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379. ESTUARINE FORAMINIFERA FROM THE RAPPAHANNOCK RIVER, VIRGINIA[1]

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ABSTRACT

Populations of benthonic foraminifera were studied from 263 samples obtained in 5 collections from the estuary, its tributaries and bordering marshes. Of the 20 species identified, 2 constitute more than 80 percent of the fauna.

Two biofacies are recognized in the estuary:

a. A basin biofacies of Elphidium clavatum Cushman in the lower part of the estuary, and
b. A shoal biofacies of Ammobaculites crassus Warren in upper reaches, shoals, and tributaries.

The biofacies are broadly related to different estuarine layers which fluctuate with river inflow and estuarine mixing. They are separable along a relatively sharp boundary where salinity is 15 ppt.

Two principal biofacies are recognized in the marshes:

a. An outer biofacies of Miliammina fusca Brady in relatively salty water, and
b. An inner biofacies of Ammoastuta salsa Cushman in freshened reaches.

These biofacies intergrade with distance across the gradient zone of the upper estuary.

Total populations increase upstream to a peak in the upper part of the estuary where tidal and seasonal variations of salinity are great. In general, the distribution of total populations (largely dead) throughout the estuary corresponds to that of the living population, except locally where tests are effectively redistributed.

Distributional features and distinctive species of foraminifera provide a basis for recognizing ancient estuarine deposits.

INTRODUCTION

The Rappahannock River estuary of Chesapeake Bay is well suited for an ecological study of foraminifera. Environmental conditions range widely and are better known than in most other estuaries. As an environment with two-way flow and unstable salinity, the estuary supports a benthic microfauna that must either adapt to or shift with environmental changes.

The purpose of this paper is to report the distribution and abundance of benthic foraminifera in the estuary and to assess their relationship with known environmental factors. An attempt is made to formulate characteristics of an estuarine fauna useful in interpreting fossil distributions.

ACKNOWLEDGMENTS

This study was largely supported by grants from the National Science Foundation Research Participation programs (NSF-G20443 and GE-471). Field sampling was done from research vessels and small craft of the Virginia Institute of Marine Science. Several students contributed to the study: John Hughes studied marsh foraminifera with support of NSF Undergraduate Research Participation funds (NSF-GI-5724) in 1962; Warren Norton studied populations at the estuary head in 1965; and Allan Hartwell traced foraminiferal variations in marsh deposits with support of NSF Undergraduate Research Participation funds (NSF-GE-6558 and GY-916).

The authors thank R. Cifelli and M. Buzas of the U. S. National Museum and James D. McLean, Jr. for helpful suggestions and for making their facilities and specimens available. The foraminifera were illustrated by Jane Davis of the Virginia Institute of Marine Science, and the figured specimens are deposited in the U. S. National Museum.

PREVIOUS WORK

Although foraminiferal faunas are rather well known from many shallow-water environments, only a few data have been published on faunas in river estuaries and estuarine marshes; for example, Parker (1952), Todd and Brönnimann (1957), Boltovskoy (1957), Behm and Grekulinski (1958), van Voorthuysen (1960), Fowler *et al.* (1966), and Bartlett (1966). Occurrences of specimens from the Rappahannock in 1962, analyzed as part of this study, are listed in Ellison *et al.* (1965). Certain aspects of the distributions are reported in Nichols and Ellison (1967).

METHODS

Field Sampling

Samples were collected throughout the estuary during each of five periods: (1) June and July, 1962; (2) June and July, 1963; (3) January, 1964; (4) March and May, 1965; and (5) June through December, 1965. Salinity and other environmental variables differed from period to period. For example, during the first collection, salinity was relatively low and the water partly mixed, whereas in the following summer of 1963 salinity was high and the water relatively well mixed. Hydrographic data obtained during each collection period are given in Ellison *et al.* (1965) and Ellison (in press).

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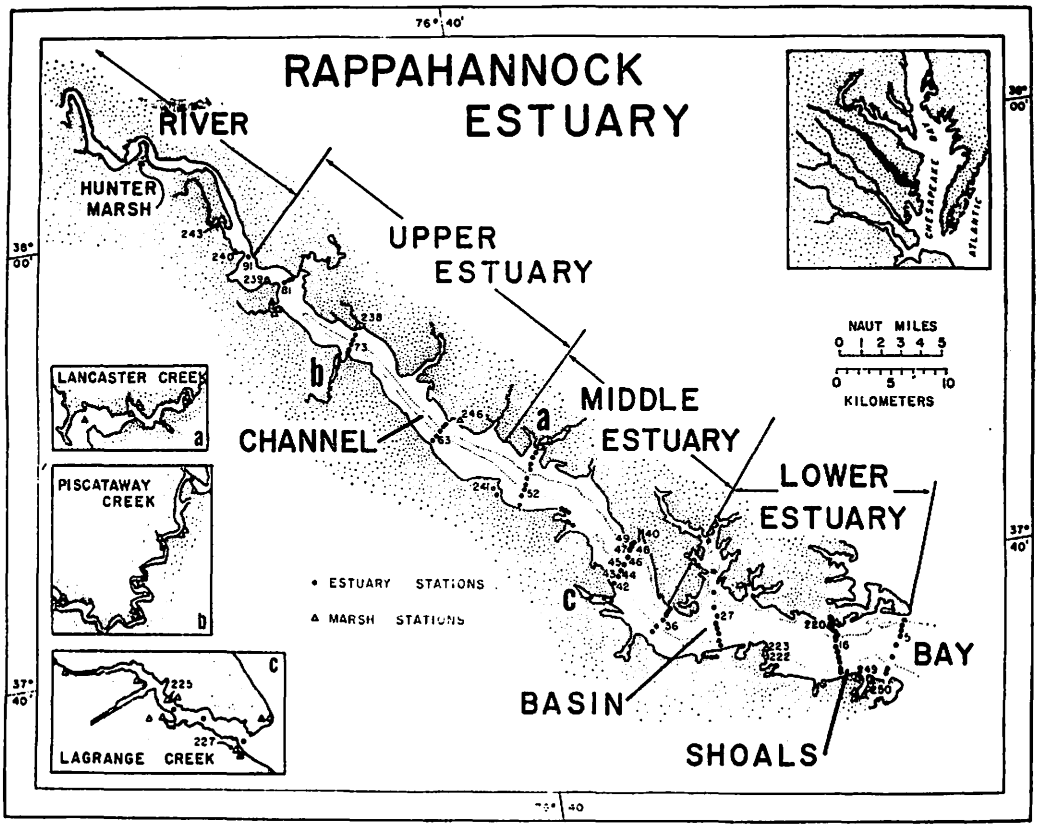


TEXT FIGURE 1

Location of Rappahannock estuary, inset, upper right (black), reaches, creeks, general bathymetry, and location of stations. Numbers for all stations are given in Ellison *et al.* (1965) and Ellison (in press).

Stations were established on transects through a range of salinity and varying water depths in the estuary and up tributary creeks as shown in text fig. 1. In marsh areas, stations were located across different zones of intertidal vegetation. Additional stations were made during each collecting period in local areas of abundant eelgrass and in areas requiring closer study.

Most samples consist of two 20 ml. portions of the top 0.39 inch (1 cm.) of wet sediment. They were collected with either a light-weight gravity corer (Nichols and Ellison, 1966) or a hand corer equipped with 2-inch (5 cm.) diameter plastic tubing that cuts a 3.1 sq. in. (20 sq. cm.) area of sediment. To obtain sufficient material in the marshes and to integrate variations typical of marsh microhabitats, three cored portions were collected at each station. Samples were preserved with neutralized formalin and stored wet.

Laboratory Procedures

Samples were washed over a sieve having 62-micron apertures and stained with rose Bengal to identify living specimens. A solution of no less than 1.0 gm. rose Bengal plus 5 ml. of phenol per 100 ml. of distilled water gave the most effective stain. Most samples were examined wet under a binocular microscope. The percentage frequency of each species was determined and the total number of foraminifera, living and dead, per 20 ml. was calculated. Procedural details are given in Ellison *et al.* (1965) and Ellison (in press).

THE ESTUARY

Like other estuaries in the Chesapeake Bay region, the Rappahannock follows the course of a former river valley cut into coastal plain sediments. Submergence of the valley during the postglacial rise of sea level formed the estuary and gave it a distinctive configuration. The 50-mile (80 km.) long estuary is narrow and funnel-shaped, varying from 4 miles wide at its mouth to 1 mile near its saline head (text fig. 1). Bluffs of Miocene sediments form a margin occasionally broken and indented by tributary creeks. Except for the large Corrotoman River entering the lower estuary, the creeks reach inland less than 3 miles. The estuary floor is molded into a narrow channel flanked by wide submerged shoals. The channel meanders gently through the upper part of the estuary with depths from 16 to 33 feet, but in the middle estuary it deepens seaward into a narrow basin 60 to 80 feet deep. A submerged sill at the mouth partly impedes upstream movement of near-bottom water, whereas near-surface water drains freely into Chesapeake Bay.

Sedimentation

The river plays a prominent role in transporting sediments to the estuary. River-borne sediments accumulate at varying rates on different parts of the estuary floor. Silty clay is the most widespread type of substratum, but in the lower estuary sand is the principal sediment of the shoals. Also, scour leaves some sand as lag deposits on bars and in deep holes of the channel floor. An account of the chemical and mineralogical properties of bottom sediments typical of substrate conditions for microfauna was given by Nelson (1960, 1961, 1962).

Vegetation

Low-lying banks along the creeks and around meander bends of the upper estuary are colonized by intertidal salt-marsh vegetation for a width of about 0.25-0.75 mile (0.32-1.20 km.). Two groups of marshes are recognized along the estuary, and within each group are two zones. The outer marsh, bathed by relatively salty water of the middle and lower estuary, is divided into a lower *Spartina alterniflora* zone which is frequently submerged and a higher *Spartina patens* zone. The inner marsh in freshened reaches of the upper estuary and the river is characterized by a narrow lower *Scirpus americana* and *Sagittaria subulata* zone and a higher widespread *Spartina cynosuroides-Typha angustifolia* zone. Submerged shoals less than 8 feet deep, in the middle and lower estuary, are irregularly covered in summer with luxuriant growths of aquatic eelgrass (*Zostera marina*) which support a variety of organisms.

Water Characteristics

From a large number of hydrographic observations by the Chesapeake Bay Institute extending over more than 20 years (Stroup and Lynn, 1963; Hires *et al.*, 1963; Stroup and Wood, 1966), the U. S. Coast and Geodetic Survey (Haight *et al.*, 1930; Nichols and Poor, 1967), and unpublished data of numerous oyster and trawl surveys of the Virginia Institute of Marine Science, the range of certain environmental parameters is known and the general hydrographic climate bearing on foraminiferal distributions can be described. During the present study the estuary was largely unpolluted and free of human influence except for oyster harvesting. For purposes of discussion, the estuary is divided into four parts: the river, and the upper, middle and lower estuary (text fig. 1).

Tide.—The tide generates the chief movement of water in the estuary and, in turn, produces short-term fluctuations in salinity and turbidity. The mean tidal range varies from 1.1 feet near the mouth to 2.6 feet at the head near Tappahannock. This headward increase results in an increase in maximum current velocity from 1.7 ft./sec. near the mouth to 3.4 ft./sec. at the head. In the upper estuary, tidal movement favors relatively free exchange between tributary creeks and the main estuary.

Temperature.—Water temperature is remarkably uniform throughout the Rappahannock at any one time. However, water temperature varies seasonally with air temperature from a monthly mean of 4°C in winter to 28°C in summer, with occasional extremes for short periods.

Turbidity.—Total concentrations of suspended sediment decrease downstream progressively from about 150 mg./l in the river to 2 mg./l at the estuary mouth. In the middle and upper estuary, concentrations also increase toward the bottom and vertical gradients are relatively high. Occasional wave agitation of bottom sediment on the shoals also contributes to the turbidity. The influence of turbidity on benthic microfauna is relatively unknown.

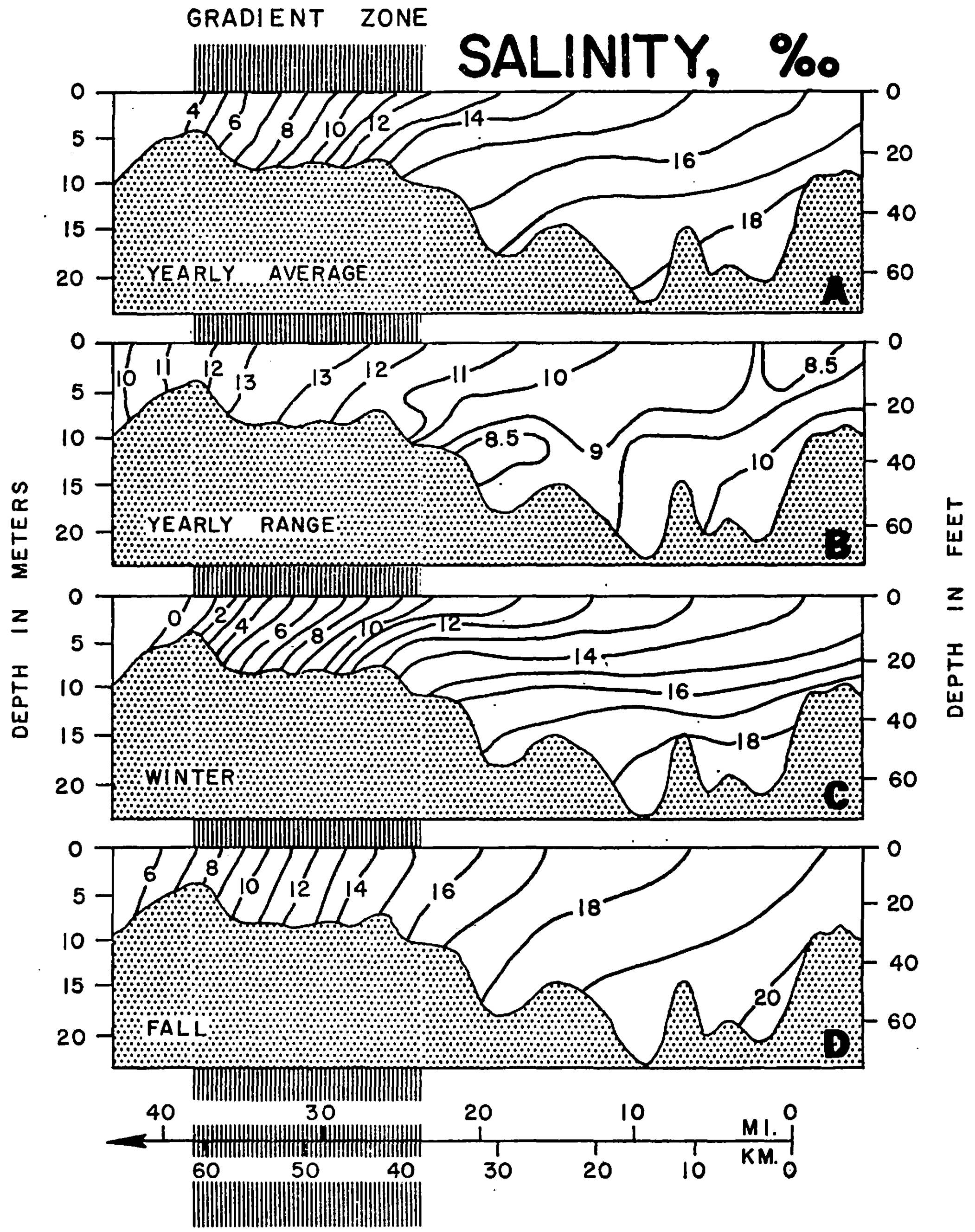
Oxygen.—During most of the year, water and near-surface sediments are well aerated by tidal mixing and atmospheric exchange. However, during late summer when the prevailing temperature is high, oxygen in deeper parts of the basin and in restricted tributary creeks is frequently depleted, owing to rapid decomposition of organic matter combined with insufficient mixing. This condition often kills fish and benthic fauna (McHugh, 1967).

Nutrients.—Total phosphate, including particulate plus soluble unreactive forms, generally increases headward most of the year. Concentrations range from about 0.6 μg at/l at the mouth to 2.2 μg at/l near the head and in spring occasionally reach 4.5 μg at/l.

Chlorophyll "a."—In summer and fall, concentrations generally increase headward from about 4.0 μg at/l in the estuary proper to more than 30.0 μg at/l at the head, but in winter and spring concentrations are relatively low ($<$ 18 μg at/l) throughout the estuary and slightly decrease with distance headward (Brehmer, personal communication).

Hydrogen ion concentration.—The pH typically diminishes with distance up the estuary, ranging from about 8.2 near the mouth to 7.1 near the head. Often in spring and summer slightly acid conditions (with pH 6.6) occur locally in near-bottom water of the upper estuary.

Salinity.—The salinity of estuary water increases seaward from nearly 0‰ at the head to an annual



TEXT FIGURE 2
Salinity distribution along the estuary length showing the zone of relatively high salinity gradient. A. - yearly average; B. - yearly range; C. - winter average; D. - fall average.

average of 16.5‰ at the mouth (text fig. 2A). This is part of a longer gradient extending 45 miles (72 km.) to the mouth of Chesapeake Bay, where the salinity is about 31‰. The seaward increase is greatest in the middle and upper estuary; in this gradient zone stratification is most pronounced and salinity fluctuates up to 5‰ daily and 13‰ annually (text fig. 2B). With seasonal fluctuations of river inflow, the vertical structure of estuarine water alternates from partly mixed to relatively well mixed.

TABLE 1

Summary of the occurrences of tests of foraminiferal species in the Rappahannock estuary, tributary creeks, and marshes

Species	Estuary and Creeks, 1962 *Frequency	Estuary and Creeks, 1962 †Abundance	Marshes, 1962 Frequency	Marshes, 1962 Abundance	Estuary and Creeks, 1963 Frequency	Estuary and Creeks, 1963 Abundance
Ammoastuta salsa	32	2.23	71	19.66	19	0.40
Ammobaculites crassus	97	68.68	73	9.33	100	68.50
Ammobaculites cf. *A. dilatatus*	17	0.08	17	0.21	32	0.49
Ammobaculites cf. *A. exiguus*	7	0.03	17	0.22	32	0.24
Ammonia beccarii var. A	15	0.11	0	0	30	3.41
Ammonia beccarii tepida	70	3.79	97	0.07	79	7.46
Arenoparrella mexicana	19	0.22	71	8.23	4	0.03
Astrammina rara	3	0.02	49	1.75	1	0.01
Elphidium clavatum var. A	42	14.19	24	0.01	81	7.01
Elphidium clavatum var. B	35	4.69	0	0	40	3.81
Elphidium clavatum var. D	0	0	0	0	47	4.31
Elphidium galvestonense	0	0	0	0	1	0.04
Haplophragmoides hancocki	15	0.21	80	3.53	5	0.04
Haplophragmoides manilaensis	10	0.08	73	2.04	1	0.01
Haplophragmoides wilberti	17	0.14	59	1.39	6	0.02
Miliammina earlandi	16	0.18	75	7.39	8	0.05
Miliammina fusca	83	4.39	88	23.79	68	2.89
Protelphidium tisburyense	13	0.20	0	0	7	0.10
Reophax nana	49	0.93	17	0.25	53	0.99
Tiphotrocha comprimata	15	0.21	56	11.22	9	0.13
Trochammina inflata	25	0.36	75	3.64	21	0.29
Trochammina macrescens	15	0.13	66	1.72	8	0.09
Trochammina squamata	10	0.32	0	0	4	0.07

*Percentage of samples in which each species was found.
†Average percentage of each species.

When river inflow is high, usually in late winter, freshening reduces surface salinity at the mouth to 14‰ and limits salty water to the lower 38 miles (61 km.) of the estuary (text fig. 2C). Like other Chesapeake estuaries, it is to be expected that mean salinity is slightly higher on the north than on the south side of the estuary owing to the influence of the Coriolis force (Pritchard, 1952).

Circulation.—An internal net circulation generated by vertical mixing of waters of different salinities is superimposed on the back and forth movement of the tide over many tidal cycles. Near-surface water flows seaward, whereas near-bottom water flows headward. Net velocities are small, less than 0.03 ft./sec. (0.9 cm./sec.) (Nichols and Poor, 1967), but in time they may disperse foraminifer tests either upstream in the channel or downstream over the shoals.

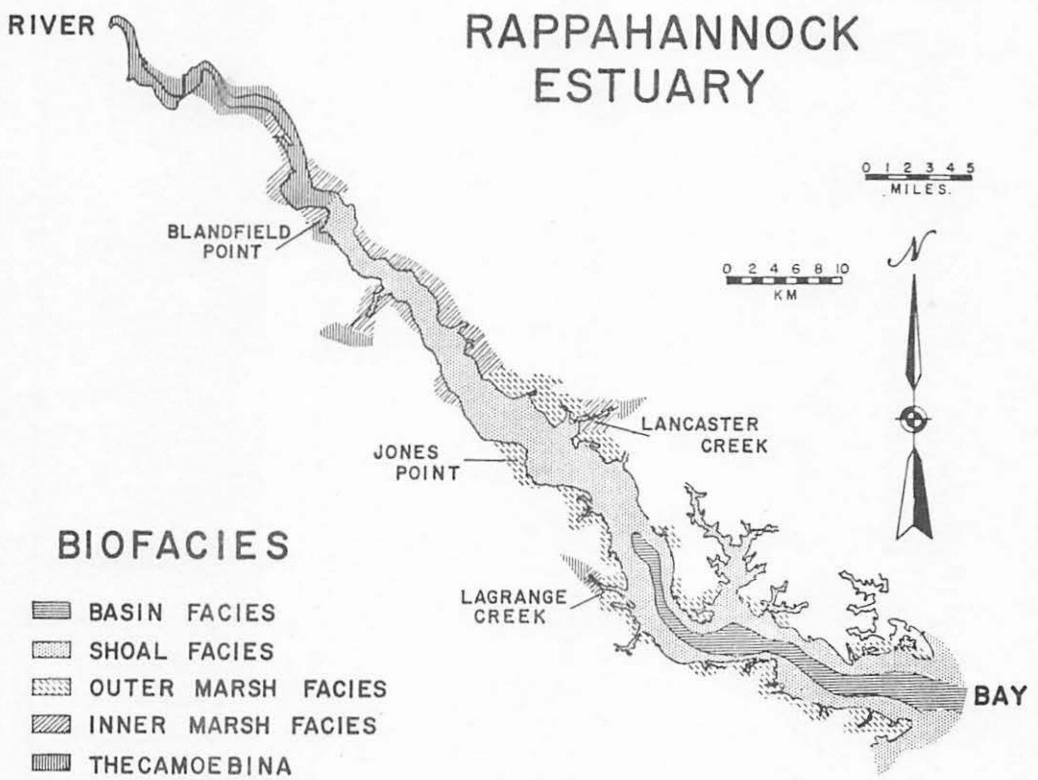
Water types.—From the circulation pattern and the distribution of salinity, two types of water are recognized in the Rappahannock estuary: (1) a low salinity, near-surface layer with a net flow down the estuary, and (2) a saline, lower layer in the basin and channel with a net flow up the estuary. Other characteristics are associated with these water types. For example, the lower layer is less turbulent than the upper layer, oxygen is occasionally depleted, and the temperature range is less than in the near-surface layer. These water types, though dynamic, generally reflect changing qualities of the water, depending on the rate of river inflow and degree of mixing between fresh and salt water.

DISTRIBUTION OF FORAMINIFERA

General Features of the Populations

The fauna comprises 19 species; two species, *Elphidium clavatum* Cushman variants and *Ammobaculites crassus* Warren, make up more than 80% of the estuary population. Samples from the upper estuary contain vast numbers of one species, *Ammobaculites crassus.* Of lesser abundance throughout the estuary are *Miliammina fusca* Brady and *Ammonia beccarii tepida* (Cushman), which together make up less than 10% of the population. Of the remaining 15 species, most average less than 1%. Faunal diversity, expressed in species per sample or in species per 300 individuals, is relatively high in the middle estuary basin and near mouths of tributary creeks and low in the upper estuary. Five species per sample is average for the estuary, nine for the marshes. Species abundance and frequency for the 1962 and 1963 collections are summarized in Table 1. Species of foraminifera are listed in the faunal reference list and illustrated in Plates 1 and 2, and text fig. 9. Species of thecamoebinids were not identified.

Total populations (*i.e.*, living plus dead) in the estuary vary from about 3 specimens to more than 10,164 per 20 ml. sample. In general, the average number of specimens per sample increases upstream



TEXT FIGURE 3

Distribution of biofacies in the estuary (basin and shoal facies) and marshes at average salinity conditions, June, 1962.

from less than 100 near the mouth to more than 2,000 per 20 ml. in the upper estuary (text fig. 4C). On the other hand, living populations are relatively small, averaging fewer than 42 specimens per 20 ml. Substantial standing crops occur along the basin shoulder at depths of 15 to 25 feet, and large living populations, reaching an estimated 500 specimens per 20 ml. sample, occur in the upper estuary, an area where total populations are also large.

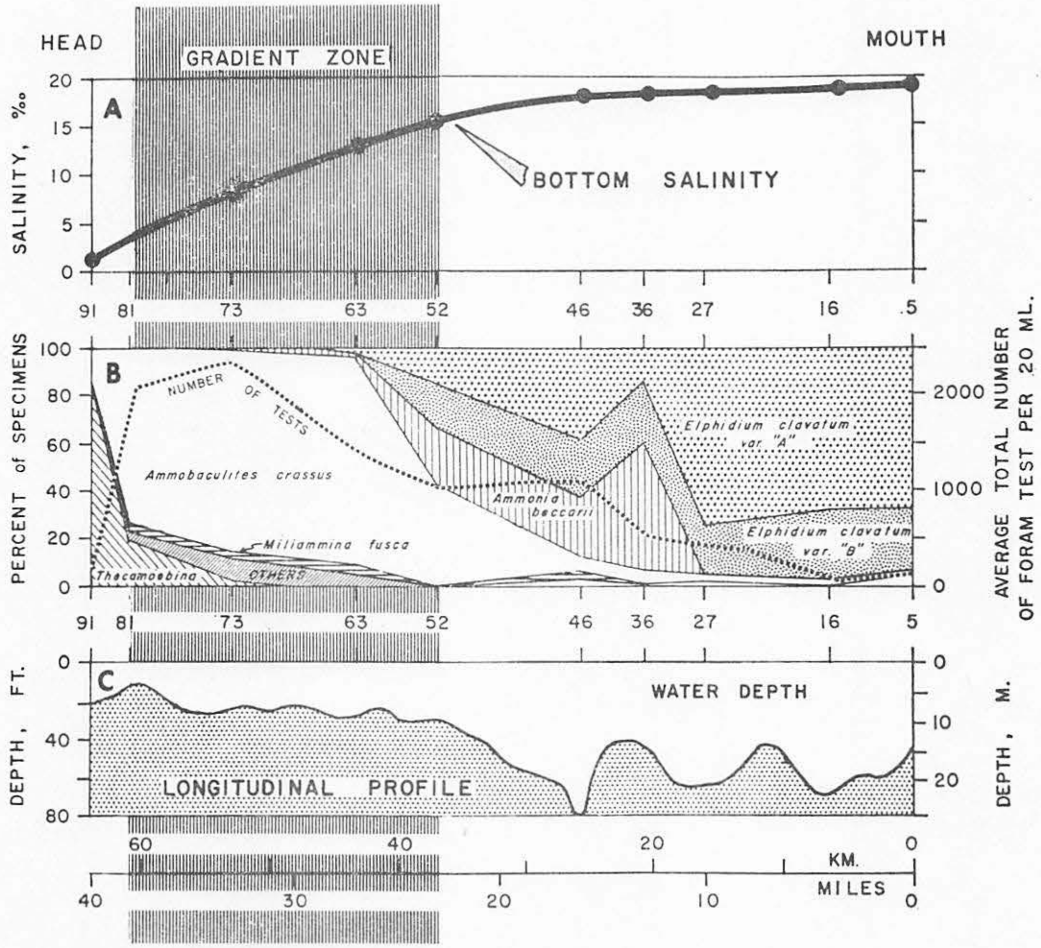
Biofacies and Faunal Composition

The distribution of the most abundant species of foraminifera permits recognition of four well-defined assemblages or biofacies: (1) basin, (2) shoal, (3) outer marsh, and (4) inner marsh. Thecamoebinids are present in the river and adjacent freshwater marshes. The disposition of biofacies is shown in text fig. 3.

The basin biofacies in deeper parts of the lower and middle estuary consists mainly of *Elphidium clavatum* variants. This facies extends headward from Chesapeake Bay to about 20 miles (32 km.) above the estuary mouth. Farther upstream, and laterally on both sides of the basin, in depths less than about 22 feet (6.7 m.), the basin facies passes into the shoal facies.

The shoal biofacies occurs on shoals throughout the estuary as well as in tributary creeks and in the channel of the upper estuary. It consists almost entirely of arenaceous species, chiefly *A. crassus*, and a few specimens of *M. fusca*, *Ammoastuta salsa*, and *Trochammina inflata*, which are also common in the marshes. This facies extends landward to bordering marshes and upstream to the river, about 45 miles (72 km.) above the mouth. At the fresh-salt transition, where salinity is 0.5‰ foraminifera are replaced by thecamoebinids. The change in faunal composition at selected stations across the estuary and along its length is shown in composite frequency diagrams (text figs. 4B, 5).

Salt marshes are characterized by several foraminiferal species that define "outer" and "inner" marshes along the estuary and, to some extent, "low" and "high" subfacies relative to the elevation of the marsh. The facies distribution generally corresponds with zones of marsh vegetation. The distribution of principal foraminiferal species along the estuary is shown in text fig. 6, and the relative abundance of marsh species in each biofacies is summarized in text fig. 7. As shown in text fig. 7, many species are widely distributed throughout the estuary. Therefore, the facies are established on



TEXT FIGURE 4

A. Distribution of bottom salinity with distance seaward, June-July, 1962.

B. Variation in species composition and total number of foram tests at channel and basin stations along the estuary length, June-July, 1962.

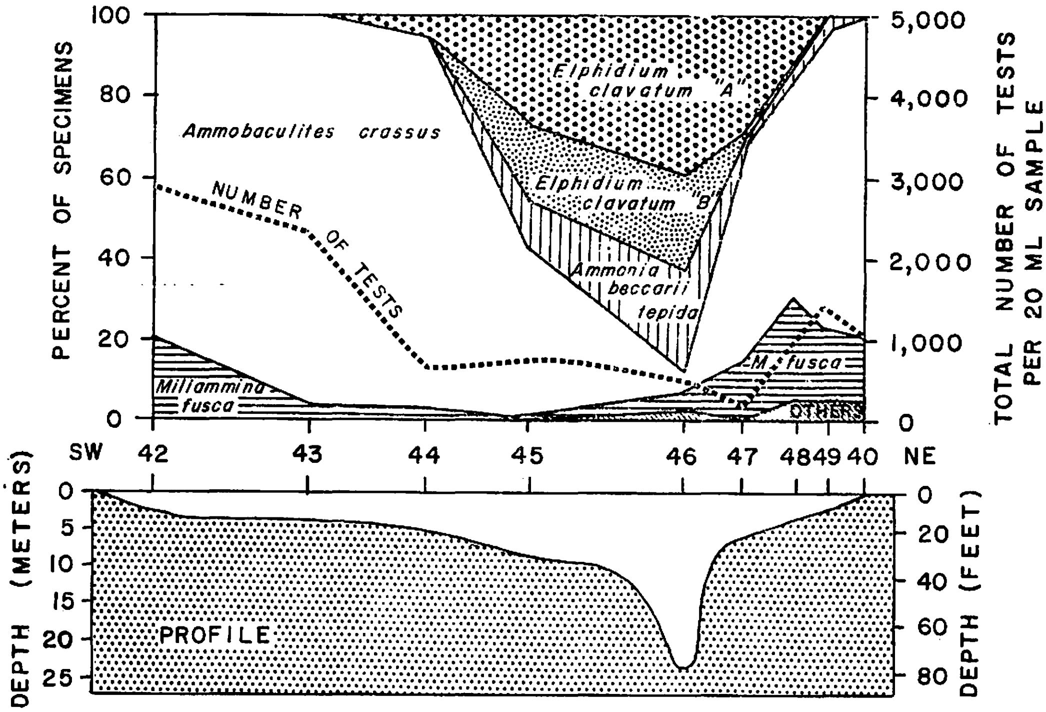
C. Corresponding longitudinal profile and water depth.

relative number of various species rather than on the unique association of a particular species with a particular habitat.

The fauna of the outer marsh biofacies along the lower and middle estuary consists of abundant *Miliammina fusca,* plus a few *Ammonia beccarii tepida* and *Trochammina inflata.* Higher parts of these marshes have fewer *M. fusca* and more *Haplophragmoides* spp. and *T. inflata* than lower parts. The fauna of the inner marsh biofacies along the upper estuary and innermost reaches of tributary creeks (text fig. 3) consists of abundant *Ammoastuta salsa* and some *Astrammina rara.* Also present are low percentages of *M. fusca, Arenoparrella mexicana* and *Trochammina inflata.* One species, *Tiphotrocha comprimata,* is widely distributed throughout all marshes and reaches greatest abundance in marshes along the middle estuary. In freshwater marshes, as in the estuary, thecamoebinids replace foraminifera.

Biofacies Boundaries

The transition between biofacies depends on estuarine mixing and bottom topography. Near the head of the basin, where the depth changes gradually along the estuary axis, the shoal and basin facies intergrade along a 10-mile (16 km.) reach of the estuary. Laterally, with a rapid change in depth, the facies boundary is abrupt. Although a few shoal species are scattered throughout the deeper areas, basin species are rarely found on the shoals, except in the middle estuary where waters are relatively well mixed. Species found in inner and outer marshes also are in part indigenous to the shoals, so that the faunal boundary between these two bio-



TEXT FIGURE 5
Lateral variation in species composition and total number of tests across the estuary, stations 40-42-49, June-July, 1962 (upper) in relation to the bottom profile (lower).

facies is gradational. Similarly, outer and inner marsh facies are gradational, except in middle-estuary tributary creeks where the marsh faunal change is sharper than in marshes of the main estuary. High and low marsh subfacies are indistinctly differentiated, though more detailed study, may, in future, show a marked distinction in association with plant zonation.

Population Variation

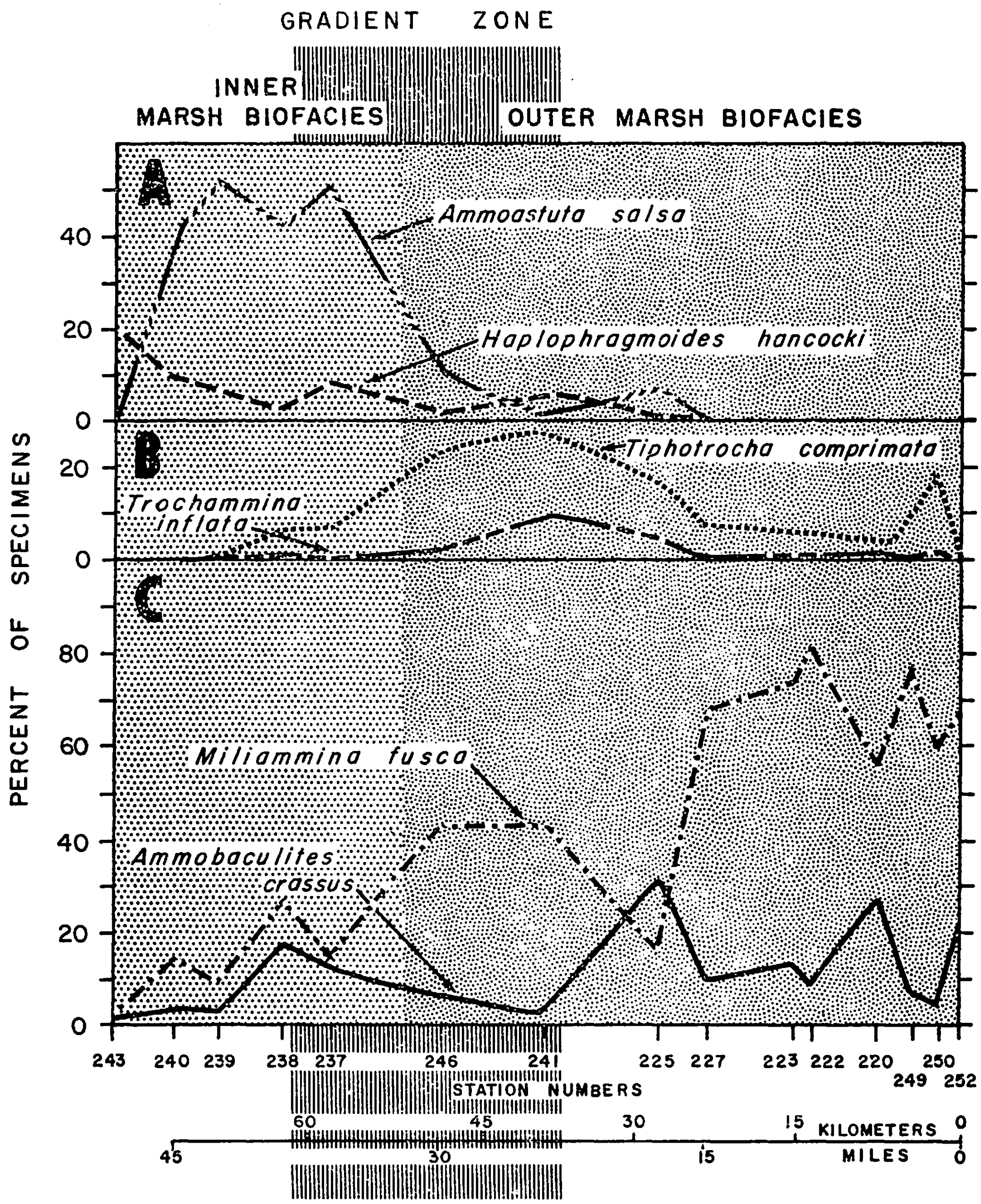
To evaluate sources of spatial variations in the populations, we collected three cores from each of several stations in the middle estuary, and these samples were counted twice. Results of the counts, reported in Ellison (in press), show that, although the percentages of tests of the common species vary only slightly, the percentages of the rarer species as well as the total numbers of tests per sample vary widely between duplicate counts and between the three samples taken at each of the stations. Therefore, the foraminiferal data, especially total numbers of tests, include some natural variations due to the non-uniform distribution of foraminifera, as well as a certain amount of experimental error. In this study we have attempted to reduce the natural variability by analyzing two combined samples for each station. Moreover, analytical errors were reduced by discounting broken specimens, improving the rose Bengal stain, and by counting up to 1000 specimens in some samples. An account of the analysis of local variation is reported by Ellison (1966).

Seasonal Variations

To study changes in the distributions from time to time, we analyzed populations of foraminifera from the estuary at four different times of the year. (Collection dates are given in the section on methods.) The distribution of total populations in each period exhibited the two principal biofacies, shoal and basin, found in the summer of 1962, but the patterns differed and the facies boundaries were located in different places (text fig. 8).

When salinity was relatively low and estuarine water moderately stratified in spring (1965), a time of high river inflow, the shoal-basin facies boundary, drawn where the percentage of *Ammobaculites* equals *Elphidium,* was in the lower estuary (text fig. 8A). Specimens of *A. crassus* were found in relatively high percentages on the shoals of the middle estuary, particularly along the southwestern side. For example, in text fig. 8A the seaward edge of the 90 percent *Ammobaculites* pattern trends diagonally across the middle estuary. Living populations, although small and variable, generally fall within the boundaries delineated by total populations.

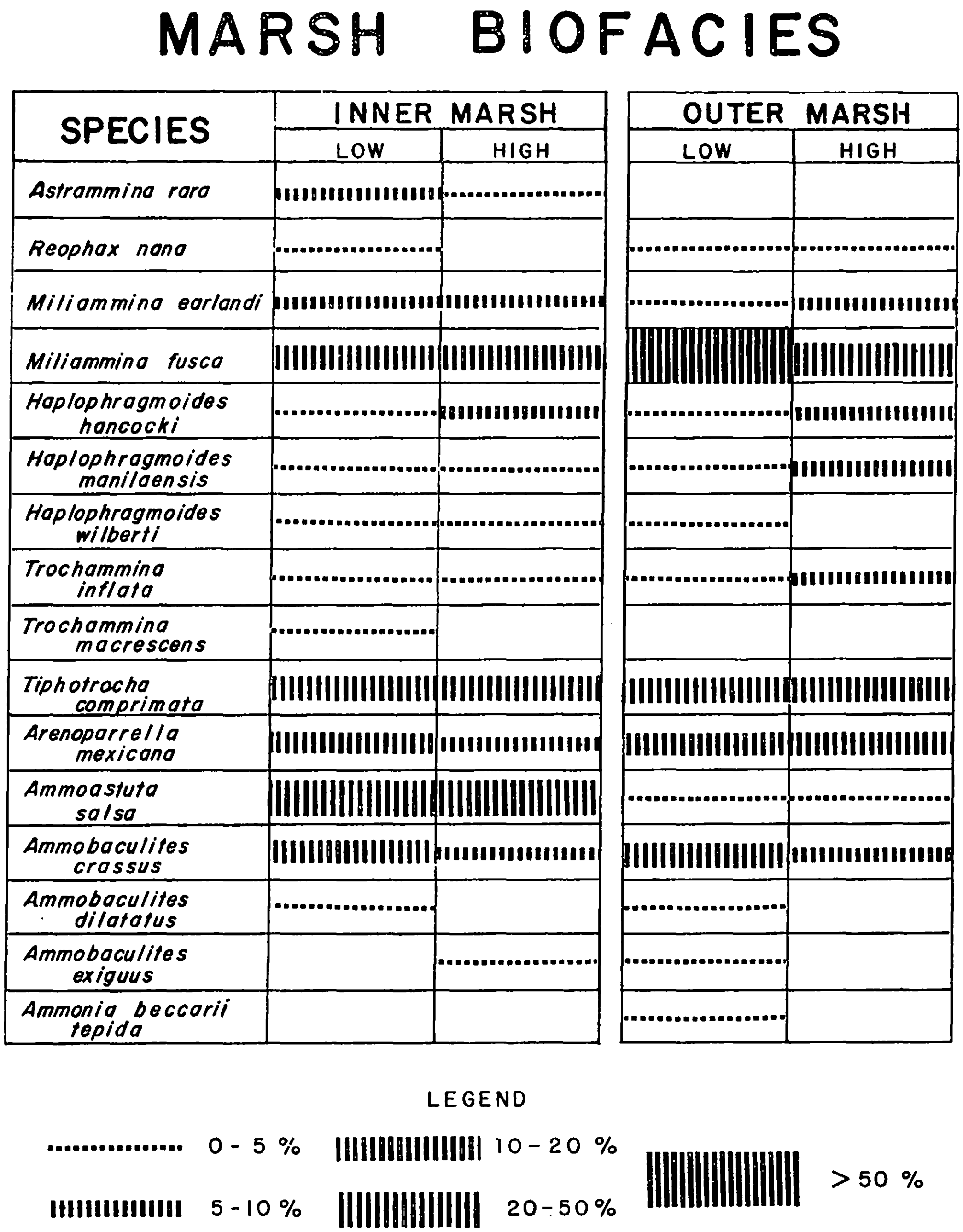
When salinity was relatively high and water well-



TEXT FIGURE 6
Variation in species composition of foraminifera from marsh stations (both "low" and "high") along the estuary length, June-July, 1962.

mixed in the summer of 1963, a time of low river inflow, the shoal-basin facies boundary reached the middle estuary. *Elphidium* was found in higher percentages on the basinward parts of the shoals and farther upstream than in the summer of 1962. Corresponding peaks for the average living and total population shifted upstream 4 to 6 miles (6.4-9.6 km.).

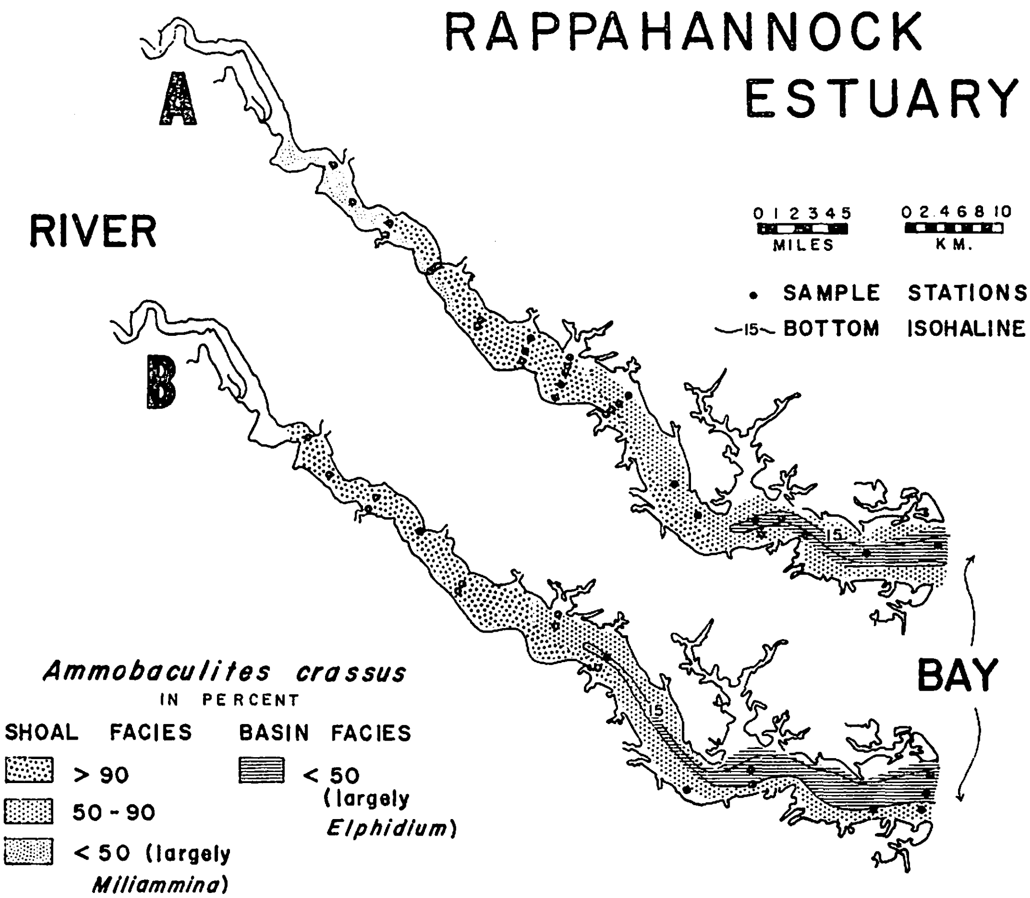
The species composition of total populations sampled in summer 1962, a time of average salinity, was compared with samples from corresponding stations in summer 1963, a time of relatively high



TEXT FIGURE 7

Relative abundance of marsh species in different biofacies, "inner" and "outer" and in subfacies "low" and "high" marsh.

salinity. This was done by summing the smallest percentages (1962 vs. 1963) for all of the species at each station. If the two years were very similar, the cumulative percentage for any single station would approach 100. On the other hand, values of less than 50 indicate major changes in the species composition at that station from one year to the next. Results presented in Table 2 indicate that differences in species composition were most pronounced in the basin of the lower estuary. These



TEXT FIGURE 8

Seasonal variations in the distribution of total *Ammobaculites crassus* in relation to bottom isohaline (‰); A. - spring, March-May, 1965; B. - winter, January, 1964.

may reflect real faunal changes, but most values were no greater than would be expected from variation inherent in benthic populations.

Using the same method of analysis, we found that adjacent stations were more alike in 1963 than in 1962 (Table 3). This greater uniformity of the distributions in 1963 accompanied higher salinity and less stratification than in 1962.

During a period of intense drought, from June through December 1965, monthly sets of samples were collected across the river-shoal facies boundary. The general increase in living foraminiferal numbers and decrease in thecamoebinids are reflected in the upstream migration of the facies boundary as a function of increasing salinity with time.

DISCUSSION

Relationship between Distribution and Environment

The two biofacies in the estuary are related to different water types. An *Elphidium* fauna inhabits the salty, lower layer in deeper parts of the lower and middle estuary, an *Ammobaculites* fauna largely occupies marginal shoals bathed by the relatively unstable and freshened upper layer, and a thecamoebinid fauna lives in the river. The facies patterns, therefore, generally parallel the depth and the boundary between water types. Furthermore, the elongate facies pattern and the water-type boundary are slightly skewed seaward on the south side of the estuary in a way that suggests the influence of the Coriolis force. Both the facies and the water types are separated by distinct boundaries.

The lateral transition between facies is very sharp. There are no physical barriers in the estuary, and tidal currents freely sweep the estuary floor and continually mix sediments and water. The abruptness of the faunal change may reflect stratification, but the causal relations are not understood. Transport of tests, particularly juveniles, in opposing upstream and downstream flows may redistribute foraminifera into areas bathed by the two estuarine

TABLE 2

Sums of least percentages for samples collected at stations in both 1962 and 1963. Percentages are those based on total tests. For station locations, see Ellison, *et al.*, 1965.

LOWER ESTUARY		MIDDLE ESTUARY		UPPER ESTUARY	
Station	Sums of least percentages	Station	Sums of least percentages	Station	Sums of least percentages
4	65.7	40	87.3	61	87.8
5	53.5*	42	77.4	63	92.4
16	29.2†	43	77.8	71	94.4
17	70.7	46	84.3	73	95.7
18	89.8	49	73.7	81	93.7
20	90.5	51	80.4	82	96.9
23	53.2*	55	93.0	101	98.0
24	49.6*	56	68.5	230	91.1
25	49.5*	57	40.7†	233	98.6
28	41.5†				
33	96.5				
36	71.4				
37	67.5				

*Questionable correspondence between members of yearly pairs.
†Significantly low degree of correspondence between members of yearly pairs.

layers, which have narrow transitions. Passive transport of barnacles and oyster larvae to sites suitable for growth has been demonstrated by Bousfield (1955) and Carriker (1951).

The position of the shoal-basin facies boundary approximately coincides with that of the 15‰ bottom isohaline (text fig. 8) at most levels of salinity studied. A similar relation was observed in the James estuary (Nichols and Norton, in press). The relationship to salinity is further strengthened by observations in tributary creeks, where the salinity gradient is sharp and the bottom shallow and smooth. As in the estuary proper, the fauna changes abruptly at about 15‰ salinity. The upstream "migration" of living foraminifera (chiefly *Ammobaculites crassus*) into reaches of the river with penetration of the salt water lends further support to the importance of salinity in controlling the distributions.

Salinity *per se* is not necessarily a causal factor affecting the distribution of all species, but it may serve as an index of dilution or mixing by river inflow that influences other conservative factors besides salinity. A number of species have a limited range along the estuary length. For example, *Ammonia beccarii tepida* ranges headward to the upper estuary where salinity averages 6‰, but it is most abundant where salinity is about 14‰. In laboratory cultures this foraminiferan ceases growing in salinities less than 7‰ and reproduces only in salinities above 13‰ (Bradshaw, 1957). Low salinity may effectively confine *Elphidium* to the middle and lower part of the estuary. *Ammobaculites crassus*, on the other hand, extends from the mouth to the head, through a salinity range from 0.5 to more than 16‰.

Although marsh foraminifera are grouped into biofacies more or less paralleling zones of vegetation, there is no sharp floral or faunal change with increasing elevation landward across the marsh or with distance along the estuary length. Instead the marsh distributions form a broad continuum along which different species appear or disappear. For example, *Ammoastuta salsa* is largely confined to the upper estuary, where salinities range from 0.5 to 12‰. Distribution of marsh foraminifera along tributary creeks is similar to that along the estuary proper at corresponding levels of salinity. The distribution of marsh species, therefore, appears to be partly controlled by salinity.

Both living and total populations increase to a peak in the upper estuary, suggesting that (1) empty tests are not redistributed on a large scale throughout the estuary after death, and (2) the large populations may be due to high production. Large stand-

TABLE 3

Sums of least percentages for pairs of adjacent stations for 1962 and 1963. (Percentages based on total tests).

	Station pairs	Sums for 1962	Sums for 1963
LOWER	4-5	36.1†	85.6
	16-17	17.3†	78.3
	17-18	79.2	58.8
	23-24	35.8†	66.9
	24-25	27.0†	72.5
	36-37	39.3†	86.0
MIDDLE	40-49	76.9	88.9
	42-49	81.4	93.2
	55-56	97.2	72.7
	56-57	94.6	42.5†
UPPER	81-82	93.7	97.4
	230-233	79.4	83.9

†Significantly low degree of correspondence between members of pairs.

ing crops of benthic foraminifera observed near the Mississippi River and Guadalupe River entrances have been related to high organic production (Lankford, 1959). In the Rappahannock, large populations are attributed to river-borne nutrients or food materials conducive to production. Monthly distributions of chlorophyll "a" and nutrients such as nitrogen and phosphate in near-surface water show these constituents increasing upstream most of the year, with highest concentrations in the marsh-fringed reaches of the river (Brehmer, personal communication). Although maximum populations do not coincide with the highest nutrient concentrations, it is possible that nutrients or food materials, or both, are significant in increasing foraminiferal production up to a point. Farther upstream, low salinity may limit foraminiferal growth or reproduction. Before these factors can be correlated, much remains to be learned about feeding habits of foraminifera and about primary productivity in benthic substrata.

PALEOECOLOGICAL IMPLICATIONS

Studies of foraminiferal distribution in estuaries such as the Rappahannock enable one to recognize and better interpret ancient estuarine deposits. Most of the species now living in the estuary range back to the middle Tertiary of the Atlantic and Gulf coasts (Bandy, 1956). These species should be valuable paleoecological guides, if one can assume that their environmental preferences have not changed, and that the distribution of fossil tests faithfully parallels that of the once-living foraminifer. Paleoecological interpretation is facilitated by combining other faunal and sedimentary characteristics with features of the foraminiferal distribution.

Like foraminiferal faunas in bays, lagoons, and around deltas, estuarine faunas have few species, with one or two dominants. There are more species near the ocean than near the river of an estuary. Although populations vary widely in size, they are commonly largest in the gradient zone of inner reaches where the salinity range is great. The faunal composition changes seaward from one that is all thecamoebinids in fresh water, to arenaceous foraminifera in the 0.5 to 15‰ salinity range, and to chiefly calcareous foraminifera at a salinity greater than 15‰.

Estuarine faunas that live in an environment of unstable salinity and opposing currents develop certain features that differ from those of other nearshore environments. An estuarine fauna is distinguished by a distinct distributional pattern. In plan view this pattern is elongate, generally paralleling the depth, but slightly asymmetrical.

The change of facies is marked, especially across the estuary. A calcareous *Elphidium* fauna extends headward in a narrow zone of the medial basin or channel. With greater stratification of estuarine water, facies boundaries become more asymmetrical and sharp.

Estuarine faunas are subject to modifications arising from addition or removal of certain species. A few specimens of marsh species may be found in the estuarine deposits, particularly along marsh-fringed reaches and at mouths of tributary creeks. Locally, fossil specimens, derived from exposures along the estuary shore or on the channel floor, are mixed into the estuarine fauna. On the other hand, the number of calcareous foraminifera may be greatly reduced or completely eliminated by post-depositional solution of tests. The resulting fossil fauna may be barren except for arenaceous specimens.

In a stratigraphic section, estuarine faunas may be expected to show marked vertical changes in abundance and composition. With long-term sedimentary aggradation, salt water intrusion will be limited, stratification reduced, and the more marine *Elphidium* fauna will be less widespread in younger than in older sediments. The facies boundary along the longitudinal axis would shift seaward as one proceeds stratigraphically up the section, and the sequence would have the general appearance of a marine regression.

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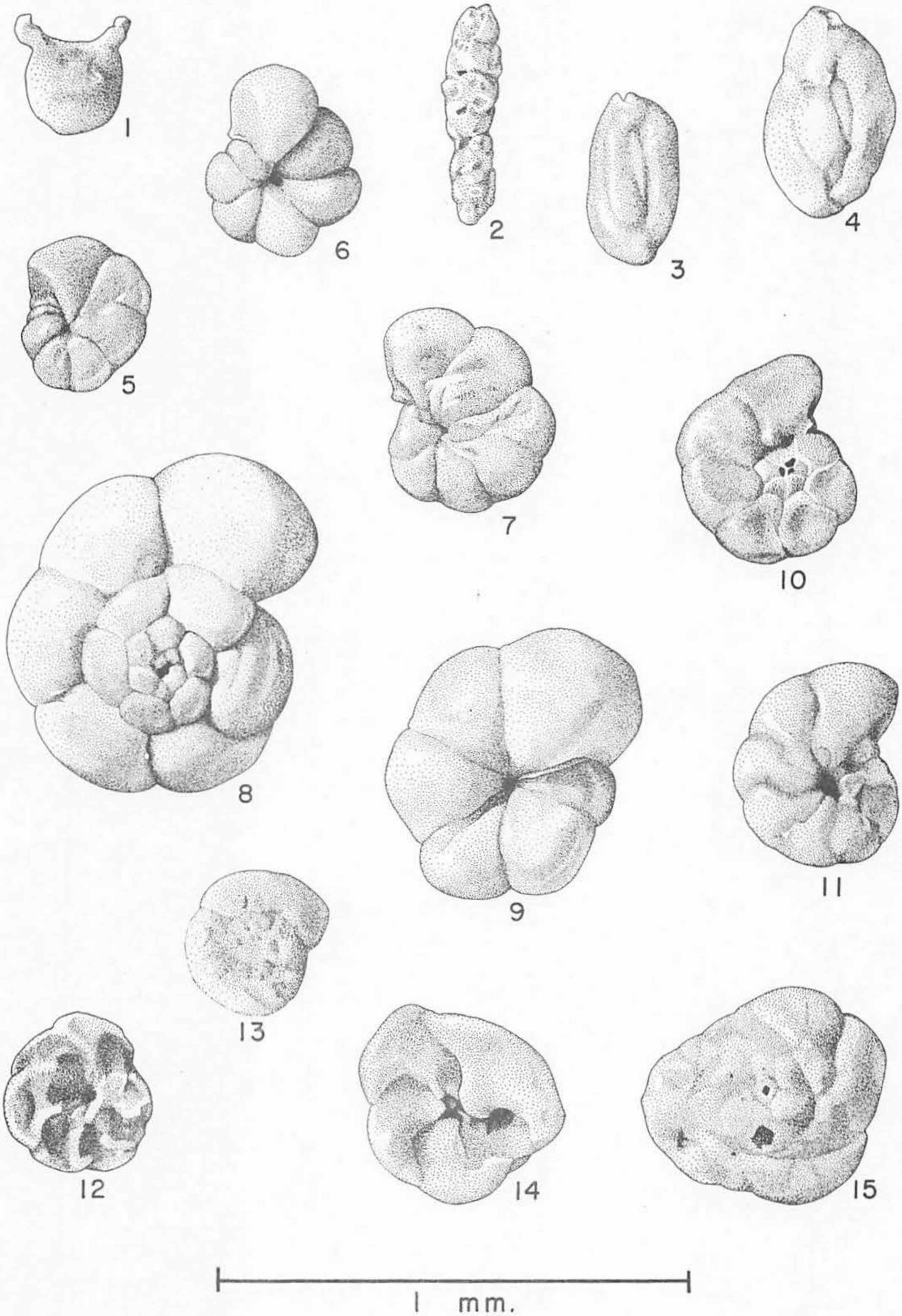
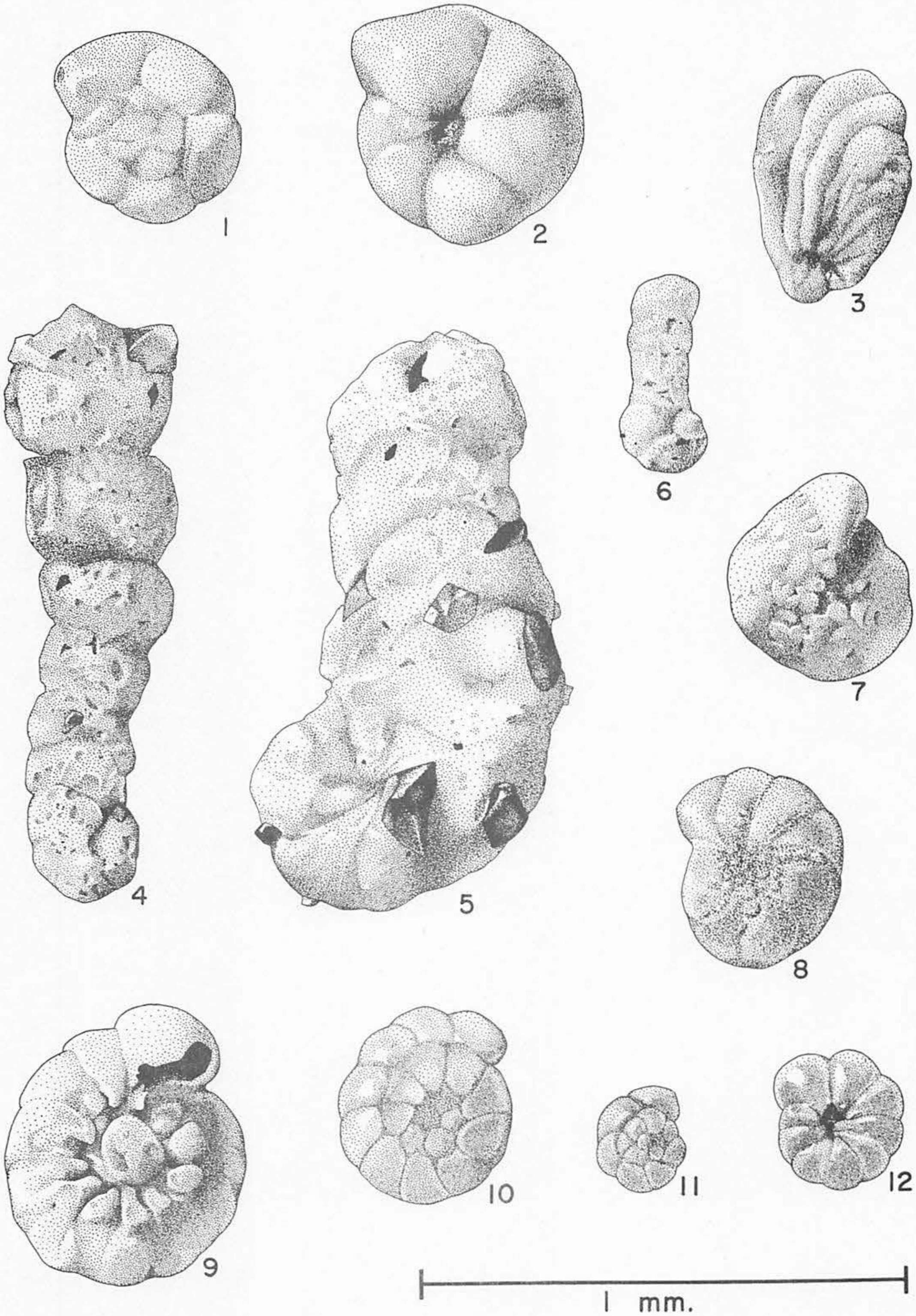


Ellison and Nichols: Estuarine Foraminifera from Virginia



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References to the original descriptions are listed below and species are illustrated in Plates 1 and 2 and text fig. 9.

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Ammobaculites crassus Warren, 1957. *Cushman Found. Foram. Res. Contr.*, 8:32, pl. 3, figs. 5-7.

Ammobaculites cf. *A. dilatatus* Cushman and Brönnimann, 1948. *Cushman Lab. Foram. Research Contr.*, 24:39, pl. 7, figs. 10, 11.

Ammobaculites cf. *A. exiguus* Cushman and Brönnimann, 1948. *Cushman Lab. Foram. Research Contr.*, 24:38, pl. 7, figs. 7, 8.

Ammonia beccarii (Linnaeus) var. A* = variety of *Nautilus beccarii* Linnaeus, 1758. *Systema naturae*, 10 ed., Holmiae, 1:710, pl. 1, figs. 1a-c.

Ammonia beccarii tepida (Cushman) = *Rotalia beccarii* var. *tepida* Cushman, 1926. *Carnegie Inst. Wash.*, Pub. 344:79, pl. 1.

Arenoparrella mexicana (Kornfeld), emend. Andersen = *Trochammina inflata* (Montagu) var. *mexicana* Kornfeld, 1931. *Stanford Univ. Dept. Geol. Contr.*, 1:86, pl. 13, figs. 5a-c.

Astrammina rara Rhumbler, 1931. In: Drygalski, E. von, *Deutsche Sübpolar Expedition 1901-1903*, W. de Gruyter, Berlin, 20:78, pl. 2, figs. 19a, b.

EXPLANATION OF PLATE 2

FIGS.		PAGE
1, 2.	*Arenoparrella mexicana* (Kornfeld). Marsh station No. 200. 1. Dorsal view of left-handed specimen showing typically subtle sutures and blocky chambers. 2. Ventral view of right-handed specimen showing radially directed sutures and excavated umbilicus.	15
3.	*Ammoastuta salsa* Cushman and Brönnimann. Marsh station No. 200. Lateral view of 10-chambered specimen.	15
4.	*Ammobaculites crassus* Warren. Estuary station No. 30. Large specimen showing trochispiral initial portion of test with vaguely visible sutures, and increasingly larger and more inflated chambers toward the aperture.	15
5.	*Ammobaculites* cf. *A. dilatatus* Cushman and Brönnimann. Estuary station No. 301. Specimen showing compressed character of test, and vaguely visible sutures that are markedly convex toward the aperture.	15
6.	*Ammobaculites* cf. *A. exiguus* Cushman and Brönnimann. Marsh station No. 220. Specimen showing subequant initial, planispiral portion of test, and uniserial portion with low chambers separated by nearly horizontal, subparallel sutures.	15
7, 8.	*Elphidium clavatum* Cushman. Estuary station No. 3. 7. Variant A; specimen showing slit-like pits marking septal bridges along the sutures, and the irregular bosses and pits in the umbilical area. 8. Variant B; specimen showing slightly arcuate, beaded sutures, and beaded umbilical area.	16
9, 10.	*Ammonia beccarii* Linnaeus variety A. Estuary station No. 23. 9. Ventral view of left-handed specimen (last chamber broken), showing thickened lappets extending toward large umbilical boss, and radially directed sutures. 10. Dorsal view of right-handed specimen showing slightly limbate, arcuate sutures.	15
11, 12.	*Ammonia beccarii tepida* (Cushman). Estuary station No. 46. 11. Dorsal view of right-handed specimen showing lobulate periphery and arcuate sutures. 12. Ventral view of right-handed specimen showing excavated umbilicus and radial sutures.	15

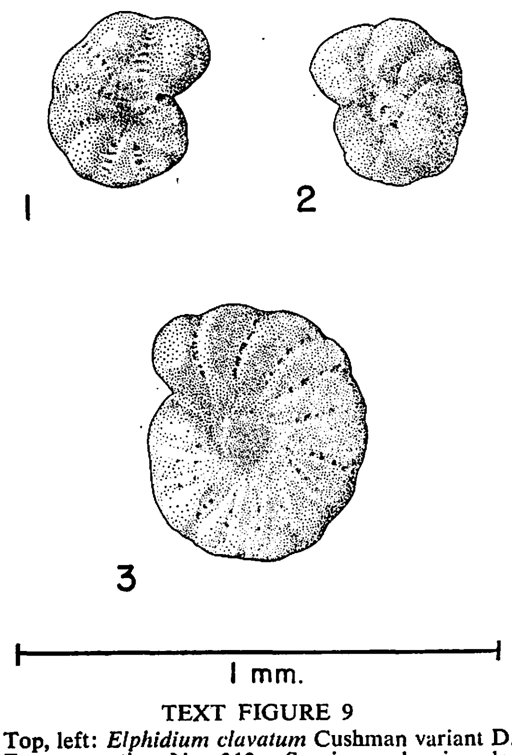
Elphidium clavatum Cushman vars. A, B, and D† = *Elphidium incertum* (Williamson) Cushman, 1930. *U. S. Nat. Mus. Bull.*, 104:18-19, pl. 7, figs. 8a, 8b, 9a, 9b = *Elphidium incertum* var. *clavatum* Cushman, 1930. *U. S. Nat. Mus. Bull.*, 104:18-19, pl. 7, figs. 10a, b.

Elphidium galvestonense Kornfeld = *Elphidium gunteri* Cole var. *galvestonensis* Kornfeld (part), 1931. *Stanford Univ. Dept. Geol. Contr.*, 1:86, pl. 15, figs. 1-3.

Haplophragmoides hancocki Cushman and McCulloch, 1939. *Allan Hancock Pacific Expeditions*, 6:79, pl. 6, figs. 5, 6.

Haplophragmoides manilaensis Andersen, 1952. *Cushman Found. Foram. Res. Contr.*, 4:22, pl. 4, figs. 8a, b.

Haplophragmoides wilberti Andersen, 1952. *Cushman Found. Foram. Res. Contr.*, 4:21, pl. 1, figs. 7a, b.



TEXT FIGURE 9

Top, left: *Elphidium clavatum* Cushman variant D. Estuary station No. 313. Specimen showing depressed sutures with small, unevenly spaced retral processes, and the excavated umbilical region.

Top, right: *Protelphidium tisburyense* (Butcher). Estuary station No. 313. Specimen showing recurved sutures that lack retral processes.

Bottom: *Elphidium galvestonense* Kornfeld. Estuary station No. 313. Large specimen showing somewhat flattened character of the test, and the numerous (15) chambers per whorl.

Miliammina earlandi Loeblich and Tappan, 1955. *Smithsonian Misc. Coll.*, 121:12, pl. 1, figs. 15, 16.

Miliammina fusca (Brady) = *Quinqueloculina fusca* Brady, 1870. *Ann. Mag. Nat. Hist.*, Ser. 4, 6:286, pl. 11, figs. 2, 3.

Protelphidium tisburyense (Butcher) = *Nonion tisburyensis* Butcher, 1948. *Cushman Lab. Foram. Res. Contr.*, 24:22, text figs. 1-3.

Reophax nana Rhumbler, 1911. *Plankton-Exped. Humboldt-Stiftung, Ergeb.*, 3:182, pl. 8, figs. 6-12.

Tiphotrocha comprimata (Cushman and Brönnimann, 1948. *Cushman Lab. Foram. Research Contr.*, 24:41, pl. 8, figs. 1-3.

Trochammina inflata (Montagu) = *Nautilus inflata* Montagu, 1808. *Testacea Brittanica*, Suppl. S. Woolmer, Exeter, Eng., p. 81, pl. 18, fig. 3.

Trochammina macrescens (Brady) = *Trochammina inflata* (Montagu) var. *macrescens* Brady, 1870. *Ann. Mag. Nat. Hist.*, Ser. 4, 6:51, pl. 11, figs. 5a-c.

Trochammina squamata Parker and Jones, 1860. Jones and Parker, 1860. *Quart. Jour. Geol. Soc. London*, 16:407, pl. 15, figs. 30, 30a-c.

**Remarks.*—Samples collected from stands of eelgrass in late summer of 1963 yielded abundant living specimens of *Ammonia beccarii* var. A. In addition, the associated sediment was sampled to determine whether the foraminifera were selectively inhabiting the grass. Most ratios for the eelgrass exceed those for the sediment. Nearly all high values result from large numbers of living *A. beccarii* var. A. In the summer this is an important epiphytic form in the Rappahannock.

†*Remarks.*—*Elphidium clavatum* exhibits considerable morphological variation. Specimens of this species in our collection are identical with material identified as *E. incertum* from Buzzards Bay (USNM 40941-40944). Other specimens are the same as those identified as *E. incertum* var *clavatum* from Buzzards Bay (USNM 41123, 41125, 41126). The shell wall of *Elphidium incertum* (Williamson) is microgranular, whereas the wall structure of our specimens is radial. Despite certain morphological divergences of our specimens from typical *Elphidium clavatum*, we regard them as belonging to that species.

In the Rappahannock River estuary, at least three morphological variants can be recognized with some confidence. These are referred to as *Elphidium clavatum* A, B, and D. Variants A and B are ubiquitous and commonly occur together, whereas D was found after 1962, and chiefly in the middle estuary.

The morphological differences of these three variants can be seen most clearly on adult specimens. Generally, variant A is opaque, with well-defined retral processes or interrupted slits along the sutures, and with the umbilical regions irregularly filled with one or more bosses. Variant B is transparent, and the sutures and umbilical regions bear glassy, bead-like processes. Measurements of several morphological characters (Buzas, 1966) showed no significant difference between these two variants. Variant D resembles imperfect specimens of *E. poeyanum* and can be recognized by its depressed sutures with retral processes that are sub-uniformly spaced and by its excavated umbilical regions. The test is coarsely perforate and superficially resembles the finely agglutinate shell of *Miliammina earlandi* or *Trochammina.*