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FORAMINIFERA IN THE ALBEMARLE ESTUARINE SYSTEM, NORTH CAROLINA: DISTRIBUTION AND RECENT ENVIRONMENTAL CHANGE

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ABSTRACT

This study investigated the surface and subsurface distributions of foraminifera (both live populations and dead assemblages) throughout the Albemarle Estuarine System (AES) to determine the utility of the modern foraminiferal assemblages as models for paleoenvironmental interpretations in this estuarine and barrier island system. Thirty-seven species were recognized in the dead assemblages from 49 stations; 19 species comprised the living populations. Cluster analysis of the dead assemblages defined five biofacies: the calcareous foraminiferal nearshore marine and inlet biofacies, and the dominantly agglutinated foraminiferal estuarine shoal, estuary, inner estuary, and marsh biofacies.

Paleoenvironmental reconstruction of three cores from the central Albemarle basin, based on the distribution of dead surface foraminiferal assemblages, recognized the inner estuarine and estuarine biofacies. Radionuclide tracers (^{210}Pb and ^{137}Cs) provided the geochronologic framework for each core. The westernmost core was capped by the inner estuarine biofacies overlying the estuarine biofacies, indicating either accumulation of a seasonal ephemeral layer of sediment from a lower brackish, upstream environment or increased freshwater discharge since the 1990's as a result of increased tropical storm and hurricane activity. The two easternmost cores indicated that, in the early 19th century, Albemarle Sound populations included calcareous foraminiferal species. These taxa were adapted to the higher salinities that resulted from several inlets that were open adjacent to the AES prior to 1828.

Taphonomic processes (test transport, test dissolution, mechanical test breakage) are active but, with the exception of test dissolution in a relatively restricted geographic area, they do not significantly alter surficial foraminiferal assemblages in the transition into subfossil assemblages. Thus, foraminiferal distributions are useful for characterizing modern estuarine environments and for interpreting paleoenvironmental changes in sediments deposited over the past few hundred years in coastal North Carolina.

INTRODUCTION

The foraminifera of Albemarle Sound, one of the largest estuarine bodies of water on the east coast of the United States, are undocumented. In this study we analyze the distribution of modern benthic foraminifera in Albemarle and adjacent sounds (the Albemarle estuarine system: AES) and test the utility of these data in reconstructing the past two centuries of environmental change in the western and central Albemarle estuarine basin. The study is part of a larger research program, the North Carolina Coastal Geology Cooperative, that aims to characterize the Quaternary geologic framework and the modern-day geologic processes of eastern North Carolina. Knowledge gained from this study will help answer critical questions concerning coastal responses to ongoing climate change and sea-level rise.

The brackish AES (Fig. 1) is comprised of several open-water sounds fed by lateral estuaries. To the east are the Outer Banks barrier islands interrupted by Oregon Inlet several kilometers southeast of Roanoke Island (Fig. 1). Oregon Inlet, the only direct contact with the Atlantic Ocean in the northern Outer Banks, directly influences salinities in the southeastern AES (Fig. 1).

The main trunk of the AES is Albemarle Sound, which extends from the mouth of the Roanoke and Chowan rivers (where salinity is zero), eastward for 90 km to Kitty Hawk Bay on the Outer Banks, where salinity is usually in single digits and lowest in spring when runoff from spring rains displaces more saline water (Giese and others, 1985; Fig. 1). To the east, the AES is composed of three open-water sounds parallel to the outer Banks, the predominantly very low brackish Currituck Sound and the variably brackish Roanoke and Croatan sounds. Croatan Sound provides the dominant hydrologic connection for the AES to Pamlico Sound and the Atlantic Ocean through Oregon Inlet, where salinity reaches the 30's (Fig. 1).

The physical hydrology and circulation in the AES is governed predominantly by the three factors of fresh water inflow, winds and astronomical tides (Wilder, 1968), although the effects of astronomical tides are restricted to the immediate vicinity of inlets (Riggs and Ames, 2003). Freshwater inflow from rivers is the dominant force in long-term circulation (Giese and others, 1985). The AES has a large surface area and moderately uniform depths, which provide adequate fetch and water depths to create wind-driven waves and wind tides on a shorter timescale (Riggs, 2002). Thus, winds exert the major influence on short-term circulation and play an integral role in mixing the estuary, causing physiochemical gradients in the water column to be small (Bowden and Hobbie, 1977).

Much of Albemarle Sound and its embayed tributaries are rimmed by a submerged perimeter platform from 1–2 m in depth (Riggs, 1996) and formed by Pleistocene deposits that are covered by a thin layer of modern sand eroded from the sediment bank shorelines (Sager and Riggs, 1998). From the perimeter platform, the estuary floor slopes gently down to the flat bottom of a central basin, approximately 6 m deep in Albemarle Sound and 2–4 m deep in embayed tributaries (Riggs, 1996). The basins are floored with organic-rich mud supplied by the Roanoke and Chowan rivers and by erosion of marginal swamp forests and salt marshes (Copeland and others, 1983; Riggs, 1996).

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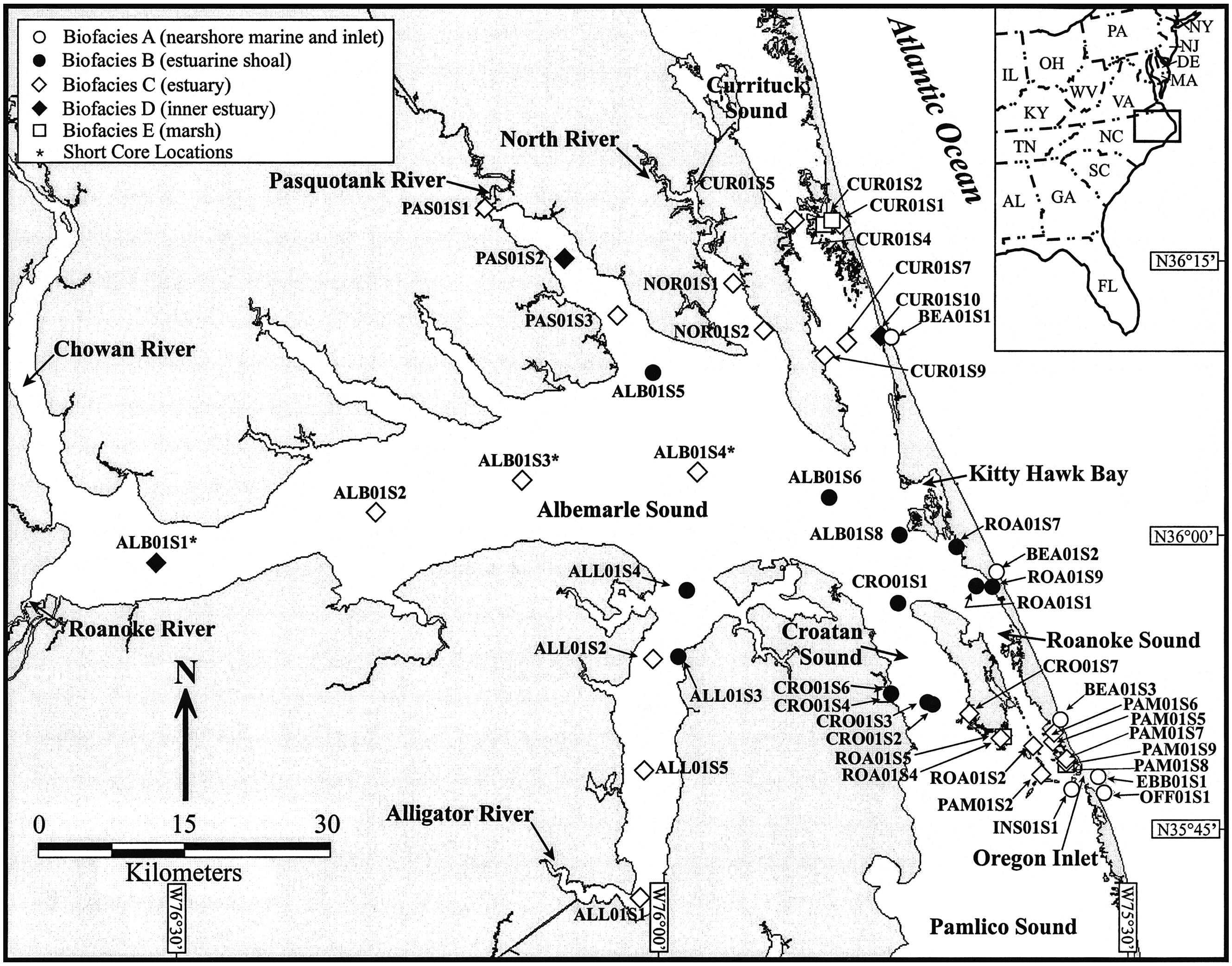


FIGURE 1. Map showing location of 49 sample stations and five biofacies (dead assemblages) in the Albemarle estuarine system. Symbols are those used on Figure 2.

PREVIOUS WORK

The distribution of benthic foraminifera on the U.S. Atlantic continental margin was summarized by Culver and Buzas (1980 and included references). In the mid-Atlantic region (Delaware, Maryland, Virginia, North Carolina, South Carolina and Georgia), estuarine foraminifera were documented by Akers (1971), Buzas (1968, 1969, 1970, 1974), Ellison (1972), Ellison and Nichols (1970, 1976), Grossman and Benson (1967), Hadley (1936), Kraft and Margules (1971), LeFurgey (1976), Miller (1953), Nichols and Ellison (1967) and Nichols and Norton (1969). More recent works on marsh foraminifera in this region include Collins (1996), Collins and others (1995), Culver and Horton (2005), Goldstein (1988), Goldstein and Harben (1993), Goldstein and Watkins (1998, 1999), Goldstein and others (1995), Hippensteel and others (2000, 2002), Horton and Culver (in press) , Spencer (2000) and Tobin and others (2005).

However, relatively few studies have documented the foraminifera of coastal North Carolina from the marshes, coastal estuaries and inner continental shelf (Miller, 1953; Grossman and Benson, 1967; Akers, 1971; Schnitker, 1971; LeFurgey, 1976; Workman, 1981; Culver and Horton, 2005; Horton and Culver, in press; Vance, 2004; Abbene, 2004). Miller (1953) recorded 42 species from brackish lagoonal and marsh environments around Mason Inlet, southern North Carolina. Nearby, Akers (1971) recognized open-ocean, lagoonal and fluvial-marine assemblages along a salinity gradient in the Neuse River. Akers (1971) also noted a marsh assemblage similar in composition to the fluvial-marine assemblage.

Southern Pamlico Sound was the subject of a study by Grossman and Benson (1967). They defined five salinity, vegetation and tidal current-related biofacies: estuarine, open-sound, saltwater lagoon, tidal delta and marsh, in environments ranging in salinity from 0.5 to 36. In northern Pamlico Sound and the adjacent Roanoke and Croatan sounds, LeFurgey (1976) documented the occurrence of live and dead foraminifera as part of an environmental impact study of the effects of dredging on the benthic environment. Lower Roanoke Sound (near Oregon Inlet) had a different living population (dominated by *Miliammina fusca* and *Elphidium selseyense* = *E. excavatum* of this study) compared to upper Roanoke Sound, Croatan Sound and northern Pamlico Sound, which were dominated by *Miliammina fusca* and *Ammobaculites cassis* (LeFurgey, 1976).

The distribution of foraminifera across the entire Pamlico Sound was documented recently by Abbene (2004). She defined four biofacies: a marine assemblage at barrier island inlets, a marsh assemblage on both mainland and back-barrier salt marshes, and two estuarine assemblages that differed in their proportions of three abundant taxa. Estuarine Biofacies A had a greater relative abundance of the agglutinated species *Ammotium salsum* and *Ammobaculites crassus* and a low relative abundance of *Elphidium excavatum*. Estuarine Biofacies B had a greater relative abundance of *Elphidium excavatum* and occurred where salinities, although seasonally variable, were generally greater than those where Estuarine Biofacies A occurred. Abbene (2004) used these modern distribution patterns to reconstruct Pamlico Sound environments in two recent time-slices, 40 years ago and 120 years ago.

Culver and Horton (2005) and Horton and Culver (in press) found that the back-barrier marsh environments of the Outer Banks contain typical marsh assemblages. However, the three different salinity settings that they studied had distinct assemblages. Changes of assemblages with elevation were present along transects at all three sites (Horton and Culver, in press). Culver and Horton (2005) investigated the vertical distribution of infaunal foraminifera at all three sites and concluded that foraminiferal assemblages (dead) and populations (live) do not differ significantly with depth and that the 0–1 cm depth interval provides an adequate model upon which paleoenvironmental or sea-level reconstructions can be based.

Offshore of North Carolina's barrier islands on the continental shelf, Schnitker (1971) documented distinctly different foraminiferal assemblages north and south of Cape Hatteras. North of the cape (i.e., offshore of the AES), Schnitker (1971) recognized a nearshore assemblage characterized by $>$50% per sample abundance of *Elphidium clavatum* (*E. excavatum* of this study) and central-shelf and shelf-edge assemblages characterized by lesser proportions of *E. clavatum*. Workman (1981) studied nearshore foraminifera off Nags Head and found similar *Elphidium*-dominated assemblages.

The previous works by Grossman and Benson (1967), Schnitker (1971), Workman (1981) and Abbene (2004) in particular, provide a useful framework of comparison for this study that documents foraminiferal distributions across the entire AES, and aid paleoenvironmental interpretations of subsurface foraminiferal assemblages recovered from short cores in the central AES.

FIELD AND LABORATORY METHODS

Push-cores and grab samples were collected at 49 stations in the AES in June and July, 2001 (Fig. 1) in environments ranging from the fringing marshes to estuarine basins and the shoreface. A 50 cm^3 aliquot of sediment was taken from the top 1 cm of each 7.60-cm-diameter push-core for foraminiferal analysis; samples were immediately preserved in the field in a 5% buffered formalin solution. At stations characterized by coarse sand, where cores could not be taken, a Ponar grab was used to collect the top 1 cm of sediment. At three core stations along the axis of Albemarle Sound (ALB01S1, ALB01S3 and ALB01S4) vertical distributions of foraminifera were studied by subsectioning shallow ($<$50 cm) push-cores. One additional push-core was collected at each of the three stations for ^{210}Pb and ^{137}Cs analysis to develop a geochronology for each core.

Surface and core subsamples preserved with a buffered formalin solution were washed through 0.710 mm and 0.063 mm sieves to remove the coarse fraction, silt, clay and formalin. The residue on the 0.063 mm sieve was stained with rose Bengal (Walton, 1952) and rewashed to remove the excess stain. Foraminifera were concentrated in sand-rich samples using a sodium polytungstate solution (density $\cong$ 2.34 g/ml) to separate the foraminifera from the sand (Munsterman and Kerstholt, 1996). All samples were dried and split into smaller aliquots using a microsplitter; approximately 300 foraminifera (randomly selected from a variable number of squares on a gridded picking tray) were picked from each sample (Buzas, 1990). Living specimens were assessed by thoroughly wetting the specimen on the slide. Specimens containing one or more chambers of deep pink-stained protoplasm were deemed to be live at the time of collection. Identification of specimens was made through comparison with the published literature and through comparison with type specimens at the National Museum of Natural History, Smithsonian Institution, Washington, D.C. The original reference for each taxon is given in Appendix A. The most abundant taxa are illustrated in Plates 1–2.

Q-mode cluster analysis (Mello and Buzas, 1968), was employed to delineate groups (representing biofacies) in the surficial (top 1 cm) live and dead foraminiferal data using the statistical software SYSTAT version 10.0. Only the most abundant foraminiferal species (27) in the dead assemblage, defined as those species that comprised 5% or more of the assemblage in any one sample, were included in the cluster analysis. Species proportions (%/100) were transformed according to 2 arc sin $\sqrt{p_i}$, where p_i is the proportion of the ith foraminiferal species within the sample (Buzas, 1979). The hierarchical clustering method (Davis, 1986) was chosen to cluster the data using Ward's linkage method and Euclidean distances.

Samples from short push-cores were analyzed for ^{210}Pb ($t_{1/2}$ = 22.3 yrs), ^{137}Cs ($t_{1/2}$ = 30.2 yrs), and ^{226}Ra ($t_{1/2}$ = 1600 yrs) by direct gamma counting on one of two low-background, high-efficiency, high-purity Germanium detectors (coaxial- and well-type). Samples were initially dried, homogenized, and packed into standardized vessels for approximately 24 hours before counting. Detectors were calibrated using natural matrix standards (IAEA-300, 312, 314) at each energy interest.

^{137}Cs activities were measured using the net counts at 661.7keV photopeak. ^{226}Ra activities were determined by allowing sediments to equilibrate for greater than three weeks and then measured indirectly using its granddaughters ^{214}Pb (295 and 351 keV) and ^{214}Bi (609 keV). Total ^{210}Pb activities were measured at the 46.5 keV peak after correcting for self-adsorption using a direct transmission method (Cutshall and others, 1983; Cable and others,

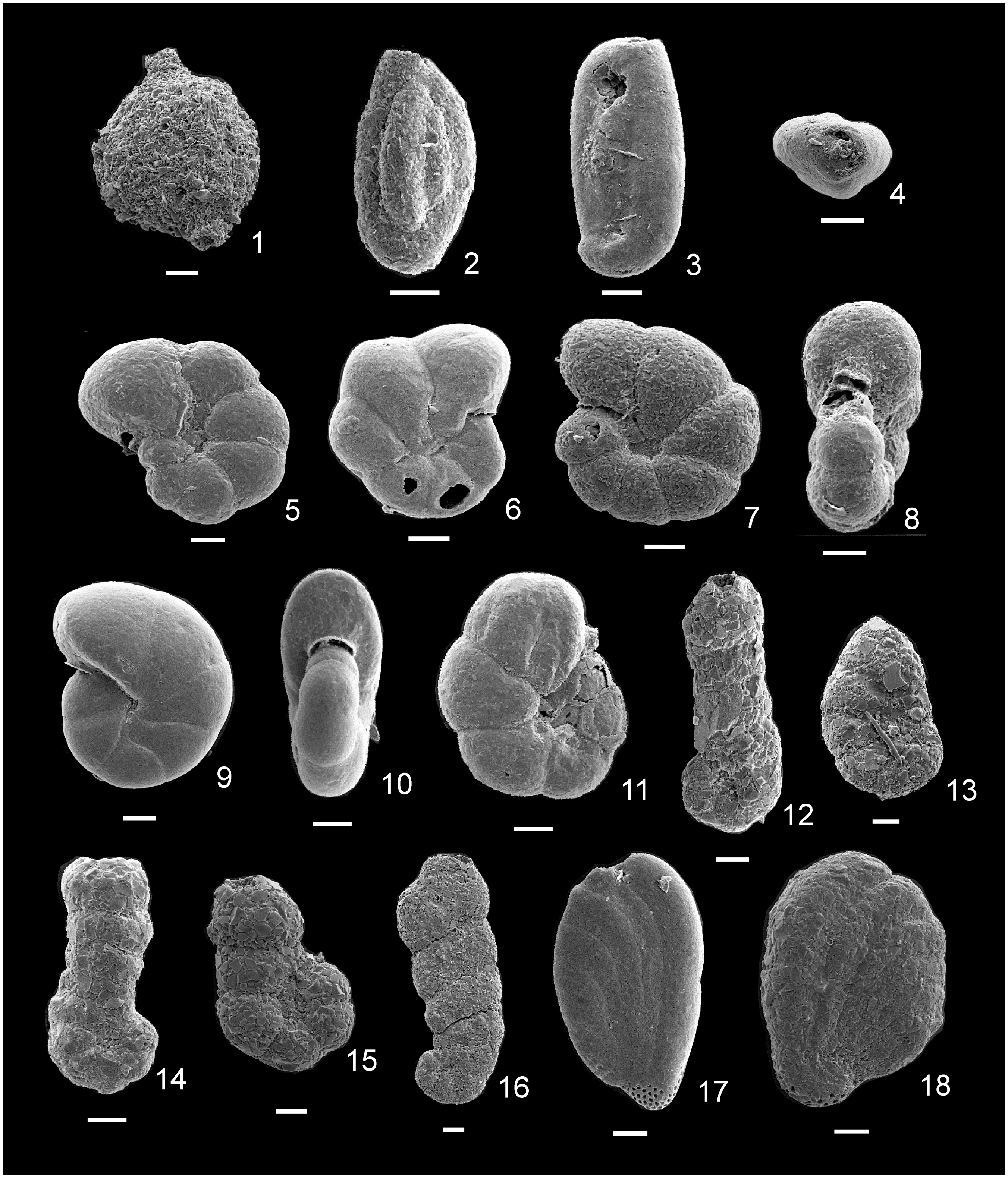


PLATE 1

(Scale bars = 100 µm) **1.** *Pseudothurammina limnetis*. **2.** *Miliammina fusca*. **3, 4.** *Miliammina petila*. **5.** *Haplophragmoides bonplandi*. **6.** *Haplophragmoides hancocki*. **7, 8.** *Haplophragmoides manilaensis*. **9, 10.** *Haplophragmoides wilberti*. **11.** *Trochamminita salsa*. **12.** *Ammobaculites crassus*. **13.** *Ammobaculites dilatatus*. **14.** *Ammobaculites exiguus*. **15.** *Ammobaculites subcatenulatus*. **16.** *Ammotium salsum*. **17, 18.** *Ammoastuta inepta*.

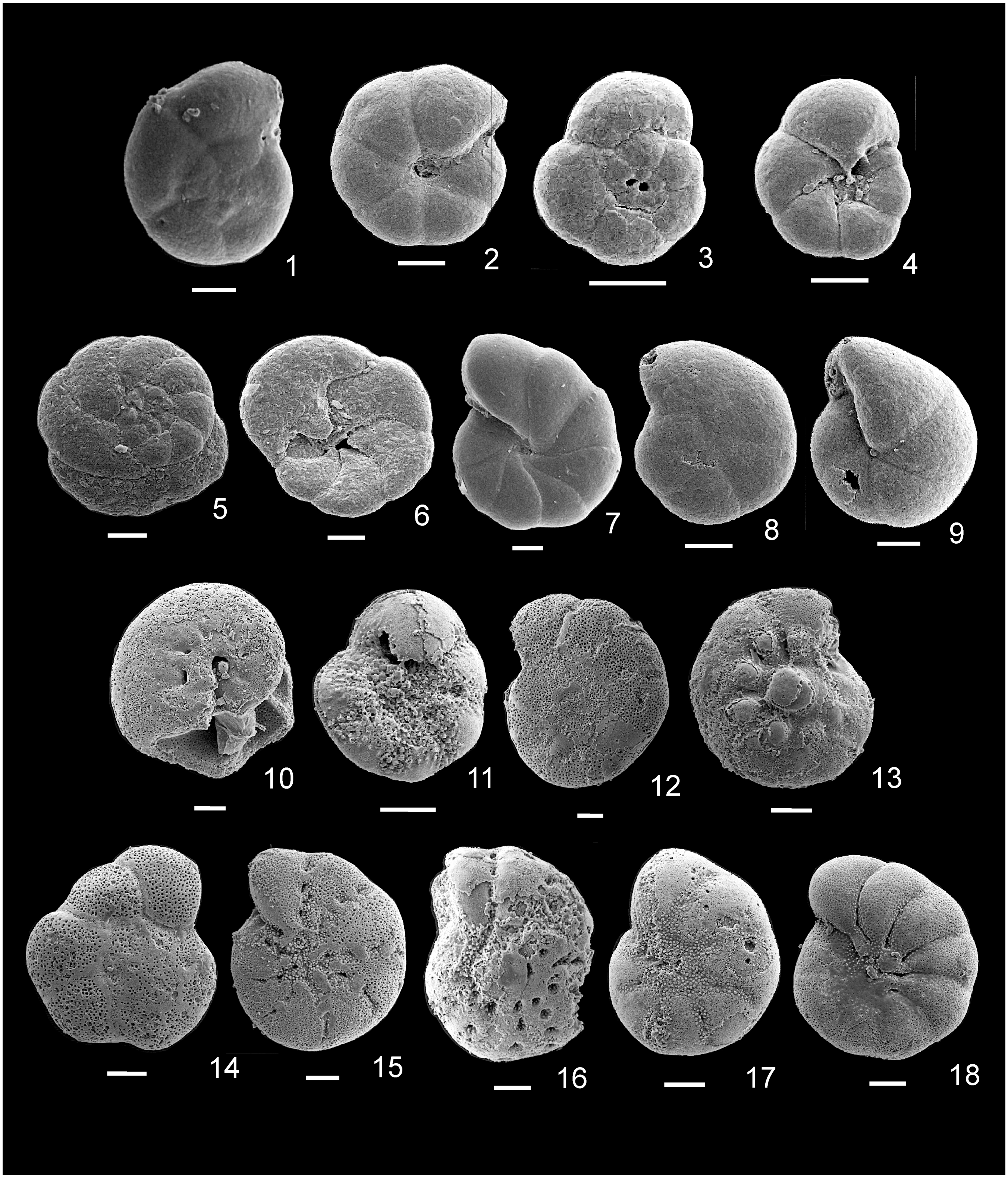


PLATE 2

(Scale bars = 100 µm) **1, 2.** *Trochammina inflata*. **3, 4.** *Siphotrochammina lobata*. **5, 6.** *Tiphotrocha comprimata*. **7.** *Jadammina macrescens* **8, 9.** *Arenoparrella mexicana*. **10.** *Hanzawaia strattoni*. **11.** *Buccella frigida*. **12, 13.** *Ammonia parkinsoniana*. **14.** *Ammonia tepida*. **15.** *Elphidium excavatum*. **16.** *Elphidium galvestonense*. **17.** *Elphidium subarcticum*. **18.** *Elphidium* sp.

2001). Excess ^{210}Pb was then calculated as the difference of total ^{210}Pb and that supported by ^{226}Ra. ^{210}Pb profiles were analyzed according to the constant flux, constant sedimentation rate (CF:CS) model (Appleby and Oldfield, 1992). The error for each radioisotope analysis was calculated by propogation of errors associated with sample, standard and background counting rates.

RESULTS

General Trends In Foraminiferal Distributions

Forty-nine stations were sampled throughout the AES from the inner estuarine environment to the inner continental shelf (Fig. 1). Thirty-seven taxa (28 agglutinated, 9 calcareous) were identified at 48 of 49 stations; one station (CUR01S6) was barren of foraminifera. Of the 37 taxa, 19 comprised the living populations (15 agglutinated, 4 calcareous) and were found at 40 of 49 stations. Census data for the live populations and dead assemblages are given in Appendices B and C.

Living Populations

The calculated number of living individuals per 50 cm^3 sample varied from one (BEA01S1) to over 6,000 (NOR01S2). Low numbers of live specimens occurred near freshwater inflow, on shoals along the perimeter platform and adjacent back barrier system, on the Oregon Inlet ebb delta shoal and the foreshore. Slightly higher numbers of live specimens occurred in the central basins of sounds and embayed tributary channels, and on fringing marshes in the central and eastern portions of the AES.

The 19 living species occurred in four general environments. Seven species lived exclusively in the fringing marsh environment, including associated runnels and microbial-bounded sand flats (*Ammoastuta inepta*, *Arenoparrella mexicana*, *Haplophragmoides bonplandi*, indeterminate agglutinated unilocular species, *Jadammina macrescens*, *Miliammina petila* and *Trochammina inflata*). Seven species occurred in both estuarine basins and fringing marsh environment (*Ammobaculites crassus*, *A. exiguus*, *A. subcatenulatus*, *Ammonia* sp., *Ammotium salsum*, *Miliammina fusca* and *Tiphotrocha comprimata*). Four species were found living exclusively in the sounds and nearshore back-barrier waters (*Ammobaculites dilatatus*, *Ammonia parkinsoniana*, *Elphidium galvestonense* and *Reophax* sp.). On the Atlantic Ocean side of the barrier system, one species, *Elphidium excavatum*, was found living on the ebb delta (EBB01S1) and the foreshore (BEA01S1).

Dead Assemblages

The calculated numbers of dead specimens per 50 cm^3 sample varied from three on a back-barrier intertidal shoal (ROA01S9) to 261,669 in a small tidal creek next to a *Juncus* marsh (ROA01S4; Table 1). In general (and as for live foraminifera), numbers per 50 cm^3 sample were lowest near freshwater inflow, on sandy perimeter platform shoals around the interior of the AES, on back-barrier and inlet shoals (flood and ebb) and on the shoreface. Specimen numbers were highest in the fringing marshes and their adjacent nearshore flats, and in the central basins of some of the eastern sounds and embayed tributaries.

The number of dead species per sample, S, varied from 3 to 16 (Table 1). High numbers occurred in fringing marshes (stations CUR01S2, CUR01S4, CRO01S4, ROA01S5) and adjacent estuarine waters (ALL01S1, CRO01S3, CRO01S6, CRO01S7, ROA01S7, ROA01S9, PAM01S5). Species richness was lowest in high-energy environments such as the foreshore (BEA01S1, BEA01S2, BEA01S3), ebb- and flood-tide delta shoals (EBB01S1, INS01S1) and some back-barrier shoals and channels (ALB01S6, CRO01S7, ROA01S2). The central basins of the sounds and embayed tributary channels and the perimeter platform and back-barrier shoals had intermediate numbers of species (4–7).

Cluster Analysis

Cluster analysis was performed on transformed proportions data for both the living populations and the dead assemblages. Although the results are similar, those for the dead assemblages only are given here; they are based on more data and provide more resolution. Ecologically meaningful groups identified by the cluster analysis are referred to below as biofacies. The average relative abundance of species within each biofacies was used to aid comparison between biofacies.

The dendrogram (Fig. 2) is composed of several nested groups; a plot of five groups produced the most ecologically meaningful pattern (Table 1, Figs. 1, 2).

Biofacies A (nearshore marine and inlet; Table 1, Figs. 1, 2) is composed of six stations located along the foreshore, shoreface and within the ebb- and flood-tidal delta complex of Oregon Inlet. Species richness (S) was generally low with the exception of shoreface station OFF01S1, where eight species were recorded (Table 1). Calculated numbers of specimens per 50 cm^3 sample were low and ranged from five (BEA01S3) to 270 (INS01S1). *Elphidium excavatum* dominated with an average relative abundance for the biofacies of 89% (Table 2). Other species in the assemblage were the calcareous taxa *Hanzawaia strattoni* (3.8%), *Elphidium subarcticum* (1.9%), *Ammonia parkinsoniana* (1.6%) and *Ammonia tepida* (0.3%). Agglutinated species were present at only two sites (BEA01S2 and OFF01S1).

Biofacies B (estuarine shoal; Table 1, Figs. 1, 2) is composed of 12 stations located along the perimeter platform (ALB01S5, ALL01S3, ALL01S4) and back-barrier sand shoals (ALB01S6, ALB01S8, CRO01S1, ROA01S1), tidal channels (CRO01S2, CRO01S3, CRO01S6) and unprotected intertidal nearshore sand flats (ROA01S7, ROA01S9). Species richness was generally low (3–5; Table 1), but stations CRO01S6 and ROA01S7 contained 10 and 14 species, respectively. Calculated numbers of specimens per 50 cm^3 sample ranged from 3 (ROA01S9) to 104,400 (ROA01S1). Estuarine stations situated near marshes (ALB01S8, ALL01S3, CRO01S1, CRO01S6, ROA01S1, ROA01S7) have a higher species richness than other stations as a result of the presence of rare marsh species transported into the estuarine environment. No species definitively characterize this biofacies because all taxa present have wide-ranging distributions within the study area. However, *Ammobaculites crassus* and

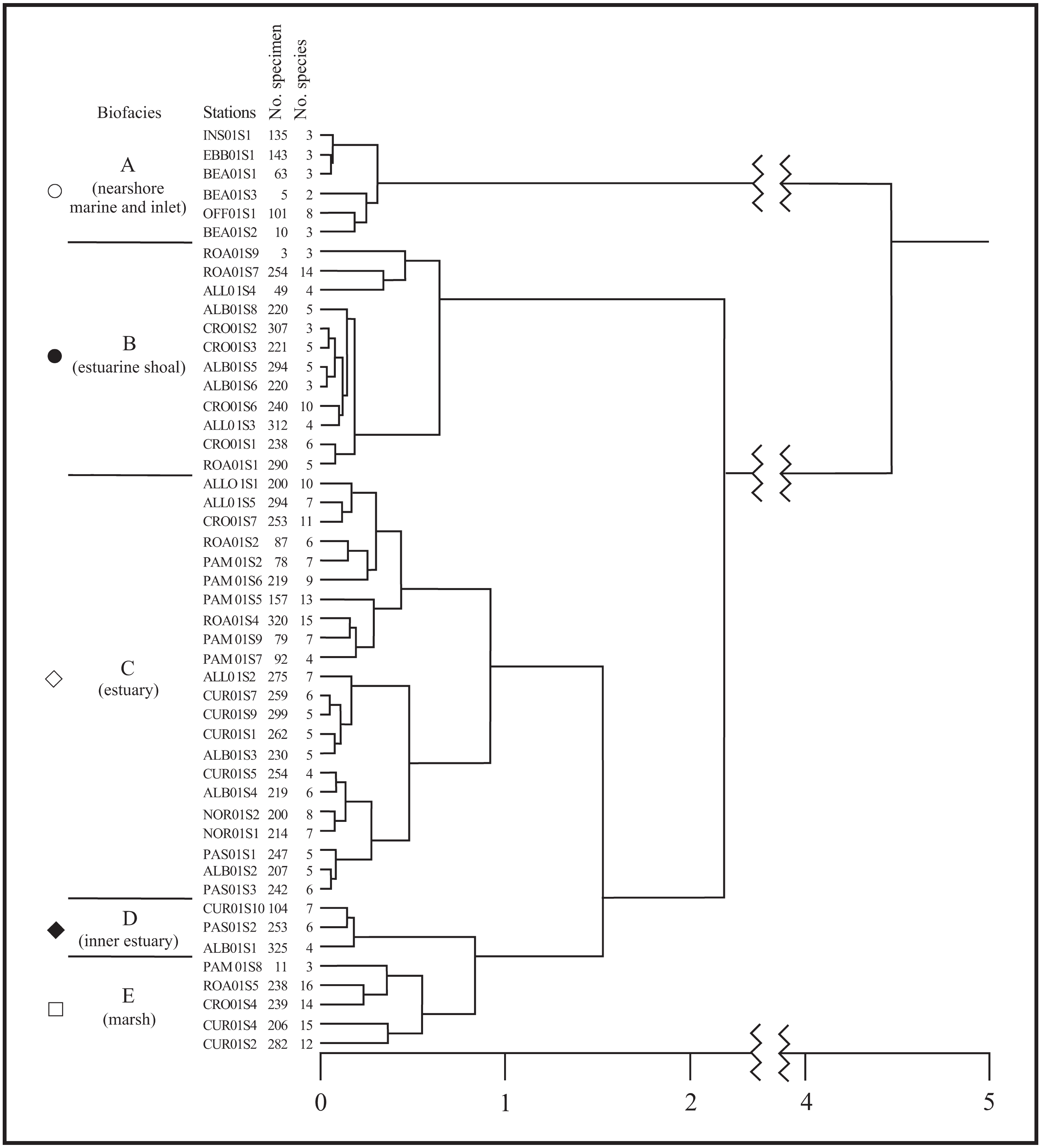


FIGURE 2. Dendrogram produced by cluster analysis (Ward's linkage, Euclidean distances) of transformed proportions data for the dead foraminifera. Only those taxa comprising 5% or more of the assemblage in any one sample were included.

Ammotium salsum have high average relative abundances in this biofacies.

Biofacies C (estuary; Table 1, Figs. 1, 2) is composed of 22 stations located in the central sound basins (ALB01S2, ALB01S3, ALBO01S4, CUR01S1, CUR01S5, CUR01S7, CUR01S9), embayed tributary channels (ALL01S1, ALL01S2, ALL01S5, NORO1S1, NOR01S2, PAS01S1, PAS01S3), intertidal nearshore sand and mud flats (ROA01S4, PAM01S5, PAM01S6, PAM01S7, PAM01S9) and higher salinity back-barrier shoals (CRO01S7, ROA01S2, PAM01S2). Species richness (S) ranged from 4 on intertidal sand flats (CUR01S7 and PAM01S7) to 15 at an intertidal creek adjacent to a fringing marsh (ROA01S4). Calculated numbers of specimens per 50 cm^3 ranged from

TABLE 1. Biofacies defined by cluster analysis of dead assemblages comprised of only those species with an abundance greater than 5% in any one sample. Station latitude and longitude are expressed in decimal degrees. Water depths are given in meters and values for species richness (S), number of specimens picked (N) and calculated number of specimens per 50 cm^3 (n) are listed for each station.

Biofacies	Environment	Stations	Latitude (°N)	Longitude (°W)	Depth (m)	S	N	n
A	Nearshore marine and inlet	INS01S1	35.7675	75.5418	1.2	3	135	270
		EBB01S1	35.7791	75.5119	2.4	3	143	143
		BEA01S1	36.1811	75.7488	0.0	3	63	63
		BEA01S3	35.8314	75.5549	0.0	2	5	5
		OFF01S1	35.7645	75.5047	9.3	8	101	101
		BEA01S2	35.967	75.6279	0.0	3	10	10
		Mean				4	76	99
B	Estuarine shoal	ROA01S9	35.9534	75.6327	0.0	3	3	3
		ROA01S7	35.9883	75.6722	0.1	14	254	2750
		ALL01S4	35.9497	75.97942	1.8	4	49	49
		ALB01S8	36.000105	75.7385	1.8	5	220	426
		CRO01S2	35.8454	75.699667	0.1	3	307	5526
		CRO01S3	35.84735	75.705317	3.0	5	221	5658
		ALB01S5	36.14732	76.01739	3.4	5	294	6615
		ALB01S6	36.034183	75.816817	3.7	3	220	5120
		CRO01S6	35.856	75.74765	1.8	10	240	8956
		ALL01S3	35.88972	75.98756	2.1	4	312	1755
		CRO01S1	35.9375	75.739833	3.7	6	238	10154
		ROA01S1	35.9526	75.6502	2.4	5	290	104400
		Mean				6	221	12618
C	Estuary	ALL01S1	35.66906	76.0323	5.2	10	200	15360
		ALL01S5	35.784567	76.026867	3.4	7	294	15120
		CRO01S7	35.8367	75.659467	1.8	11	253	35683
		ROA01S2	35.8127	75.528817	0.6	6	87	87
		PAM01S2	35.780767	75.57725	0.6	7	78	78
		PAM01S6	35.8207	75.5621	0.1	9	219	2336
		PAM01S5	35.812	75.5645	0.5	13	157	2355
		ROA01S4	35.81665	75.6207	0.6	15	320	261669
		PAM01S9	35.7946	75.5478	0.1	7	79	876
		PAM01S7	35.7948	75.5478	0.1	4	92	613
		ALL01S2	35.88659	76.01678	4.3	7	275	22629
		CUR01S7	36.17595	75.79755	2.1	6	259	66304
		CUR01S9	36.163667	75.821683	0.0	5	299	127163
		CUR01S1	36.283867	75.8239	0.9	5	262	15120
		ALB01S3	36.05002	76.1665	5.8	5	230	12295
		CUR01S5	36.287577	75.856417	1.5	4	254	16256
		ALB01S4	36.05669	75.96653	5.5	6	219	31392
		NOR01S2	36.18685	75.891733	2.7	8	200	57600
		NOR01S1	36.230017	75.92555	3.0	7	214	13696
		PAS01S1	36.298583	76.209633	2.4	5	247	5601
		ALB01S2	36.2167	76.3333	5.5	5	207	5624
		PAS01S3	36.200783	76.058383	4.0	6	242	13403
		Mean				7	213	32785
D	Inner estuary	CUR01S10	36.1813	75.7583	0.3	7	104	104
		PAS01S2	36.252533	76.11905	3.7	6	253	12144
		ALB01S1	35.975	76.5833	5.2	4	325	10400
		Mean				6	227	7549
E	Marsh	PAM01S8	35.7945	75.5477	0.1	3	11	13
		ROA01S5	35.8163	75.6207	0.0	16	238	34272
		CRO01S4	35.855117	75.751817	0.0	14	239	8749
		CUR01S4	36.283583	75.805483	0.2	15	206	5028
		CUR01S2	36.283975	75.8278	0.1	12	282	2689
		Mean				12	195	10150

78 on a back-barrier sand shoal adjacent to Oregon Inlet (PAM01S2) to 261,669 at ROA01S4. *Ammotium salsum* dominated and *Ammobaculites crassus*, *Miliammina fusca* and *Ammobaculites subcatenulatus* were important subsidiary species. The marsh taxa *Ammoastuta inepta*, *Haplophragmoides bonplandi*, *H. wilberti*, *Arenoparrella mexicana*, *Trochammina inflata* and *Tiphotrocha comprimata*, and some agglutinated and calcareous estuarine species, which live in higher salinity environments around Oregon Inlet and the southern portions of Roanoke and Croatan sounds (e.g., *Ammobaculites exiguus*, *Reophax* sp., *Ammonia parkinsoniana* and *Ammonia* sp.) were present but rare (Table 2).

Biofacies D (inner estuary; Table 1, Figs. 1, 2) is composed of three stations, two within the inner reaches of the estuary (ALB01S1, PAS01S2) and one on an intertidal sand flat adjacent to a marsh (CUR01S10). Species richness (S) ranged from 4 to 6 (Table 1) and

TABLE 2. Average relative abundance for the species comprising the dead assemblages in each biofacies.

Species	Biofacies A Nearshore marine and inlet	Biofacies B Estuarine shoal	Biofacies C Estuary	Biofacies D Inner estuary	Biofacies E Marsh
Ammoastuta inepta		0.5	1.0	0.6	7.7
Ammobaculites crassus	2.5	67.6	23.1	9.4	16.8
Ammobaculites dilatatus	0.3	3.6	1.6	0.7	0.8
Ammobaculites exiguus	0.2	0.2	0.7		0.1
Ammobaculites subcatenulatus		0.6	5.3	49.3	3.7
Ammobaculites sp.			0.1		
Ammonia parkinsoniana	1.6		0.2		
Ammonia tepida	0.3				
Ammonia sp. (organic lining)		0.1	0.8	0.3	0.1
Ammotium salsum		20.7	56.4	22.7	6.0
Arenoparrella mexicana	0.2		0.3		3.0
Buccella frigida	0.1				
Elphidium excavatum	88.8		0.1		
Elphidium galvestonense	0.1				
Elphidium subarcticum	1.9				
Elphidium sp.	0.1				
Hanzawaia strattoni	3.8				
Haplophragmoides bonplandi		0.1	0.1		4.1
Haplophragmoides hancocki					1.2
Haplophragmoides manilaensis		0.7	0.1		1.8
Haplophragmoides wilberti		3.5	0.3		1.2
Jadammina macrescens		1.1	0.6	0.6	7.0
Miliammina fusca		0.7	7.3	16.4	23.1
Miliammina petila		0.2	0.1		9.8
Pseudothurammina limnetis					1.6
Reophax nana					0.2
Reophax sp.			0.1		5.5
Siphotrochammina lobata			0.1		0.2
Tiphotrocha comprimata	0.2	0.2	0.4		3.2
Trochammina compacta					0.1
Trochammina inflata			0.7		0.8
Trochammina lobata					
Trochammina "*squamata*"			0.1		
Trochamminita irregularis					1.4
Trochamminita salsa			0.2		0.6
Indeterminate aggl. unilocular sp.		0.1			
Indeterminate organic lining			0.1		

calculated numbers of specimens per 50 cm^3 sample ranged widely, from 104 (CUR01S10) to 12,144 (PAS01S2). *Ammobaculites subcatenulatus* dominated the assemblage (49%, average relative abundance, Table 2) and *Ammotium salsum* (23%), *Miliammina fusca* (16%) and *Ammobaculites crassus* (9%) were important subsidiary taxa.

Biofacies E (marsh; Table 1, Figs. 1, 2) is composed of four fringing marsh stations (CUR01S2, CUR01S4, CRO01S4, ROA01S5) located along the shorelines of the eastern sounds, and one station on an intertidal sand flat at the mouth of a tidal creek adjacent to Oregon Inlet (PAM01S8). Very few specimens (11) were recovered from PAM01S8 and this sample probably clustered with ROA01S5 and CRO01S4 because these three samples have similar proportions of *Ammobaculites crassus* and *Miliammina fusca*. Calculated numbers of specimens per 50 cm^3 sample ranged widely, from 13 (PAM01S8) to 34,272 (ROA01S5). Average species richness for Biofacies E was

TABLE 3. Living foraminiferal populations recorded at depth in three cores in western (ALB01S1C2) and central (ALB01S3C2, ALB01S4C2) Albemarle Sound. Species richness (S), numbers of living specimens picked (N) and calculated specimens per 50 cm³ (n) are listed for each interval where living specimens were found.

Core	Depth (cm)	S	N	n	*Ammobaculites crassus*	*Ammobaculites dilatatus*	*Ammobaculites subcatenulatus*	*Ammotium salsum*	*Miliammina fusca*
ALB01S1C2	0-1	1	2	64					2
	1-2	1	3	120					3
	3-4	2	2	8				1	1
	4-6	1	1	4					1
	6-8	1	1	5				1	
	8-10	1	1	3				1	
	22-25	1	1	60				1	
ALB01S3C2	0-1	3	15	831	1			12	2
	1-2	3	3	196	1		1	1	
	2-3	3	15	1543	1		1	13	
	3-4	4	10	514	1		1	6	2
	4-6	2	6	785	1			5	
	6-8	3	7	1680	3		1	3	
	8-10	2	7	4032			1	6	
ALB01S4C2	0-1	2	17	2448	7			10	
	1-2	1	6	823				6	
	2-3	2	13	3403		3		10	
	3-4	2	10	3200	2			8	

12, with the highest species richness (16) at ROA01S5. Seven species (Table 2) were common in Biofacies E: *Miliammina fusca* (average relative abundance of 23%), *Ammobaculites crassus* (17%), *M. petila* (10%), *A. inepta* (8%), *Jadammina macrescens* (7%), *Ammotium salsum* (6%) and *Reophax* sp. (6%).

DOWN-CORE FORAMINIFERAL DATA

Living Populations

The living populations in three cores in the western and central Albemarle Sound (ALB01S1C2, ALB01S3C2 and ALB01S4C2; Fig. 1) were composed of the five species *Ammobaculites crassus*, *A. dilatatus*, *A. subcatenulatus*, *Ammotium salsum* and *Miliammina fusca* (Table 3). Numbers of living species in the cores varied from one to four and calculated numbers of live specimens per 50 cm³ varied from 3 to ~4,000 (Table 3). The highest numbers of live specimens were generally in the upper 2–4 cm of sediment. Calculated numbers of live specimens per 50 cm³ per interval were lowest in ALB01S1C2 and increased at the slightly higher salinity stations ALB01S3C2 and ALB01S4C2.

The maximum depth of living foraminifera in ALB01S1C2 was 22–25 cm; the next deepest record of live specimens was in the 8–10 cm interval (Table 3). *Miliammina fusca* occurred down to 6 cm, whereas *A. salsum* occurred in deeper samples. Living foraminifera (mostly *A. salsum*) were present down to 8–10 cm in ALB01S3C2 (Table 3). In ALB01S4C2 (Table 3), living foraminifera were present to only 4 cm.

Dead Assemblages

Fifteen taxa were recorded in dead assemblages in the cores (Table 4). Comparison of dead foraminiferal assemblages down-core (Table 4) with those of the surface (Tables 1, 2) indicates that only two biofacies, C and D, are recognizable in the cores (Table 4). Biofacies C (estuary) was present at 6–37 cm in ALB01S1C2 and in all samples from ALB01S3C2 and ALB01S4C2. Biofacies D (inner estuary) was present only in the upper 6 cm of ALB01S1C2.

DISCUSSION

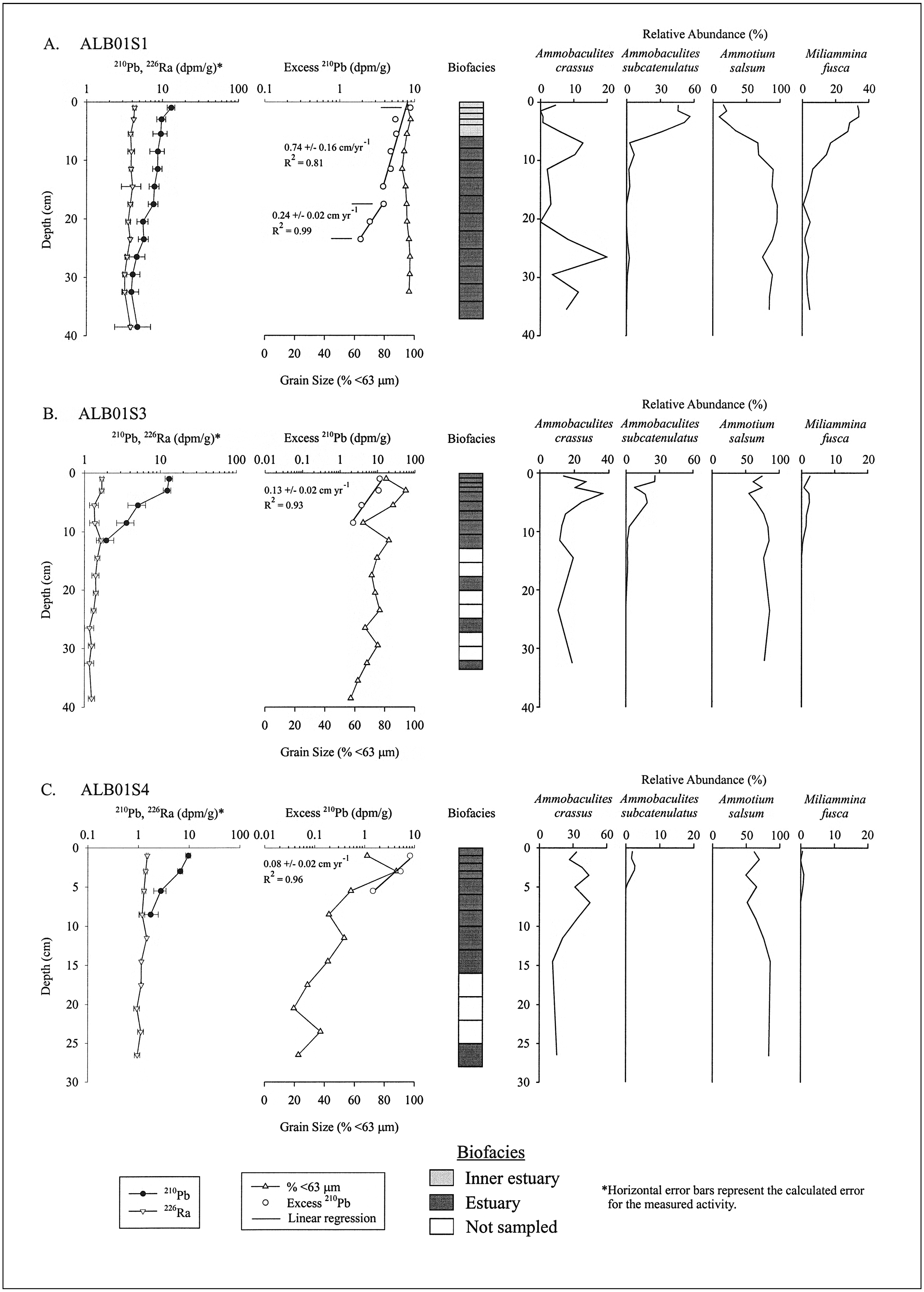
TAPHONOMY

Surface Data

Comparison of the distribution of the living populations and the dead assemblages in surface sediments shows that

TABLE 4. Species richness (S), total number of specimens picked (N), calculated numbers of specimens per 50 cm^3 (n), biofacies and counts of specimens per species per interval for dead assemblages down-core.

Core	Depth (cm)	S	N	n	Biofacies	*Ammoastuta inepta*	*Ammobaculites crassus*	*Ammobaculites dilatatus*	*Ammobaculites subcatenulatus*	*Ammonia* sp. (organic lining)	*Ammotium salsum*	*Arenoparrella mexicana*	*Elphidium excavatum*	*Haplophragmoides bonplandi*	*Miliammina fusca*	*Reophax nana*	*Reophax* sp.	*Trochammina inflata*	*Trochammina* "*squamata*"	Indeterminate organic lining
ALB01S1C2	0-1	4	325	10528	D		15		149		53				108					
	1-2	3	291	11760	D				133		59				99					
	2-3	4	271	1755	D		2		153		24				92					
	3-4	4	295	1192	D		2		150		59				84					
	4-6	4	230	916	D		13		75		79				63					
	6-8	5	314	1718	C		40	4	8		209				53					
	8-10	5	280	899	C		29	1	19		191				40					
	10-13	4	247	3406	C		5		5		222				15					
	13-16	5	184	184	C		5	5	5		162				7					
	16-19	4	317	5187	C		10	1			304				2					
	19-22	2	234	742	C						223				11					
	22-25	5	287	17280	C		24	1	2		256				4					
	25-28	4	336	1596	C		67		9		247				13					
	28-31	5	221	884	C		8	9	2		196				6					
	31-34	4	288	810	C		33		1		245				9					
	34-37	5	293	3780	C		23	9	1		247				13					
ALB01S3C2	0-1	5	230	6439	C	1	31		20		172				6					
	1-2	6	247	16364	C	2	66		21	3	151				4					
	2-3	6	288	31166	C	1	59		7	4	215				2					
	3-4	6	264	14091	C	2	96		15	1	144				6					
	4-6	6	301	48320	C	1	73		19	3	198				7					
	6-8	6	350	47258	C	4	52		13	6	270				5					
	8-10	6	290	71760	C	2	37		3	3	241				4					
	10-13	6	259	150336	C	2	30		1	5	220				1					
	13-16	5	360	155077	C	2	70		2	9	277									
	22-25	4	272	74606	C	7	29			2	234									
	31-34	6	296	30446	C		56			7	230			1			1		1	
	40-42	7	245	3920	C	2	45				192	3	1					1		
ALB01S4C2	0-1	6	219	33840	C	1	73	5	4		135				1					
	1-2	6	328	45806	C		88	4	6		228							1		1
	2-3	5	307	83782	C	2	117		9		178				1					
	3-4	7	324	106880	C	2	143	8	6	2	160				3					
	4-6	5	322	206080	C	3	102			4	211				2					
	6-8	5	301	173376	C	3	136			6	155					1				
	8-10	3	318	228960	C		108			6	204									
	10-13	5	279	160704	C	2	58	1		6	212									
	13-16	4	294	282240	C		35			5	253									1
	25-28	3	298	24429	C		47	1			250									


A. ALB01S1
B. ALB01S3
C. ALB01S4
210Pb, 226Ra (dpm/g)*
Excess 210Pb (dpm/g)
Biofacies
Relative Abundance (%)
Ammobaculites crassus
Ammobaculites subcatenulatus
Ammotium salsum
Miliammina fusca
Depth (cm)
Grain Size (% <63 µm)
0.74 +/- 0.16 cm/yr-1
R2 = 0.81
0.24 +/- 0.02 cm yr-1
R2 = 0.99
0.13 +/- 0.02 cm yr-1
R2 = 0.93
0.08 +/- 0.02 cm yr-1
R2 = 0.96
210Pb
226Ra
% <63 µm
Excess 210Pb
Linear regression
Biofacies
Inner estuary
Estuary
Not sampled
*Horizontal error bars represent the calculated error for the measured activity.

at least three important taphonomic processes are active. First, marsh foraminifera are being transported into the estuarine environment, most likely due to marsh shoreline erosion and flushing of the fringing marshes during wind-tide and rainfall flooding of the marsh surface. Transport of a few estuarine and marsh foraminifera onto the inner shelf is occurring through Oregon Inlet and, conversely, a few open-shelf foraminifera (e.g., *Elphidium subarcticum*) are being transported into the back-barrier inlet shoal environment. Second, dissolution of calcareous foraminiferal tests is occurring in the nearshore back-barrier estuarine environment. At PAM01S5, *Ammonia parkinsoniana* comprised 29% of the live population, whereas this species only comprised 5% of the dead assemblage at the same station. This could be explained by dissolution of calcareous tests at this site, resulting in a relative increase in abundance of agglutinated species in the dead assemblage (e.g., Scott and Medioli, 1980a, b; Murray and Alve, 1999 a, b). Alternatively (or in addition), sampling could have taken place following a reproductive episode. Third, mechanical destruction of calcareous tests in the high-energy foreshore and inlet environments also probably destroys specimens; all specimens recorded in these environments are relatively robust and of similar size (no juveniles are present).

Down-core Data

The two dominant infaunal living species (*Ammotium salsum* and *Miliammina fusca*) were also the dominant taxa in the dead assemblage. They occurred live in very low numbers and so would not significantly affect total (live plus dead) assemblages if these were the subject of study (i.e., the total assemblage is, essentially, the dead assemblage).

In the two central Albemarle cores (ALB01S3C2 and ALB01S4C2) agglutinated foraminiferal tests were often pyrite filled, indicating reducing conditions and lower pH. The presence of *Ammonia* sp. organic linings in ALB01S3C2 and ALB01S4C2 (Table 4) indicates dissolution of calcareous tests. A single dead specimen of *Elphidium excavatum* was found at the base of ALB01S3C2 at 42 cm depth (Table 4).

Paleoenvironmental Implications

Down-core radionuclide trends (Fig. 3) in ALB01S1C1, ALB01S3C1 and ALB01S4C1 were used to develop a geochronology within which foraminiferal-based paleoenvironmental changes in western and central Albemarle Sound (Table 4) could be placed. The dead foraminiferal surface assemblages were used as the basis for paleoenvironmental interpretations.

The dead assemblage in ALB01S1C2 (Fig. 1) documents a shift at 6 cm depth from a dominantly brackish estuarine basin assemblage dominated by *Ammotium salsum* (Biofacies C) to a more diverse, inner estuarine basin assemblage characterized by co-dominance of *Ammobaculites subcatenulatus* and *Miliammina fusca* with lower proportions of *A. salsum* (Biofacies D). Based on sedimentation rates calculated from excess ^{210}Pb (Fig. 3a), this change occurred sometime in the early to middle 1990's. This period corresponds with increased hurricane and tropical storm activity along the North Carolina coast which could have increased freshwater inflow from the Roanoke and Chowan rivers (Riggs and Ames, 2003), thus causing Biofacies C (estuarine assemblage) to be replaced up-core by the lower salinity Biofacies D (inner estuary assemblage). An alternative explanation is that the upper 6 cm of sediment may be an ephemeral layer of sediment (including foraminiferal tests) derived and transported from fresher reaches of the estuary. Corbett and others (2004) have used radionuclide data to document such processes following recent hurricanes.

In cores ALB01S3C2 and ALB01S4C2, radionuclide trends indicate sedimentation rates of 0.13 ± 0.03 cm yr^{-1} and 0.08 ± 0.02 cm yr^{-1}, respectively. Therefore, 1 cm of sediment in ALB01S3C2 and ALB01S4C2 represents approximately ten years of sediment accumulation. Only estuarine Biofacies C was present in these cores (Table 4; Fig. 3b, c).

In the surficial data, *Ammonia* sp. was found living only in the various back-barrier estuarine environments near Oregon Inlet with salinities greater than 8. Bottom salinities at ALB01S3 and ALB01S4 were 4 and 5, respectively, and, based on data from Williams and others (1973), salinities at these stations range from nearly fresh to 5. However, in ALB01S3C2 and ALB01S4C2 in central Albemarle Sound (Fig. 1), *Ammonia* sp. organic linings were present in several samples (Table 4). In ALB01S3C2, linings occurred from 32.5 cm (250 yr BP, assuming steady-state accumulation) to 1.5 cm (12 yr BP); in ALB01S4C2 they occurred from 14.5 cm (181 yr BP) to 3.5 cm (44 yr BP). The presence of *Ammonia* sp. at depth in ALB01S3C2 and ALB01S4C2 suggests that Albemarle Sound was under more marine influence approximately two centuries ago. Inlets are known to have connected Currituck and Roanoke sounds to the Atlantic Ocean prior to 1828 (Dunbar, 1958); these probably caused Albemarle Sound to have slightly more saline waters at that time. A single specimen of the calcareous species *Elphidium excavatum* in the deepest interval (40–42 cm) in core ALB01S4C2 also indicates the presence of slightly higher salinity conditions in Albemarle Sound approximately two centuries ago.

CONCLUSIONS

Even though few specimens were picked, foraminiferal live populations in the AES show similar distributional patterns to dead foraminiferal assemblages. Five biofacies are recognized in the dead assemblages. The nearshore marine and inlet biofacies was characterized by a calcareous assemblage dominated by *Elphidium excavatum*. The other

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Figure 3. Paleoenvironmental analysis of short push-cores taken along the axis of Albemarle Sound, showing distribution of biofacies down-core, relative abundance of dominant taxa, radiochemical tracer profiles (horizontal error bars represent the calculated error range for the measured activity), and grain-size for A) ALB01S1, B) ALB01S3, and C) ALB01S4. Geochronology of cores is based on average sedimentation rates.

four biofacies, estuarine shoal, estuary, inner estuary and marsh, were dominated by the agglutinated taxa *Ammobaculites crassus*, *Ammotium salsum*, *Ammobaculites subcatenulatus* and *Miliammina fusca*, respectively.

Relatively small proportions of foraminiferal tests are transported between the various biofacies by tidal currents, wind-driven currents and rainfall sheet wash. Dissolution of calcareous tests occurs in nearshore back-barrier estuarine environments and greatly increases the proportions of agglutinated tests in dead assemblages compared to live populations. Mechanical destruction of calcareous tests occurs in high-energy nearshore marine and inlet environments.

Although clearly prevalent and widespread, these taphonomic processes do not, in general, destroy the integrity of biofacies in subsurface core material. Using the surficial dead assemblage data as a model upon which paleoenvironmental interpretations are made, subsurface foraminiferal data from three cores in the central Albemarle basin indicate that, approximately two centuries ago, the bottom waters of the sound were slightly more saline than they are today. This interpretation concurs with the known presence of additional inlets connecting the back-barrier estuaries with the Atlantic Ocean at this time. Foraminiferal assemblages in the westernmost core in Albemarle Sound indicate either accumulation of a seasonal ephemeral layer of sediment from a lower brackish, upstream environment, or increased freshwater discharge since the early 1990's as a result of increased tropical storm and hurricane activity.

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APPENDIX A

Original references to the taxa identified to the species level

Ammoastuta inepta (Cushman and McCulloch): *Ammoastuta ineptus* Cushman and McCulloch, 1939, p. 89, pl. 7, fig. 6.

Ammobaculites crassus Warren: *Ammobaculites crassus* Warren, 1957, p. 32, pl. 3, figs. 5–7.

Ammobaculites exiguus Cushman and Brönnimann: *Ammobaculites exiguus* Cushman and Brönnimann, 1948b, p. 38, pl. 7, figs. 7, 8.

Ammobaculites subcatenulatus Warren: *Ammobaculites subcatenulatus* Warren, 1957, p. 32, pl. 3, figs. 11–13.

Ammobaculites dilatatus Cushman and Brönnimann: *Ammobaculites dilatatus* Cushman and Brönnimann, 1948b, p. 39, pl. 7, figs. 10, 11.

Ammonia parkinsoniana (d'Orbigny): *Rosalina parkinsoniana*, d'Orbigny, 1839, p. 99, pl. 4, figs. 25–27.

Ammonia tepida (*Cushman*): *Rotalia beccarii* Linnaeus var. *tepida* Cushman, 1926, p. 79, pl. 1.

Ammotium salsum (Cushman and Brönnimann):. *Ammobaculites salsus* Cushman and Brönnimann, 1948a, p. 16, pl. 3, figs. 7–9.

Arenoparrella mexicana (Kornfeld): *Trochammina inflata* (Montagu) var. *mexicana*, Kornfeld, 1931, p. 86, pl. 13, fig. 5.

Buccella frigida (Cushman): *Pulvinulina frigida* Cushman, 1922, p. 14.

Elphidium excavatum (Terquem): *Polystomella excavata* Terquem, 1875, p. 20, pl. 2, figs. 2a, b.

Elphidium galvestonense Kornfeld, *Elphidium gunteri* Cole var. *galvestonensis*, Kornfeld, 1931, p. 87, pl. 15, fig. 1.

Elphidium subarcticum Cushman: *Elphidium subarcticum* Cushman, 1944, p. 27, pl. 3, figs. 34, 35.

Hanzawaia strattoni (Applin): *Truncatulina americana* Cushman var. *strattoni* Applin in Applin and others, 1925, p. 99, pl. 3, fig. 8.

Haplophragmoides bonplandi Todd and Brönnimann: *Haplophragmoides bonplandi* Todd and Brönnimann, 1957, p. 23, pl. 3, fig. 2.

Haplophragmoides hancocki Cushman and McCulloch: *Haplophragmoides hancocki* Cushman and McCulloch, 1939, p. 79, pl. 6, figs. 5, 6.

Haplophragmoides manilaensis Andersen: *Haplophragmoides manilaensis* Andersen, 1953, p. 22, pl. 4, fig. 7.

Haplophragmoides wilberti Andersen: *Haplophragmoides wilberti* Andersen, 1953, p. 21, pl. 4, fig. 7.

Jadammina macrescens (Brady): *Trochammina inflata* (Montagu) var. *macrescens* Brady, in Brady and Robertson, 1870, p. 47, pl. 11, figs. 5a–c.

Miliammina fusca (Brady): *Quinqueloculina fusca* Brady, in Brady and Robertson, 1870, p. 47, pl. 11, figs. 2, 3.

Miliammina petila Saunders: *Miliammina petila* Saunders, 1958, p. 88, pl. 1, fig. 15.

Pseudothurammina limnetis (Scott and Medioli): *Thurammina*(?) *limnetis* Scott and Medioli, 1980b, p. 43, 44, pl. 1, figs. 1–3.

Reophax nana Rhumbler: *Reophax nana* Rhumbler, 1911, p. 182, pl. 8, figs. 6–12.

Siphotrochammina lobata Saunders: *Siphotrochammina lobata* Saunders, 1957, p. 3, pl. 9, figs. 1, 2.

Tiphotrocha comprimata (Cushman and Brönnimann): *Trochammina comprimata* Cushman and Brönnimann, 1948b, p. 41, pl. 8, figs. 1–3.

Trochammina compacta Parker: *Trochammina compacta* Parker, 1952, p. 458, p. 2, figs. 13–15.

Trochammina inflata (Montagu): *Nautilus inflatus* Montagu, 1808, p. 81, pl. 18, fig. 3.

Trochammina lobata Cushman: *Trochammina lobata* Cushman, 1944, p. 18, pl. 2, fig. 10.

Trochamminita irregularis Cushman and Brönnimann: *Trochamminita irregularis* Cushman and Brönnimann, 1948a, p. 17, pl. 4, figs. 1–3.

Trochamminita salsa (Cushman and Brönnimann): *Labrospira salsa* Cushman and Brönnimann, 1948a, p. 16, pl. 3, figs. 5–6.

APPENDIX B

Relative abundance (percent) of live foraminifera in surface samples

	BEA01S1G1	EBB01S1G1	ALB01S1C2	ALB01S2G1	ALB01S3C2	ALB01S4C2	ALB01S5C2	ALB01S6C2	ALB01S8C2	ALL01S3C2	ALL01S4C2	ALL01S5C2	PAS01S1C2	PAS01S2C2	PAS01S3C2	NOR01S1C2	NOR01S2C2	CUR01S1C2
Ammoastuta inepta																		
Ammobaculites crassus					6.7	41.2	12.5	68.1	89.0				25.0		100.0	33.3	4.3	5.0
Ammobaculites dilatatus									1.4									
Ammobaculites exiguus																		
Ammobaculites subcatenulatus									1.4					12.5				
Ammonia parkinsoniana																		
Ammonia sp. (organic lining)																		
Ammotium salsum				100.0	80.0	58.8	62.5	31.9	8.2				50.0	12.5		66.7	95.7	95.0
Arenoparrella mexicana																		
Elphidium excavatum	100.0	100.0																
Elphidium galvestonense																		
Haplophragmoides bonplandi																		
Jadammina macrescens																		
Miliammina fusca			100.0		13.3		25.0			100.0	100.0	100.0		75.0				
Miliammina petila																		
Reophax sp.																		
Tiphotrocha comprimata													25.0					
Trochammina inflata																		
Indeterminate aggl. unilocular sp.																		
Number of live specimens picked	1	2	2	1	15	17	8	69	73	2	2	3	4	16	1	3	23	20

APPENDIX B. Extended.

CUR01S2G1	CURO1S4G1	CUR01S5C2	CUR01S7G1	CUR01S9G1	CUR01S10G1	CRO01S1C2	CRO01S2G1	CRO01S3C2	CRO01S4G1	CRO01S7C2	ROA01S1C2	ROAO1S2G1	ROA01S4C2	ROA01S5G1	ROA01S7G1	PAM01S2G1	PAM01S5G1	PAM01S6G1	PAM01S7G1	PAM01S8G1	PAM01S9G1
									35.3												
	10.9				13.3	36.4	80.0	41.7		6.3	100.0	16.7	20.0	14.8	66.7	75.0	7.5	39.7	0.5	5.2	4.0
												16.7					0.6				0.6
																	1.1	2.7	1.5	0.4	1.7
	34.8		12.5		26.7																
																	28.7				
										6.3		50.0		3.7				5.5			0.6
33.3	21.7	100.0	87.5	100.0		63.6	20.0	58.3		6.3		16.7		7.4	23.8	25.0	48.3	52.1	74.0	78.3	91.9
									5.9					14.8							
																	1.1				
									11.8												
	4.3								11.8												
66.7	28.3				60.0				17.6	81.3			80.0	48.1	9.5		12.6		24.0	9.7	1.2
									17.6												
																				1.5	
														3.7							
														7.4							
																				4.9	
6	46	12	8	1	15	22	5	12	17	16	7	6	5	27	21	4	174	73	196	267	173

APPENDIX C
Relative abundance (percent) of dead foraminifera in surface samples

	BEA01S1	BEA01S2	BEAO1S3	INS01S1	EBB01S1	OFF01S1	ALB01S1	ALB01S2	ALB01S3	ALB01S4	ALB01S5	ALB01S6	ALB01S8	ALL01S1	ALL01S2	ALL01S3	ALL01S4	ALL01S5	PAS01S1	PAS01S2	PAS01S3
Ammoastuta inepta								0.5	0.4	0.5			0.5	11.0	1.5	1.3	2.0	3.1		0.8	0.4
Ammobaculites crassus		10.0				5.0	4.6	22.7	13.5	33.3	72.8	72.3	78.6	35.0	9.5	70.8	93.9	33.0	13.4	7.1	18.6
Ammobaculites dilatatus						2.0				2.3			5.5		0.4			1.0	1.2	2.0	
Ammobaculites exiguus						1.0							0.5								
Ammobaculites subcatenulatus							45.8	18.8	8.7	1.8	0.3	0.9							21.5	45.5	26.0
Ammobaculites sp.																					
Ammonia parkinsoniana	1.6			0.7	2.1	5.0															
Ammonia tepida						2.0															
Ammonia sp. (organic lining)											0.3				0.4						0.4
Ammotium salsum							16.3	54.1	74.8	61.6	26.2	25.9	14.5	33.5	82.9	23.7	4.1	47.6	58.3	35.6	47.1
Arenoparrella mexicana						1.0								1.5	0.4			0.3			
Buccella frigida					0.7																
Elphidium excavatum	96.8	80.0	80.0	96.3	97.2	82.2															
Elphidium galvestonense				0.7																	
Elphidium subarcticum		10.0		1.5																	
Elphidium sp.				0.7																	
Hanzawia strattoni	1.6		20.0			1.0															
Haplophragmoides bonplandi																					
Haplophragmoides hancocki																					
Haplophragmoides manilaensis														0.5				0.3			
Haplophragmoides wilberti																					
Jadammina macrescens														2.5							
Miliammina fusca							33.2	3.9	2.6	0.5	0.3			9.0	5.1	4.2		14.6	5.7	9.1	6.2
Miliammina petila														0.5							
Pseudothurammina limnetis																					
Reophax nana																					
Reophax sp.																					
Siphotrochammina lobata														0.5							
Tiphotrocha comprimata						1.0															
Trochammina compacta																					
Trochammina inflata																					
Trochammina lobata																					
Trochammina "squamata"																					
Trochamminita irregularis																					
Trochamminita salsa														5.0							
Indeterminate aggl. unilocular sp.												0.9									
Indeterminate organic lining													0.5	1.0							1.2
Total no. specimens picked	63	10	5	135	143	101	325	207	230	219	294	220	220	200	275	312	49	294	247	253	242

APPENDIX C. Extended.

NOR01S1	NOR01S2	CUR01S1	CUR01S2	CUR01S4	CUR01S5	CUR01S7	CUR01S9	CUR01S10	CRO01S1	CRO01S2	CRO01S3	CRO01S4	CRO01S6	CRO01S7	ROA01S1	ROA01S2	ROA01S4	ROA01S5	ROA01S7	ROA01S9	PAM01S2	PAM01S5	PAM01S6	PAM01S7	PAM01S8	PAM01S9
1.9	1.0		25.5	1.0				1.0				11.7	0.8	2.4			0.3	0.4	2.0							
32.7	25.0	6.9	1.1	1.9	32.3	14.7	12.0	16.3	63.4	73.9	73.8	11.7	70.0	30.8	52.1	59.8	19.7	32.8	55.9	33.3	34.6	11.5	27.9	2.2	36.4	19.0
4.2	2.0	0.4		0.5		3.5	1.0		0.4	1.6	0.5		0.4		1.7		13.4	3.4		33.3		1.3		4.3		1.3
						0.4							0.4		0.3	4.6	0.3	0.4	0.8		6.4					3.8
8.4	7.5	10.3	0.4	18.0	7.5	2.7	4.0	56.7	0.4			0.4	1.3						4.7							
																										1.3
																						5.1				
	0.5							1.0					0.8	1.2		2.3		0.4			1.3	3.8	7.8			
46.7	60.0	82.1		20.4	59.8	78.4	82.3	16.3	34.9	24.4	24.9	8.4	24.6	44.7	44.5	26.4	48.4	1.3	1.2		44.9	38.9	51.1	68.5	0.0	48.1
				0.5								9.2		2.0			0.9	5.5	0.4			2.5				
																					1.3	0.6				
0.5	0.5			7.8								10.5	0.4	0.4			0.3	2.1	0.4				0.5			
				1.5								0.4						4.2				0.6				
			1.1	5.8								2.1		0.4			0.3		7.9				0.5			
			1.1	0.5					0.4		0.5	3.8		3.6			0.3	0.8	7.9	33.3		2.5				
			18.4	12.6				1.9				2.5	0.8	1.2			0.3	1.3	12.2		1.3		7.3			
5.6	3.5	0.4	7.1	5.8	0.4	0.4	0.3	6.7	0.4		0.5	26.8	0.4	12.6	1.4	5.7	12.8	39.5	0.8		9.0	12.7		25.0	36.4	24.1
			35.5	7.8								5.0		0.8			0.3	0.8	2.8							
			5.3									2.5														
																	0.9	0.8								
																	0.3	0.4				2.5			27.3	
			0.4									0.4											0.5			1.3
			0.7	9.2								3.3				1.1	0.9	2.5	2.8			2.5	4.6			
																		0.4				0.6				
												1.3					0.3	2.9	0.4			14.0				1.3
																						0.6				
																					1.3					
			1.4	5.8																						
			2.1	1.0																						
							0.3																			
214	200	262	282	206	254	259	299	104	238	307	221	239	240	253	290	87	320	238	254	3	78	157	219	92	11	79