



Rapid Holocene coastal change revealed by high-resolution micropaleontological analysis, Pamlico Sound, North Carolina, USA

Candace Grand Pre ^{a,b}, Stephen J. Culver ^{a,*}, David J. Mallinson ^a, Kathleen M. Farrell ^c, D. Reide Corbett ^{a,d}, Benjamin P. Horton ^b, Caroline Hillier ^e, Stanley R. Riggs ^a, Scott W. Snyder ^a, Martin A. Buzas ^f

^a Department of Geological Sciences, East Carolina University, Greenville, NC 27858, USA

^b Sea Level Research Laboratory, Department of Earth and Environmental Science, University of Pennsylvania, Philadelphia, PA 19104, USA

^c North Carolina Geological Survey, Raleigh Field Office and Core Repository, MSC 1620, Raleigh, NC 27699, USA

^d Institute for Coastal Science and Policy, East Carolina University, Greenville, NC 27858, USA

^e Argos Ecology Ltd, Annfield Plain, Durham, DH9 7XN, UK

^f Department of Paleobiology, National Museum of Natural History, Smithsonian Institution, Washington, D.C., 20560, USA

ARTICLE INFO

Article history:

Received 15 September 2010

Available online 5 August 2011

Keywords:

Foraminifera

Diatoms

Holocene

Paleoenvironments

ABSTRACT

Foraminiferal analyses of 404 contiguous samples, supported by diatom, lithologic, geochronologic and seismic data, reveal both rapid and gradual Holocene paleoenvironmental changes in an 8.21-m vibracore taken from southern Pamlico Sound, North Carolina. Data record initial flooding of a latest Pleistocene river drainage and the formation of an estuary 9000 yr ago. Estuarine conditions were punctuated by two intervals of marine influence from approximately 4100 to 3700 and 1150 to 500 cal yr BP. Foraminiferal assemblages in the muddy sand facies that accumulated during these intervals contain many well-preserved benthic foraminiferal species, which occur today in open marine settings as deep as the mid shelf, and significant numbers of well-preserved planktonic foraminifera, some typical of Gulf Stream waters. We postulate that these marine-influenced units resulted from temporary destruction of the southern Outer Banks barrier islands by hurricanes. The second increase in marine influence is coeval with increased rate of sea-level rise and a peak in Atlantic tropical cyclone activity during the Medieval Climate Anomaly. This high-resolution analysis demonstrates the range of environmental variability and the rapidity of coastal change that can result from the interplay of changing climate, sea level and geomorphology in an estuarine setting.

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Introduction

An understanding of the Holocene evolution of coastal regions is of fundamental importance when projecting the effects of climate change into the future. Such is the case for the Outer Banks barrier islands of North Carolina (Fig. 1A), a natural resource, along with the sounds and wetlands behind them, upon which the state's coastal economy of tourism and recreational and commercial fisheries is largely based.

Recent multidisciplinary research (e.g., Riggs and Ames, 2003; Culver et al., 2007, 2008; Mallinson et al., 2008, 2010a,b; Horton et al., 2009; Kemp et al., 2009a) has demonstrated the considerable changes in coastal configuration that have characterized the Outer Banks region over the past 10,000 yr. Sea level has risen ca. 35 m during that period, at first rapidly at approximately 5 mm/yr and then, from ca. 4000 yr

ago until the beginning of the 20th century, at a much slower rate of ca. 1 mm/yr (Horton et al., 2009; Kemp et al., 2009a). The initial rapid rise flooded a late Pleistocene drainage system and these estuarine waters were later cut off from the Atlantic Ocean by the Holocene formation of the Outer Banks barrier islands (Mallinson et al., 2008). At the end of the 19th century the rate of relative sea-level rise tripled to ca. 3 mm/yr (Kemp et al., 2009a). It is anticipated that the 20th century rate of relative sea-level rise will be exceeded in the 21st century during a period of climate warming (IPCC, 2007) with possible increased frequency and intensity of hurricane activity in the western Atlantic (e.g., Knutson et al., 2010). Thus, further changes to the coastal system are to be expected in the future.

Reconstruction of Holocene coastal environmental change is enhanced through the actualistic application of various microfossil groups, particularly foraminifera, diatoms and pollen (e.g., Cronin et al., 1999). However, for logistical reasons, few micropaleontological studies of estuarine deposits (e.g., Karlson et al., 2000; Cronin et al., 2000) have employed a high-resolution approach. We report here the high-resolution foraminiferal and associated diatom data from an 8.21 m vibracore (PS03) taken in southern Pamlico Sound, North Carolina (Fig. 1A). We compare these datasets and their paleoenvironmental

* Corresponding author. Fax: +1 252 328 4391.

E-mail address: culvers@ecu.edu (S.J. Culver).

signals, comment on post-depositional processes that might obscure details of the record of environmental change, document two intervals of rapid coastal environmental change, postulate the likely agent of these changes, and indicate possible future changes to the North Carolina coast in the context of these data.

Study area

Pamlico Sound (Fig. 1A), part of the second-largest estuarine system in the contiguous United States, is 100–140 km long and 35 to 50 km wide and covers approximately 4350 km² (Pietrafesa et al., 1986). This estuary is bordered by Hatteras, Ocracoke, and Portsmouth islands, together constituting the Outer Banks. Three low-brackish estuaries drain into the Sound (Pietrafesa et al., 1986) and three inlets connect it to the Atlantic. Astronomical tides in Pamlico Sound are negligible (Riggs and Ames, 2003), wind tides being the predominant driver of circulation (Wells and Kim, 1989). Normal wind tides are generally less than 0.3 m, while storm tides may elevate the water level by 1 m to 1.5 m, and, rarely, up to 3 m during major hurricanes (Pilkey et al., 1998). The salinity of the sound ranges from 0.5 at the rivers to 36 at the inlets with an average of 20 (Wells and Kim, 1989).

The geologic framework has a direct influence on the morphology and dynamics of the modern barrier island/estuarine system (Riggs et al., 1995). Pamlico Sound overlies a drowned river valley (Pamlico Creek) (Riggs and Ames, 2003; Mallinson et al., 2010a) which, in the latest Pleistocene and early Holocene, accumulated fluvial sediments until post-glacial sea-level rise flooded the valley and estuarine conditions prevailed (Riggs and Ames, 2003; Culver et al., 2007). Figure 1B illustrates the drainages of Pamlico Creek and the paleo-Neuse and paleo-Tar-Pamlico rivers based on seismic data (Mallinson et al., 2010a). The modern northern barrier islands are perched upon a Pleistocene high while the southern barrier islands are immediately offshore of the Hatteras Flats inter-stream divide (HFID) (Riggs et al., 1995; Mallinson et al., 2010a).

Methods

Decimeter-scale micropaleontological and sedimentological analyses of more than 100 vibracores and several much longer (up to 68 m) rotasonic cores in southern Pamlico Sound and the adjacent Outer Banks barrier islands (Fig. 1) provide an understanding of the Holocene evolution of this region (Abbene et al., 2006; Culver et al., 2006, 2008; Rosenberger et al., 2006; Twamley et al., 2006; Hale et al., 2007). Vibracores (up to 9 m in length) are stored in the core repository of the Department of Geological Sciences at East Carolina University and rotasonic cores are stored in the North Carolina Geological survey core repository. Core PS03, taken in 6.5 m of water in southeastern Pamlico Sound (Fig. 1), was chosen based on its length (8.21 m) and location (in the Pamlico Creek thalweg), for a high-resolution (centimeter-scale) micropaleontological study in an attempt to tease out greater detail of Holocene environmental change.

Foraminifera

Four hundred and four contiguous 2-cm samples from PS03 were dried, weighed, disaggregated through soaking, and washed over a 63-micron sieve to remove silt and clay. The sand fraction was dried, weighed and planktonic and benthic foraminifera were concentrated using sodium polytungstate floatation (Munsterman and Kerstholt, 1996). In studies of foraminiferal assemblages, 300 specimens per sample are often picked (Buzas, 1990). However, for this high-resolution marginal marine study, where species diversity is low and many samples are to be analyzed, 100 specimens per sample were picked. Similar studies have shown that this number is sufficient to provide meaningful results (Cronin et al., 2000; Karlson et al., 2000). Identifications of foraminifera were confirmed via comparison with type specimens lodged in the Smithsonian Institution.

Q-mode cluster analysis (Mello and Buzas, 1968), utilized to recognize patterns in the data, included only those taxa ($n=25$) that composed 2% or more of the assemblage in any one sample; that is, rare taxa were excluded. Planktonic foraminifera were included in the analysis as a single, grouped taxon. Two analyses were run on the 259 samples that contained foraminifera: (1) a stratigraphically constrained analysis (samples considered in strict stratigraphic order) was run in CONISS on transformed abundances [$2\arcsin \sqrt{p}$ (p = proportional abundance)] based on unweighted Euclidean distances; and (2) an unconstrained analysis (samples clustered regardless of stratigraphic order) was run on transformed abundances in SYSTAT using Ward's linkage and Euclidean distances. In addition, values for Fisher's alpha, a measure of species diversity, were obtained for each sample from tabulations in Hayek and Buzas (1997).

Diatoms

The top meter of PS03 was sampled at 4-cm intervals, the remainder at 12 cm intervals. Diatom sample preparation followed Zong and Horton (1999) and valves were identified by reference to Hendey (1964) and van der Werff and Huls (1958–1966). Species nomenclature follows Hartley (1986), and ecological classification was based on Hudstedt (1953, 1957), Denys (1991, 1992), Vos and de Wolf (1993) where polyhalobous equates to fully marine; mesohalobous to brackish water; oligohalobous–halophilous to brackish–fresh; oligohalobous indifferent to fresh–brackish; and halophobous to fresh water. A stratigraphically constrained cluster analysis was run in CONISS on transformed abundances [$2\arcsin \sqrt{p}$ (p = abundance)] based on unweighted Euclidean distances. The analysis included only those taxa ($n=40$) that constituted 2% or more of the assemblage in any one sample.

Sedimentology

The core was logged for texture, bounding surfaces, and other sedimentologic and biogenic attributes using a modification of Folk's (1980) approach. A graphic log was produced using a process-based method that determines grain size independently from composition. The graphic log for PS03 provides a continuous record of textural parameters such as principal grain-size class and relative percentages of gravel, sand and mud (G:S:M) size fractions. In conjunction with symbols that depict bounding surfaces and attribute symbols, these help define a process-based event stratigraphy.

Age estimates

Accelerator Mass Spectrometry (AMS) dating on calcareous foraminiferal tests was implemented near distinct lithologic boundaries. Each of six samples was composed of approximately 1000 specimens of *Elphidium excavatum*. Only well-preserved specimens were picked from assemblages comprising small to large specimens. Thus, the specimens were not present as size-sorted sedimentary particles, but rather the specimens were picked from what were most likely in situ populations. A sample of organic-rich clay from near the base of the core provided a bulk conventional C-14 age estimate. Radiocarbon and stratigraphic information were calibrated using OxCal (ver. 3.10) (Bronk Ramsey, 2005), the AMS estimates were calibrated using the marine04.14c data set (Hughen et al., 2004), and the bulk-carbon sample was calibrated using intcal04.14c (Reimer et al., 2004). The marine calibration dataset incorporates a time-dependent global ocean reservoir correction of about 400 yr. The absolute chronology should be treated with caution due to local spatio-temporal variations in the ΔR (Southon et al., 2002).

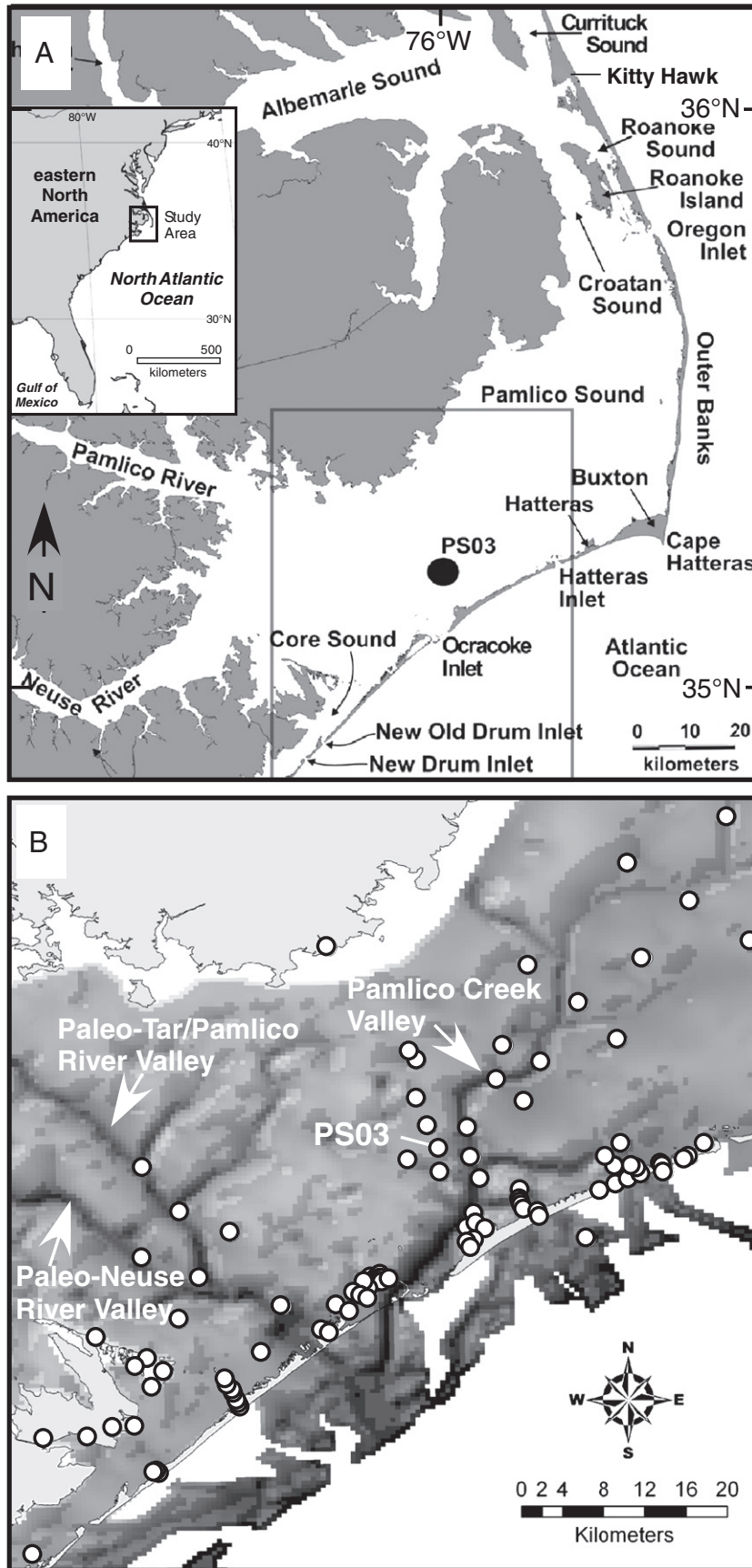


Figure 1. A, Map of the Albemarle-Pamlico estuarine system (APES) in North Carolina showing the location of vibracores including PS03 (large black dot; latitude 35.183972°N, longitude 76.013361°W) and long rotasonic cores (small black dots). Box indicates area of Figure 1B. B, Map (based on seismic data; Mallinson and others, 2010a) of the paleodrainages of the last glacial maximum river systems showing the location of vibracores, including vibracore PS03 near the thalweg of Pamlico Creek.

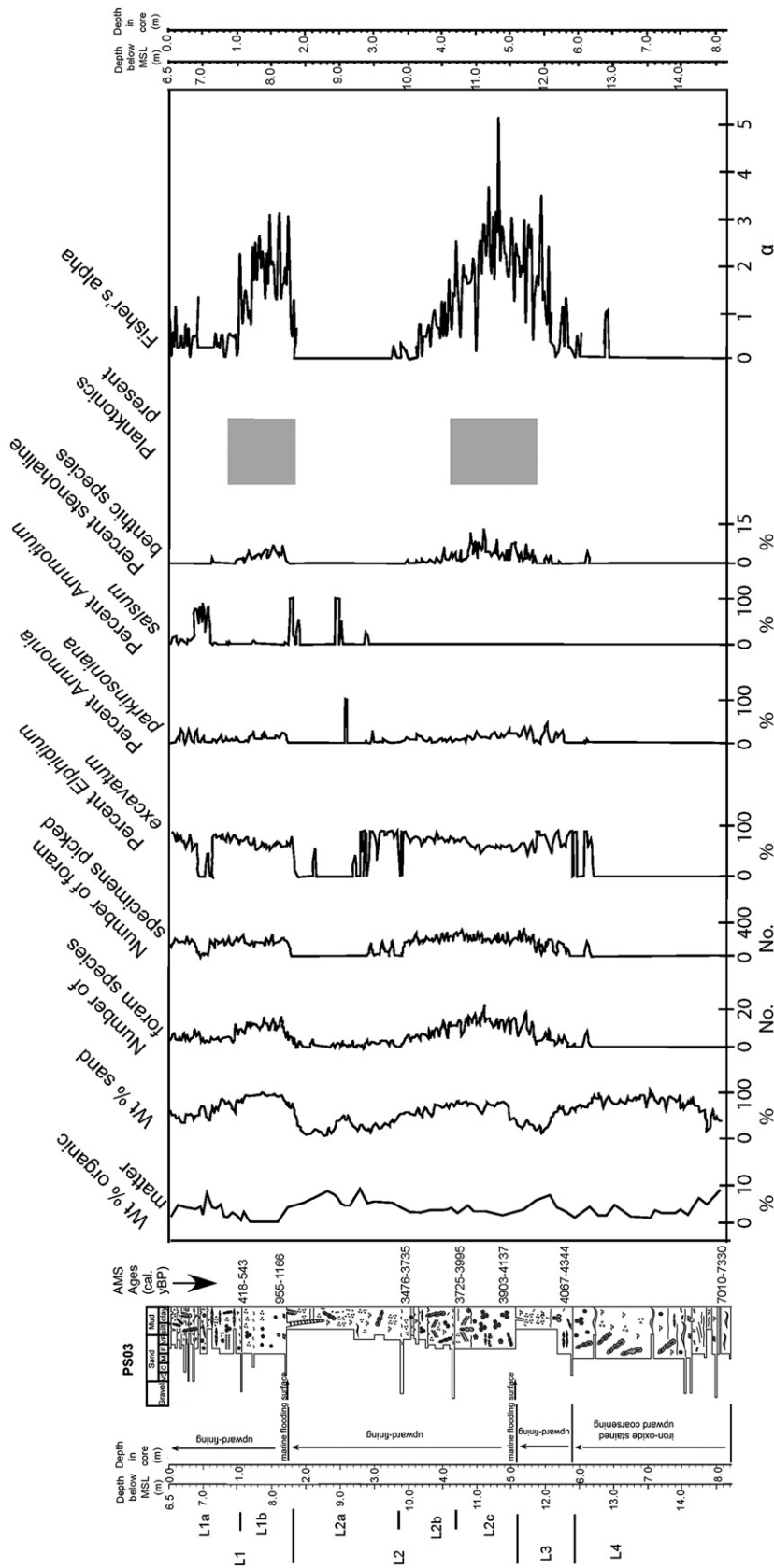


Figure 2. Lithologic log of vibracore PS03. Lithologic units (L1–4), calibrated AMS radiocarbon ages on *Elphidium excavatum* samples and a conventional age on bulk organic matter are shown. Weight percent organic matter, percent sand, summary foraminiferal data, and percents of dominant foraminiferal taxa are plotted adjacent to the log. Values for Fisher's alpha, a measure of species diversity, are shown for all samples containing foraminifera. Key to symbols in lithologic log is given in Fig. 5.

Results and paleoenvironmental interpretations

Sedimentary log and radiocarbon age estimates

Vibracore PS03 includes four mud-rich burrowed units, with little preserved primary stratification (L4–L1, Fig. 2). Color ranges from dark gray muds to light gray muddy sand. Muddy beds have a blocky, massive appearance with a pervasive pelletal fabric cross-cut by larger-scale, mud-lined burrows. The basal unit, L4, (8.21 to 5.88 m) is incomplete but apparently coarsens upward. L4 is overlain by three upward-fining units (L3–L1; Fig. 2). Contacts between units are marked by abrupt changes in grain size and mud content, and downward extending burrows. Thin (<1 cm) lags of coarse to very coarse sand, or gravel-sized clasts that include quartz, whole or broken shells, or muddy intraclasts commonly overlie contacts.

L4 commences with thin (ca. 2 cm) wavy interbeds of sand, mud, and shell-hash gravel overlain by thicker beds of burrowed, muddy medium sand with mud drapes separating beds. A conventional ^{14}C age estimate on bulk organic matter from 8.19 to 8.09 m is 7330–7010 cal yr BP (Table 1; Fig. 2).

Above its basal lag, L3 (5.88 to 5.06 m) is ca. 20 cm of fine, muddy sand cross-cut by large-scale mud-lined burrows. It fines upwards into an organic-rich mud with a pelletal fabric. An AMS age estimate on *E. excavatum* from 5.76 to 5.74 m is 4344–4067 cal yr BP (Table 1; Fig. 2).

L2 (506 to 172 cm) has three subunits. A fine, muddy sand with burrows (L2c; 5.06 to 4.17 m) is bedded and overlain by a package (L2b; 4.17 to 3.42 m) of several rhythmic interbeds of fine to very fine muddy sand. The uppermost subunit (L2a; 3.42 to 1.72 m) begins at a shell hash layer, and fines upwards from very fine sand to mud with a burrowed, pelletal fabric. An AMS age estimate from 4.98 to 4.96 m near the base of L2c is 4137–3903 cal yr BP and one from near the top of L2c (4.36 to 4.34 m) is 3995–3725 cal yr BP (Table 1, Fig. 2A). An AMS age estimate from near the top of L2b (3.54 to 3.52 m) is 3735–3476 cal yr BP (Table 1; Fig. 2A).

L1 has two subunits: a lower, burrowed muddy sand (L1b; 1.72 to 1.07 m) has basal intraclasts; this is overlain to the top of the core by wavy beds of shell hash, very fine to fine muddy sand and mud (L1a). An AMS age estimate from near the base of L1b (1.70 to 1.68 m) is 1166–955 cal yr BP and one from near the top (1.10 to 1.08 m) is 543–418 cal yr BP (Table 1; Fig. 2A).

Foraminifera

Constrained cluster analysis

The lowermost ca. 2.00 m of core PS03 were barren of foraminifera. Samples between ca. 3.00 and 2.00 m were either barren or contained very few foraminifera (Figs. 2 and 3). Six groups (F-1 to F-6), with boundaries at 0.62 m, 1.82 m, 2.66–2.70 m, 4.38 m and 5.38 m (Fig. 3), were defined. Because many of the less abundant taxa do not occur in all samples within a group, the average percent for each species per group is often low (Table 2).

Cluster group F-6 (6.20 to 5.38 m), like most other groups (Table 2, Figs. 2 and 3), is dominated by *E. excavatum* (80.5%), *Ammonia parkinsoniana* (16.7%) and *Ammonia tepida* (1.7%) are relatively abundant subsidiary taxa. Planktonics are absent and open-shelf taxa are restricted to the upper part of this segment of core. The assemblage is typical of high-brackish areas (salinity ca. 25) of Pamlico Sound today (Abbene et al., 2006).

Cluster group F-5 (4.38 to 5.38 m) contains 64.2% *E. excavatum* and has a few relatively abundant subsidiary taxa (*A. parkinsoniana*, 23%; *A. tepida*, 3.3%; and *Elphidium mexicanum*, 3%) (Table 2; Fig. 3). Higher salinity conditions are indicated by the abundance of *E. mexicanum* (this taxon is abundant in high-brackish Core Sound today; Pruitt et al., 2010), the presence of several small, well preserved, typical open-shelf (Schnitker, 1971) stenohaline benthic taxa (*Cibicides lobatulus*, *Hanzawaia strattoni*, *Trifarina angulosa* and *Valvulineria* sp. A), and planktonics (Table 2, Fig. 2). Planktonic foraminifera are encountered rarely in the modern Pamlico Sound and, when present, immediately adjacent to barrier islands and their inlets (Grossman and Benson, 1967; Abbene et al., 2006; Pruitt et al., 2010), are relatively large and often worn. In PS03, in comparison, planktonics are small, delicate, and well preserved and, where present, occur in abundances typical of the mid shelf (Schnitker, 1971).

Cluster group F-4 (2.66–2.70 to 4.38 m) is composed of 83.6% *E. excavatum*, and 11% *A. parkinsoniana* (Table 2; Figs. 2 and 3). Estuarine *Ammotium salsum* occurs in the upper part of this segment of core whereas open-shelf benthic taxa and planktonics occur in the lower part.

Cluster group F-3 (1.82 to 2.66–2.70 m) is distinctive as it is dominated by *A. salsum* (46.7%) and *Trochammina ochracea* (33%) with *E. excavatum* as a subsidiary species (20%) (Table 2; Figs. 2 and 3). F-3 also has few samples and few species. Similar assemblages occur today in low- to medium-brackish parts of Pamlico Sound (Abbene et al., 2006), Albemarle Sound (Vance et al., 2006) and the Chesapeake Bay estuarine system (Ellison and Nichols, 1970).

In Cluster group F-2 (0.62 to 1.82 m), *E. excavatum* constitutes 73.6%, *A. parkinsoniana* 15.8%, *A. tepida* (3.3%) and *A. salsum* 2.6%. However, F-2 also contains significant percentages of open-shelf stenohaline benthic taxa and planktonics (Table 2; Figs. 2 and 3). The taxonomic composition and the preservational characteristics of foraminiferal assemblage of F-2 are the same as those of F-5.

Cluster group F-1 (0 to 0.62 m) is dominated by *E. excavatum* (55.6%) with *A. salsum* (25.5%) and *A. parkinsoniana* (13.7%) as important subsidiary species (Table 2; Figs. 2 and 3). These are typical dominant taxa of medium- to high-brackish salinity areas of Pamlico Sound (Grossman and Benson, 1967; Abbene et al., 2006). Several taxa (*Arenoparrella mexicana*, *Jadammina macrescens*, *Trochammina inflata*, *Trochammina* sp. and *Trochammina "squamata"*) are restricted to F-1. These are all typical marsh species (Kemp et al., 2009b) that have been transported into Pamlico Sound from the fringing salt marshes (Abbene et al., 2006).

Unconstrained cluster analysis

An unconstrained cluster analysis was performed to investigate the detailed pattern of foraminiferal assemblages across lithologic

Table 1

Radiocarbon age data for core PS03. All dates, except PS03 8.1 (conventional C-14 age estimate) are AMS age estimates. The radiocarbon data and stratigraphic information were calibrated using OxCal (ver. 3.10) (Bronk Ramsey, 2005). The AMS samples (*Elphidium excavatum*) were calibrated using the marine04.14c data set (Hughen et al., 2004) and the organic-rich mud sample was calibrated using intcal04.14c (Reimer et al., 2004).

Sample ID	Laboratory #	Material	Depth (m) in core	Depth (m) below MSL	$\delta^{13}\text{C}$	^{14}C yr BP	Age error	cal yr BP (2 σ range)
PS03 108-110	Beta 196737	<i>Elphidium excavatum</i>	1.08–1.10	7.58–7.60	−1.9	860	40	418–543
PS03 168-170	Beta 196738	<i>Elphidium excavatum</i>	1.68–1.70	8.18–8.20	−5.2	1510	40	955–1166
PS03 352-354	Beta 203610	<i>Elphidium excavatum</i>	3.52–3.54	10.02–10.04	0.0	3700	40	3476–3735
PS03 434-436	Beta 199579	<i>Elphidium excavatum</i>	4.34–4.36	10.84–10.86	−3.2	3900	40	3725–3995
PS03 496-498	NOSAMS OS47553	<i>Elphidium excavatum</i>	4.96–4.98	11.16–11.18	−2.1	4010	35	3903–4137
PS03 574-576	Beta 203609	<i>Elphidium excavatum</i>	5.74–5.76	12.24–12.26	−3.1	4130	40	4067–4344
PS03 8.1	Beta 120354	Organic-rich mud	8.1	14.59–14.64	−25.0*	6290	70	7010–7330

* estimated.

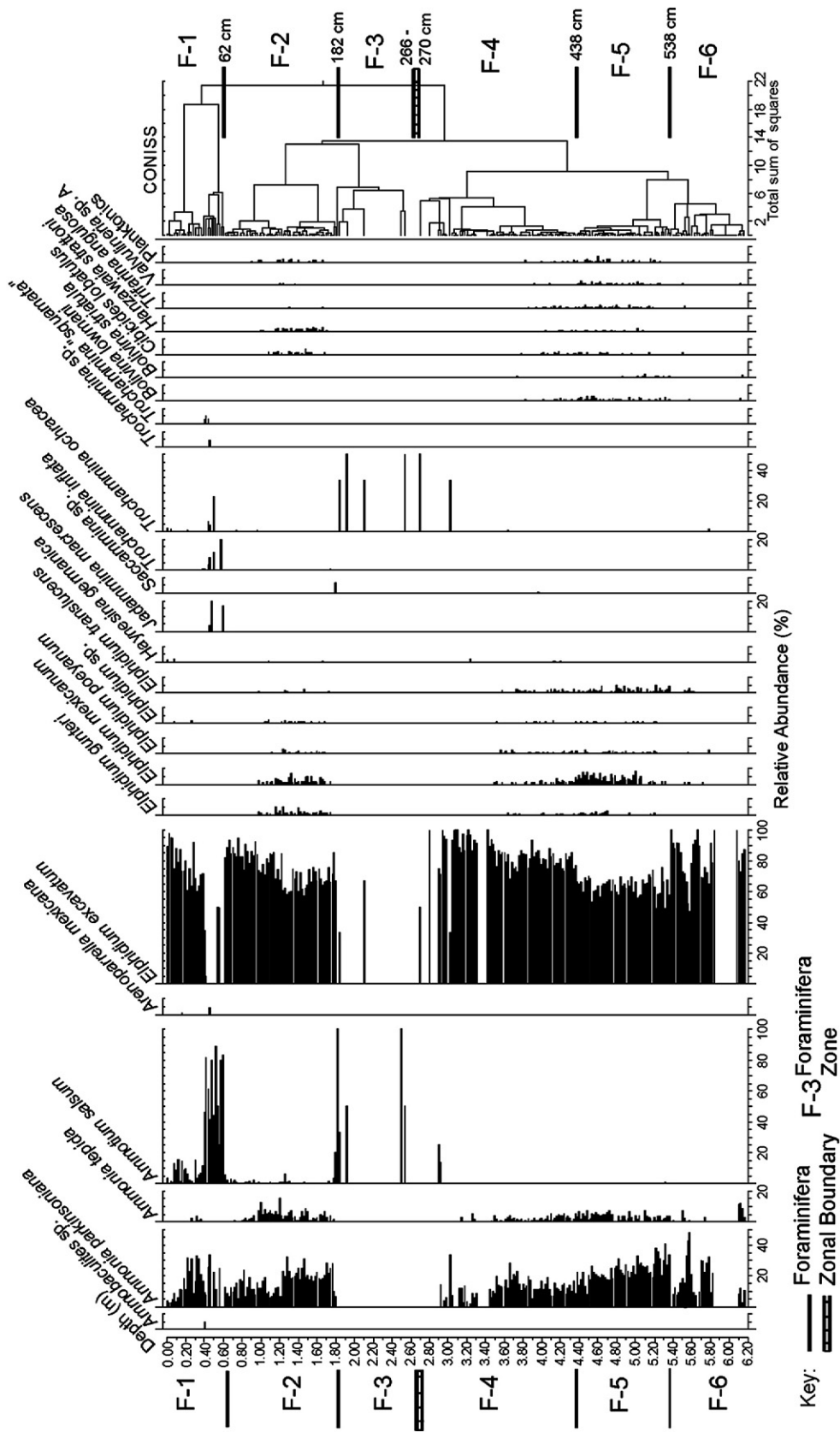


Figure 3. Graphically represented relative abundances of foraminifera in PS03 and dendrogram resulting from stratigraphically constrained cluster analysis of these data. Cluster groups F-1 to F-6 and their boundaries are indicated.

Table 2

Stratigraphically constrained cluster analysis of foraminifera: average percent of foraminifera for each cluster group. x indicates less than 0.1%.

	Group 1	Group 2	Group 3	Group 4	Group 5	Group 6
	32	60	5	71	50	28
	samples	samples	samples	samples	samples	samples
<i>Ammobaculites</i> sp.	0.1	0	0	0	0	0
<i>Ammonia parkinsoniana</i>	13.7	15.8	0	11	23	16.7
<i>Ammonia tepida</i>	0.3	3.3	0	1.4	3.3	1.7
<i>Ammotium salsum</i>	25.5	2.6	46.7	0.6	x	0
<i>Arenoparrella mexicana</i>	0.2	0	0	0	0	0
<i>Elphidium excavatum</i>	55.6	73.6	20	83.6	64.2	80.5
<i>Elphidium gunteri</i>	0	0.8	0	0.1	0.3	0
<i>Elphidium mexicanum</i>	0	1.2	0	0.6	3	0.1
<i>Elphidium poeyanum</i>	0	0.3	0	0.4	0.4	0.1
<i>Elphidium</i> sp.	0.1	0.2	0	0.1	0.2	0
<i>Elphidium translucens</i>	0	0.1	0	0.4	1.4	0.3
<i>Haynesina germanica</i>	0.1	x	0	0.1	0	0
<i>Jadammina macrescens</i>	1.3	0	0	0	0	0
<i>Saccamina</i> sp.	0	0.1	0	x	0	0
<i>Trochammina inflata</i>	1.4	0.2	0	0	0	0
<i>Trochammina ochracea</i>	1.2	x	33	1.2	0	x
<i>Trochammina</i> sp.	0.1	0	0	0	0	0
<i>Trochammina "squamata"</i>	0.4	0	0	0	0	0
<i>Bolivina lowmani</i>	0	0	0	0.1	0.7	0.1
<i>Bolivina striatula</i>	0	0	0	x	0.2	0.1
<i>Cibicides lobatulus</i>	0	0.3	0	0.1	0.2	x
<i>Hanzawaia strattoni</i>	0	0.5	0	0.1	0.2	0
<i>Trifarina angulosa</i>	0	x	0	0.1	0.5	x
<i>Valvulineria</i> sp. A	0	0.1	0	x	0.6	0.1
planktonics	0	0.2	0	0.1	0.5	0

boundaries. Four groups (F-A, F-B, F-C and F-D) were recognized (Fig. 4). F-A, equivalent to F-2 and F-5 of the constrained cluster analysis, contains small, well preserved, open-shelf benthic foraminifera and planktonics (Fig. 4), and occurs within parts of the core with low percent organic matter, high percent sand, and high numbers of foraminiferal species and specimens (Figs. 2 and 5). F-B, F-C, and F-D are equivalent to F-1, F-3, F-4 and F-6 of the constrained cluster analysis, have estuarine foraminiferal assemblages (dominated by varying percentages of *E. excavatum*, *A. parkinsoniana*, *A. tepida* and *A. salsum*) (Fig. 4) and occur within parts of the core with high percent organic matter, low percent sand, and low numbers of species and specimens (Figs. 2 and 5). F-B (dominated by *E. excavatum* and *Ammonia* spp.; Fig. 4) is interpreted as a high-brackish (salinity ca. 25) assemblage. F-C (similar to F-B but with *A. salsum* and *T. ochracea*; Fig. 4) is interpreted as a mid- to low-brackish (salinity ca. <20) assemblage. Samples belonging to F-D contain only *E. excavatum* (Fig. 4) and have scattered occurrences within sections of the core beneath ca. 2.75 m that are characterized by estuarine F-B and F-C (Fig. 5); an undefined estuarine environment is indicated.

Fisher's alpha

A plot of values of Fisher's alpha per sample with core depth (Fig. 2) illustrates a pattern that corresponds with those revealed by cluster analysis. Fisher's alpha (diversity) increases gradually up-core from ca. 6.00 m to ca. 4.50 m. Values then decrease up-core at around the same rate to ca. 3.00 m. A ca. 1.00 m thick core segment barren of foraminifera is succeeded at ca. 1.80 m by a very rapid increase in diversity to ca. 1.50 m followed by a gradual decrease up-core to values that stabilize at ca. 1.00 m core depth.

Diatoms

Constrained cluster analysis

Diatoms are generally abundant and generally well preserved in PS03. Polyhalobous diatoms dominate with a variable but significant contribution from mesohalobous taxa. Oligohalobous and halophobous diatoms are rare and have a patchy distribution (Fig. 6). Constrained cluster analysis defined four groups (D-1 to D-4) with boundaries at 0.94–1.04 m, 1.96–2.18 m, and 5.56–5.66 m (Fig. 6).

Cluster group D-4 (7.84 to 5.66 m) is dominated by the polyhalobous taxa *Paralia sulcata* (marine planktonic; Vos and de Wolf, 1993), *Diploneis bombus* and *Grammatophora oceanica*. The mesohalobous (estuarine; Vos and de Wolf, 1993) taxon *Cyclotella striata* is present in low percentages (Fig. 6). Estuarine conditions are indicated.

Cluster group D-3 (2.18 to 5.56 m) is dominated by the polyhalobous *P. sulcata* and the tycho planktonic (indicative of estuarine conditions; Denys, 1991) taxa *Coscinodiscus eccentrica*, *Delphineis surirella* and *Cymatosira belgica*. Lower (D-3b; 4.10 to 5.56 m) and upper (D-3a; 4.00 to 2.18 m) subgroups are delineated (Fig. 6). The polyhalobous taxa *D. surirella*, *Raphoneis amphicerus* and *Raphoneis nitida* are slightly more abundant in D-3b whereas the polyhalobous taxa *Plagiogramma staurorophorum* and *Actinopterychus senarius* are slightly more abundant in D-3a.

Of the four groups, cluster group D-2 (1.96 to 1.04 m) has the highest percentages of the marine planktonic species *Paralia sulcata* and the lowest percentages of the estuarine *C. striata* (Fig. 6). D-2 also has lower percentages of tycho planktonic species (indicative of estuarine conditions) than D-3 and D-1. The section of core characterized by D-2 thus has a more marine influence than any other parts of core PS03.

Cluster group D-1 is dominated by the polyhalobous *P. sulcata*, *Eunotogramma dubium*, *C. belgica*, *Cocconeis scutellum* (marine/brackish epiphyte; Denys, 1991; Vos and de Wolf, 1993) and the mesohalobous (estuarine; Vos and de Wolf, 1993) *C. striata* (Fig. 6). Estuarine conditions are indicated.

Discussion

Open marine benthic and planktonic foraminifera in Pamlico Sound

The nature of benthic foraminiferal assemblages and their distribution in the modern Pamlico and Albemarle sounds and adjacent barrier islands and inner shelf is well established in the literature. In general, the low-brackish, estuarine Albemarle, Currituck, Roanoke and Croatan sounds, together with the estuarine rivers that flow into them and into Pamlico Sound, are characterized by low-diversity agglutinated benthic assemblages dominated by *Ammotium*, *Ammobaculites* and *Miliammina* (Vance et al., 2006). Similarly, salt marsh assemblages are agglutinated in nature and dominated by *Arenoparrella*, *Jadammina*, *Miliammina*, *Tiphrotrocha* and *Trochammina* (Kemp et al., 2009b).

Pamlico Sound has variable salinity and energy conditions. Typically low diversity assemblages are dominated by *A. salsum*, *E. excavatum* and *A. parkinsoniana*. *Ammotium* is predominant at low salinities and *Elphidium* and *Ammonia* at higher salinities (Abbene et al., 2006). Core

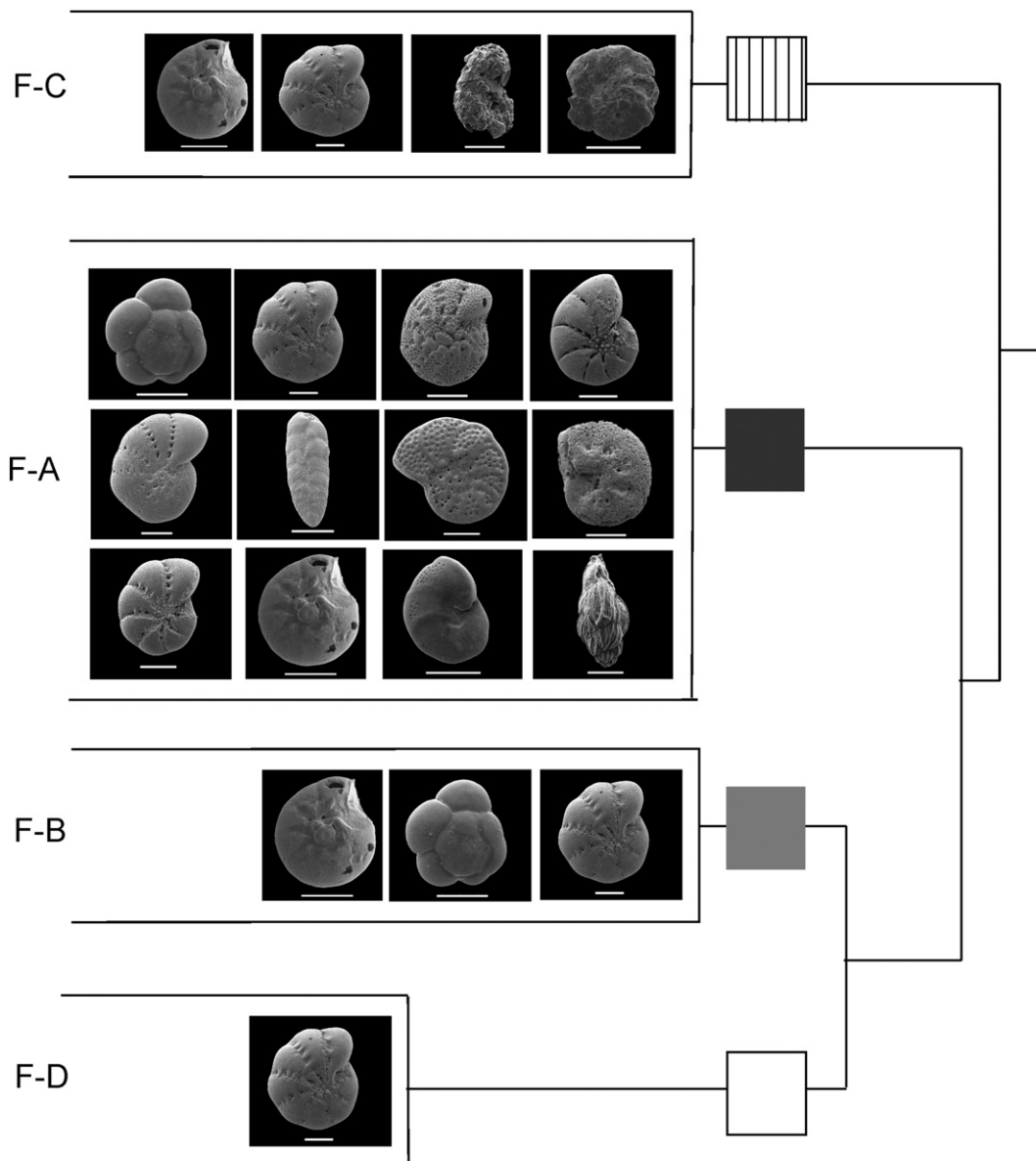


Figure 4. Diagrammatic representation of the dendrogram resulting from an unconstrained cluster analysis of foraminiferal relative abundance data. Cluster groups F-A to F-D and images of typical taxa of each group are indicated. Variably shaded boxes match the key to cluster group membership on Fig. 5.

Sound has near open-shelf salinities and diverse benthic assemblages dominated by *E. excavatum*, *E. mexicanum*, *Elphidium galvestonense*, *Elphidium gunteri*, *A. parkinsoniana* and *Quinqueloculina* spp. (Pruitt et al., 2010).

Barrier island sands are often barren of foraminifera but overwash and inlet sands can contain variably diverse assemblages typical of the shoreface and inner shelf. *E. excavatum* dominates but *A. parkinsoniana*, *Buccella inusitata*, *Elphidium subarcticum*, *H. strattoni*, *Nonionella atlantica* and *Quinqueloculina* spp. are abundant (Abbene et al., 2006; Robinson and McBride, 2006; Smith et al., 2009). Assemblages are generally composed of relatively large, often worn, size-sorted specimens. Planktonic foraminifera can occur but specimens are rare and generally large and worn.

The basinal (central) region of Pamlico Sound (ca. 5 to 6 m water depth) is floored by muddy sand or sandy mud (Wells and Kim, 1989). Vibracores from the basin have a similar lithology and contain estuarine foraminiferal assemblages similar to modern Pamlico Sound basinal assemblages (varying percentages of *E. excavatum*, *A. parkinsoniana* and *A. salsum*; Abbene et al., 2006; Foley et al., 2006; Metger et al., 2008). Much of PS03 has these typical estuarine assemblages, but the burrowed

sands from 5.06 to 4.17 m (L2c) and 1.72 to 1.07 m (L1b) core depth contain very distinctive foraminiferal assemblages (Fig. 4); relatively small specimens with variation in test size that is typical of an unsorted, in situ assemblage. These small specimens are also very well preserved; the thin last chamber is commonly present and tests are glassy in appearance. Although dominated by *E. excavatum* and *A. parkinsoniana*, like many estuarine regions and the adjacent inner shelf, assemblages from the two muddy sand intervals (L2c and L1b) in PS03 (Figs. 2 and 5) are of relatively high diversity by virtue of the presence of many stenohaline taxa (Table 3) typical of the modern mid to outer shelf off North Carolina (Schmitker, 1971; Culver and Buzas, 1980). The more abundant of these taxa (those constituting >2% of the assemblage in any one sample) are included in the cluster analyses (Figs. 3–5) and, together with the presence of planktonics, are responsible for the discrimination of assemblages F-2 and F-5 in the constrained cluster analysis and assemblage F-A in the unconstrained cluster analysis.

The diversity of planktonics in the sand intervals (L2c and L1b) is almost as great as that of the benthics. Twenty-two planktonic taxa were recorded (Table 3) and several constitute ca. 1% of assemblages. Assemblages with this diversity and these proportions of planktonic

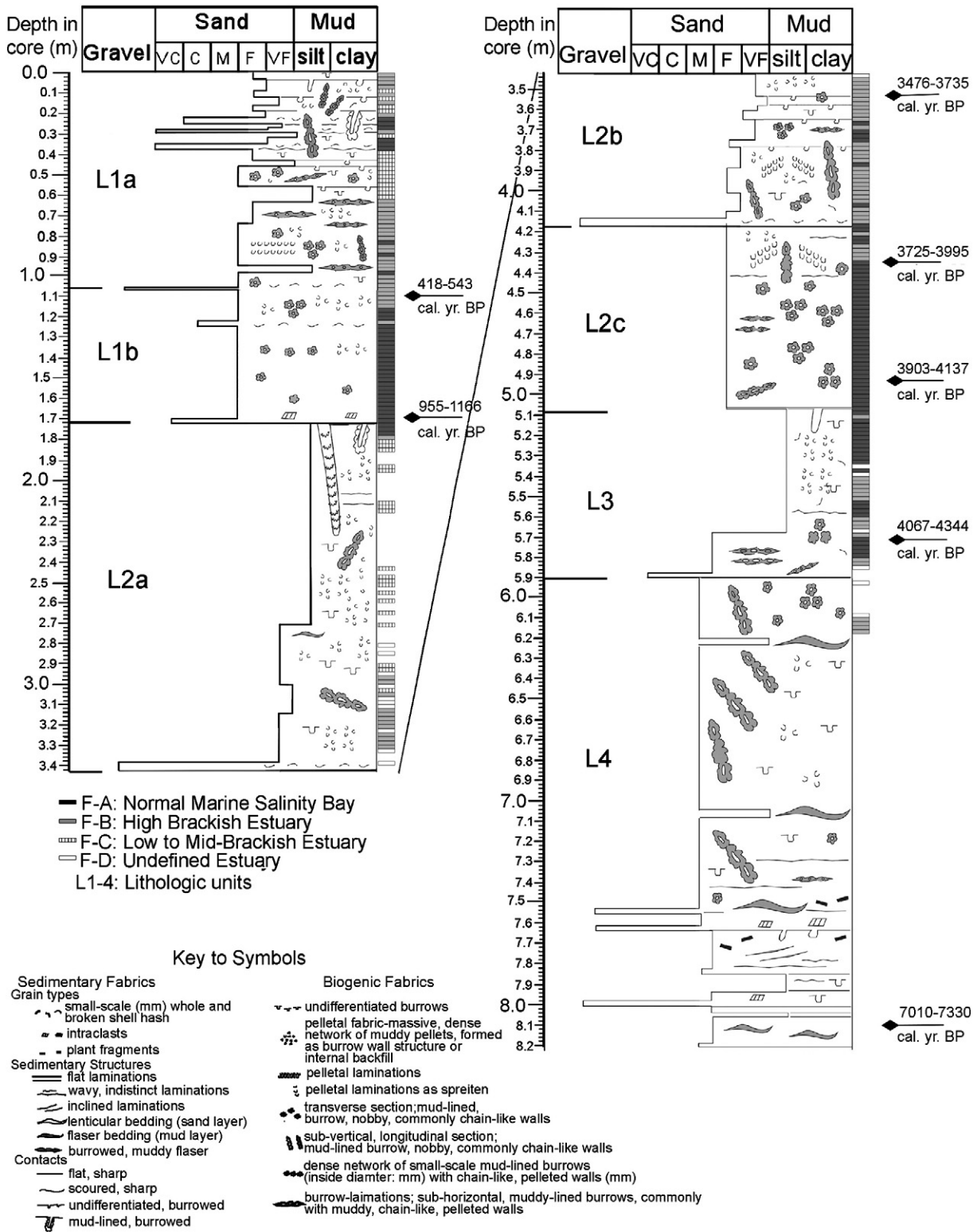


Figure 5. Lithologic log of vibracore PS03 showing unconstrained cluster group (F-A to F-D) membership of every sample containing foraminifera. Lithologic units (L1 to 4) are also indicated.

specimens only occur on the mid to outer shelf today (Schnitker, 1971). Further, some taxa (e.g., *Globigerinoides ruber* and *Globorotalia menardii*) are typical inhabitants of subtropical Gulf Stream waters (Bé and Hamlin, 1967). For these taxa to occur in the southern Pamlico Sound basin in such abundance and diversity, there must have been open and extensive connectivity with Atlantic Ocean waters. Assemblages of open-shelf aspect have been recorded in several

additional southern Pamlico Sound vibracores to the west of PS03 (Rosenberger et al., 2006; Metger et al., 2008) and foraminiferal and sedimentologic data from several vibracores immediately to the north and west of Cape Hatteras indicate the presence of inlets with large flood tide deltas ca. 1000 yr ago (McDowell et al., 2009).

In summary, foraminiferal assemblages F-2 and F-5 (and F-A) cannot be interpreted as having been deposited in overwash or flood

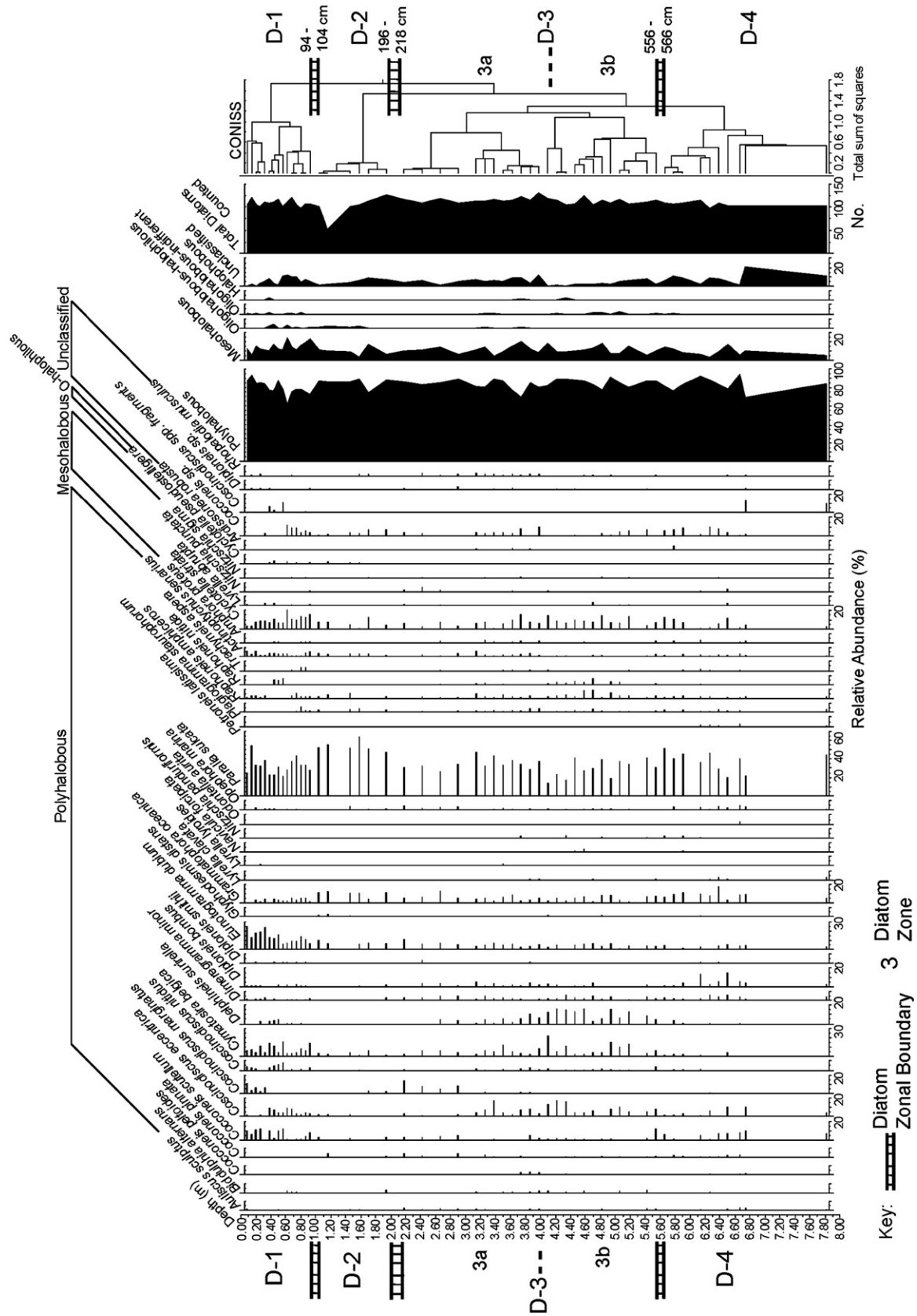


Figure 6. Graphically represented relative abundances of diatoms in P503 and dendrogram resulting from stratigraphically constrained cluster analysis of these data. Cluster groups D-1 to D-4 and their boundaries are indicated.

Table 3

Stenohaline benthic foraminiferal taxa and planktonic foraminiferal taxa recorded in lithologic units L2c (5.06 to 4.17 m) and L1b (1.72 to 1.07 m) in vibracore PS03.

Stenohaline benthic taxa	Planktonic taxa
<i>Asterigerina carinata</i>	<i>Globigerina bulloides</i>
<i>Asterigerinata mamilla</i>	<i>Globigerina quinqueloba</i>
<i>Bolivina lowmani</i>	<i>Globigerina rubescens</i>
<i>Bolivina pseudopunctata</i>	<i>Globigerina</i> cf. <i>Globigerina bulloides</i>
<i>Bolivina striatula</i>	<i>Globigerina</i> cf. <i>Globigerina decoraperta</i>
<i>Buccella depressa</i>	<i>Globigerina</i> sp.
<i>Buccella inusitata</i>	<i>Globigerinita glutinata</i>
<i>Bulminella elegantissima</i>	<i>Globigerinita</i> cf. <i>Globigerinita uvula</i>
<i>Cassidulina crassa</i>	<i>Globigerinoides obliquus</i>
<i>Cibicides fletcheri</i>	<i>Globigerinoides ruber</i>
<i>Cibicides lobatulus</i>	<i>Globigerinoides</i> cf. <i>Globigerinoides ruber</i>
<i>Cibicides refulgens</i>	<i>Globigerinoides ruber cyclostomus</i>
<i>Elphidium poeyanum</i>	<i>Globigerinoides sacculifer</i>
<i>Elphidium subarcticum</i>	<i>Globigerinoides trilobus</i>
<i>Elphidium translucens</i>	<i>Globorotalia menardii</i>
<i>Eoepionidella pulchella</i>	<i>Globorotalia</i> sp.
<i>Epistominella</i> sp.	<i>Globorotaloides</i> (?) sp.
<i>Fissurina laevigata</i>	<i>Neogloboquadrina dutertrei</i>
<i>Fursenkoina fusiformis</i>	<i>Neogloboquadrina</i> cf. <i>N. dutertrei</i>
<i>Globocassidulina subglobosa</i>	<i>Neogloboquadrina pachyderma</i>
<i>Globulina gibba</i>	<i>Neogloboquadrina</i> cf. <i>N. pachyderma</i>
<i>Guttulina australis</i>	<i>Neogloboquadrina</i> sp.
<i>Guttulina lactea</i>	
<i>Hanzawaia strattoni</i>	
<i>Nonionella atlantica</i>	
<i>Nonionella auricula</i>	
<i>Planulina ariminensis</i>	
<i>Rectobolivina advena</i>	
<i>Reussella atlantica</i>	
<i>Rosalina floridana</i>	
<i>Sagrina pulchella primitiva</i>	
<i>Stetsonia minuta</i>	
<i>Trifarina angulosa</i>	
<i>Valvulineria</i> sp.	
<i>Webbiniella concava</i>	

tide delta sand. They are distinct in their composition (more diverse and containing many stenohaline benthic taxa and Gulf Stream planktonics), their preservation (very well preserved, little wear and breakage, variably sized tests), their abundance (ca. one order of magnitude greater abundance per unit volume of sediment than assemblages in flood tide delta sand), their location (in the deeper Pamlico Sound basin to the northwest of the coarser sand shoals comprising overwash lobes and flood tide deltas), and their presence in muddy sand considerably finer than typical flood tide delta or overwash sand (e.g., Robinson and McBride, 2006; Smith et al., 2009).

Comparison of micropaleontological and sedimentological data sets

Diatom samples are all dominated by the planktonic polyhalobous taxon *P. sulcata* with various contributions from mesohalobous taxa such as *C. striata*, which is indicative of estuarine conditions. Taxonomically distinct groups do not occur. Thus, diatoms are of secondary importance to foraminifera in recognizing environmental change in PS03. Cluster group D-2 contains the highest proportions of *P. sulcata* and the lowest proportions of *C. striata* and occurs in PS03 at the same general depth as foraminiferal group F-2 and lithologic unit L1b. Thus, the foraminiferal, diatom and lithologic data set concur in indicating that lithologic unit L1b has the greatest open marine influence in the entire core.

The lithologic log of PS03 indicates distinct, albeit burrowed boundaries between a basal coarsening upwards unit (L4) and three overlying fining upwards units (L3–L1) (Fig. 2). L2 is further subdivided into three subunits (L2a to L2c) and L1 into two subunits (L1a and L1b). The depth of the boundaries between these units and subunits is summarized in Fig. 7.

Constrained cluster analysis of the foraminiferal data defines six major groups (F-6 to F-1) whose boundaries differ considerably in depth from those of the lithologic units (Figs. 3 and 7). This can be explained by consideration of an example, a subgroup boundary within cluster group F-2 (0.62 to 1.82 m) at 1.16 m. This approximates the depth of the boundary between lithologic subunits L1a and L1b (1.07 m) (Figs. 2, 5, and 7). The reason why this correlation and others throughout the core are only approximate is revealed by the results of the unconstrained cluster analysis. Figure 5 shows that that the top four samples of L1b, otherwise characterized (with one exception) by unconstrained foraminiferal assemblage F-A, belong to assemblage F-B, which characterizes the lower ca. 0.30 m of the overlying lithologic unit L1a.

Thus, the distribution of unconstrained cluster groups across lithologic boundaries indicates that specimens of foraminifera from the overlying unit are displaced downwards by burrowing (presumably by metazoans) up to 0.30 m into the underlying unit (Fig. 5). For example, L4 is barren of foraminifera with the exception of six samples from the uppermost 0.30 m (Figs. 5 and 7), a section disturbed by a large burrowing bivalve, *Cyrtopleura costata*, which is preserved in life position and likely burrowed down from the overlying L3, which contains abundant foraminifera.

Foraminifera are reworked upwards into overlying units but not as extensively as downwards. For example, three samples near the base of L1a (Fig. 5) contain unconstrained assemblage F-A (open shelf). Similarly, a few samples in L2b (Fig. 5) contain unconstrained open-shelf assemblage F-A in a section otherwise characterized by high-brackish estuarine assemblage F-B. Displacement of foraminifera downwards by burrowing activity and reworking upwards explains why lithologic boundaries, reflections of environmental change, do not correlate exactly with boundaries of constrained foraminiferal cluster groups.

Bioturbation notwithstanding, the pattern of species diversity (Fisher's alpha) up-core shows excellent correlation with lithologic units. The two peaks of diversity (Fig. 2) occur in the middle of sandy units (L2c and L1b) that contain planktonic foraminifera and stenohaline benthic foraminifera. A gradual increase in alpha up-core to the lower peak probably reflects down-core bioturbation (Fig. 5) but the gradual decrease above that peak is congruent with decreasing grain-size, indicating gradual change to a lower energy environment up-core (Fig. 2). In comparison, the upper peak is reached over a much shorter vertical interval of core, indicating relatively little down-core bioturbation (Fig. 5). The decrease in diversity up-core records change to variable environmental conditions as indicated by the lithologic complexity of the upper ca. 0.50 m of the core (Fig. 2). Given that benthic foraminiferal species diversity generally increases offshore on the Atlantic continental shelf (e.g., Gibson and Buzas, 1973), the correlation of high diversity with the two sandy units containing planktonic foraminifera confirms the unusual "offshore" nature of the foraminiferal assemblages in L2c and L1b.

Diatom data, although not as high resolution as the foraminiferal data, also provide evidence of displacement of diatoms down-core by burrowing at lithologic boundaries. Indeed, diatom assemblages are apparently displaced farther than foraminifera. The three boundaries between the four diatom cluster groups are 0.20 to 0.30 m deeper than the foraminiferal boundaries of the constrained cluster analysis (Fig. 7), which we have seen are themselves the result of downward burrowing. Nevertheless, the boundaries of cluster group D-2 (characterized by the diatom assemblage with the most marine influence in core PS03) at 1.04 and 1.96 m depth correlate quite well with the boundaries of L1b (characterized by an open-shelf foraminiferal assemblage) with boundaries at 1.07 and 1.72 m (Figs. 6 and 7).

Holocene evolution of southern Pamlico Sound

Placed in the context of the extensive geologic data (>100 cores, 3000 km of seismic lines, 200 km of ground penetrating radar data,

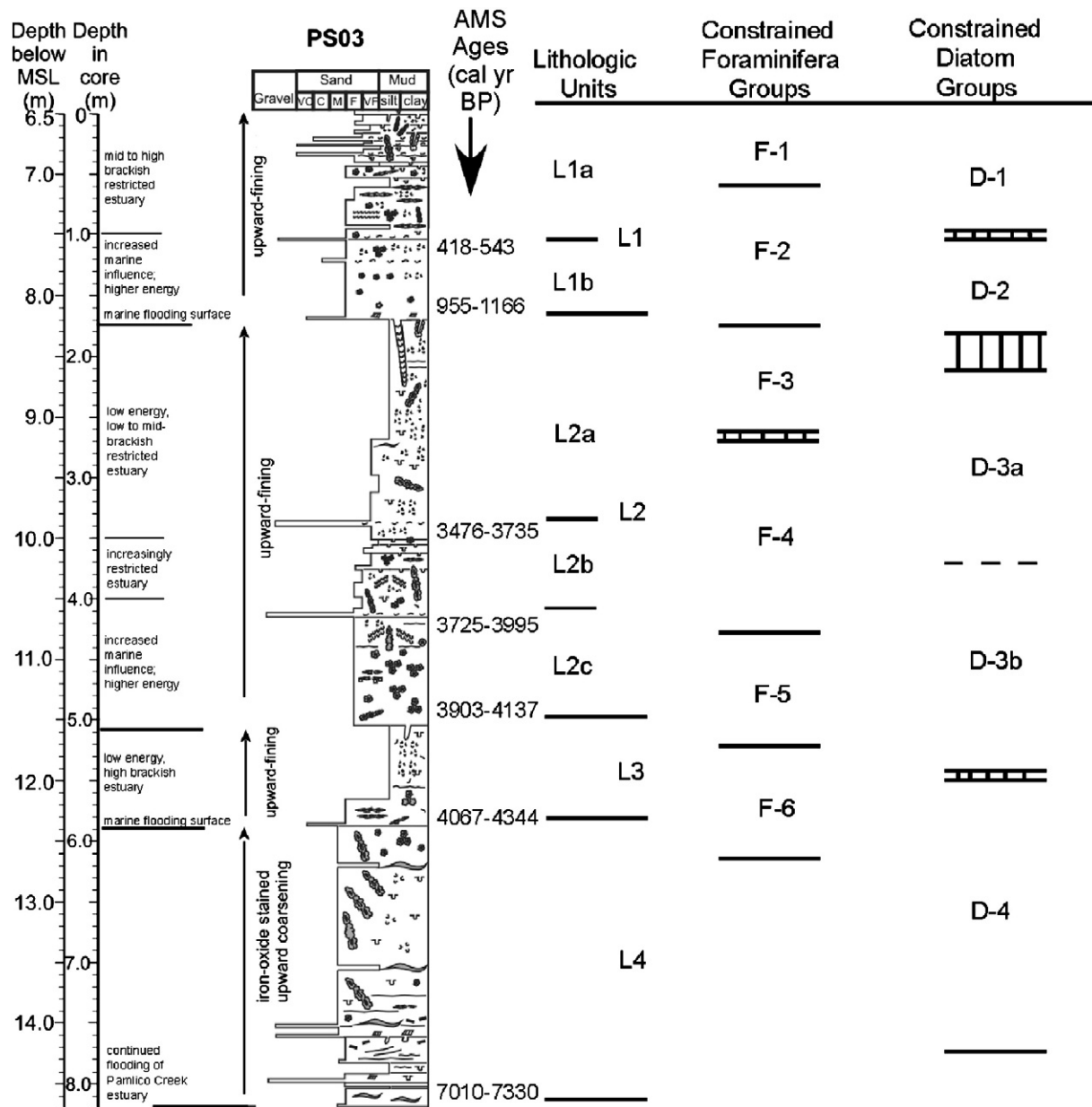


Figure 7. Comparison of depths of boundaries between lithologic units, foraminiferal groups defined by constrained cluster analysis, and diatom groups defined by constrained cluster analysis.

>100 C-14, OSL and AAR age estimates) available for this coastal region (e.g., Riggs and Ames, 2003; Mallinson et al., 2005, 2008, 2010a,b; Parham et al., 2007; Culver et al., 2007, 2008; Horton et al., 2009; Kemp et al., 2009a,b; Wehmiller et al., 2010), the high-resolution micropaleontological data derived from PS03 allows the Holocene evolution of the southern Pamlico Sound region to be reconstructed.

Rapidly rising relative sea level (ca. 5 mm/yr) (Horton et al., 2009) began to flood into the main drainages (Mallinson et al., 2010a) of the paleo-Tar/Pamlico/Neuse rivers (Figs. 1B and 8A) approximately 9000 yr ago. The foraminiferal and sedimentological record of many cores indicates that a southwestward-flowing tributary (Pamlico Creek) became an increasingly broad estuary separated from the Atlantic Ocean by a low, late Pleistocene interstream divide to the southeast (Fig. 8A). By ca. 7000 yr ago, sea level had risen enough to flood the interstream divide leaving several, low-lying islands. Barrier islands must have been present (Fig. 8B) given the extensive fine-grained estuarine sediments of this age recorded in many Pamlico

Sound cores. The exact disposition of the barrier islands is unknown but they must have been located up to several kilometers seaward of the current barrier islands (Fig. 8B).

Around 4000 to 4350 cal yr BP, core PS03 records a reduction in grain size from medium sand containing estuarine diatoms (Fig. 6) to silt and clay containing a high-brackish estuarine foraminiferal assemblage dominated by *A. parkinsoniana* and *E. excavatum* (Figs. 2, 4, and 5). These extremely low-energy estuarine conditions, perhaps related in part, to near complete barrier islands with few inlets, continued at the site of core PS03 for just a few hundred years. Around 4000 yr ago, sediments suddenly coarsened (Fig. 5) to a muddy sand containing an in situ benthic foraminiferal assemblage typical of the inner to mid shelf (Figs. 2, 4, and 5) and significant numbers of planktonic foraminifera (Figs. 2 and 3), including *G. ruber* and *G. menardii*, which only occur today in the warm, northeastward flowing Gulf Stream. Their presence indicates that the barrier islands must have been severely disrupted (Fig. 8C). At this time, the rate of relative sea-level rise had decreased to ca. 1 mm/yr (Horton et al., 2009)

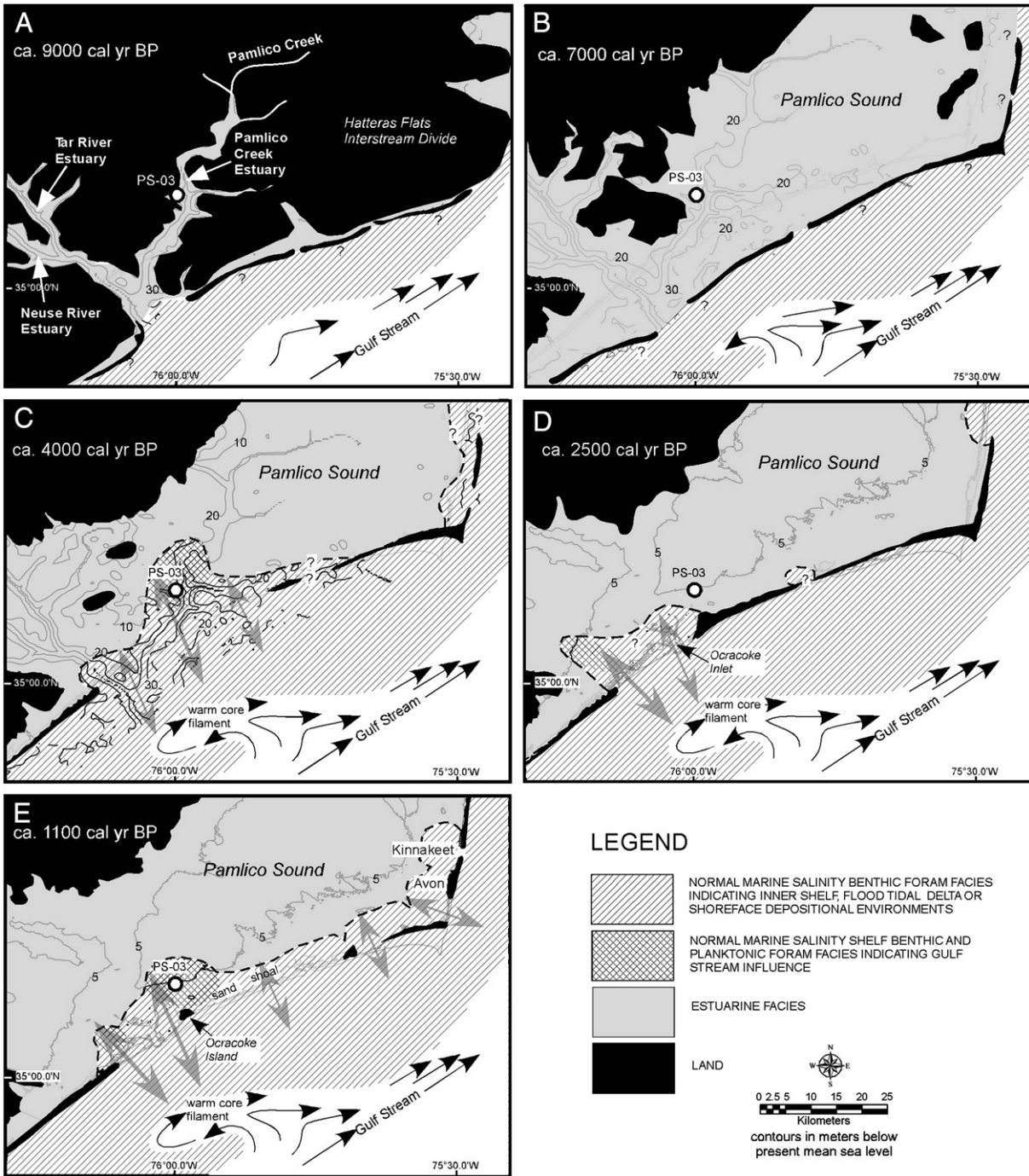


Figure 8. Paleoenvironmental reconstructions of the southern Pamlico Sound region for five Holocene time-slices. A, ca. 9000 cal yr BP. Initial flooding of the latest Pleistocene–early Holocene river drainages to form narrow estuaries. The Hatteras Flats Interstream Divide separates Pamlico Creek from the Atlantic Ocean. B, ca. 7000 cal yr BP. Hatteras Flats Intestream Divide is almost completely flooded. Estuarine conditions characterize Pamlico Sound indicating the presence of barrier islands. Contours indicate the depth (m below present mean sea level) to the late Pleistocene surface and define the paleotopography that controlled the timing of flooding and morphology of Pamlico Bay. C, ca. 4000 cal yr BP. Destruction of an extensive section of barrier island allows normal salinity waters, derived from northward migrating Gulf Stream warm-core filaments, to be advected into the southern Pamlico basin in response to wind-forcing. Gray arrows indicate tidal exchange. D, ca. 2500 cal yr BP. Barrier islands have essentially reformed and almost the entire Pamlico Sound has estuarine conditions. Contours indicate modern bathymetry (m below mean sea level). E, ca. 1100 cal yr. BP. Barrier island destruction along the southern Outer Banks resulted in a shallow, submarine sand shoal over which normal marine waters were advected. The Cape Hatteras region exhibited several inlets with large flood-tide deltas (McDowell et al., 2009). E modified from Culver et al. (2007).

but the rate of sediment accumulation in this coarser grained unit increased, presumably because accommodation space was available.

Commencing ca. 3700 yr ago, shelf foraminiferal assemblages were replaced by high-brackish estuarine assemblages (Figs. 2–5). These, in turn, were replaced gradually up-core by low-brackish estuarine foraminiferal assemblages dominated by *A. salsum* (Figs. 2–5). Coincident

with these biotic changes was a reduction in grain size as the Pamlico basin once more became more fully estuarine (Figs. 2 and 5). These changes must have resulted from the gradual reformation of the barrier islands separating the Pamlico basin from the Atlantic Ocean (Fig. 8D). OSL age estimates (ca. 2500 cal yr BP) on beach ridge sand at Kitty Hawk, to the north of the study area (Mallinson et al., 2008) indicate that islands of

this vintage represent the early stages of the modern Outer Banks barrier island system and were located very close to their current positions.

Approximately 1100 yr ago, the southern portion of Pamlico Sound underwent another rapid and fundamental environmental change. Low-energy estuarine mud is overlain with an abrupt contact by higher energy, burrowed muddy fine to medium sand (Figs. 2 and 5). At this contact, low-diversity estuarine foraminiferal assemblages are overlain by high-diversity foraminiferal assemblages containing typical stenohaline continental shelf benthic species (Figs. 2–5) and planktonic foraminifera (Fig. 2) that, offshore of North Carolina today, are restricted to warm waters of the northward flowing Gulf Stream. This unit also contains the highest percentages of the marine planktonic species *P. sulcata* recorded in this study and lowest percentages of the estuarine taxon *C. striata* (Fig. 6).

What could have caused the sudden environmental perturbations that occurred approximately 4000 and 1100 yr ago? The North Carolina coastline is particularly subject to strikes by hurricanes that are known to cause degradation of barrier islands, including reduction to subtidal shoal platforms (Otvos and Carter, 2008). We postulate that hurricanes (either single major storms or sets of smaller storms) significantly impacted the barrier islands along the southern margin of the Pamlico Sound on these two occasions causing the destruction of large segments of barriers (Culver et al., 2007). It is proposed that that Gulf Stream waters, associated with frontal filaments (Pietrafesa et al., 1985) and containing planktonic foraminifera, were advected into the southern Pamlico Basin thus raising the ambient salinity and allowing living benthic populations typical of the inner to mid shelf to be established (Figs. 8C, E).

These barrier destruction events are essentially synchronous with intervals of rapid Holocene climate change (Mayewski et al., 2004) at 4200–3800 and 1200–1100 cal yr BP and are coincident with transgressive surfaces in Delaware Bay, New Jersey, USA (Leorri et al., 2006). Barrier island destruction by hurricane-force winds has recently been posited for the Minas Passage in the Bay of Fundy (Shaw et al., 2010) leading to leading to the near-instantaneous change from mesotidal to macrotidal conditions in the Minas Basin ca. 3400 cal yr BP. The tidal range in Pamlico Sound would have increased also following barrier island breakdown.

Vibracores through the modern southern Outer Banks indicate that, during the ca. 1100 cal yr BP event, barrier island sand was smeared out into a tens of kilometers long, shallow submarine shoal (a single morphological entity or a coalescence of several large flood-tide deltas) containing size-sorted, poorly preserved inner shelf benthic foraminifera (Rosenberger et al., 2006; Twamley et al., 2006; Hale et al., 2007). The fine sand containing stenohaline benthic and planktonic foraminifera accumulated in deeper water to the north of this generally medium sand shoal. Radiocarbon age estimates of calcareous foraminiferal material in core PS03 indicate that the barrier islands were not extensively reestablished for 500 to 600 yr (Fig. 2). Similar evidence for an extensive submarine shoal associated with the 4000 cal yr BP event has not been found and is unlikely to be preserved. Barrier islands can form, change morphology and fragment on decadal timescales (e.g., Otvos and Carter, 2008). Thus, we suggest that continued open-marine influence over several centuries indicates continued influence of strong cyclonic storms.

The timing of 1100 cal yr BP barrier island destruction agrees well with that of a peak in Atlantic tropical cyclone activity during the Medieval Climate Anomaly ca. 1100 to 900 yr (Mann et al., 2009) and an interval of apparent increased rate of sea-level rise (e.g., Gonzalez and Tornqvist, 2009, based on radiocarbon age estimates of basal saltmarsh peats; Kemp, 2009; Kemp et al., 2011, based on radiocarbon age estimates and foraminiferal assemblages of saltmarsh peats) and of coastal change (Mallinson et al., 2011). Increased hurricane activity during this period of warmth could have led to the temporary destruction of the southern Outer Banks barrier islands allowing oceanic waters to influence the physical environment and biota of the previously estuarine southern Pamlico Sound.

A succeeding interval of reduced tropical cyclone activity (Mann et al., 2009) and reduced rate of relative sea-level rise during the Little Ice Age (Kemp et al., 2009a) was characterized by barrier island regrowth. Indeed, the earliest map (Cumming, 1966) drawn by the first English visitors to North Carolina (AD 1590) show a series of short barrier islands separated by numerous inlets, the majority of which have closed over the past few centuries.

A new phase of barrier island evolution is currently under way in the Outer Banks region. The rate of relative sea-level rise increased significantly between AD 1881 and AD 1906 to a 20th century mean rate of 3.2 mm/yr (Kemp et al., 2009a) and a period of possibly increased intensity hurricane activity is upon us (Knutson et al., 2010). Large segments of the barrier islands along the Outer Banks have undergone severe erosion during the past century, mainly on the oceanic side but also on the estuarine side (Riggs and Ames, 2003). These factors suggest that a repeat of the medieval barrier island destruction, which occurred during similar conditions of warm climate and increased rate of relative sea-level rise, is possible. The vulnerability of the Outer Banks, and other Atlantic and Gulf barrier islands, to inlet formation and larger scale destruction is further exacerbated by anthropogenic curtailment of natural barrier island self-sustaining processes (Smith et al., 2008).

Conclusions

High-resolution foraminiferal data supported by diatom and sedimentological data allow for a detailed paleoenvironmental reconstruction of environmental change over the past ca. 9000 yr in southern Pamlico Sound. The foraminiferal data in vibracore PS03 correlate closely with the lithologic variations and sedimentary facies, although bioturbation down-core and reworking up-core smears foraminiferal boundaries across lithologic boundaries. The data record the initial flooding of a river drainage followed by 9000 yr of estuarine conditions interrupted by two intervals of open-marine influence each lasting ca. 400 to 600 yr. Temporary destruction of large segments of the Outer Banks barrier islands by hurricanes is postulated. The 1150 to 500 cal yr BP interval of increased marine influence coincides with an increased rate of sea-level rise and a peak in Atlantic tropical cyclone activity during the Medieval Climate Anomaly.

Vibracore PS03 records Holocene paleoenvironmental changes that might not have been recognized if high-resolution foraminiferal analysis had not been applied to this estuarine core. Clearly, the logistics of such an approach mean that contiguous sampling is not possible when several or many cores are the subject of study. The work reported herein does, however, indicate that a high-resolution approach on one or two selected cores, or on selected core segments, should be considered if sedimentologic facies sequences indicate sudden changes in energy and, hence, changes in the sedimentary environment in estuarine cores.

Acknowledgments

We thank I. Abbene, D. Ames, J. Foley, J. Jett, M. Hale, K. McDowell, L. Metger, J. Ricardo, J. Rosenberger, C. Smith, D. Twamley, D. Vance, J. Watson and J. Woods for their assistance. The efforts of Stephen Gallagher and an anonymous reviewer are greatly appreciated. The Cushman Foundation and the U.S. Geological Survey (cooperative agreement 02ERAG0044) provided funding for this project. Acknowledgement is also made to the donors of The American Chemical Society Petroleum Research Fund for partial support of this research.

References

- Abbene, I.J., Culver, S.J., Corbett, D.R., Buzas, M.A., Tully, L.S., 2006. Foraminifera of Pamlico Sound, North Carolina, over the past century. *Journal of Foraminiferal Research* 36, 135–151.
- Bé, A.W.H., Hamlin, W.H., 1967. Ecology of recent planktonic foraminifera, Part 3, Distribution in the North Atlantic during the summer of 1962. *Micropaleontology* 13, 87–106.

- Bronk Ramsey, C., 2005. OxCal Program, v. 3.
- Buzas, M.A., 1990. Another look at confidence limits for species proportions. *Journal of Paleontology* 64, 842–843.
- Cronin, T., Colman, S., Willard, D., Kerhin, R., Holmes, C., Karlson, A., Ishman, S., Bratton, J., 1999. Interdisciplinary environmental project probes Chesapeake Bay down to the core. *Eos, Transactions, American Geophysical Union* 80 (237), 240–241.
- Cronin, T., Willard, D., Karlson, A., Ishman, S., Verardo, S., McGeehin, J., Kerhin, R., Holmes, C., Colman, S., Zimmerman, A., 2000. Climatic variability in the eastern United States over the past millennium from Chesapeake Bay sediments. *Geology* 28, 3–6.
- Culver, S.J., Buzas, M.A., 1980. Distribution of Recent Benthic Foraminifera off the North American Atlantic Coast. *Smithsonian Contributions to the Marine Sciences* 6, 1–512.
- Culver, S.J., Ames, D.V., Corbett, D.R., Mallinson, D.J., Riggs, S.R., Smith, C.G., Vance, D.J., 2006. Foraminiferal and sedimentary record of late Holocene barrier island evolution, Pea Island, North Carolina. *Journal of Coastal Research* 22, 836–846.
- Culver, S.J., Grand Pre, C.A., Mallinson, D.J., Riggs, S.R., Corbett, D.R., Foley, J., Hale, M., Metzger, L., Ricardo, J., Rosenberger, J., Smith, D.G., Smith, C.W., Snyder, S.W., Twamley, D., Farrell, K., Horton, B.P., 2007. Late Holocene barrier island collapse: Outer Banks, North Carolina, USA. *The Sedimentary Record* 5, 4–8.
- Culver, S.J., Farrell, K.M., Mallinson, D.J., Horton, B.P., Willard, D.A., Thieler, E.R., Riggs, S.R., Snyder, S.W., Wehmiller, J.F., Bernhardt, C.E., Hillier, C., 2008. Micropaleontologic record of Late Pliocene and Quaternary paleoenvironments in the northern Albemarle Embayment, North Carolina, USA. *Palaeogeography, Palaeoecology, Palaeoclimatology* 264, 54–77.
- Cumming, W.P., 1966. North Carolina in Maps. North Carolina Department of Archives and History, Raleigh, NC.
- Denys, L., 1991. A check-list of the diatoms in the Holocene deposits of the western Belgian coastal plain with a survey of their apparent ecological requirements. 1. Introduction, ecological code and complete list. *Belgische Geologische Dienst, Professional Paper* 1991/2 (246), 1–41.
- Ellison, R.L., Nichols, M.M., 1970. Estuarine Foraminifera from the Rappahannock River, Virginia. *Contributions from the Cushman Foundation for Foraminiferal Research* 21, 1–17.
- Foley, J., Culver, S.J., Corbett, D.R., Mallinson, D.J., Riggs, S.R., 2006. Sedimentological and foraminiferal indications of Holocene environmental change in Pamlico Sound, North Carolina. *Geological Society of America, Abstracts with Programs* 38 (3), 16.
- Folk, R.L., 1980. *Petrology of Sedimentary Rock*. Hemphill Publishing Company, Austin, Texas.
- Gibson, T.G., Buzas, M.A., 1973. Species diversity: patterns in modern and Miocene foraminifera of the eastern margin of North America. *Geological Society of America Bulletin* 84, 217–238.
- Gonzalez, J.L., Tornqvist, T.E., 2009. A new late Holocene sea-level record from the Mississippi Delta: evidence for a climate/sea level connection? *Quaternary Science Reviews* 28, 1737–1749.
- Grossman, S., Benson, R.H., 1967. *Ecology of Rhizopoda and Ostracoda of southern Pamlico Sound region, North Carolina*. Kansas University, Paleontology Contributions 44, 1–82.
- Hale, M., Culver, S.J., Mallinson, D., Riggs, S.R., 2007. Late Holocene back-barrier evolution of Ocracoke Island, Outer Banks, North Carolina. *Geological Society of America, Abstracts with Programs* 39 (2), 96.
- Hartley, B., 1986. A check-list of the diatoms of the freshwater, brackish and marine diatoms of the British Isles and adjoining coastal waters. *Journal of the Marine Biological Association of the United Kingdom* 66, 531–610.
- Hayek, L.C., Buzas, M.A., 1997. *Surveying Natural Populations*. Columbia University Press, New York.
- Hendey, N.I., 1964. An introductory account of the smaller algae of British Coastal Waters, *Bacillariophyceae* (Diatoms). Fishery Investigation Series N. HMSO, London.
- Horton, B.P., Peltier, W.R., Culver, S.J., Drummond, R., Engelhart, S.E., Kemp, A.C., Mallinson, D., Thieler, E.R., Riggs, S.R., Ames, D.V., Thomson, K.H., 2009. Holocene sea-level changes along the North Carolina coastline and their implications for glacial isostatic adjustment models. *Quaternary Science Reviews* 28, 1725–1736.
- Hudstedt, F., 1953. Die systematik der Diatomeen in ihren Beziehungen zur Geologie und Ökologie nebst einer Revisions des Halobian-Systems. *Svensk Botanisk Tidskrift* 47, 509–519.
- Hudstedt, F., 1957. Die diatomeenflora des Fluss-systems der Weser im Gebiet der Hansestadt Bremen. *Abhandlungen der Naturwissenschaftlichen Bremen* 34, 181–440.
- Hughen, K.A., Baillie, M.G.L., Bard, E., Bayliss, A., Beck, J.W., Bertrand, C., Blackwell, P.G., Buck, C.E., Burr, G., Cutler, K.B., Damon, P.E., Edwards, R.L., Fairbanks, R.G., Friedrich, M., Guilderson, T.P., Kromer, B., McCormac, F.G., Manning, S., Bronk Ramsey, C., Reimer, P.J., Reimer, R.W., Remmele, S., Southon, J.R., Stuiver, M., Talamo, S., Taylor, F.W., van der Plicht, J., Weyhenmeyer, C.E., 2004. Marine04 marine radiocarbon age calibration, 0–26 cal kyr BP. *Radiocarbon* 46, 1059–1086.
- IPCC (Intergovernmental Panel on Climate Change), 2007. *Climate Change 2007: The Physical Science Basis*. In: Solomon, S., Qin, D., Manning, M., Chen, Z., Marquis, M., Averyt, K.B., Tignor, M., Miller, H.R. (Eds.), *Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*. Cambridge University Press, Cambridge, UK and New York.
- Karlson, A.W., Cronin, T.M., Ishman, S.E., Willard, D.A., Kerhin, R., Holmes, C.W., Marot, M., 2000. Historical trends in Chesapeake Bay dissolved oxygen based on benthic foraminifera from sediment cores. *Estuaries* 23, 488–508.
- Kemp, A.C., 2009. High resolution studies of late Holocene relative sea-level change (North Carolina, USA). Unpublished PhD dissertation, University of Pennsylvania.
- Kemp, A.C., Horton, B.P., Culver, S.J., Corbett, D.R., Van de Plassche, O., Gehrels, R., Douglas, B., 2009a. The timing and magnitude of recent accelerated sea-level rise. *Geology* 37, 1035–1038.
- Kemp, A.C., Horton, B.P., Culver, S.J., 2009b. Distribution of modern salt-marsh foraminifera in the Albemarle-Pamlico estuarine system of North Carolina, USA: implications for sea-level research. *Marine Micropaleontology* 72, 222–238.
- Kemp, A.C., Horton, B.P., Donnelly, J.P., Mann, M.E., Vermeer, M., Rahmsdorf, S., 2011. Climate related sea-level variations over the past two millennia. *Proceedings of the National Academy of Sciences*. doi:10.1073/pnas.1015519108 6 pp.
- Knutson, T.R., McBride, J.L., Chan, J., Emanuel, K., Holland, G., Landsea, C., Held, I., Kossin, J.P., Srivastava, A.K., 2010. Tropical cyclones and climate change. *Nature Geoscience* 3, 157–217.
- Leorri, E., Martin, R.E., McLaughlin, P.P., 2006. Holocene environment and parasequence development of the St. Jones estuary, Delaware (USA); foraminifera as proxies of natural climatic and anthropogenic environmental change. *Palaeogeography, Palaeoclimatology, Palaeoecology* 241, 590–607.
- Mallinson, D.J., Riggs, S.R., Thieler, E.R., Culver, S.J., Farrell, K., Foster, D.S., Corbett, D.R., Horton, B., Wehmiller, J.F., 2005. Late Neogene and Quaternary evolution of the northern Albemarle Embayment (mid-Atlantic continental margin, USA). *Marine Geology* 217, 97–117.
- Mallinson, D.J., Burdette, K., Mahan, S., Brook, G., 2008. Optically stimulated luminescence age controls on late Pleistocene and Holocene lithosomes, North Carolina, USA. *Quaternary Research* 69, 97–109.
- Mallinson, D.J., Culver, S.J., Riggs, S.R., Thieler, E.R., Foster, D., Wehmiller, J., Farrell, K., Pierson, J., 2010a. Regional seismic stratigraphy and controls on the Quaternary evolution of the Cape Hatteras region of the Atlantic passive margin, USA. *Marine Geology* 268, 16–33.
- Mallinson, D.J., Smith, C.W., Culver, S.J., Riggs, S.R., Ames, D.V., 2010b. Geological characteristics and spatial distribution of paleo-inlet channels beneath the Outer Banks barrier islands, North Carolina, USA. *Estuarine, Coastal and Shelf Science* 88, 175–189.
- Mallinson, D.J., Smith, C.W., Mahan, S., Culver, S.J., McDowell, K., 2011. Barrier island processes and response to late Holocene climate patterns: outer banks barrier islands, North Carolina, USA. *Quaternary Research* 76, 46–57.
- Mann, M.E., Woodruff, J.D., Donnelly, J.P., Zhang, Z., 2009. Atlantic hurricanes and climate over the past 1,500 years. *Nature* 460, 880–883.
- Mayewski, P.A., Rohling, E.E., Stager, J.C., Karlen, W., Maasch, K.A., Meeker, L.D., Meyerson, E.A., Gasse, F., van Kreveland, S., Holmgren, K., Lee-Thorp, J., Rosqvist, G., Rack, F., Staubwasser, M., Schneider, R.R., Steig, E.J., 2004. Holocene climate variability. *Quaternary Research* 62, 243–255.
- McDowell, K.L., Mallinson, D.J., Culver, S.J., Walsh, J.P., 2009. Holocene geologic development of the central Hatteras Flats and Buxton beach ridges, Outer Banks, North Carolina. *Geological Society of America, Abstracts with Programs* 41 (1), 51.
- Mello, J.F., Buzas, M.A., 1968. An application of cluster analysis as a method for determining biofacies. *Journal of Paleontology* 42, 747–758.
- Metzger, L., Culver, S., Mallinson, D., Riggs, S., 2008. Holocene paleoenvironmental change in southern Pamlico Sound, North Carolina. *Geological Society of America, Abstracts with Programs* 40 (4), 22.
- Munsterman, D., Kersthoft, S., 1996. Sodium polytungstate, a new non-toxic alternative to bromoform in heavy liquid separation. *Review of Palaeobotany and Palynology* 91, 417–422.
- Otvos, E.G., Carter, G.A., 2008. Hurricane degradation–barrier development cycles, northeastern Gulf of Mexico: landform evolution and island chain history. *Journal of Coastal Research* 24, 463–478.
- Parham, P.R., Riggs, S.R., Culver, S.J., Mallinson, D., Wehmiller, J.F., 2007. Quaternary depositional patterns and sea-level fluctuations, northeastern North Carolina. *Quaternary Research* 67, 83–99.
- Pietrafesa, L.J., Janowitz, G.S., Witman, P.A., 1985. Physical oceanographic processes in the Carolina Capes. In: Atkinson, L.P., Menzel, D.W., Bush, K.A. (Eds.), *Oceanography of the Southeastern Continental Shelf*. American Geophysical Union, Washington, D.C., pp. 23–32.
- Pietrafesa, L.J., Janowitz, G.S., Chao, T.Y., Weisberg, R.H., Askari, F., Noble, E., 1986. *The Physical Oceanography of Pamlico Sound: UNC Sea Grant Publication No. UNC-WP-86-5*.
- Pilkey, O.H., Neal, W.J., Riggs, S.R., Webb, C.A., Bush, D.M., Pilkey, D.F., Bullock, J., Cowan, B.A., 1998. The North Carolina shore and its barrier islands: restless ribbons of sand. *Living with the shore*. Duke University Press, Durham.
- Pruitt, R.J., Culver, S.J., Buzas, M.A., Corbett, D.R., Horton, B.P., Mallinson, D.J., 2010. Modern foraminiferal distribution and recent environmental change in Core Sound, North Carolina, USA. *Journal of Foraminiferal Research* 40, 344–365.
- Reimer, P.J., Baillie, M.G.L., Bard, E., Bayliss, A., Beck, J.W., Bertrand, C., Blackwell, P.G., Buck, C.E., Burr, G., Cutler, K.B., Damon, P.E., Edwards, R.L., Fairbanks, R.G., Friedrich, M., Guilderson, T.P., Hughen, K.A., Kromer, B., McCormac, F.G., Manning, S., Bronk Ramsey, C., Reimer, R.W., Remmele, S., Southon, J.R., Stuiver, M., Talamo, S., Taylor, F.W., van der Plicht, J., Weyhenmeyer, C.E., 2004. IntCal04 terrestrial radiocarbon age calibration, 0–26 cal kyr BP. *Radiocarbon* 46, 1029–1058.
- Riggs, S.R., Ames, D.V., 2003. *Drowning the North Carolina Coast: Sea-Level Rise and Estuarine Dynamics: North Carolina Sea Grant Program, Publication No. UNC-SG-03-04*. Raleigh, NC.
- Riggs, S.R., Cleary, W.J., Snyder, S.W., 1995. Influence of inherited geologic framework on barrier shoreface morphology and dynamics. *Marine Geology* 126, 213–234.
- Robinson, M.M., McBride, R.A., 2006. Benthic foraminifera from a relict flood-tide delta along the Virginia/North Carolina Outer Banks. *Micropaleontology* 52, 67–80.
- Rosenberger, J.E., Culver, S.J., Corbett, D.R., Mallinson, D.J., Riggs, S.R., 2006. Late Holocene back-barrier development of Portsmouth Island, Outer Banks, North Carolina. *Geological Society of America, Abstracts with Programs* 38 (3), 15.
- Schnitker, D., 1971. Distribution of foraminifera on the North Carolina continental shelf. *Tulane Studies in Geology and Paleontology* 8, 169–215.
- Shaw, J., Amos, C.L., Greenberg, D.A., O'Reilly, C.T., Parrott, D.R., Patton, E., 2010. Catastrophic tidal expansion in the Bay of Fundy, Canada. *Canadian Journal of Earth Science* 47, 1079–1091.
- Smith, C.G., Culver, S.J., Riggs, S.R., Ames, D., Corbett, D.R., Mallinson, D., 2008. Geospatial analysis of barrier island width of two segments of the Outer Banks,

- North Carolina, USA: anthropogenic curtailment of natural self-sustaining processes. *Journal of Coastal Research* 24, 70–83.
- Smith, C.G., Culver, S.J., Mallinson, D.J., Riggs, S.R., Corbett, D.R., 2009. Recognizing former flood tidal delta deposits in the Holocene stratigraphic record from the Outer Banks, North Carolina, USA. *Stratigraphy* 6, 61–78.
- Southon, J., Kashgarian, M., Fontugne, M., Metivier, B., Yim, W.W.S., 2002. Marine reservoir corrections for the Indian Ocean and southeast Asia. *Radiocarbon* 44, 167–180.
- Twamley, D.F., Culver, S.J., Mallinson, D.J., Riggs, S.R., Corbett, D.R., 2006. Holocene geologic development of the Hatteras Village area, Outer Banks, North Carolina. *Geological Society of America, Abstracts with Programs* 38 (3), 15.
- Vance, D.J., Culver, S.J., Corbett, D.R., Buzas, M.A., 2006. Foraminifera in the Albemarle estuarine system, North Carolina: distribution and recent environmental change. *Journal of Foraminiferal Research* 36, 15–33.
- Van der Werff, H., Huls, H., 1958–1966. *Diatomeenflora van Nederland*. De Haef, The Netherlands. Published privately.
- Vos, P.C., de Wolf, H., 1993. Diatoms as a tool for reconstruction of sedimentary environments in coastal wetlands: methodological aspects. *Hydrobiologica* 269 (270), 285–296.
- Wehmiller, J.F., Thieler, E.R., Miller, D., Pellerito, V., Bakeman Keeney, V.R., Riggs, S.R., Culver, S., Mallinson, D., Farrell, K., York, L.L., Pierson, J., Parham, P., 2010. Aminostratigraphy of surface and subsurface Quaternary units, Coastal Plain of North Carolina, USA. *Quaternary Geochronology* 5, 459–492.
- Wells, J.T., Kim, S.Y., 1989. Sedimentation in the Albemarle–Pamlico lagoonal system: synthesis and hypothesis. *Marine Geology* 88, 263–284.
- Zong, Y., Horton, B.P., 1999. Diatom-based tidal-level transfer functions as an aid in reconstructing Quaternary history of sea-level movements in Britain. *Journal of Quaternary Science* 14, 153–167.