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High-Resolution of Paleoenvironmental Reconstruction and Sea-Level History in Delaware Bay, the East Coast of U.S.A.

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미국동부 델라웨어만의 고정밀도 해수면역사와 고환경 복원

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The closely spaced cores were analyzed to find detailed reconstruction of paleoenvironments and sea-level changes along the Delaware Bay coast. Three areas, Kitts Hummock Beach marsh, the St. Jones River marsh, and Bowers marsh near the St. Jones River's mouth, were chosen because these areas are compose of their own geomorphic characteristics and sea-level history. Since significance of the stratigraphic correlations was to determine sedimentary facies and paleoenvironments, multidisciplinary methods such as lithological description, grain-size analysis, organic/inorganic content, water content, mineral composition, botanical analysis, micropaleontological analysis, and ^{14}C datings were performed. Five major divisions of marsh environments were recognized in the stratigraphic sections: freshwater marsh, initial freshwater marsh, slightly brackish marsh, brackish marsh, and salt marsh. Most of the lower part in the stratigraphic sections show freshwater marsh. On the top of this, either brackish marsh or tidal flat/tidal stream was recorded. The pre-Holocene sediments consist of sand, mud, and sandy mud. The pre-Holocene configuration played an important role for developing the Holocene paleoenvironmental changes. The irregular configuration of the pre-Holocene surface within short distances permitted the concurrent development of variable environments such as freshwater marsh, brackish marsh or salt marsh at similar elevations. The freshwater marsh in this case was formed in the areas of isolation, so saline-water cannot encroach upon these areas. This complex development of paleoenvironments leads to a difficulty in stratigraphic correlation and interpretation of local relative sea-level changes. The deposition of subsurface sediments was affected by sediment supply, compaction, fluvial activity, biological competition, local tectonics and isostacy, climate and local relative sea-level changes. It was interpreted that the positions in the changes from freshwater environments to brackish environments or vice versa are the turning points of transgressions and regressions. Therefore, multiple transgressions and regressions were identified in the stratigraphic sections of the study area.

자세한 고환경복원 및 해수면 변화를 파악하기 위하여 델라웨어만 중부연안에서 조밀한 코어를 채취 분석하였다. 연구지역은 키즈호머크해변, 세인트존스강, 세인트존스강 하구의 바월즈해변의 습지지역으로 각자 고유의 지형적인 특성과 해수면역사를 기록하고 있다. 층서대비에서 가장 중요한 것은 퇴적상과 고환경을 세분하는 것이며 이를 위하여 본 연구에서는 암상분석, 입도분석, 유기물과 무기물의 비, 함수율비, 광물구성성분, 식물상의 분석, 고생물학적 분석, 탄소연대측정 등을 사용하였다. 연구지역에서 습지환경은 담수습지, 초기담수습지, 약기수습지, 기수습지, 염수습지로 다섯등분하였다. 습지환경 외에는 조간대환경과 하천환경이 간혹 발견되었으며, 전홀로세층의 퇴적물은 사질, 니질, 사니질 퇴적물로 구성되어 있다. 층서의 하부는 담수습지가 대부분이며 그 위에 기수습지나 조간대 내지 조간대 내의 하천환경으로 나타났다. 전홀로세의 지형형태가 홀로세 고환경변화에 중요

한 영향을 미쳤다. 해수면이 상승하거나 하강하면서 염수나 기수환경을 형성하는 과정에도 해수의 영향이 미치지 않는 고립된 지역에서 담수환경이 형성되었다. 같은 시기에 유사한 고도에서 담수환경과 기수환경이 형성되는 것은 바로 전홀로세층의 불규칙한 지형에 기인한 것이다. 따라서 이러한 복잡한 고환경 형성은 층서대비나 지역적 상대적 해수면 변화에 대한 해석에 어려움을 가져왔다. 연구지역에서 퇴적층은 퇴적물 공급, 고결작용, 하천활동, 생태계내의 경쟁, 지역적인 지구조적운동, 지각평형, 기후 그리고 지역적인 상대적인 해수면 변화에 의해서 영향을 받았다. 담수환경과 기수환경의 반복이 여러 층에서 발견되었는데 이 시점마다 해침이나 해퇴가 일어난 것으로 판단된다. 따라서 연구지역에서는 여러번의 해침과 해퇴가 일어난 것으로 본다.

INTRODUCTION

The Delaware coast is mainly characterized by two physiographic provinces: one is the Delaware Bay coast and the other is the Atlantic Ocean coast (Fig. 1). Many previous workers have studied marshes, estuaries, and barriers along the Delaware coasts (Kraft, 1971; Elliott, 1973; John, 1977; Allen, 1974, 1978; Belknap and Kraft, 1977, 1981, 1985; Kraft and Chrzastowski, 1985; Chrzastowski, 1986; Fletcher, 1986; Khalequzzaman, 1989; Whallon, 1989; Stedman, 1990) The Holocene sediments filled the antecedent pre-Holocene valleys in response to the local relative sea-level changes (Belknap, 1975; Kraft, 1976; Belknap and Kraft, 1977). Richter (1974) produced an isopach map of Holocene mud in the Delaware marshes, which illustrated the geometry of the Holocene sediments.

There are several different interpretation of sea-level changes along the Atlantic Ocean coasts. Kraft (1976) and Belknap and Kraft (1977) reconstructed sea-level curve with substantial ^{14}C data in the Delaware coast. Local relative sea-level curve drawn by them is a continuous rise with different rates during the Holocene Epoch. On the other hand, Van Pelt (1991) and Fletcher et al. (1993) reported several fluctuations of sea-level in the Delaware wetlands. Chung et al (1994) applied the concept of a fractal geometry to the sea-level history in the Delaware coasts. More details of the subsurface stratigraphic record in many different tidal marshes must be studied to understand actual lateral movement and vertical stackings of sedimentary environments by utilizing numerous and closely spaced cores in an extensive area.

STUDY AREA

Delaware Bay and Atlantic Ocean coasts are shown in Fig. 1. The present tidal creeks such as Duck Creek, the Leipsic River, the St. Jones River, the Murderskill River, the Mispillion River, the Broadkill River, and the Lewes Creek were part of the ancestral fluvial drainages during the last glacial time. Outcrops in the coastal plain of Delaware consist of Cretaceous, Tertiary, and Quaternary sediments (Jordan, 1964). In previous work (Kraft, 1971; Kraft and John, 1976, 1979; Kraft and Chrzastowski, 1985; Kraft et al., 1987a, 1987b), a typical stratigraphy of Delaware coasts is the vertical stackings of open bay mud, barrier sand, backbarrier marsh mud, lagoonal mud, fringing marsh mud, and pre-Holocene sediments from top to bottom. Kraft et al. (1992) included freshwater marsh facies in the stratigraphic sections mostly found from the basal peat. The high-resolution stratigraphic frameworks have been required for understanding the detailed sea-level history. To do so, the pinpoint of transgressive or regressive boundaries should be recognized in the stratigraphic records. In this study, to achieve the goal, a very closely spaced coring has been conducted to reduce the missing information from stratigraphic sequences. Most core intervals are about 100 m, and some of them are much closer, i.e., almost 50 m in distance.

Since the closely spaced coring method already creates an increasing number of cores within localized areas, it requires lots of cores when we investigate large areas regionally. These thoroughly collected cores can maximize information of highly resolving stratigraphic correlation which provides a strong confidence for detailed markers of stratigraphic changes from vertical sedimentary sequences, which eventually helps finding precise transgressive and regressive boundaries. However,

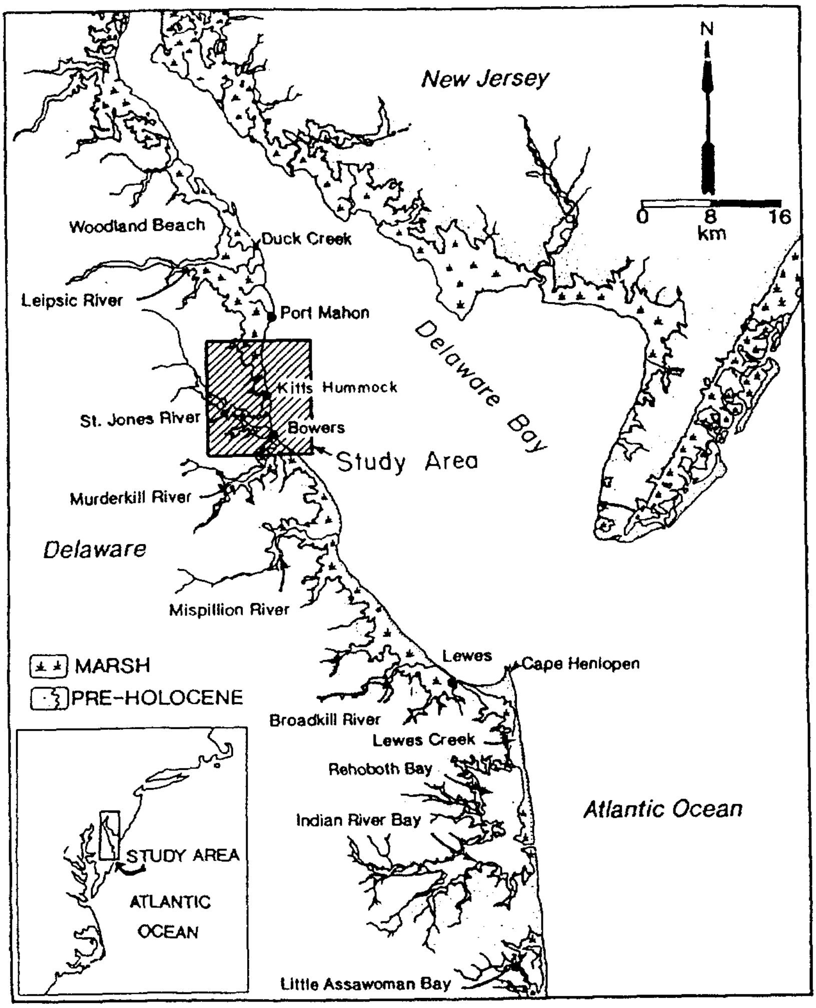

Fig. 1. The Delaware Bay estuary and part of the Atlantic Ocean coast. Box with an oblique line is the study area.

each localized wetlands has a possibility of each unique characteristics of stratigraphic record. For instance, sediment supply from upland drainages can affect surrounding areas, especially lowlands near and within the wetlands. The wetland developments are also affected by different factors such as subsidence (including anthropogenic subsidence), sediment supply and distribution, fluvial activity, groundwater influence, neotectonics, sea-level changes, isostacy and biological activity.

In this paper, fifteen cores from three areas, Kitts Hummock Beach marsh, the St. Jones River marsh, and Bowers marsh near the St. Jones River's mouth, were selected to determine paleoenvironmental reconstruction and sea-level history. The box with a oblique line in Fig. 1 is the main study area for this work. This box was expanded to see three transects, i.e., Transects 3, 4, and 5 (Fig. 2). The substantial dataset can provide checking the complex and unique wetlands in each localized area, so that one localized area might not be misinterpreted for developing a new model of paleoenvironmental reconstruction. The more similar stratigraphic record is found in sedimentary sequences among different areas, the higher possibility of findings for regional to global scale of sea-level history in the study area.

METHODS

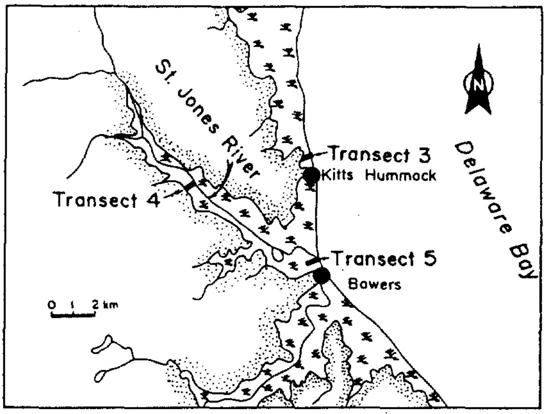

Fig. 2. The study area. Transects 3 to 5 are shown in this figure.

Table 1. Classification of wetlands. The salinity ranges are shown in parentheses.

Marshes	Freshwater Marshes (0-0.5‰)	Nontidal type (0‰)
		Tdial type(0-0.5‰)
	Slightly Brackish Marshes (0.5-5‰)	
	Brackish Marshes (5-18‰)	
	Salt Marshes (18-30‰)	
Swmaps	Wooded Swamps (0‰)	
	Scrub-shrub Swamps (0‰)	
Hardwood Forests (0‰)		
Bog (0‰)		
Freshwater Lakes and Ponds (0‰)		
Freshwater Lakes and Ponds (0‰) ·		
Tidal Creeks and Streams (0‰‰)		
Salt Pans (>18‰)		

Multidisciplinary methods were used for finding more detailed stratigraphic records. The methods can be divided into field surveys and laboratory analyses. The basic field surveys included records of geomorphic characteristics such as the distance from uplands, the location and size of tidal creeks, the distance from the creeks, vegetation types, elevations, tidal range differentiation, etc. Also, with the aid of Eijelkamp gouge coring method, stratigraphic sequences were described and sometimes immediately interpreted on the fields. The advantage of Eijelkamp gouge coring method provided information in the field for us to choose the next coring location in order to find different stratigraphic record. Consequently, most of the cores are Eijelkamp gouge cores. Samples were collected from cores on the field for the further laboratory analyses.

The laboratory works comprised basic core description, weight loss-on-ignition (LOI), grain size analysis, plant identification, foraminifera and other microfossil analysis. macrofauna identification, mineral composition, and ^{14}C dating. Basically, more techniques added to help differentiating stratigraphic facies, the better resolutions of stratigraphic sequences increase.

PRESENT WETLANDS

The present wetlands are complex due to difference in geomorphic features, vegetation types, and formation and distance of tidal creeks and streams, and fluvial activity. Therefore, the classifications of the present surface wetlands are variable. Here, the following description of wetland classification is more or less based on the dominant vegetation types with respect to salinity ranges (Table 1). First, the present wetlands comprise marshes, swamps, hardwood forests, bogs, freshwater floodplains and streams, freshwater lakes and ponds (including lakes and ponds formed by artificial dams), tidal creeks and streams, and salt pans. Salinity range is very important in dividing marine-influenced wetlands and nonmarine-influenced wetlands (Table 1). Swamps, hardwood forests, freshwater floodplains and streams, and freshwater lakes and ponds contain no salt in the water (salinity: 0‰). In the marshes, four more subenvironments are divided. They are freshwater marshes (salinity range: 0-0.5‰), slightly brackish marshes (0.5-5‰), brackish marshes (5-18‰), and salt marshes (18-30‰). In the freshwater marshes, nontidal type of freshwater marshes is purely freshwater-type (0‰) but tidal freshwater marshes have a salinity range of 0-0.5‰. Here is the unit of salinity and means parts per thousand. The swamps are also further divided into wooded swamps and scrub-shrub swamps. These two are all freshwater environments and have no salinity in the water.

These different types of surface vegetations and of geomorphic characteristics can be used for a beginning of stratigraphic interpretation. Without a precise information of the present environments from core locations and surrounding areas, it is difficult in understanding changes of paleoenvironments in the stratigraphic records. In this study area, most of areas contain salt to brackish marsh plants, some reeds and bushes

RECONSTRUCTION OF PALEOENVIRONMENTS

Three transects, 3, 4, and 5 (Figs. 3 to 5), from the study area were selected for the reconstruction of paleoenvironments and sea-level history. The three locations are Kitts Hummock Beach marsh, St. Jones River marsh, and Bowers marsh near the St. Jones River's mouth (Fig. 2). Most of the gouge auger cores were collected at closely spaced intervals in order to observe changes of the paleoenvironments. It is generally known that the pre-Holocene surface is irregular (Richter, 1974; Belknap and Kraft, 1985). However, information of the pre-Holocene surface within a very short distance was not clearly known in which this affects local environmental changes and associated local sea-level changes.

In three transects, numbers of transgressions and regressions were recognized and labeled as T1, T2, T3, etc. for transgressive events, while R1, R2, R3, etc. for regressive events. When T or R has double, i.e., TT or RR, it means that boundaries of transgressions and regressions are very sharp. Each number of transgressions and regressions in one transect does not indicates the simultaneous event of transgressions and regressions in other transects. For instance, T1 merely means the first occurrence of transgression in one particular stratigraphic section. That number even does not represent the first occurrence of transgression from the beginning of the Holocene unless the cores penetrated the pre-Holocene surface.

Kitts Hummock Beach Marsh

Four cores were retrieved from the coast to inland, at an average distance of 100 m (Fig. 3). The locations of the cores, are near the northern end of the coastal town of Kitts Hummock. A pre-Holocene headland forest is only about 500 m to the west of these core locations. Mudflat sediments were exposed in the nearshore during the time of low tide. This unusual widespread deposition of soft, water-saturated mud in front of the beach is directly related to the experimental breakwater project done by the U.S. Army Corps of Engineers. Several jetties and breakwater were built in front of the beach area (about 20-25 m extended from the beach).

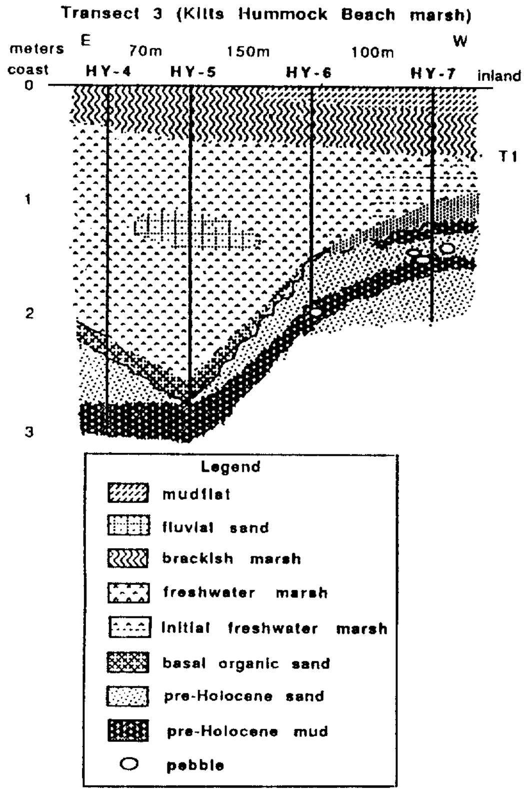

Fig. 3. Transect 3 in Kitts Hummock Beach marsh. Transect 3 crossed from east to west indicates from the coast to inland. T1 indicates the first occurrence of transgressive boundary in this transect.

Transect 3 (Fig. 3) shows a gentle slope of the pre-Holocene surface and thick freshwater marsh deposits. The brackish marsh deposits occurred at a depth of about 30 cm to 58 cm. The encroachment of saline-water occurred at a shallower depth in these cores than in other areas. The reason for the late contact of saline-water is due to the presence of a pre-Holocene topographic highland, and possibly human interference. Cores HY-6 and HY-7 have mudflat deposits in the uppermost section of the cores. These mudflat deposits contain 30-40% small rootlets. This top section is now submerged due to the lack of nutrient supply and water circulation.

Eight sedimentary units were recognized in transect 3: pre-Holocene sediments, basal organic sand, initial freshwater marsh, freshwater marsh, brackish marsh, fluvial sand, and mudflat (Fig. 3). Initial freshwater marsh is a transitional stage from fluvial mudflat to freshwater marsh which means that freshwater-type vegetation started anchoring in the mudflat deposit. The fluvial sand in core HY-5 and the initial freshwater marsh in core HY-7 occurred isolatedly from other depositional environments. The color of basal organic sand is very-dark-gray (2.5Y N 3/1 based on Munsell soil color charts, 1975) to black (2.5Y N 2/1). The pre-Holocene sediments

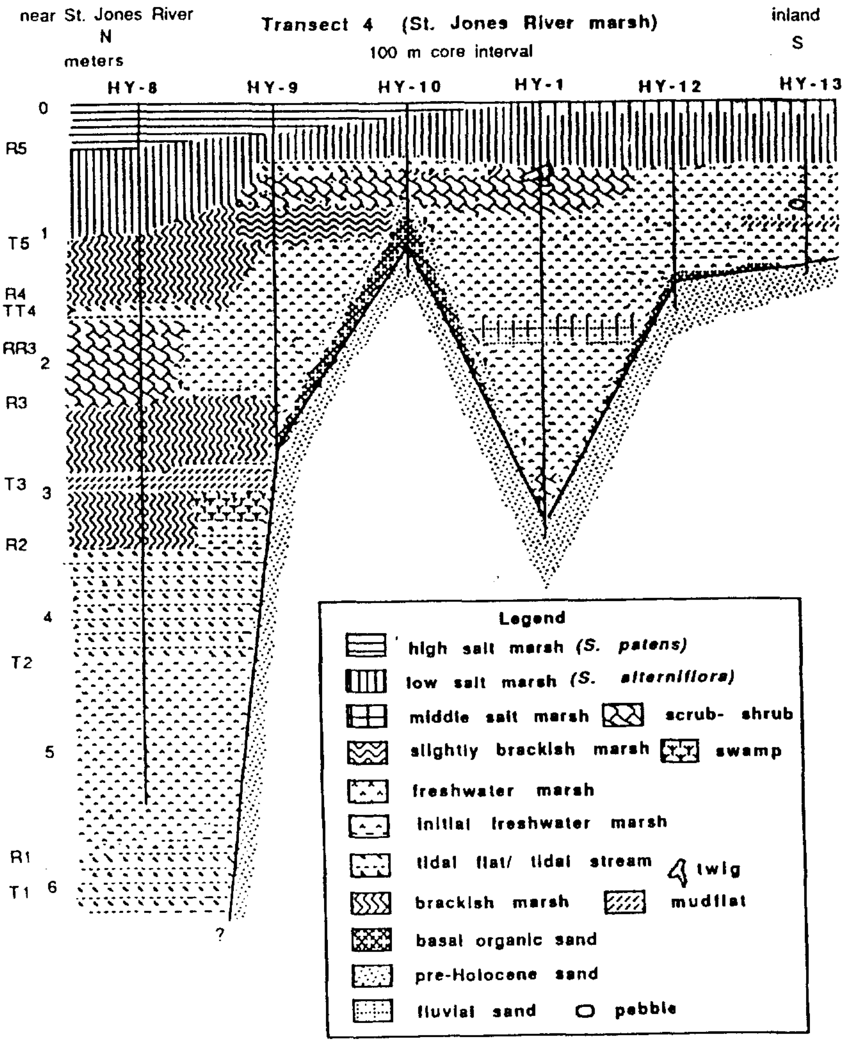

Fig. 4. Transect 4 near the St. Jones River. The transect is located 5 km inland from the Bowers Beach. T indicates transgressions, while R indicates regressions. TT and RR mean the sharp transgressions and regressions in the stratigraphic section.

comprise pre-Holocene sand and mud. Except core HY-5, both the pre-Holocene sand and the pre-Holocene mud occurred. In particular, core HY-7 shows the alternation of the pre-Holocene sand and mud. It might be inferred from this core that the other three core sites also contain this alternation if the cores were penetrated deeper. Pebbles, about 1.5 cm in diameter, are found on the top of or in the pre-Holocene mud. It is indicated that the changes of high energy regimes occurred in the pre-Holocene sand and mud environments. In this transect, only one transgressive event (T1) was recognized.

St. Jones River Marsh

Six closely located sites were chosen, and cores of HY-8 to HY-13 were taken from north to south in the marsh near the St. Jone River in which Highway 113 of Delaware is nearby (Fig. 4). Each core location is about 100 m apart. These core sites are 5 km inland from the town of Bowers (see Fig. 2). The town of Bowers is located in front of Delaware Bay. All the cores penetrated the pre-Holocene sand deposits, except core HY-8. Core HY-8 is located near the bank of the St. Jones River. It is noticed that the slope of the pre-Holocene surface is sharply steep from the site of core HY-9 to the site of core HY-8. Based on the work of Richter (1974), the depth of the pre-Holocene surface at the location of core HY-8 should be at a depth of approximately 9 to 10 m. Richter (1974) reported that depth of the pre-Holocene surface in this area ranges from about 4 m to over 9 m. Contrarily, the results shown in transect 4 (Fig. 4) present that this depth estimate may be incorrect because the depth of the pre-Holocene surface ranges from 1.2 m to 3.3 m in cores HY-9 to HY-13. Therefore, the depth of the pre-Holocene surface in the inland side of this marsh is much shallower than Richter's some inferred depth ranges.

Twelve sedimentary units were recognized in transect 4 (Fig. 4). They are salt marsh, slightly brackish marsh, brackish marsh, freshwater marsh, initial freshwater marsh, scrub-shrub, swamp, tidal flat/tidal stream, mudflat, fluvial sand, basal organic sand, and pre-Holocene sand. The salt marsh is divided into low, middle, and high salt marsh. The elevation of the pre-Holocene surface in core HY-10 played an important role in protecting the area of cores HY-11 to HY-13 from saline-water intrusion until the saline-water reached the height of the pre-Holocene surface in core HY-10 and continued its inundation into the land. This is one example of the importance to recognize the irregularity of the pre-Holocene surface over short distances in order to understand the development of paleoenvironments. If only one core were collected from the location of core HY-11 and represented this area, this result would have misled interpreting the actual paleoenvironmental reconstruction to wrong one. The selection of samples for ^{14}C dating is incredibly important for choosing right environments for sea-level history. For instance, core HY-11 (Fig. 4) contains thick fresh marsh deposits (about 2 m thick). The thick freshwater marsh unit was possible to be deposited because the higher elevation of pre-Holocene surface in the site of core HY-10 can protect the area of core site of HY-11 from the intrusion of saline-water which must kill freshwater-type vegetation. In this case, if we select organic to peat deposit of freshwater marsh from core HY-11, ^{14}C dating would not represent the time of sea-level rise or fall.

Five transgressions and five regressions were recognized in transect 4 (Fig. 4). The most recent regression (R5) is interpreted based on the number and types of species of foraminifera. Even though paleoenvironmental interpretations, in conjunction with other interdisplinary methods, form the basis of the multiple transgressions and regressions, stratigraphic correlation (transect 4; Fig. 4) along these six cores should be the fundamental framework of all paleoenvironmental interpretation and its application to the interpretation of transgressions and regressions. TT4 means fourth events of sharp transgression in transect 4. RR3 also applied to sharp regression events.

Bowers Marsh near the St. Jones River's Mouth

Transect 5 (Fig. 5) is oriented approximately

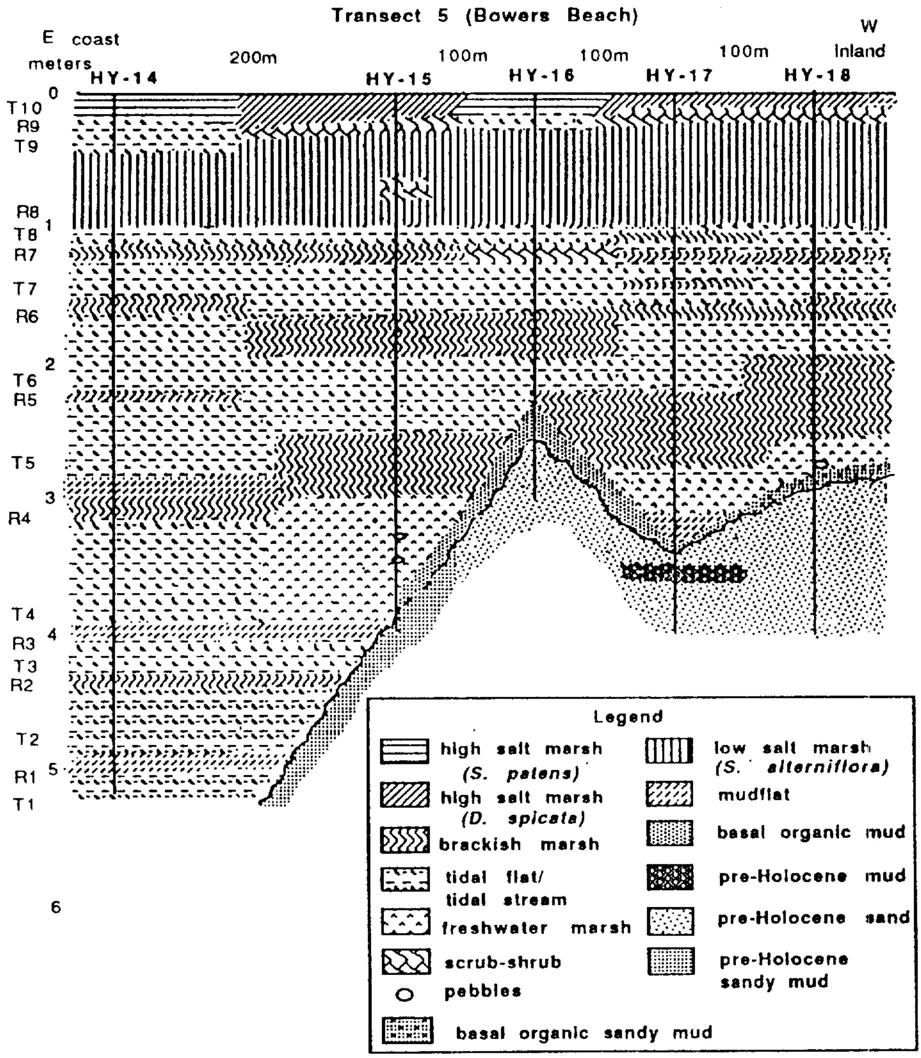

Fig. 5. Transect 5 in Bowers marsh near the St. Jones River's mouth. Here, also T indicates transgressive boundaries and R indicates regressive boundaries.

northeast-southwest to the south of the St. Jones River's mouth. The present surface contains scrub-shrub (mostly *Iva frustescens* and *Baccharis hamilifolia*) behind the beach and salt grasses (*Spartina patens, Spartina alterniflora,* and *Distichlis spicata*). The houses were built along the beach, which protected marsh behind them from high energy such as waves and currents coming from Delaware Bay. Interestingly, the abandoned pier is now buried in this marsh, indicating the open bay water reached this area, or the St. Jones River's mouth was located in this marsh area at that time and switched to the north. It is obvious that the sea-water reached here during the time of human settlement.

In transect 5 (Fig. 5), five core locations (cores HY-14 to HY-18) from the coast (east) to inland (west) were selected in order to observe the subsurface sections in this area. The present surface vegetation is either *Spartina patens* or *Distichlis spicata*, except near mosquito control ditches, in which tall *Spartina alterniflora* is dominant. Most of the cores (HY-15 to HY-18) penetrated pre-Holocene surface, except core HY-14 which is located near the St. Jones River's mouth. Core HY-14 penetrated to a total depth of 520 cm. Richter (1974) inferred that the depth of the pre-Holocene surface near the St. Jones River's mouth is about 8 m only on the basis of one boring data. Since core HY-14 could not reach the pre-Holocene surface, it is accepted that Richter's report might be correct near the site of core HY-14. Otherwise, the inland marsh of this area has a pre-Holocene depth range of 2.3 m to 3.3 m.

Eight sedimentary units were recognized in transect 5 (Fig. 5). They are salt marsh, brackish marsh, freshwater marsh, scrub-shrub, mudflat, tidal flat/tidal stream, basal organic sediments, and pre-Holocene sediments. Scrub-shrub deposits consist of the vegetation type of *Baccharis* and *Iva*. These genera grow in freshwater to brackish environments, especially in a little higher elevation than other marsh grass-growing areas. The salt marsh can be divided into two: low and high marsh. Here, the high marsh again can be further divided into two on the basis of vegetation type. They are *S. patens* marsh and *D. spicata* marsh. The basal organic sediments and the pre-Holocene sediments are further divided based on grain size. First, the basal organic sediments are divided into basal organic sandy mud and basal organic mud. For the pre-Holocene sediments, three divisions are recognized: pe-Holocene sand, pre-Holocene sandy mud, and pre-Holocene mud.

As seen in transect 5 (Fig. 5), several alternations of marsh deposits and tidal flat/tidal stream deposits are shown. These alternations which were overlooked in previous studies are important indicators of transgressive and regressive events. Ten transgressions and nine regressions were recognized in transect 5 (Fig. 5). T1 indicates the first occurrence of a transgression in these cores of transect 5. ^{14}C dating was conducted for one sample at 383-400 cm in core depth, which is right below the boundary of T4. The date of this sample is 2,130$\pm$90 yrs B.P. Therefore, seven transgressions and six regressions were recognized during the period of about 2,000 years.

DISCUSSION

The selection of the study area is important because the observation of the present environments represents the top part of stratigraphy, resulting from all factors such as local relative sea-level changes, sediment supply, compaction, climate, fluvial activity, local tectonics and isostacy, and biological competition. The boundary among tidal freshwater, slightly brackish, and brackish marsh is more difficult to draw than that between salt marsh and brackish marsh or among subenvironments of salt marsh because more variable and dominant plant species mixed growing adjacently without showing a sharp boundary among them. The nontidal freshwater marsh was not found in the survey area but this might exist farther inland and deeper in the subsurface sediments.

The lower section of the Holocene sedimentary sequences mostly contain freshwater marsh or fluvial deposit, indicating fluvial activity. But the physiographic position and elevation of the pre-Holocene surface are as important as fluvial activity which influenced the distribution of freshwater environments in the subsurface sediments.

The alternation of brackish marsh deposits (and/or slightly brackish marsh deposits and freshwater marsh deposits) and tidal flat/tidal stream deposits (and/or estuary deposits and lagoon deposits) was used to identify transgressions and regressions since tidal marsh deposits are either the leading edge of transgressions or the trailing edge of regressions. Each alternation can be counted as one transgression and one regression. With ^{14}C dating, the precise chronological boundary of multiple transgressions and regressions can be identified for new detailed sea-level curves. A full investigation of new detailed sea-level curves would require hundreds of ^{14}C dates.

The irregular configuration of the pre-Holocene surface within a short distance permitted the development of freshwater marsh and brackish or salt marsh at the same or similar elevation. This complex development of paleoenvironments leads to a difficulty in stratigraphic correlation and interpretation of local relative sea-level changes. The position and elevation of the pre-Holocene surface is very important in understanding the successions of paleoenvironmental changes. The formation and thickness of a particular environment were controlled not only by the distance from the river (either tidal or fluvial) systems or the uplands, but also by the geomorphic features of the pre-Holocene surface. All these complexities can be solved by a detailed work from closely spacing cores which allow a better understanding of variable paleoenvironments during the Holocene Epoch.

The example of three transects, transects 3-5 (Figs. 3-5), shows the evidence of multiple transgressions and regressions. Transect 3 shows only one transgressive event but transect 4 shows five transgressive events and five regressive events and transect 5 contains 10 transgressive events, and 9 regressive events. The sample collected from 383-400 cm in core depth of HY-8-88-G in transect 5 was dated as 2,130±90 yrs B.P. The boundary of this core depth represents R3 and right below T4. Therefore, seven transgressions and six regressions can be identified within about 2,000 years in this transect. This evidence is contradictory with the previous sea-level curve by Kraft (1976). On the other hand, Van Pelt (1991) and Fletcher et al. (1994)'s sea-level fluctuations in Delaware Bay is well related to this evidence.

The numbers of transgressions and regressions were primarily controlled by the geomorphic features of the pre-Holocene surface and the distance from coasts. The distance from the fluvial system also affected these multiple transgressions and regressions. Sediments deposited on the former high interfluves contained few transgressions and regressions because the arrival time of saline-water would be later than those on the former low interfluves and in the paleovalleys. More precise time boundary of the detailed alternation of the brackish marsh and the tidal flat/tidal stream can be only provided by more ^{14}C dates. These can be done in future investigation.

Most of the upper section contain salt marsh which again can be divided into high, middle, and low salt marsh. The major part of the upper stratigraphic section in the study area comprises low salt marsh, which contains *Spartina alterniflora.*

Basal organic sediments, formerly called basal peat, have a similar grain size of the pre-Holocene sediments. Only difference between the basal organic sediments and the pre-Holocene sediments are the thickness and color of these sediments. Hence, the basal organic sediments might be part of the pre-Holocene sediments. Some of the basal organic deposits were formed in early Holocene freshwater environments. This interpretation is possible with the occurrence of the adjacent freshwater marsh, freshwater mudflat, and fluvial deposits. The basal organic deposits mostly have black to dark color. Black or dark color of the basal organic sediments might be related to groundwater influence.

SUMMARY AND CONCLUSIONS

1) Fifteen closely spaced cores along the upper Delaware Bay coast demonstrate the need for revision of some previous interpretations.

2) Several events of transgressions/regressions are identified in some stratigraphic sections. Transect 5 in Bowers Marsh contains ten transgressive events and nine regressive events. Among these, seven transgressions and six regressions occurred during about 2,000 years. These fluctuations of local relative sea-level might occur within the bracket of the continuous local sea-level rise during the Holocene Epoch. The significance and magnitude of sea-level fluctuations can be further investigated with more ^{14}C dating method in the future.

3) Five major divisions of marsh environments were recognized in the stratigraphic sections. They are freshwater marsh, initial freshwater marsh, slightly brackish marsh, brackish marsh, and salt marsh. Except marsh environments, mudflat, tidal flat/ tidal stream, fluvial sand, basal organic sediments, and pre-Holocene sediments were identified.

4) Extensive nontidal freshwater marsh and other wetlands are recognized in the lower part of the Holocene stratigraphy in this study. These sedimentary units were deposited before marine transgressions occurred. Fluvial activity related to freshwater marsh (tidal and nontidal types) has slow-

ly diminished by the saline-water encroachment with respect to local sea-level rises. The interpretation of freshwater marsh as salt marsh by previous workers resulted in paleoenvironmental reconstructions very different from the present report.

5) Tidal flat/tidal stream, which is the succession of fresh marsh and a strong indicator of saline-water intrusion, is predominant and volumetrically the largest sedimentary deposits within the Holocene sedimentary record.

6) The isopach map done by the previous work might need some revisions, especially in the areas of high interfluves. Most of the high interfluves are composed of thinner sedimentary deposits than those reported previously.

7) The morphology of the pre-Holocene surface in coastal areas is a very important control on the thickness and environmental record of Holocene sedimentary sequences. Isolated depressions formed by the pre-Holocene irregular surface within short distances contain the freshwater marsh, while other locations were approached by the saline water.

8) The detailed investigation of coastal environments is imperative because of the complex development of many environments, which are controlled by the position and elevation of the pre-Holocene surface, freshwater input, the rates of local sea-level rise and fall, biological competition, and climate changes during the Holocene Epoch.

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