.*

Environments Compared	Source of Variation	Degrees of Freedom	Sum of Squares	Mean Squares	F Statistic	P[a]
Estuarine	Factor	1	11.593	11.593	24.26	0.000
Riverine	Error	112	53.529	0.478		
	Total	113	65.122			
Estuarine	Factor	1	21.902	21.902	172.20	0.000
Palustrine	Error	121	15.390	0.127		
	Total	122	37.292			
Estuarine	Factor	1	22.860	22.860	142.06	0.000
Floodplain	Error	63	10.138	0.161		
	Total	64	32.998			
Riverine	Factor	1	85.536	85.536	220.80	0.000
Palustrine	Error	147	56.171	0.387		
	Total	148	141.707			
Riverine	Factor	1	6.203	6.203	10.60	0.002
Floodplain	Error	87	50.919	0.585		
	Total	88	57.122			
Palustrine	Factor	1	74.337	74.337	558.42	0.000
Floodplain	Error	96	12.780	0.133		
	Total	97	87.117			

[a] Probability that the two population means are the same

position, the basal sands are interpreted as non-tidal fluvial channel deposits.

RESULTS

Six cores were obtained at Duck Creek (Figure 6). These cores consist of mud, peat, and sand. Sand is only found at the base of the cores, and it is only present in four of the six cores (Figure 6). Generally, these sand units are massive, although in core DC1 one set of tabular cross-beds approximately 10 cm thick was observed. A layer of peat overlies the sand on the north side of the

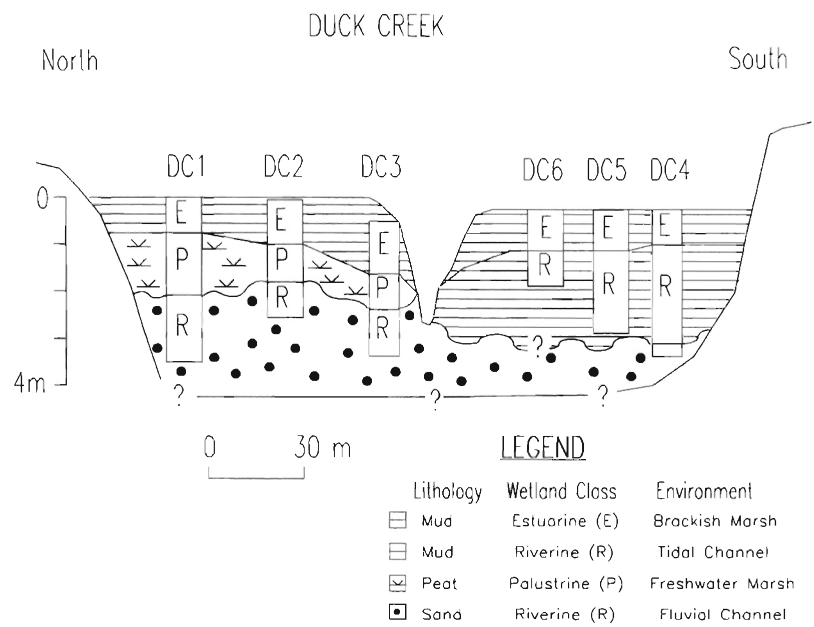

Figure 6. Cross-section of Duck Creek.

Table 3. *Mean values and 95% confidence intervals of LOI analyses from floodplain, riverine, estuarine, and palustrine environments (based on pooled standard deviation of untransformed data).*

Environment	Number of Samples	Mean (%)	95% C.I.
Floodplain	20	5.4	1.8–8.9
Riverine	71	11.2	9.3–13.1
Estuarine	45	18.9	16.5–21.3
Palustrine	78	44.3	42.5–46.1

Note: The pooled standard deviation is 9.62%

valley. In core DC1, a sample from the base of this peat unit yielded a radiocarbon date of 11,480 ± 150 YBP (Figure 7). On the south side of the valley, the peat layer is absent. It has either been removed by lateral migration of a meander bend (Figure 2), or else the peat was never present here. A tidal riverine channel mud immediately overlies the fluvial channel sand in the south side of the valley. Mud is the uppermost unit in all of the cores.

Four depositional environments have existed at Duck Creek during the Holocene (Figure 6): a fluvial channel (a freshwater riverine wetland according to the NWI classification), a freshwater palustrine wetland, an oligohaline estuarine wetland, and a tidal river channel (an oligohaline riverine wetland). The latter three environments were identified using statistical analyses of LOI values; the fluvial channel was identified by its texture and stratigraphic position (as described above).

The oldest environment at Duck Creek is represented by the riverine sand at the bases of the cores. The basal sand is overlain by peat which was deposited in a freshwater palustrine wetland. Radiocarbon dates at the base and near the top of the peat suggest that a freshwater palustrine wetland environment occupied areas marginal to the channel from the earliest Holocene to about 1,000 YBP (Figure 7). The uppermost muddy units of the cores represent the modern oligohaline estuarine and riverine wetlands classified by the NWI at this site (TINER, 1985).

At the Leipsic River, 3–5 m of peat, mud, sandy mud, muddy sand, and sand were recovered in five vibracores (WHALLON, 1989) and three hand-driven cores (Figure 8). The vibracores were taken in tidal channels which drain the palustrine wetlands marginal to the Leipsic River, while the hand-driven cores were taken from the wetland surface. All of the cores consist predominantly of

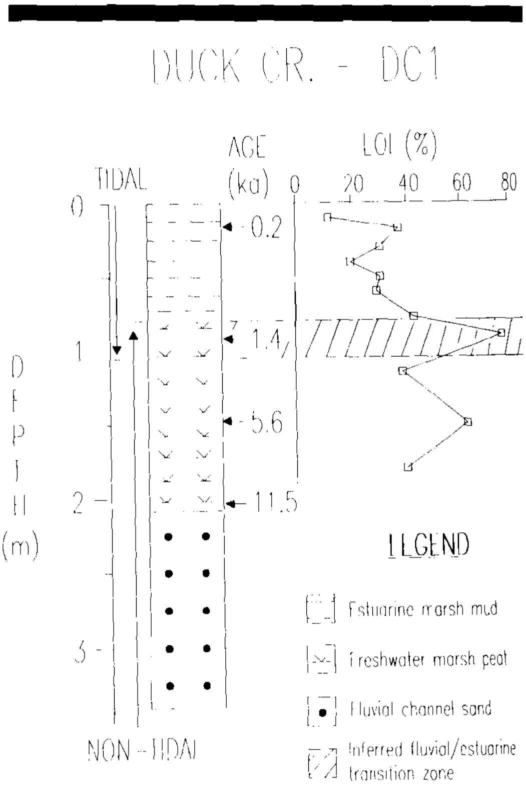

Figure 7. Log of core DC1 illustrating LOI analyses, dated horizons, range of tidal influence referred from sea level history, and distributions of mud, peat, and sand. Only the oldest dated horizon is actually from core DC1. The others are transposed from core DC3. The uppermost horizon is dated using pollen analyses (BRUSH, 1989; BRUSH *et al.*, 1982). All other horizons are dated using radiocarbon methods.

peat, with occasional beds of the other lithologies. Beds of sand and sandy mud 30–50 cm thick form the basal units of four of the cores. In core LR90-DC-3, a layer of sandy mud near the base of the core is sandwiched between beds of mud (Figures 8 and 9). In addition, the base of core LR90-DC-3 consists of approximately 60 cm of dense light gray (5 Y 6/1) to gray (5 Y 4/1) muddy sand and sandy mud. These sediments are denser and lighter in color than the brown (10 YR 2/2 to 5 YR 3/4) and dark gray (N3) sediments which overlie them. The color and texture of these basal deposits are characteristic of the Miocene Calvert Formation in the area (PICKETT and BENSEN, 1983). Thus, core LR90-DC-3 penetrates the entire thickness of Holocene sediments of the Leipsic River.

Three depositional environments are suggested

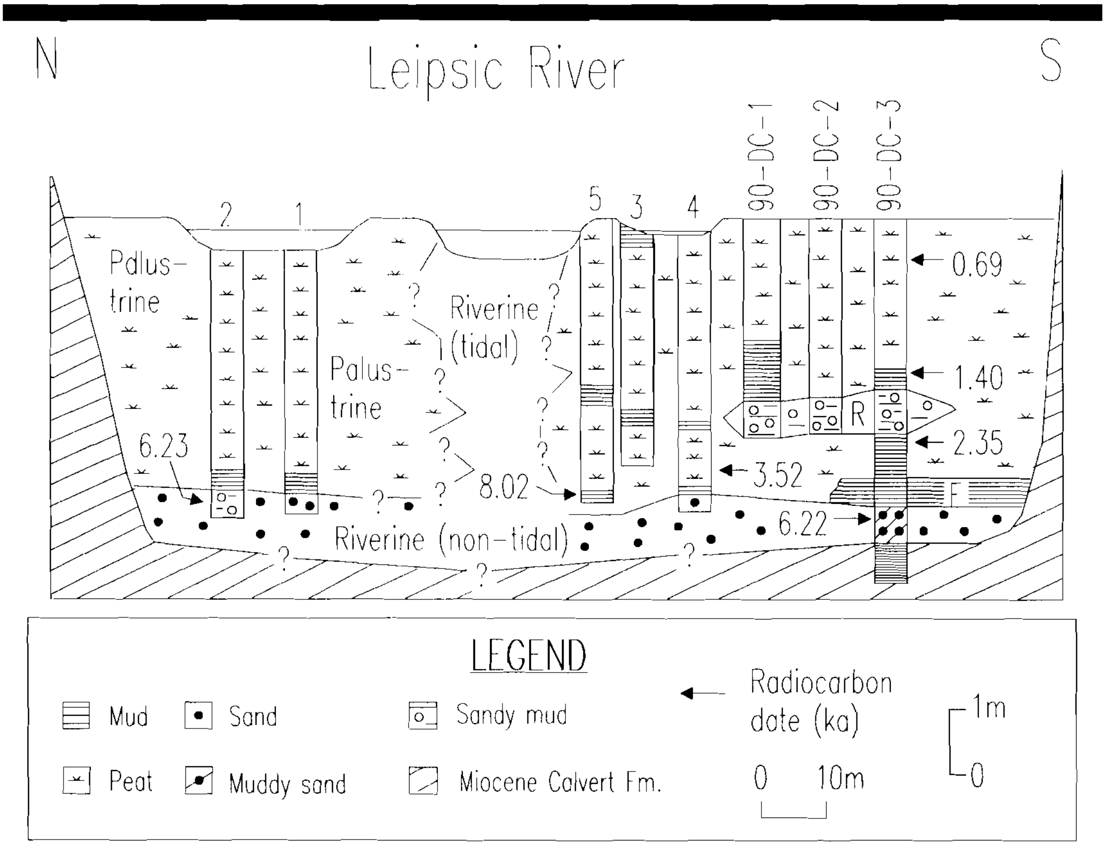

Figure 8. Cross-section of the Leipsic River.

by the lithologies sampled at the Leipsic River. The basal sandy units are interpreted as non-tidal fluvial channels. LOI analyses of the peat and mud unit which comprises most of the remaining lithologies are consistent with a palustrine wetland environment. A unit of mud 25 cm thick in core LR90-DC-3 has the characteristically low LOI signature of a floodplain (though only 4 LOI analyses were obtained from this unit).

A fourth depositional environment is also illustrated in Figure 8—the muddy deposits of the modern tidal Leipsic River. The extent of these deposits is unknown, as no cores were taken from the modern channel. Thus, the distribution of the tidal riverine facies illustrated in Figure 8 is schematic.

Radiocarbon dates from the Leipsic River yield ages of 8,020 ± 100 YBP, 6,230 ± 270 YBP, 6,222 ± 99 YBP, 3,515 ± 170 YBP, 2,351 ± 80 YBP, 1,400 ± 100 YBP, and 693 ± 80 YBP (Figure 8). These dates suggest that the valley of the Leipsic River has consisted of fluvial channels, floodplains, and associated palustrine non-tidal wetlands for at least 8,000 years. Furthermore, because few floodplain deposits were encountered in the cores, palustrine wetlands were probably the dominant depositional environment in the valley of the Leipsic River during the Holocene.

SEA-LEVEL HISTORY AND HOLOCENE ACCUMULATION RATES

Figure 10 illustrates the spatial and temporal relationships of 16 horizons dated by radiocarbon for this study and the local relative sea-level curve of KRAFT (1976) (also presented by BELKNAP and KRAFT, 1981; FLETCHER, 1988; and FLETCHER *et al.*, 1990). Early Holocene dates (for example those older than 5,000 YBP) lie many meters above the sea-level curve. This large discrepancy cannot be accounted for by compaction (it should be noted that the elevations of dated horizons have not been adjusted for the influence of compaction) or

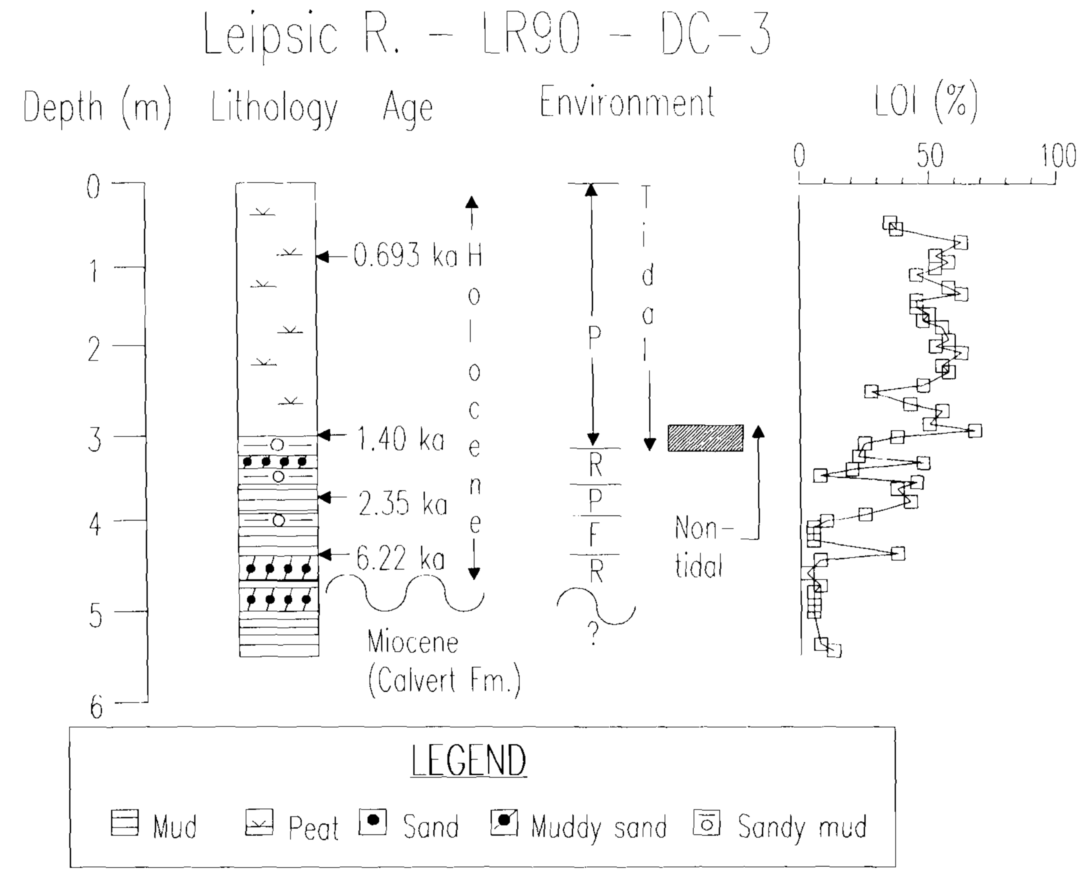

Figure 9. Log of core LR90-DC-3 (denoted 90-DC-3 in Figure 8) illustrating LOI analyses, dated horizons, inferred range of tidal influence, distribution of lithologies, and environmental interpretations (P = palustrine, R = riverine, F = floodplain).

by errors in estimating the elevations of the dated horizons (FLETCHER, 1988; FLETCHER *et al.*, 1990). Rather, these results suggest that the dated horizons were deposited well above any possible marine influence in a non-tidal, fluvial environment. Because the Delaware sea-level curve and the data from the present study converge within the last thousand years or so, tides probably became an important influence in the study area during this period.

The relationship between Delaware's sea-level history and the stratigraphy of the wetland deposits at Duck Creek is illustrated in Figure 7. This relationship is necessarily schematic, for sedimentologic data alone do not provide a precise means of determining when these environments became tidal. This is not surprising, for the head of tide is not a fixed point. Rather, the head of

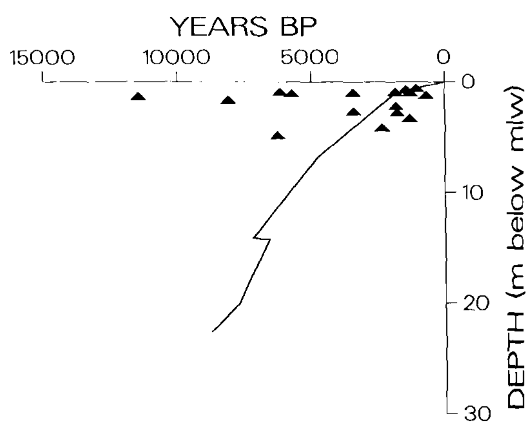

Figure 10. Comparison on the local relative sea-level curve of KRAFT (1976) (solid line) with the elevations of dated horizons from the present study (triangles).

tide will migrate under a variety of influences (high fluvial discharge, estuarine storms, *etc.*) over relatively short time periods, and therefore a precise boundary which delimits tidal and non-tidal environments probably cannot be defined. However, because tides generally extend well into a freshwater fluvial system, the beginning of tidal influence must have occurred below the contact between the estuarine mud and the palustrine peat at Duck Creek. This observation is supported by the current existence of a tidal freshwater environment at the Leipsic River.

These arguments, when combined with Delaware's sea-level history and the dated horizons presented in Figure 7, suggest that Duck Creek became tidal 1,000–2,000 years ago. This temporal range is indicated in Figure 7 as the "fluvial/estuarine transition zone". Not surprisingly, the fluvial/estuarine transition zone is not marked by any change in lithology or by any other sedimentologic discontinuity. A similar analysis for the Leipsic River suggests that this area probably became tidal more recently, perhaps 1,200–1,500 years ago (Figure 9) (the greater precision of this estimate relative to the estimate for Duck Creek is possible because of the greater length of core LR90-DC-3).

The radiocarbon dates and other data presented above suggest that accumulation rates in these valleys must have been low during the Holocene relative to rates of Holocene sea-level rise. All of the dated intervals in the cores yield an average accumulation rate (uncorrected for the influence of compaction) of 0.86 ± 0.69 mm/yr, a value which is similar to the 0.78 mm/yr determined by ORSON *et al.* (1990) for cores from tidal freshwater wetlands along the Delaware River. This average, however, includes accumulation in several different environments. If intervals within specific environments are selected, an accumulation rate of 0.78 ± 0.92 mm/yr is obtained for freshwater palustrine wetlands, a value which is somewhat higher than the 0.4 mm/yr quoted by ORSON *et al.* (1990) and FLETCHER *et al.* (*unpublished data*) for similar environments along the Delaware Bay. The accumulation rate for estuarine wetlands is 1.3 mm/yr, a rate which exactly equals the average rate of sea-level rise for the Delaware coast during the past 2,000 years (FLETCHER *et al.*, 1990).

DISCUSSION

The results presented above have interesting implications for stratigraphic models of transgressive sedimentary sequences, and also for facies models of fluvial overbank sedimentation on low relief coastal plains.

Figure 11 illustrates a hypothetical transgressive sedimentary sequence which would be formed by a future sea-level rise of approximately 8 m at the Duck Creek site. In constructing Figure 11, it has been assumed: (1) that enough sediment has been available to maintain the surface of estuarine wetlands as sea level rose, and (2) that rates of shore erosion will be low enough to maintain the shore of Delaware Bay downstream of the present study area. Deep valley fills similar to that of Figure 11 have been documented on the estuarine coast at the mouths of nearly all the rivers of the Delaware Coastal Plain which flow into Delaware Bay (BELKNAP and KRAFT, 1977; CHRZASTOWSKI, 1986; FLETCHER *et al.*, 1990; RICHTER, 1974; YI and KRAFT, 1989; YI *et al.*, 1991).

The geometry of the sedimentary units illustrated in Figure 11 is based on the data presented above and also on data obtained in numerous studies of the Delaware coast (most recently summarized by FLETCHER *et al.* (1990)). The unconformity above the present mean high water (*i.e.*, the present topography) was taken directly from the 1:24,000 Smyrna Quadrangle. This surface is higher to the NE because the profile cuts across a N-S trending scarp which passes through the study area (K. Ramsey, *personal communication*). The stratigraphic units below mean high water are essentially those of Figure 6, while units above mean high water are predictions based on the stratigraphic models of CHRZASTOWSKI (1986), FLETCHER *et al.* (1990), KRAFT and CHRZASTOWSKI (1985), and others. The thin palustrine peat deposits which immediately overlie the unconformity on the southwestern side of the cross-section have been described by YI and KRAFT (1989). They represent the preserved record of small palustrine wetlands which often form at the landward edge of estuarine tidal wetland systems. These wetlands are not located near rivers; rather, they are located between uplands and tidal estuarine wetlands where freshwater is probably provided by emerging groundwater. Similar freshwater wetland deposits have been described beneath modern salt marshes by BLOOM (1964), DAVIS (1910), KAYE and BARGHOORN (1964), KELLEY *et al.* (1988), and MEYERSON (1972).

Figure 11 suggests that the lower boundary of a transgressive sedimentary sequence is a complex stratigraphic surface. At the bottom of the river

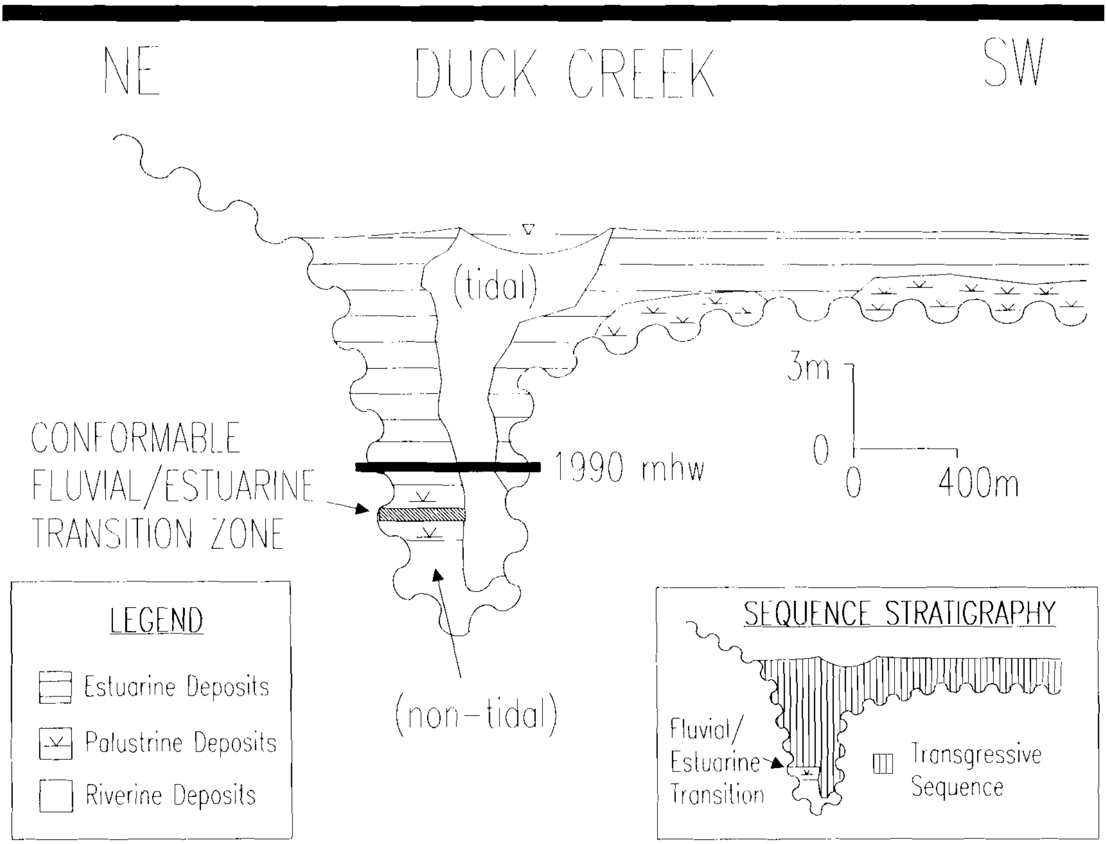

Figure 11. Hypothetical cross-section and sequence stratigraphy of Duck Creek after a future sea-level rise of about 8 m illustrating the geometry of riverine (both tidal and non-tidal), palustrine, and estuarine deposits.

valley, an unconformity develops by fluvial incision during periods of low sea level; the unconformity predates the transgression and the fluvial deposits which immediately overlie it are essentially regressive. On the NE side of the valley, the lower boundary of the transgressive sequence is located within a uniform palustrine peat. This transition is conformable. On the SW side of the valley, a meandering tidal river has removed the palustrine peat through lateral migration and deposited channel facies in its place; here, the transition is unconformable. As transgressive deposits begin to bury the upper valley wall and interfluves, sediments are deposited on a pre-existing erosion surface; here, the lower boundary of the transgressive sequence is an unconformity as has been recognized by DEMAREST and KRAFT (1987), KRAFT and CHRZASTOWSKI (1985), YI and KRAFT (1989), and others. Thus, the base of the transgression bears a complicated relationship to the underlying strata: it is conformable within wetland valley deposits and unconformable on interfluves and where later meander migration has removed pre-existing wetland sediments. Because river valleys only occupy a relatively small proportion of a coastal plain landscape, the unconformable boundary covers a much greater area than the conformable boundary (as was observed by DEMAREST and KRAFT (1987)). However, the conformable boundary has a relatively high preservation potential; while the unconformable boundary may be removed or modified by subsequent transgressive shoreface erosion and ravinement (BELKNAP and KRAFT, 1981).

The widespread occurrence of Holocene palustrine peat deposits at relatively high elevations and the relative paucity of floodplain deposits demonstrates that perennially inundated wetlands occupied most of the valleys of the study area during the Holocene. Apparently, the sediment yield of the coastal plain was too low for overbank sedimentation to build extensive floodplains by vertical accretion. This conclusion is supported by (1) the low modern sediment yield of the Delaware coastal plain (MANSUE and COMMINGS, 1974), and (2) the current widespread existence of extensive non-tidal palustrine wetlands in modern river valleys of the Delaware Coastal Plain (DAIBER, 1976; TINER, 1985).

CONCLUSIONS

(1) Sediments deposited in riverine, estuarine, and palustrine wetlands of tidal rivers of central Delaware may be distinguished by LOI. Mean LOI values of floodplain, riverine, estuarine, and palustrine deposits are 2–9%, 9–13%, 17–21%, and 43–46%.

(2) Palustrine wetlands dominated areas marginal to the rivers of the study area during most of the Holocene. These wetlands were not influenced by tides until 1,000/2,000 years ago.

(3) The transition from non-tidal to tidal palustrine sedimentation is conformable in these deposits, except where the transition was subsequently removed by lateral migration of tidal rivers. Thus, the lower boundary of a transgressive sedimentary sequence is primarily conformable within a valley fill. Where a transgressive sedimentary sequence overlies paleointerfluves, however, the lower sequence boundary is an unconformity.

(4) During the Holocene, coastal plain rivers of central Delaware did not build extensive floodplains because insufficient sediment was available for vertical accretion.

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□ RÉSUMÉ □

Les valeurs des pertes sur ignition (PSI) sont de 2–9% pour les plaines inondables non saturées, 9–13% pour les terres humides des rivières, de 12–21% pour celles des estuaires et des 43–46% pour celles des marécages. Ces données concernent les plaines alluviales littorales des vallées de rivières du centre du Delaware. On a utilisé les différentes signatures des PSI, les datations au radiocarbone, et la courbe locale des variations relatives du niveau de la mer pour reconstruire l'histoire holocène des vallées dans la zone étudiée.

Au début de l'Holocène, la quantité de sédiments fournie par la plaine littorale du Delaware était trop faible pour que les rivières puissent construire des plaines d'inondation subaériennes exposées. Par contre, les vases riches en matières organiques et les tourbières s'accumulaient dans les terres humides des milieux palustres non tidaux inondés en permanence. Ces milieux existaient déjà 11,000 ans BP, bien avant toute possible influence d'une élévation du niveau de la mer. Le niveau de ces dépôts et l'histoire des niveaux marins du Delaware suggèrent que l'influence tidale a commencé il y a 1,000 à 2,000 ans. La transition d'un milieu soumis à des conditions fluviatiles vers des conditions estuariennes se fait sans changement lithologique ou sans discontinuité vers le sommet des tourbières. Ainsi, la base de la transgression holocène est, dans ces vallées, conforme, sauf lorsque la migration latérale des chenaux de marée a enlevé la transition conforme. En dehors des vallées, pourtant, la base de la séquence transgressive est en majorité non conforme. Ainsi, la transgression préservée côté terre sur la côte du Delaware est entourée à sa base par une surface stratigraphique complexe qui est tout d'abord conforme pour les remplissages de vallées, mais qui est non conforme dans les paléointerfluves.—*Catherine Bousquet-Bressolier, Géomorphologie E.P.H.E., Montrouge, France.*

□ RESUMEN □

Estuarios, riberas, planicies costeras no saturadas y las zonas húmedas pantanosas de la planicie costera fluvial del valle central de Delaware poseen una pérdida media sobre ignición (LOI) de 2–9%, 9–13%, 17–21%, y 43–46%, respectivamente. Estas formas diferentes del LOI fueron usadas junto con el fechado por radiocarbono y las curvas locales del nivel del mar relativo de Delaware para reconstruir la historia del Holoceno de los valles del área. Durante el inicio del Holoceno, el límite del sedimento de la planicie costera de Delaware era demasiado bajo para que los ríos construyeran extensas planicies inundables. En su lugar, barros orgánicos y turbas se acumularon en las tierras húmedas, y en las pantanosas no inundadas por la marea. Estos ambientes existieron hace 11,000 años AP, previo a cualquier influencia posible del ascenso del nivel del mar. La elevación de éstos depósitos y la historia del nivel del mar de Delaware sugieren que la influencia de la marea comenzó hace 1,000–2,000 años. La transición de las condiciones, fluvial a estuarina ocurrió sin ningún cambio litológico o discontinuidad cercana a la parte más alta de un pantano uniforme de turba. Además, la base de la secuencia transgresiva del Holoceno se acomodó en estos valles, excepto donde las migraciones laterales por las corrientes de marea removieron la transición. Sin embargo fuera de los valles, la base de la secuencia trangresiva es de mayor discordancia. Por lo tanto, la secuencia transgresiva preserveda tierra adentro desde la costa de la Bahía de Delaware está limitada en su base por una superficie estratigráfica compleja donde es primariamente acomodado el relleno de los valles pero no lo son sobre los paleocauces.—*Néstor W. Lanfredi, CIC-UNLP, La Plata, Argentina.*

□ ZUSAMMENFASSUNG □

Die Sedimente nicht vollständig wassergesättigter Überschwemmungsebenen sowie der fluvialen, ästuarinen und palustrischen Feuchtgebiete von Flußtälern der Küstenebene in Zentral-Delaware weisen mittlere Glühverluste von 2–9%, 9–13%, 17–21% bzw. 43-46% auf. Diese charakteristischen Glühverluste werden gemeinsam mit Radiokarbondaten und der lokalen relativen Meeresspiegelschwankungskurve von Delaware für eine Rekonstruktion der holozänen Talentwicklung im Untersuchungsgebiet herangezogen. Während des frühen Holozäns reichte die Sedimentzufuhr aus der Küstenebene Delawares für den Aufbau ausgedehnter, subaerischer Überflutungsebenen durch die Flüsse nicht aus. Stattdessen wurden in ständig überfluteten, nicht von den Gezeiten beeinflußten palustrischen Feuchtgebieten Torfe und Schlamm mit hohen Gehalten an organischer Substanz akkumuliert. Diese Sedimentationsmilieus existierten bereits um 11,000 BP und damit eindeutig vor einer möglichen Beeinflussung durch den Anstieg des Meeresspiegels. Das Niveau der Ablagerungen sowie die relative Meeresspiegelkurve von Delaware deuten darauf hin, daß sich ein Einfluß der Gezeiten erst seit 1,000–2,000 Jahren bemerkbar machte. Der Übergang von fluvialen zu ästuarinen Bedingungen erfolgt ohne lithologischen Wechsel und ohne Diskontinuität nahe der Oberfläche eines homogenen palustrischen Torfes. Deshalb ist in den Tälern die Basis der holozänen transgressiven Sequenz konkordant; außer an den Stellen, wo der konkordante Übergang durch die Verlagerung von Gezeitenströmen beseitigt wurde. Außerhalb der Täler ist jedoch die Basis der holozänen transgressiven Sequenz durch eine Diskordanz gekennzeichnet. Die Basis der transgressiven Sequenz, die landeinwärts der Küste der Delaware Bay erhalten ist, stellt somit eine komplizierte stratigraphische Grenze dar mit Konkordanz in den Talfüllungen und Diskordanz im Bereich der einstigen Wasserscheiden. —*Jürgen Wunderlich, Department of Geography, University of Marburg, Germany.*