Sea-level rise acceleration and the drowning of the Delaware Bay coast at 1.8 ka

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ABSTRACT

Cores from Delaware Bay tidal marshes separated by over 100 km reveal correlative transgressive overlap boundaries dated at 1.8 to 2.0 ka. Sedimentary facies at these boundaries that show strong marine influence abruptly (but conformably) overlie facies showing strong terrestrial influence. The transgressive overlap boundaries correlate with a transgression in wetland deposits of the New Jersey shore of Delaware Bay, further suggesting the occurrence of a significant regional sea-level movement. Because other mechanisms (rapid subsidence, autocompaction, rapid lateral erosion by tidal streams, and reduced sediment supply) are less likely, we propose that these transgressive facies transitions were produced by an acceleration in the rate of sea-level rise at 1.8 ka in the Delaware Bay.

INTRODUCTION

Sea-level movements provide one of the dominant controls on the development of coastal landforms and coastal stratigraphic sequences. This fact is evident in current theories of the development of barrier islands, barrier lagoons (Oertel et al., 1992), tidal wetlands, and estuaries (Fletcher et al., 1992) and in leading theories for explaining the current widespread erosion along many of the nation's shorelines (Bruun, 1988; Pilkey and Thieler, 1992). In addition, the stratigraphy of coastal sedimentary sequences is often explained in terms of the competing effects of sea-level movements and sediment supply (Vail et al., 1977); this point of view has been validated over a variety of spatial and temporal scales (Posamentier et al., 1992). Understanding past sea-level movements assumes even greater significance in light of the projected acceleration in rates of coastal submergence caused by global warming (Wigley and Raper, 1992). Although sea-level movements are known to have occurred at various rates through the Holocene (Pirazzoli, 1992), it is still unknown whether the rates projected for the next century (Wigley and Raper, 1992) are in fact physically realistic. Because the economic and environmental impact of future accelerated sea-level rise could be severe, it is extremely important to conduct high-resolution analyses of the geologic record to better determine the potential for future sea-level movements.

The histories of sea-level movement are often complex, and numerous interpretations of sea-level behavior can be found in the literature (Pirazzoli, 1992). Holocene sea-level researchers have produced many local relative sea-level histories, few of which reflect eustasy. The early hope for reconstructing Holocene global sea level has been forestalled by the complex system of local factors that contaminate the record of sea-level history (Emery and Aubrey, 1991).

Comparisons of regional sea-level histories have been more encouraging. For example, radiocarbon dating of basal peats on the subsiding U.S. mid-Atlantic coast has clearly documented a regional pattern of rapid early Holocene sea-level rise, followed by a mid-Holocene deceleration, and a second deceleration prior to ~2 ka (Stuiver and Daddario, 1963; Belknap and Kraft, 1977; Finkelstein and Ferland, 1987; van de Plassche et al., 1989; van de Plassche, 1990) (Fig. 1). All these studies, however, postulate a smoothly decelerating rate of sea-level rise during the Holocene for the mid-Atlantic region.

Several researchers working on circum-Atlantic coasts have suggested more complex Holocene sea-level histories that involve higher-frequency fluctuations in the rate of sea-level rise superimposed on the average pattern of Holocene submergence. These include studies of local relative sea-level movements in the Netherlands (van de Plassche, 1982), Great Britain (Shennan, 1986), South Carolina (Gayes et al., 1992), Connecticut (van de Plassche, 1991; Varekamp et al., 1992), and Fennoscandia (Morner, 1976). Furthermore, a detailed study of Wolfe Glade, a salt marsh located behind Cape Henlopen near the Delaware Atlantic coast (Fig. 2), has revealed repeated transgressions and regressions that suggest a history of short-term fluctuations in the local rate of sea-level rise (Fletcher et al., 1991, unpublished data).

Tidal wetlands are strongly influenced by local factors not necessarily related to regional sea level, including variations in sediment supply, tidal channel processes, compaction, and the supply of freshwater from the upland drainage basin. As a result, a stratigraphic record of repeated transgressions and regressions in tidal wetland deposits cannot be interpreted in terms of regional sea-level movements unless (1) these other factors can be discounted and (2) the transgressions and regressions can be correlated over a wide area.

GEOLOGIC SETTING AND STRATIGRAPHIC METHODS

Salt marshes and other tidal wetlands of the U.S. mid-Atlantic region occupy former fluvial valleys and interfluves that have been flooded by the late Wisconsin and Holocene sea-level rise (Kraft, 1971). The stratigraphy of these marshes consists of facies from marsh subenvironments and adjacent upland and subtidal (marine)

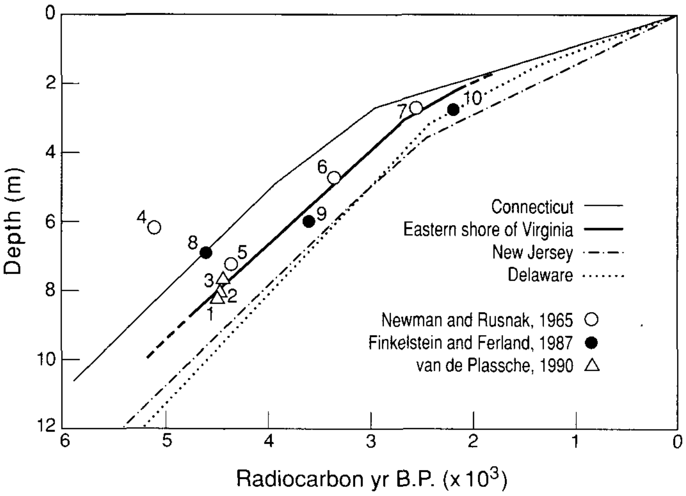

Figure 1. Mid-Atlantic Holocene sea-level histories (after van de Plassche, 1990).

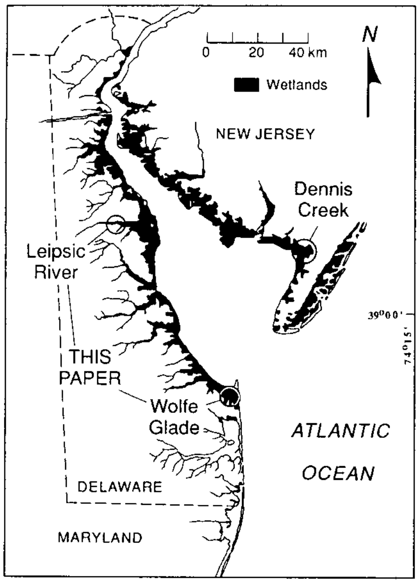

Figure 2. Site locations where 1.8 ka transgressive overlap boundary has been observed in marsh cores: Wolfe Glade and Leipsic River, Delaware, and Dennis Creek, New Jersey (Meyerson, 1972).

subenvironments that indicate specific elevational ranges relative to paleo–mean low water (van de Plassche, 1991). Cores from within single marsh systems often reveal correlative lithostratigraphic units that may display repeated transgressive and regressive facies contacts, often recognizable throughout the marsh.

Facies contacts where sediment from a more marine-influenced environment overlies sediment from a less marine-influenced environment have been termed transgressive overlap boundaries and the reverse strata termed regressive overlap boundaries by van de Plassche (1991). Both types of boundary contacts may be either abrupt or gradational depending on the relative rates of sea-level change and sedimentation within the marsh. Relative sea-level trends interpreted from these correlative, intramarsh records reflect marine tendencies. A transgressive overlap boundary records a positive marine tendency, where the rate of sea-level rise exceeds the rate of marsh sedimentation. A regressive overlap boundary records a negative marine tendency, where the rate of marsh sedimentation exceeds the rate of sea-level rise. Whether the relative sea-level changes recorded in a single marsh result from regional sea-level movements (i.e., "geoidal eustasy," Morner, 1976), as opposed to local, site-specific effects, can be established only by regional correlation of dated overlap boundaries. Once a regional correlation has been established, the record of dated overlap boundaries will define a regionally synchronous marine tendency that can then be interpreted in terms of regional forcing mechanisms.

Wolfe Glade, Delaware

Within wetland deposits of Wolfe Glade, terrestrial sediments are generally peats or muddy peats containing freshwater microfauna and flora, but which have a reduced sand content (except for fluvial-channel and interfluvial, highland deposits), lower bulk sedimentary iron content (Varekamp, 1991) and high loss-on-ignition values. Marine sediments preserved in this system exhibit decreased loss-on-ignition values, high bulk iron content, halophytic plant fragments, marine microfauna and microflora, and in many cases shell fragments and a sandy matrix (Fletcher et al., 1991, unpublished data).

Cores of Wolfe Glade sediments have revealed a relative sea-level history characterized by at least five transgressive overlap boundaries. These boundaries represent five accelerations in the rate of sea-level rise relative to marsh sedimentation rate. The youngest of these boundaries observed at Wolfe Glade, T_6 (Fig. 3), is dated at 1.8 ±0.2 ka (Fletcher et al., 1991, unpublished data). Four calibrated radiocarbon dates provide limits for the chronology of this event (Table 1): (1) sample GX-15835 (1.850–2.339 ka) from a palustrine marsh peat overlain by gray silty mud deposited in a low marsh (modern elevation differences of these subenvironments suggest that this contact represents a minimum 0.5 m rise in relative sea level); (2) sample GX-16214 (1.540–1.880 ka) from a palustrine marsh peat overlain by gray clayey mud with marine mollusk fragments and (rare) plant fragments deposited below mean low water (a minimum 1.0 m rise in relative sea level); (3) sample GX-16221 (1.620–2.029 ka) from a palustrine marsh peat overlain by gray clayey mud with *Spartina alterniflora* fragments deposited on a subtidal flat or low marsh (a minimum 0.5–0.7 m rise in relative sea level); and (4) sample GX-16220 (1.560–2.149 ka) from *Spartina alterniflora* fragments deposited in a low marsh or on a subtidal flat overlying the palustrine peat of GX-16221, which thus postdates the transgression.

Leipsic River Valley, Delaware

The Holocene deposits of freshwater and brackish reaches of the tidal Leipsic River (Pizzuto and Rogers, 1992) record a transgressive episode dated at ~1.8 ka (Table 1). Cores from a transect across the Alston Branch, a tributary of the Leipsic River (Fig. 3), show that basal freshwater fluvial sand, mud, and peat are overlain by an extensive muddy unit deposited in a marine subtidal environment. Above this, continued peat deposition records the return to palustrine conditions following the transgression. The transgressive overlap boundary marking the marine rise can be correlated through six cores (Fig. 3). Although not shown here, cores from upstream and downstream of this site record the same muddy unit in an identical stratigraphic position. The mud is interpreted as a transitional marine facies on the basis of its lithology and the presence of brackish diatoms (Sherman, 1992, unpublished data). Pizzuto and Rogers (1992) have demonstrated that the peat deposits of the area are characteristic of palustrine environments.

A peat sample from below the muddy unit has a calibrated sidereal age of 1.891–2.060 ka (Table 1). This demonstrates that the transgressive overlap boundary at the base of the marine mud correlates remarkably well with the T_6 event defined at Wolfe Glade. Further evidence of a correlative age is provided by an additional date from a core located upstream of the cross section shown in Figure 3 where the transgressive overlap boundary is dated at 1.720–1.930 ka (Table 1).

Dennis Creek, New Jersey

Meyerson (1972), studying the history of the Dennis Creek marsh in New Jersey, took 17 cores and performed detailed lithologic, pollen, and paleosalinity analyses. The cores showed repeated alternating lithologies that are qualitatively similar to those of Wolfe Glade. Furthermore, paleosalinity and pollen data indicate a history of repeated transgressions and regressions. The most dramatic transition revealed in the cores was interpreted by Meyerson (1972) as a major transgression that occurred at ~1.8 ka. This event correlates with the T_6 event defined at Wolfe Glade and also observed at the Leipsic River.

As shown in Figure 3, lithofacies between three cores at Dennis Creek were correlated by Meyerson (1972) to reflect a "major transgression of the sea . . . at around 1800 years B.P." Core 6, the seawardmost core, displays a marked transgressive overlap boundary at −3.7 m where a high-marsh facies is overlain by a subtidal mud, reflecting a minimum local relative sea-level rise of 0.7 to 1.0 m. A date of 2.150 ka (±110 ^{14}C yr) was reported by Meyerson (1972) from deeper in core 6 at a depth of ~7 m. Core 8 contained a distinct transgressive overlap boundary where high-marsh brown peat is overlain by low-marsh facies. However, these are shortly overlain, in turn, by high-marsh peats that were dated at 1.335 ka (±95 ^{14}C yr). The transgression at 1.8 ka was so extensive, according to Meyerson

(1972), that the landwardmost site (core 16) was influenced by a raised water table and developed into a palustrine marsh. A date from core 16 directly above the contact of the newly formed freshwater marsh and the underlying basal sands places the transgressive episode prior to 1.760 ka (±120 ^{14}C yr).

DISCUSSION AND CONCLUSIONS

The regionally correlative transgression in tidal wetland deposits of Delaware Bay could have been caused by the following processes: (1) laterally migrating tidal streams, (2) autocompaction, (3) short-term increases in the rate of regional subsidence, (4) reduction in sediment supply, and (5) an acceleration in the rate of regional relative sea-level rise.

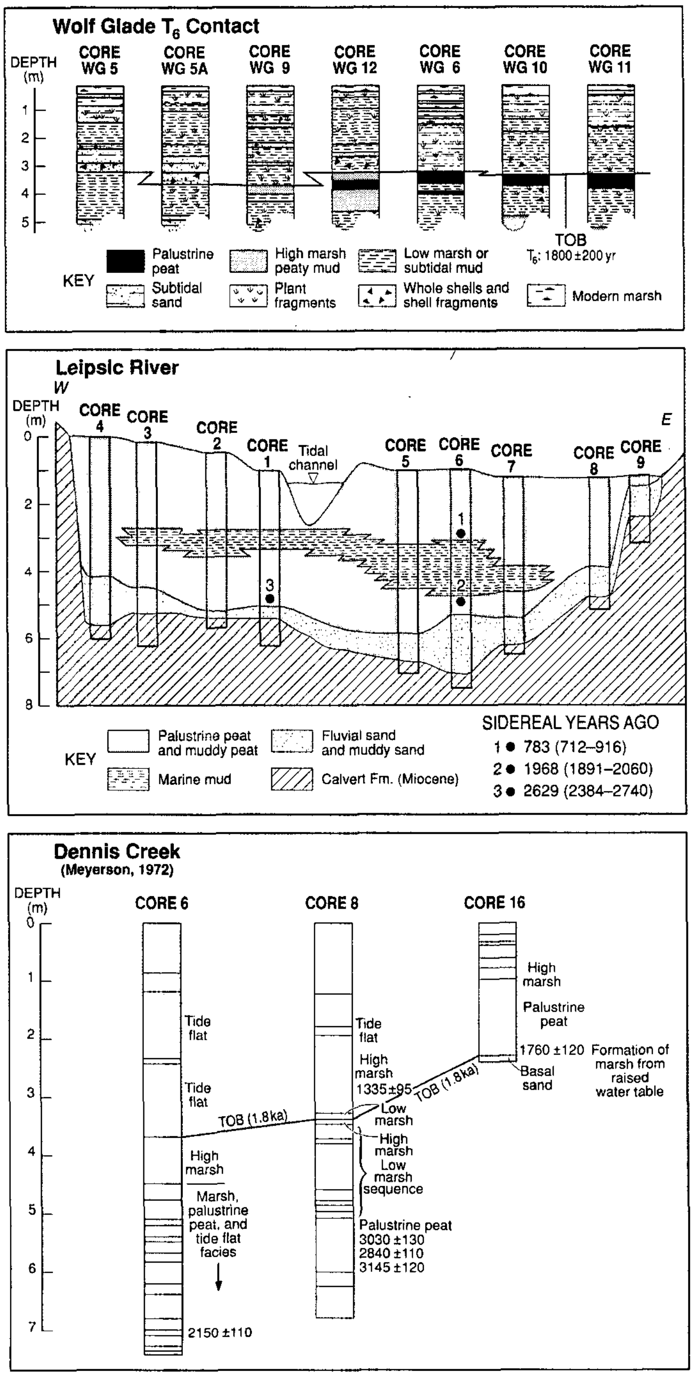

Figure 3. Cross sections of marshes where the acceleration at 1.8 ka has been discovered. TOB—transgressive overlap boundary.

Laterally migrating tidal streams could create transgressive contacts in tidal wetland deposits. Contacts caused by this process would be erosional surfaces overlain by tidal-channel facies. Although we have observed such contacts in some of our cores, the transgressive overlap boundaries described here do not show evidence of erosion. Rather they appear as drowning events represented by rapid, conformable facies transitions with frequently preserved vertical plant stems and roots at the contact. Additional evidence against lateral migration as an explanation for the observed transgressive overlap boundaries includes the following: (1) modern rates of lateral migration by tidal streams in these wetlands are very low (Garofalo, 1980); (2) many cores of tidal-stream facies presented by others (e.g., Chrzastowski, 1986) indicate little lateral movement of tidal channels over periods of thousands of years, and (3) transgressive overlap boundaries caused by lateral migration should not be regionally correlative.

Autocompaction (Kaye and Barghoorn, 1964; Bloom, 1964; Belknap, 1975; Allen, 1978) and subsidence (Davis, 1987; Holdahl and Morrison, 1974) can clearly influence local relative rates of sea-level rise. However, deposits of widely varying thickness and lithology should not undergo synchronous accelerated rates of autocompaction. A rapid acceleration in rates of regional subsidence is also unlikely, as these processes operate on longer time scales than those considered here.

A regional transgression could also be caused by a regional reduction in the amount of sediment available for vertical accretion in tidal marshes. Coastal plain estuaries, however, are strongly insulated from changes in sediment yield in their watersheds. Phillips (1991), for example, has estimated that nearly all of the sediment produced in the Pee Dee watershed is stored well upstream of the estuary. Furthermore, coastal plain tributaries to Delaware Bay carry little sediment (Mansue and Commings, 1974), so changes in the sediment yield of local tributaries such as the Leipsic River are unlikely to have had a substantial influence on marsh evolution. Thus, a regional decrease in sediment supply at 1.8 ka is not a likely cause of the regional transgression described here. We observe, however, that detailed pollen analyses and a regional paleoclimatic history of the Delmarva Peninsula would help to clarify this issue further.

Having rejected other possible mechanisms, we propose that the most likely cause of the transgressions described here was an acceleration in the rate of regional sea-level rise in Delaware Bay at 1.8 ka. We also observe that this transgressive event may have occurred over an even larger area: van de Plassche (1991) and Varekamp et al. (1992) have presented stratigraphic evidence for the transgressive drowning of salt marshes in Connecticut at ~1.8 ka. Finally, we note that although the mechanism responsible for such short-term increases in the rate of sea-level rise is unknown,

TABLE 1. RADIOCARBON DATES RELEVANT TO TRANSGRESSIVE CONTACT

Sample no.	Sample type (location*)	^{14}C age	Calibrated age
Wolfe Glade			
GX-15835	Palustrine peat (below TOB)	2095 +/-205	2074 (1850-2339)
GX-16214	Palustrine peat (below TOB)	1775 +/-150	1716 (1540-1880)
GX-16221	Palustrine peat (below TOB)	1885 +/-170	1843 (1620-2029)
GX-16220	*Spartina alterniflora* (above TOB)	1910 +/-245	1864 (1560-2149)
Leipsic River			
AB91-4-1-405-409	Basal palustrine peaty mud	2480 +/-80	2629 (2384-2740)
AB91-4-6-369-374	Palustrine peat (below TOB)	2010 +/-70	1968 (1891-2060)
AB91-4-6-202-208	Woody peat (above marine unit)	880 +/-80	783 (712-916)
AB91-3-2-250-252	Palustrine peat (below TOB)	1880 +/-100	1838 (1720-1930)
Dennis Creek (after Meyerson, 1972)			
	Palustrine peat (above TOB)	1760 +/-120	n/a
	High marsh peat (above TOB)	1335 +/-95	n/a
	Basal low marsh plant fragments (?)	2150 +/-110	n/a

*TOB—transgressive overlap boundary.

Varekamp et al. (1992) and Fletcher et al. (unpublished) correlated similar sea-level movements with climatic changes as recorded in Northern Hemisphere neoglaciations, and they further suggested that changes in the surface topography of the Atlantic Ocean related to Gulf Stream dynamics such as meandering (Varekamp et al., 1992) or accelerations and decelerations in the current (Fletcher et al., unpublished; Fairbridge, 1992) could provide a potential (though speculative) mechanism for producing regional, climatically driven short-term variations in the rate of sea-level rise.

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REFERENCES CITED

Allen, E.A., 1978, Petrology and stratigraphy of Holocene coastal-marsh deposits along the western shore of Delaware Bay [Ph.D. thesis]: Newark, University of Delaware, 287 p.

Balknap, D.F., 1975, Dating of late Pleistocene and Holocene relative sea levels in coastal Delaware [M.S. thesis]: Newark, University of Delaware, 95 p.

Belknap, D.F., and Kraft, J.C., 1977, Holocene relative sea-level changes and coastal stratigraphic units on the northwest flank of the Baltimore Canyon Trough geosyncline: Journal of Sedimentary Petrology, v. 47, p. 610–629.

Bloom, A.L., 1964, Peat accumulation and compaction on a Connecticut coastal marsh: Journal of Sedimentary Petrology, v. 39, p. 599–603.

Bruun, P., 1988, The Bruun Rule of erosion by sea-level rise: A discussion on larger-scale two- and three-dimensional usages: Journal of Coastal Research, v. 4, p. 627–648.

Chrzastowski, M.J., 1986, Stratigraphy and geologic history of a Holocene lagoon system: Rehoboth Bay and Indian River Bay, Delaware [Ph.D. thesis]: Newark, University of Delaware, 337 p.

Davis, G.H., 1987, Land subsidence and sea-level rise on the Atlantic Coastal Plain of the United States: Environmental Geology and Water Science, v. 10, p. 67–80.

Emery, K.O., and Aubrey, D.G., 1991, Sea levels, land levels, and tide gauges: New York, Springer-Verlag, 237 p.

Fairbridge, R.W., 1992, Holocene marine coastal evolution of the United States, *in* Fletcher, C.H., and Wehmiller, J.F., eds., Quaternary coasts of the United States: Marine and lacustrine systems: SEPM Special Publication 48, p. 9–20.

Finkelstein, K., and Ferland, M.A., 1987, Back-barrier response to sea-level rise, eastern shore of Virginia, *in* Nummedal, D., et al., eds., Sea-level fluctuation and coastal evolution: Society of Economic Geologists and Paleontologists Special Publication 41, p. 145–155.

Fletcher, C.H., Van Pelt, J.E., Sherman, J., and Brush, G.S., 1991, High resolution sea-level and climate history of the middle to late Holocene from wetland sediments of Delaware Bay: Geological Society of America Abstracts with Programs, v. 23, no. 5, p. A352.

Fletcher, C.H., Knebel, H.J., and Kraft, J.C., 1992, Holocene depocenter migration and sediment accumulation in Delaware Bay: A submerging marginal marine sedimentary basin: Marine Geology, v. 103, p. 165–183.

Garofalo, D., 1980, The influence of wetland vegetation on tidal stream migration and morphology: Estuaries, v. 3, p. 258–270.

Gayes, P.T., Scott, D.B., Collins, E.S., and Nelson, D.D., 1992, A late Holocene sea-level fluctuation in South Carolina, *in* Fletcher, C.H., and Wehmiller, J.F., eds., Quaternary coasts of the United States: Marine and lacustrine systems: SEPM Special Publication 48, p. 155-160.

Holdahl, S.R., and Morrison, N.L., 1974, Regional investigations of vertical crustal movements in the U.S. using precise relevelings and mareograph data: Tectonophysics, v. 23, p. 373–390.

Kaye, C.A., and Barghoorn, E.S., 1964, Late Quaternary sea-level change and crustal rise at Boston, Massachusetts, with notes on the autocompaction of peat: Geological Society of America Bulletin, v. 75, p. 63–80.

Kraft, J.C., 1971, Sedimentary facies patterns and geologic history of a Holocene marine transgression: Geological Society of America Bulletin, v. 82, p. 2131–2158.

Mansue, L.J., and Commings, A.B., 1974, Sediment transport by streams draining into the Delaware Estuary: U.S. Geological Survey Water-Supply Paper 1532-H, 10 p.

Meyerson, A.L., 1972, Pollen and paleosalinity analyses from a Holocene tidal marsh sequence, Cape May County, New Jersey: Marine Geology, v. 12, p. 335–357.

Morner, N.A., 1976, Eustatic changes during the last 8000 years in view of radiocarbon calibration and new information from the Kattegat region and other northern European coastal areas: Palaeogeography, Palaeoclimatology, Palaeoecology, v. 19, p. 63–85.

Newman, W.S., and Rusnak, G.A., 1965, Holocene submergence of the eastern shoreline of Virginia: Science, v. 148, p. 1464–1466.

Oertel, G.F., Kraft, J.C., Kearney, M.S., and Woo, H.J., 1992, A rational theory for barrier lagoon development, *in* Fletcher, C.H., and Wehmiller, J.F., eds., Quaternary coasts of the United States: Marine and lacustrine systems: SEPM Special Publication 48, p. 77–87.

Phillips, J.D., 1991, Fluvial sediment delivery to a Coastal Plain estuary in the Atlantic drainage basin of the United States: Marine Geology, v. 98, p. 121–134.

Pilkey, O.H., and Thieler, E.R., 1992, Erosion of the United States Shoreline, *in* Fletcher, C.H., and Wehmiller, J.F., eds., Quaternary coasts of the United States: Marine and lacustrine systems: SEPM Special Publication 48, p. 3–7.

Pirazzoli, P.A., 1992, World atlas of Holocene sea-level changes: Amsterdam, Elsevier, 300 p.

Pizzuto, J.E., and Rogers, E.W., 1992, The Holocene history and stratigraphy of palustrine and estuarine wetland deposits of central Delaware: Journal of Coastal Research, v. 8, no. 4 (in press).

Posamentier, H.W., Allen, G.P., and James, D.P., 1992, High-resolution sequence stratigraphy—The east Coulee Delta, Alberta: Journal of Sedimentary Petrology, v. 62, p. 310–317.

Shennan, I., 1986, Flandrian sea-level in the Fenland: I—The geographical setting and evidence of relative sea-level changes: Journal of Quaternary Science, v. 1, p. 119–154.

Stuiver, M., and Daddario, J.J., 1963, Submergence of the New Jersey coast: Science, v. 142, p. 451.

Vail, P.R., Mitchum, R.M., Jr., and Thompson, S., III, 1977, Seismic stratigraphy and global changes of sea level from coastal onlap, *in* Payton, C.E., ed., Seismic stratigraphy—Applications to hydrocarbon exploration: American Association of Petroleum Geologists Memoir 26, p. 63–81.

van de Plassche, O., 1982, Sea-level change and water-level movements in the Netherlands during the Holocene: Mededelingen Rijks Geologische Dienst, v. 36, 93 p.

van de Plassche, O., 1990, Mid-Holocene sea-level change on the eastern shore of Virginia: Marine Geology, v. 91, p. 149–154.

van de Plassche, O., 1991, Late Holocene sea-level fluctuations on the shore of Connecticut inferred from transgressive and regressive overlap boundaries in salt-marsh deposits: Journal of Coastal Research Special Issue 11, p. 159–179.

van de Plassche, O., Mook, W.G., and Bloom, A.L., 1989, Submergence of coastal Connecticut 6000–3000 (^{14}C) years B.P.: Marine Geology, v. 86, p. 349–354.

Varekamp, J.C., 1991, Trace element geochemistry and pollution history of mudflat and marsh sediments from the Connecticut coastline: Journal of Coastal Research Special Issue 11, p. 105–123.

Varekamp, J.C., Thomas, E., and van de Plassche, O., 1992, Relative sea-level rise and climate change over the last 1500 years: Terra Nova Special Issue on Global Change, v. 4, p. 293–304.

Wigley, T.M.L., and Raper, S.C.B., 1992, Implications for climate and sea level of revised IPCC emissions scenarios: Nature, v. 357, p. 293–300.

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