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Foraminiferal Analysis of the Miramichi Estuary*

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Introduction

The Miramichi Estuary, approximately 40 miles in length, drains eastern and central New Brunswick. The bay empties into the Gulf of St. Lawrence, but a complete exchange of water is prohibited by a string of barrier islands which prevents extensive intermingling of bay and sea water.

By definition, an estuary is"... a semi-enclosed coastal body of water having a free connection with the open sea and within which the sea-water is measurably diluted with fresh water deriving from land drainage. " (Cameron and Pritchard, 1963, p. 306).

Assemblages of benthic foraminifera have been assigned to specific biofacies. The trends between the observed foraminiferal distribution and abundance, and the physical-chemical environmental parameters have been noted.

Previous Work

Cross (1951) conducted a general survey of the hydrography of Miramichi Bay, dealing mainly with the effects of sedimentation and erosion. Bousfield (1958) discussed the topography and submarine geology of the estuary. Bartlett (1966) collected and analyzed foraminiferal assemblages from 79 samples taken from the estuary in order to ascertain the effects of environmental parameters on special assemblages. Herzer (1966) collected sediment samples from 21 stations along the estuary in order to determine variations in the sedimentary environment. The present work is an extension of that conducted by Bartlett.

Method of Study

Sixteen samples were collected along the length (approximately 40 miles) of the estuary (Fig. 1) during August 1967. All samples were obtained using the Eckmann dredge. Only the top centimetre of each sample was studied. A mixture of methyl alcohol and Rose Bengal solution was added as a preservative. Depth, temperature, salinity, and pH of the surface and bottom waters were measured at each station. Silica, phosphate, sulphate, nitrate, nitrite, and turbidity of surface and bottom waters were analyzed with a portable, field Hach kit.

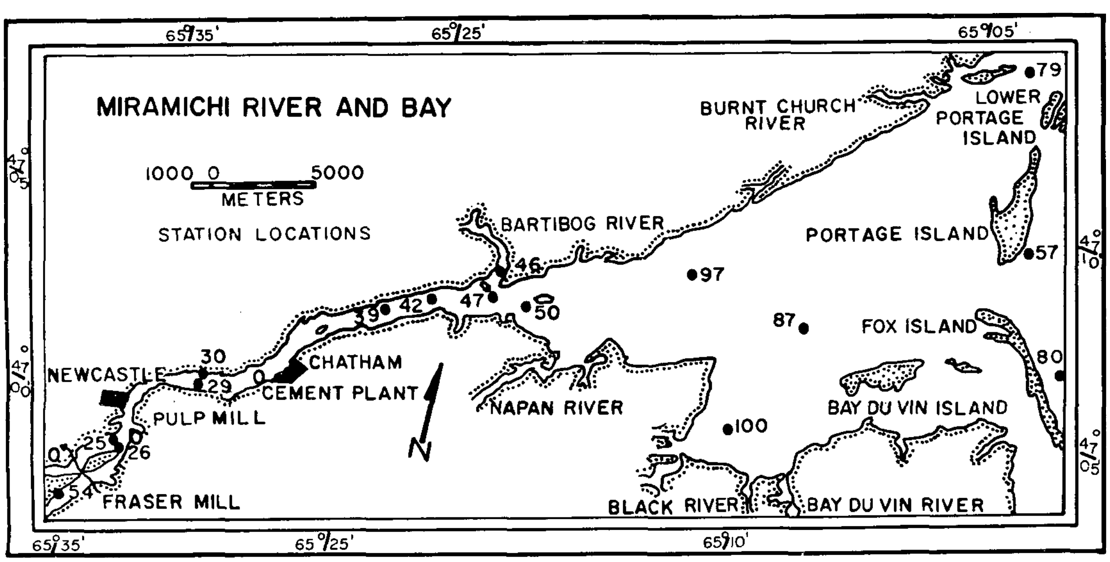

Fig. 1 Station locations, Miramichi Estuary

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The mechanical analysis of this data was performed at Queen's University during the winter of 1967-68. The samples were divided into two portions. One portion was picked for foraminifera, with a maximum pick of 300 per station; and the remaining portion was retained for sediment size analysis (Krumbein and Pettijohn, 1938).

Oceanography

Topography and Submarine Physiography

The average water depth of the Miramichi Estuary varies from four metres at lowest normal tides to five metres at highest tides (Bousfield, 1955). Deposits of sand extend in from the Gulf of St. Lawrence (mainly along the northern coast) to the centre of the bay. Mud flats cover the inner and southern bay bottom. Inshore shallows consisting of sandy mud, small stones, and eel grass are present in the river as well as in the bay. Occasional outcrops of soft sandstone are found along the bay margins and along the river banks as far as Newcastle.

Tides and Currents

Tides occur in a fortnightly cycle which has a peak of two equal high waters and two equal low waters per day and drops to one high water and a prolonged stand of low water per day (Cross, 1951). The combined effects of river discharge plus tidal outflow produce a prolonged ebb tide which encourages a net, seaward migration of river sediments and associated fauna.

Surface currents vary from 1.5 to 3 knots at the entrance of the bay and in the river during mid-flood and ebb tides (Bousfield, 1955). Herzer (1966) found that currents are rotary in a counterclockwise direction throughout the bay except in the openings between the barrier islands where they are reversing. Offshore currents, moving southward, have built a long, wide bar (station 80) extending southeastward between the deflected river channel and the open gulf.

Bottom Temperature and Salinity

The measured variation of bottom temperature during late August was less than 5°C along the length of the estuary; the average bottom temperature was 22°C. There are, however, marked diurnal and seasonal temperature changes. Bartlett (1966) found that shallow nearshore areas may undergo a 15°C change in a 24-hour period during June and July. He also found that temperatures approach 0°C in these nearshore areas during December and January. Such drastic temperature changes necessitate a hardy, eurythermal fauna.

Bottom salinities range from 25.1°/oo at station 79 to 23.0°/oo at station 54. Salinities at any one station can fluctuate as much as 5°/oo depending on the state of the tide.

A salt-water wedge extends as far upstream as station 39. The salt-water wedge has a significant impact on benthic foraminiferal communities, as it enables calcareous euryhaline foraminifers to penetrate much further upstream.

The minimum, survival salinities for foraminifers impose a definite limit to benthic migration. These salinity limits fluctuate up and down the river depending on the amount of river discharge. Rainfall, which makes nearshore shallow areas especially liable to extremes of dilution, exerts a profound influence on species distribution.

Pollution

Effluent from pulp mills contains, in addition to other mill wastes, sulphite liquor and as much as 0.1% pulp fibres which are lost in the milling process (Tully, 1949). The organic constituents are fermented aerobically to carbon dioxide and water in both fresh- and sea-water media. Tully believed that the immediate oxygen demand is due chiefly to the fermentation of the sugar and is supplemented by the slower demand of the lignin. He concluded that the fermentation of sulphite liquor requires approximately 1,000 pounds of oxygen for each ton of pulp produced; and that pollution poisoning may be attributed to a combination of this high oxygen demand, excessive water acidity, direct toxic effects of the sulphite liquor and the presence, in bulk, of pulp fibres. He further concluded that in concentrations of less than 100 parts per million the effect of sulphite liquor on living organisms in sea water is small, but with concentrated waste-sulphite liquor (1, 000 parts per million) mortality ensues because the dissolved oxygen is reduced below 5 parts per million. The Fraser Pulp Mill is located immediately upstream of stations 25 and 26. It releases effluent into the water in the vicinity of these stations and the sediments therefrom contain a high concentration of pulp fibres. Sulphate concentration in this area is low (330 parts per million at station 54) in contrast to stations further out in the estuary where sufficient time and distance from the point of discharge has permitted the sulphite liquor from the pulp mill to become exidized to sulphate. Although the Hach kit does not measure sulphite concentrations, the low sulphate content in the vicinity of the mill effluent strongly suggests that sulphite is probably high. This accounts, in part at least, for the sparse living benthic populations in this area.

Nutrition

Large, foraminifer populations in Miramichi Bay support Darnell's hypothesis (1967) that ". . . due to the availability of large quantities of dead protoplasm, shallow bottoms and moving water, the estuary especially may be thought of as a thin mud containing many nutritious opportunities for the consumer species. " Foraminifera often flourish off the mouths of tributaries where, despite lowered salinities, the high mortality rate of fresh water phytoplankton plus the plentiful soil nutrients provide a rich food source. In the Bay du Vin area, phytoplankton concentrate as a result of tributary influx, warmer surface waters, and slower transport rates due to the Coriolis effect. Because of the consolidation of this organic material within the clay

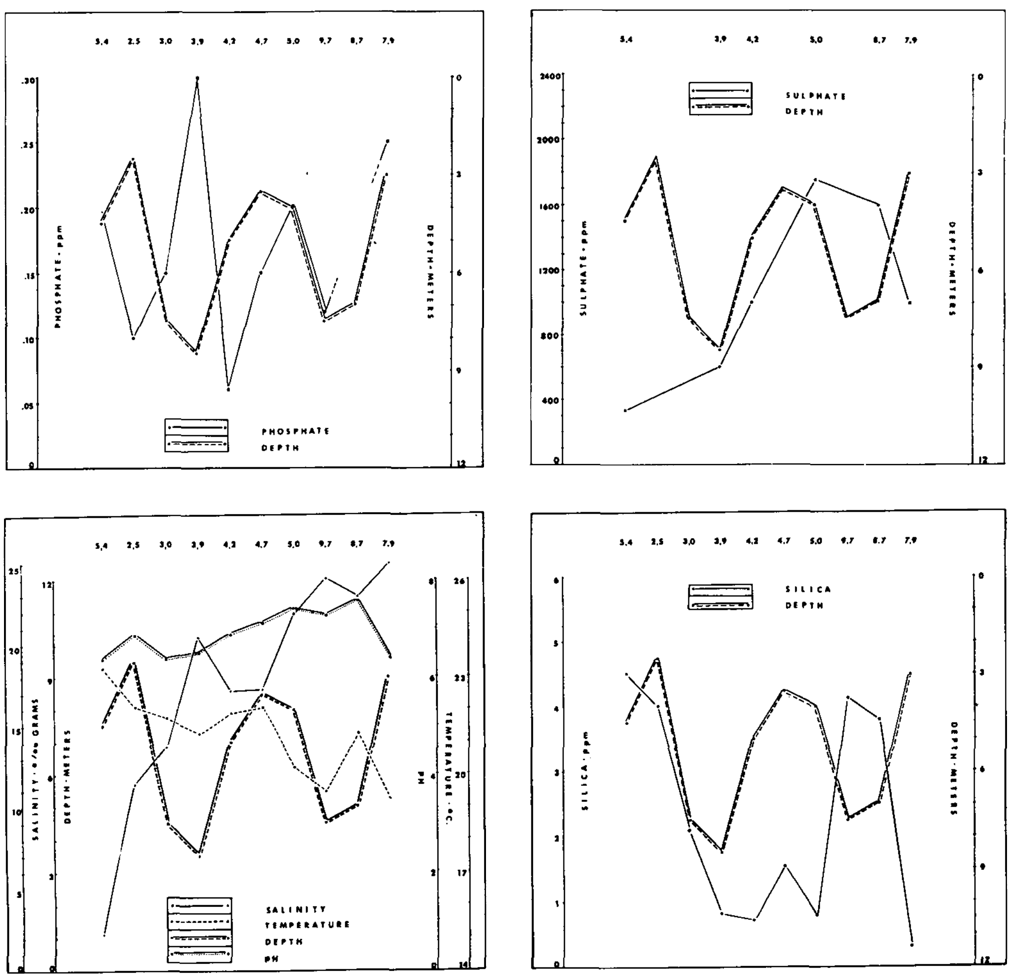

Fig. 2 Physical and chemical parameters along a longitudinal traverse

fraction of the substrate, large foraminifer populations flourish here.

Experiments performed by Bradshaw (1955), Lee et al (1961), and Myers (1943) suggest that foraminifera are selective feeders. Although a given species might accept various foods, it appears that certain combinations are more beneficial than others. If this is the case, nutrient associations and their locations may considerably influence the species distribution in a given niche.

From regional observation and as a broad generalization, the wide variability in ion distribution from station to station may well account for sporadic population distributions. Population assemblages as well as distributions can change radically on a micro-environmental scale as a result of variable ion composition of the water and sediment with which the fauna come in contact.

Physical and Chemical Parameters

Physical and chemical data are inadequate to define the entire environment. However, certain trends have been observed (Fig. 2).

Hydrogen ion concentration (pH) and salinity increase seaward, whereas temperature decreases and bears an inverse relationship to salinity. Increasing salinity coincides with an increase in the proportion of the calcareous, foraminiferal, benthonic fauna.

Seaward from the river mouth, and into the estuary proper, an increase in phosphate coincides with an increase in depth, whereas upstream, the phosphate content is in inverse ratio to the depth. The latter situation may be more apparent than real because station 39 is located in a deeper-than-average part of the river and station 25 is in a heavily polluted area.

The high concentration of silica in the river is probably a direct result of land runoff. The second peak of silica concentration in the bay headwaters is probably a result of the combined discharge of the Bartibog, Napan, Black, and Bay du Vin Rivers. Arenaceous foraminiferal species predominate where silica concentrations are high.

Sulphate increases seaward within the river as the sulphite liquor from the pulp mills is gradually oxidized; decrease seaward within the bay is due to dilution and dispersal of river waters. Sulphate increase is associated with an increase in faunal number. The writer feels, however, that sulphate is environmentally independent, and that it is purely a transport phenomenon.

Turbidity, nitrate, and nitrite measurements were too few to make reasonable trend predicitons.

Sedimentology

Sediments range from sand to clay. The coarsest sediments are found at station 57, at the mouth of the bay on the seaward side of Portage Island, and at station 80, which is located to the southeast of station 57 on an offshore bar. Coarse sand, with broken shell fragments and high concentrations of mica, are found at both of these stations. The material is well sorted, as the silts and clays have been winnowed out by the high energy of the beach environment.

The central bay is a broad, shallow, tidal flat and is covered with sandy silt (station 87) and clayey sand (station 97). An extensive river channel is not developed here because of the impedance and dispersal of the river current as it loses velocity and carrying power on reaching the bay and encountering marine tides.

The present study supports the observations of Emery and Stevenson (1957) that the channel deposits represented by stations 30 and 39 are much finer than those deposits lying between the channel and the shores represented by stations 25, 26 and 54. In nearshore shallows, the river current dominates over tidal flow; sands are deposited and the fines swept on. In the channel the sediment-laden river current is slowed markedly by saline flood tide waters depositing sand, silt and clay with little or no sorting.

Physical Description of the Sediments

At the sediment-water interface throughout most of the estuary there is a thin layer of brown to red-brown, oxidized material of soupy consistency. It appears to be in a constant state of suspension probably as a result of current action. The most prolific foraminiferal populations are found within or close to this layer because the looseness of the sediment allows maximum ion exchange and oxygenation of the substrate. Because the layer is rich in organic material, prolific benthic fauna exist within it, particularly at stations 100, 87 and 97. Work done by Darnell (1967) supports this hypothesis.

As a general rule, the darker the sediment colour, the more foetid the odour it emits. This is especially noticeable in the fine silts and clays of station 30. Anaerobicity results from an in situ demand for oxygen which exceeds the amount that can be supplied by simple diffusion across the mud-water interface. Much of the anaerobic respiration involves sulphur reduction with the evolution of hydrogen sulphide.

Beach and bar sediments of stations 57 and 80 are buff in colour, porous, and odourless. Where pollution of the water is obvious, the underlying sediments are often dark, as for example, at station 26. Coal-tar dust, a darkening agent, is present at station 30.

Salt Water Retention

The high porosity of the coarse sands allows salt water from the flood tides to infiltrate the sediments. For this reason, this water is easily flushed out and replaced by fresher water from the ebb tides.

Silts and clays are relatively impermeable. Once salt water is trapped within them, it cannot easily escape nor can it be easily flushed out during times of fresh water influx.

Station 42 consists of sand with a 20% silt matrix. The silt acts to reduce the overall porosity of the sand so that more saline flood waters are held within the sediment during the more dilute ebb-water cycle. As a result, sediments of station 42 are considerably more salty than would have been anticipated from measurements of the water salinity directly above the substrate. The higher salinity within the sediment allows foraminifera, which will not usually tolerate salinities below 20 °/oo, to penetrate as far up the estuary as station 42 even though bottom water salinities are lethal.

Bottom pH and Eh

Substrate pH ranges from acidic, 6.4 at station 30, to alkaline, 7.6 at station 57. Alkaline environments are found in sandy areas, while acidic environments are found in finer sediments adjacent to intertidal and back-bay areas where floral growth and clay content are high. In such areas relatively little transfer of ions occurs across the clay-water interface. Decaying organic material therein uses all of the available oxygen and little life can survive in these highly reducing environments. Hydrogen ion values in the estuary vary both daily and seasonally depending upon the exchange of ions between the sediment layers and the surrounding sea water.

The oxidation-reduction (Eh) values indicate existing oxidizing conditions at the mud-water interface, whereas a reducing environment exists a few centimetres below this interface. Foraminiferal life is thus limited to the top few centimetres of substrate above the reduction zone.

Foraminiferal Assemblages

Twelve species of foraminifera are found at the sample locations in the estuary, and 3 species of Thecamoebina are found exclusively in the river.

An arenaceous fauna, consisting predominantly of *Miliammina fusca* with occasional *Trochammina* spp. plus thecamoebinids occupies the upper reaches of the river (Fig. 3). These forms appear well adapted to an environment characterized by marked diurnal salinity changes.

A calcareous, or *Elphidium*, fauna consisting predominantly of the *E. incertum* "complex", *E. orbiculare*, and *E. margaritaceum*, occupies the lower reaches of the river and the entire bay (Fig. 3). The writer considers *Elphidium clavatum* and *E. incertum* to be two end members or morphological extremes of the same species. Hence, rather than classifying them as two separate species, they are treated as varieties of the same species - the *E. incertum* "complex" (Bartlett, 1965). Populations consisting of this calcareous fauna rapidly diminish where the salinity drops below 20°/oo. (Buzas, 1965; Bartlett, 1964, 1965, and 1966). Living populations have been found where the water salinity falls below this lower limit but the writer suspects that the mud sediment supplies the necessary survival salinity.

The greatest population numbers occur in the central and southern portions of the bay while lowest population numbers are found further up the river; where salinities drop below 20°/oo. The largest living population is found at station 100, in the southwestern portion of the bay.

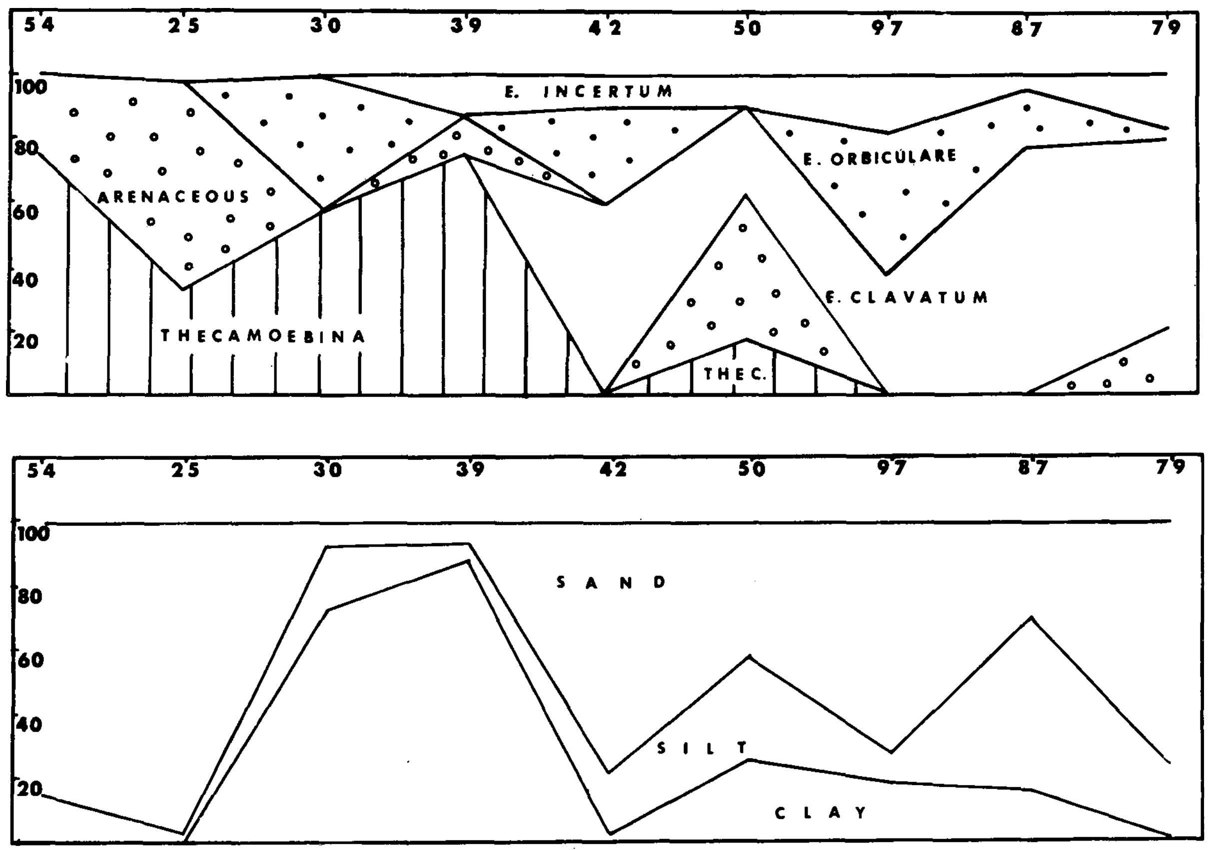

Fig. 3 Faunal and sediment distributions in a longitudinal section of the Miramichi Estuary.

Foraminifera and Environmental Relationships

At stations 57 and 80 (Fig. 1), along the outer margin of the bay-mouth bar, the open ocean distributes and dilutes the dissolved mineral nutrients and, therefore, uniform physical-chemical conditions prevail. Bottom salinities, still brackish, average 24°/oo; bottom temperatures average 19°C. Water depth is less than five metres and the substrate consists of uniformly coarse, well sorted, unimodal sands. A great many broken, unidentifiable fragments occur here as a result of tidal turbulence.

Station 57 is located in the beach intertidal zone. One species, represented by two specimens, belonging to the *Elphidium incertum* "complex" is found here. The high energy environment of the coarse unstable substrate is amenable to very few organisms.

Quinqueloculina seminulum and *E. clavatum* are found at station 80 which is located on an offshore bar formed by southeasterly longshore currents.

Station 79 supports a more prolific, nearshore fauna because the substrate, which has a high proportion of sand, permits free ion exchange with the surrounding waters; yet it contains enough silt to trap any organic nutrients within the sediments. E. clavatum is the dominant species, but E. orbiculare and other nearshore, marsh species such as Ammotium cassis, Trochammina spp., Bucella frigida and Eggerella advena are present. The high energy of this environment, combined with strong semi-daily salinity changes, discourages large population numbers, although the small size of the adults of the Elphidium species suggest favourable environmental conditions (Bartlett and Tapley, in press). The combination of these two antagonistic effects produces a small total population with a large living fraction.

The most prolific living and total foraminifer populations are found in the bay, represented here by stations 87 and 100. Elphidium clavatum dominates the population and is found in association with marsh fauna such as E. orbiculare, E. margaritaceum, Miliammina fusca, Trochammina ochracea and Cribrostomoides crassimargo. The large living population, in combination with the dwarf size of the adults of the Elphidium species which indicate early growth and rapid maturation, signifies favourable environmental conditions. The substrate, in both cases, consists of a clayey, sandy silt which provides both porosity in the sand fraction for free ion exchange, and mineral and organic retention in the clay-silt matrix. Eel grass (Zostera marina), combined with extensive mussel (Mytilus edulis) banks and the abundance of fresh plankton which collects off the mouths of the Bay du Vin and Black Rivers at station 100, provides a fertile source of organic nutrients. Strong tidal action has produced an almost uniform bottom salinity of 23.0°/oo and a bottom temperature of 21.4°C. The higher concentration of sulphate in the south central part of the bay suggests Coriolis influence on the circulation patterns of the bay. The effect of high sulphate concentration on the fauna is unknown but cannot be inhibitive judging from population vigour. Silica concentrations do not appear to have hindered or enhanced the growth and development of the predominantly calcareous elements of this population.

Station 97 is located at a depth of 7.5 metres in the river channel in the central bay. The bottom sediment consists of sand with an admixed silt-clay matrix. The brackish salinity, 24.1°/oo, and warm temperature, 19.4°C, particularly suit this environment for a large Elphidium fauna. The large size of the adult living and dead tests, plus the lack of juvenile forms indicates removal of sediment by current activity. E. orbiculare dominates the special assemblage in association with members of the E. incertum "complex".

Station 50 is located in the mouth of the river-bay head area. River water meets sea water at this point, resulting in considerable turbidity. Due to reduced currents, the river deposits its load rapidly. As a result, a small, low island immediately off station 50 has formed. The sediment consists of a poorly sorted mixture of clay, silt, and sand. Sulphate concentrations are higher here than at any other station measured, probably due to a cumulative oxidation of all the sulphite liquor from various pulp mills along the river. The high salinity, 22.0°/oo, is due to oceanic influence. The foraminiferal population is low, probably because of the rapid sedimentation. Miliammina fusca, in association with thecamoebinids, dominates the population, but they are undoubtedly found here only as a result of river transport because salinities are much too high to support a living fauna of Thecamoebina and the sedimentation is too rapid to support extensive Miliammina colonies. Members of the E. incertum "complex" are also found here. The salinities are high enough to permit Elphidium growth and development but it is doubtful whether the environment is suitable for an extensive population.

The river and the bay represent two different habitats. The bay, with higher salinities, shallower depths, and more oceanic affinities, supports a calcareous assemblage of which E. clavatum is dominant. The river, when not under the modifying marine influences at the mouth, supports an arenaceous Miliammina assemblage and, in fresh water, Thecamoebina. The high silica content of the river is probably important to this arenaceous fauna for the construction of their tests. The great differences between bay and river fauna in both composition and number, are first reflected by stations 46 and 47 which are located at the bay head, off the mouth of Bartibog River.

Station 46, at a depth of 2.5 metres, has a very low bottom salinity of 10.7°/oo. Silica and phosphate content are fairly high, probably the result of land runoff. The substrate consists of poorly sorted, coarse sand and gravel. The salinity is too high for Thecamoebina growth and sediment deposition is too rapid for extensive arenaceous populations.

Station 47 is subject not only to strong semi-diurnal salinity changes, but also to variable fresh water dilution from Bartibog River. The strong effects of ocean tides combined with a variable influx of fresh water make this area unsuitable for even limited development of either arenaceous or calcareous faunae.

Station 42, west of the river mouth, was taken midway between two branches of the river channel, at a depth of five metres. The substrate here consists of a silty sand. The bottom salinity is 17. 5°/oo but, despite this low salinity, a thriving calcareous fauna is present. The large living fraction would rule out the possibility of a mobile death assemblage. Consequently, the writer feels that the presence of this thriving Elphidium fauna is a result of the retention of saline flood waters within the extensively developed silt-clay matrix. E. clavatum again dominates the assemblage in association with E. orbiculare, E. margaritaceum and Bucella frigida.

The persistence of the saline wedge well up the river is demonstrated at this station where bottom salinities reach 20. 5°/oo. The bottom sediment consists of a flocculated clay. Its low permeability restricts ion exchange to such an extent that the substrate has become highly reducing, hence toxic to benthic life. Thecamoebinids and Miliammina fusca are found here. However, the writer feels that it is mainly a mobile death assemblage.

Station 30, located in the main channel in 7. 5 metres of water, is surrounded by pulp mills (Fig. 1). Deposition of flocculated clays in the channel plus coal-tar and pulp-mill wastes has produced a reducing, toxic environment detrimental to benthic growth.

Station 25 lies at the river fork immediately upstream from Newcastle and is in the near-shore shallows midway between two pulp mills. The bottom salinity if 11. 4°/oo. Despite the coarse, sandy, slightly acidic substrate (acidity is probably a reflection of pulp mill effluent) total populations for the locality are relatively high. The writer has been unable to determine what percent of this population is in situ. As Miliammina fusca thrives in nearshore areas, it probably represents an in situ assemblage. However, the Thecamoebinids have probably been transported here from further up river where the water is fresh.

Station 54 is located at the limits of penetration of the salt water. Salinity is extremely low, 2. 3°/oo, but it does vary up to 5. 0°/oo with the tide. Silica content is high whereas sulphate content is low. The substrate consists of coarse sands and granules with a silt matrix. The salinity is too low for foraminifera to live. Thecamoebina flourish in fairly shallow, fresh-water, turbulent environments (Ronai, 1955). Station 54 marks the maximum penetration of live thecamoebinids into the estuary.

Biofacies Relationships

Tow main biofacies exist: the river fauna, extending from station 54 to station 50, and the bay fauna, extending from station 97 to station 80 (Fig. 1). The river biofacies is readily separable into two biotopes, the nearshore-shallows and the channel. The bay biofacies can also be divided into two biotopes, the nearshore shallows-central tidal flat and the bay-mouth bar-beach. As certain genera and some species of foraminifera in the estuary are environmentally selective, distinctive faunal assemblages are associated with these biofacies.

The river biofacies, and in particular the nearshore biotope, is characterized by an arenaceous fauna composed predominantly of Miliammina fusca in association with Trochammina spp. The Miliammina fauna prefers the coarse sediments and the algae Enteromorpha and Zostera, which are found in nearshore biotopes. This fauna thrives in intertidal to continuously inundated brackish waters and is less commonly found in the deeper river channel substrates. Thecamoebinids occur in the fresh water areas of the river biofacies.

The bay biofacies is characterized by a calcareous Elphidium fauna. According to Bartlett (1964, 1965) and Buzas (1965), E. incertum "complex" is most prolific in shallow (less than 10 metres brackish water, where salinities range from 22°/oo to 25°/oo. It is found in all substrates, but prefers the sandy-silt substrates found in the nearshore shallows-central tidal-flat biotope of stations 100, 87, 97 and 79. The larger opaque forms are found most often in the nearshore, turbulent, or outer shelf environments of stations 57 and 80. In the back-bay areas, such as stations 100 and 87, species are smaller, more translucent, and have a more variable external morphology. E. orbiculare is most prolific in the transition zone between the river and bay biofacies in a shallow but slightly less saline brackish water environment where salinities range from 20°/oo - 25°/oo.

Acknowledgements

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APPENDIX A

FAUNAL ASSEMBLAGE	STATIONS															
	54	25	26	29	30	39	42	46	47	50	97	87	100	79	57	80
Ammotium cassis														5		
Bucella frigida							2							1		
Centropyxis arenatus	1	4			4	1			1	1						
Cribrostomoides crassimargo		1										1				
Difflugia urceolata						5										
Eggerella advena												1	2	2		
Elphidium clavatum		1					105	2		3	70	149	175	50	3	6
Elphidium incertum			1			1	15			1	34	9	3	14	2	
Elphidium margaritaceum							1						11			
Elphidium orbiculare				1	3		50	1			81	34	2	2		
Miliammina fusca		33		3		1		4	1	4			5			
Pontigulasia compressa	2	13								1						
Quinqueloculina seminulum																1
Trochammina lobata	1									1				4		
Trochammina ochracea													2	5		
Trochammina squamata														1		
TOTAL	4	52	1	4	7	8	173	7	2	11	185	193	201	84	5	7
JUVENILE							20			2	8	85	47	6	0	4
LIVING							77				45	89	87	33	1	4

APPENDIX B
Faunal Reference List

Ammotium cassis (Parker) = Lituola cassis Parker, 1870, in Dawson, Can. Nat. No. 5, vol. 5, pp. 177, 180, fig. 3.

Bucella frigida (Cushman) = Pulvinulina frigida Cushman, 1922, Cont. Can. Biol., No. 9 (1921), p. 144.

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