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Agglutinated foraminifera and thecamoebians from the Late Carboniferous Sydney coalfield, Nova Scotia: paleoecology, paleoenvironments and paleogeographical implications

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ABSTRACT

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Agglutinated foraminifera and arcellaceans ("thecamoebians") were examined from Carboniferous (late Westphalian–Stephanian) cyclothems in the Sydney Basin of Nova Scotia. Four distinctive assemblages are documented from the coal-bearing strata, and indicate deposition took place on an extensive coastal platform. The eastern part of the basin is dominated by *Ammobaculites–Ammotium* assemblages that indicate estuarine–low marsh paleoenvironments. Relationships between test size, grain size within the test, and grain size of the substrate are used to differentiate between upper mudflat and lower mudflat sub-facies within estuarine facies. Mixed assemblages dominated by *Trochammina*, *Ammotium* and *Ammobaculites* indicate vegetated substrates, analogous to modern lower marsh environments, and flanked the estuarine system in the eastern and western areas of the basin. Rich *Trochammina* and thecamoebian assemblages are restricted to the western area of the basin, indicating deposition within the upper part of the tidal range. *Trochammina* assemblages, typically found underlying coal seams, may indicate vegetated substrates equivalent to modern high marsh facies. Thecamoebian assemblages, dominated by an agglutinated difflugid type, indicate freshwater paleoenvironments. Encystment of the thecamoebian populations suggests paleoenvironments were short lived.

Introduction

Invertebrate fossil groups are widely used as paleoenvironmental indicators, based on the distribution of their modern representatives. However, in the older part of the geological record fossils are less likely found with living representatives. Marginal marine environments of the Carboniferous are particularly difficult to investigate because, with the possible exception of the mudflat-dwelling brachiopod *Lingula* (Craig, 1952), there is little known communality between Carboniferous faunas and those from equivalent modern environments. Invertebrate assemblages from fully marine to terrestrial deposits of the Carboniferous (Calver, 1968) have been interpreted based on their position within sedimentological successions, rather than from actualistic comparisons with modern biotas. Although such faunal successions permit relative salinity estimates, the precise habitats or salinity tolerances of particular fossils within these associations are uncertain (Calver, 1968). Even the terrestrial "end member" species of Carboniferous invertebrate communities cannot be firmly placed within the freshwater (<0.5‰ salinity) realm.

The Late Carboniferous Sydney Mines Formation of Cape Breton, Nova Scotia, which contains eastern Canada's main economic coal seams, had long been attributed to a fluvial depositional setting (e.g. Hacquebard and Donaldson, 1969; Rust et al., 1987). The apparent absence of marine fossils, such as conodonts, goniatites and ammonoids, and abundance of traditionally used

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freshwater indicators including ostracods, bivalves, gastropods and shark teeth, (Masson and Rust, 1984), was used in support of this interpretation. The thin, extensive nature of the coal seams, however, suggested that the depositional setting was likely to have been paralic rather than freshwater (Hacquebard and Donaldson, 1969), and extensive thin limestones and carbonaceous shales resemble the marine bands of the European coalfields (Ramsbottom, 1979; Masson and Rust, 1990). Recent documentation of eleven complete cyclothems within the Sydney Mines Formation (Gibling, 1992; White et al., 1993, this issue) further supports deposition under marine influence.

In this paper, we discuss the distribution of agglutinated foraminiferal and thecamoebian assemblages in the cyclothems of the Sydney Mines Formation. Marsh foraminifera which are most commonly agglutinated forms (i.e. those that use foreign particles to build a test or shell) are distributed in well-established vertical zonations related to tidal amplitude in modern marsh and estuarine settings (Scott and Medioli, 1980; Scott et al., 1991). Such assemblages have proven to be powerful tools in the investigation of marginal marine paleoenvironments and Quaternary sea-level changes (Scott and Medioli, 1978, 1986), and their applicability to the ancient record has been well established for Cretaceous strata (Wall, 1976; Wightman, 1990a,b). Thecamoebians are a dominantly freshwater group today, and are potentially important paleoecological indicators because of their ability to encyst and survive adverse environmental conditions, including desiccation, salinity changes, nutrient depletion or reduced pH (Medioli et al., 1990a,b). Reports of fossilized thecamoebians, however, are scarce [except for some Cretaceous forms documented by Medioli et al. (1990a,b)] and focus mainly on the Holocene record. In association with the initial work that documented the cyclothemic stratal patterns in the Sydney Mines Formation (Bird, 1987), Thibaudeau and Medioli (1986) provisionally identified thecamoebians and several agglutinated foraminiferal species. Subsequent detailed study (Wightman et al., 1992a,b) confirms that these groups are present and are associated with all the major coal seams.

The foraminiferal *assemblages* we describe here were first documented by Wightman et al. (in press). Prior to Wightman et al. (in press), marsh foraminiferal assemblages have not previously been reported from strata older than Early Cretaceous (Wightman, 1990a,b), although certain genera are known from the early Palaeozoic. As stated above, the literature on fossil thecamoebians is minimal, and the oldest records are from Cretaceous and younger deposits (Medioli et al., 1990a,b). The paucity of information concerning thecamoebians and "marsh" foraminiferal assemblages from pre-Cretaceous strata may be partly due to limited interest in these groups. The increase in knowledge of these protozoans enables determination of Carboniferous paleoecology and paleoenvironments with unusual confidence through direct comparison with the present-day ecological distribution of these groups, since the species appear to have changed little since the Carboniferous.

Because most of our Carboniferous material has never before been illustrated, we are unable at this stage to make taxonomic assignments at the species level, and use open nomenclature in this paper. We are currently working on the formal taxonomy of our material, and will document this at a later date.

Regional setting

The Sydney Basin of Cape Breton Island, Nova Scotia (Fig. 1), represents the onshore part of a basin that extends eastwards for at least 450 km beneath the Laurentian Channel and Grand Banks of Newfoundland. Development of the epicontinental basin after the mid-Devonian Acadian Orogeny was accompanied by periods of subsidence that were likely thermally induced (Bradley, 1982). Subsidence continued through to the latest Carboniferous or Early Permian. A full account of the tectonic setting of the Sydney Basin is given by Gibling et al. (1987).

The Sydney Mines Formation is well exposed along the northeast coast of Cape Breton Island (Fig. 1), and represents the upper 500 m of the

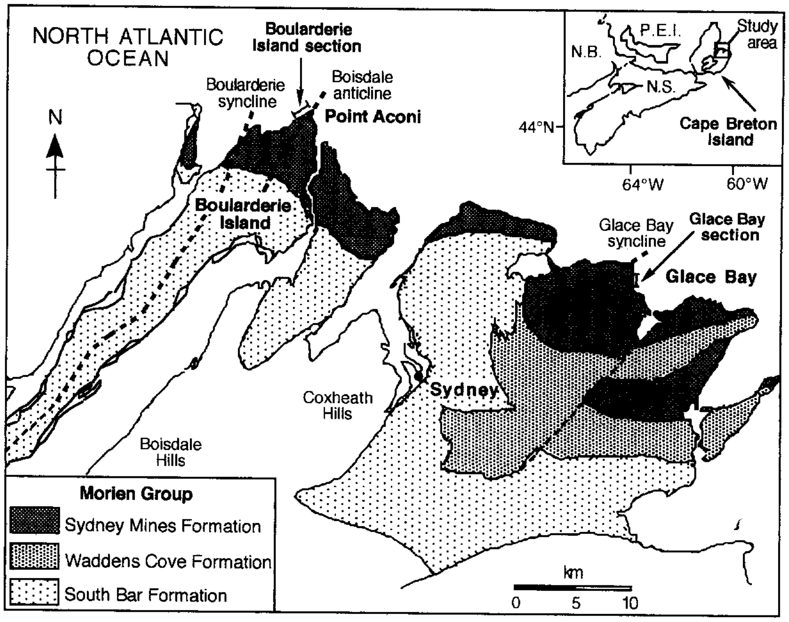


Fig. 1. Location map of the Sydney Basin, N.S., showing the onshore distribution of the formations of the Morien Group, and sections studied.

Westphalian B to Stephanian coal-bearing Morien Group (Fig. 2). The lower part of the Morien Group, comprising the South Bar and Waddens Cove formations, contains mainly uneconomic coal seams. Sedimentologically, the Sydney Mines Formation is composed of sandstone and gray and red mudstone with limestones and economic coals (Rust et al., 1987). The major coal seams are up to 4.3 m thick and extend for at least 45 km across the onshore part of the basin. Intercalation of red mudstones with gray, coal-bearing strata forms the basis for the recognition of eleven cyclothems, about 40 m in average thickness. A detailed description and interpretation of the cyclothems is given elsewhere (Bird, 1987).

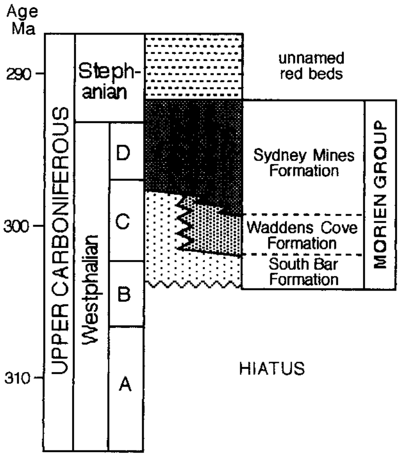


Fig. 2. Stratigraphic framework of the Morien Group.

Study areas and sampling localities

Two areas were studied to obtain full stratigraphic coverage of the Sydney Mines Formation in outcrop. In the Glace Bay area (Fig. 3), a section on the northern limb of the Glace Bay syncline extends eastwards from Dominion Beach to Timmins Point and covers the stratigraphic interval from the Emery to Bouthillier coal seams (Fig. 4). On the southern limb of the syncline, the section extends from the wildfowl sanctuary to the base of the Marconi Historic monument and covers the interval from the Bouthillier to Hub coal seams (Fig. 4). In the Boularderie Island area (Fig. 5), the section commences south of Black Rock Point and extends to Point Aconi, covering the stratigraphic interval between the Stony and Point Aconi coal seams (Fig. 4). Low tide is essential for complete access to the sections.

A total of 103 samples was collected from the

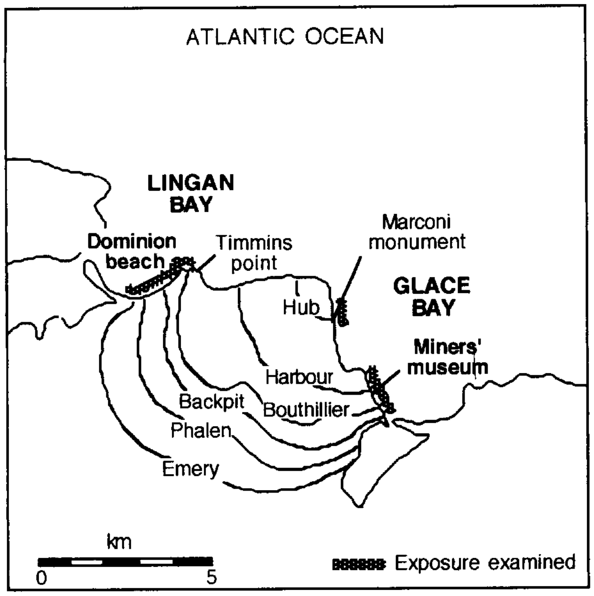


Fig. 3. Location map of the sections examined in the Glace Bay area, showing positions of the major coal seams.

sections. Only the finer-grained (siltstone and finer) strata were sampled as experience has shown us that coarser-grained strata are usually barren of foraminifera. Beds were excavated a few centimeters to ensure that the samples were fresh and free from slumped contamination. Sample distribution is shown in Fig. 4.

Sample processing and observation methods

Various techniques were used to extract the microfossils. Methods used depended on the lithology, and in some cases several methods were used on a given sample and the results compared. Samples were, whenever possible, mechanically broken into smaller (< 1 cm diameter) pieces and sieved free of rock flour before treatment. The time required to process the samples depended on their composition, and ranged from two days for soft claystones to several weeks for indurated siltstones. Only soft samples disaggregated completely, and in some cases only a few grams of residue were obtained after several weeks of repeated processing. Full details of processing methods used are given in Brazier (1979) and Thomas and Murney (1981). Best results were obtained for mudstones and clay-rich siltstones using industrial detergent (such as the Fisher brand "Versaclean"). Clay-poor siltstones responded well to repeated treatment in a saturated sodium sulphite solution which was allowed to crystallize. Calcareous rocks were treated with 10% formic acid; acetic acid also works well and is considerably cheaper but much slower. Organic-rich shales were treated with sodium hypochlorite (bleach) with good results. The use of solvents to process organic-rich shales, however, was not successful.

Following breakdown, the samples were washed through a 45 μm stainless steel sieve and the residues oven dried. Dry residues were sieved into >1 mm, >500 μm, >250 μm, >125 μm, >63 μm and >45 μm size fractions, examined and picked for microfossils using a binocular microscope. Because of the difficulty in obtaining a consistent volume of residue from the various lithologies, most samples had to be examined from a qualitative perspective, although in some instances several hundred specimens were picked.

The majority of specimens had low surface relief due to compaction of the enclosing sediment, and were difficult to recognize. Foraminiferal sutures were typically indistinct, and in many cases their presence had to be assumed from the position and shape of the chambers. A low angle of incidence of the light source, however, assisted in the identification of many test features. Immersion of specimens in glycerin on a glass slide and observation with transmitted light enabled recognition of chambers and, in some cases, apertures. The scanning electron microscope was routinely used as an observational tool in the search for apertural and other details, as well as for specimen photography. Specimens illustrated in transmitted light (in glycerin) were photographed using the Tessovar system.

Results

Overview of foraminiferal and thecamoebian assemblages

Three main agglutinated foraminiferal assemblages (Plate I) are recognized on the basis of the dominant foraminiferal genera: (1)

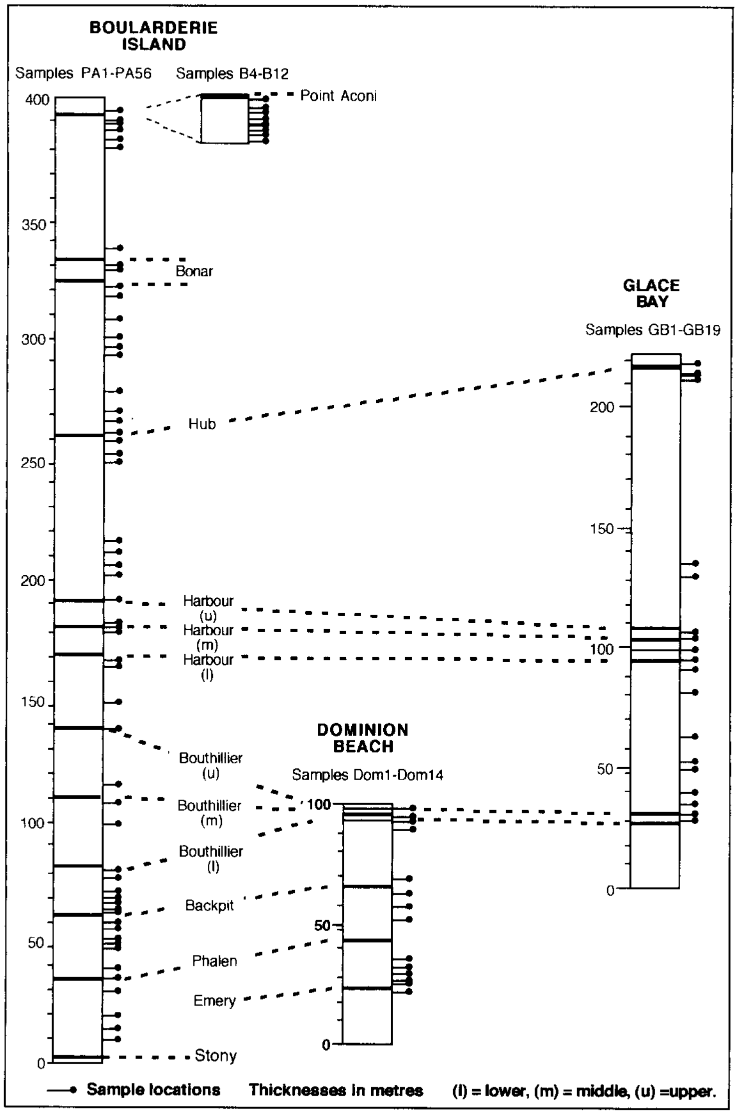


Fig. 4. Stratigraphic intervals examined in each section (schematic), with sample locations.

Ammobaculites–Ammotium, (2) mixed *Trochammina–Ammobaculites–Ammotium* and (3) *Trochammina*-dominated assemblages. In addition to the dominant genera, other forms recognized include *Reophax*, *Miliammina*, *Haplophragmoides*, *Ammomarginulina* and *Spiroplectammina*. The latter genera, where found, are associated with *Ammobaculites–Ammotium* and mixed assemblages. Rare specimens of uncertain affinity have also been observed, including two tubular morphogroups possibly related to *Hyperammina* or *Dendrophrya*, and a calcareous form that has similarities with *Lenticulina*.

A number of morphologically distinct forms have been recognized within the main generic groups, and may represent either several different species, or ecophenotypic variants of one species. The morphotypes will be the focus of detailed taxonomic study at a later date.

In addition to the foraminifera, a thecamoebian assemblage is recognized. It is dominated by xenogenous (agglutinated) forms similar in appearance

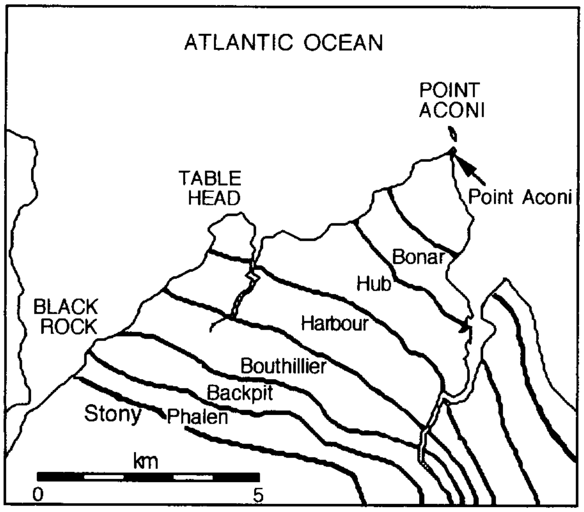


Fig. 5. Location map of the section examined on Boularderie Island, showing positions of the major coal seams.

to modern *Difflugia*. Other forms present are morphologically similar to modern *Nebela* and *Centropyxis*. The thecamoebian assemblage rarely contains foraminifera, although thecamoebians are locally found in the *Trochammina* assemblage.

Composition and stratigraphic distribution of the assemblages

The Ammobaculites–Ammotium *assemblage*

This assemblage typically occurs in siltstone facies, although it has also been recognized in an organic-rich shale within a coal seam split. Specimen size and grain size of the wall appear related to sediment size, with the largest specimens (<2 mm length) being found in the coarsest facies, and the smallest (0.06 mm) individuals occurring in organic-rich shales. Most material is poorly preserved, although fine details of the aperture, coil and chambers have been seen in a number of specimens. Degree of preservation does not appear related to facies or specimen size.

Morphological variants of *Ammobaculites* and *Ammotium* are observed in our material. This assemblage also contains *Trochammina*, *Reophax*, *Haplophragmoides*, *Spiroplectammina*, *Ammomarginulina* and *Miliammina*.

Poorly preserved, elongate forms present in this assemblage could be fragments of the straight portion of any of the uncoiled genera noted above.

PLATE I

Scale bar 100 μm; Specimens photographed under SEM unless otherwise indicated.

1, 2, 5. *Trochammina* sp. 1. 1, ventral view showing finely agglutinated test wall and a large final chamber. 2, dorsal view of 1, showing part of the trochispire. 5, ventral view of 1, in glycerin with transmitted light. Dark area represents the chambers of the previous whorl (arrowed). From the *Trochammina* assemblage in the seat earth underlying the Point Aconi coal seam.

3. *Trochammina* sp. 2, ventral view, finely agglutinated (fine silt) specimen showing lobate periphery and open umbilicus (arrowed).

4. *Trochammina inflata*, ventral view of recent specimen from a saline marsh, Mississippi Delta. Compare test outline with 3.

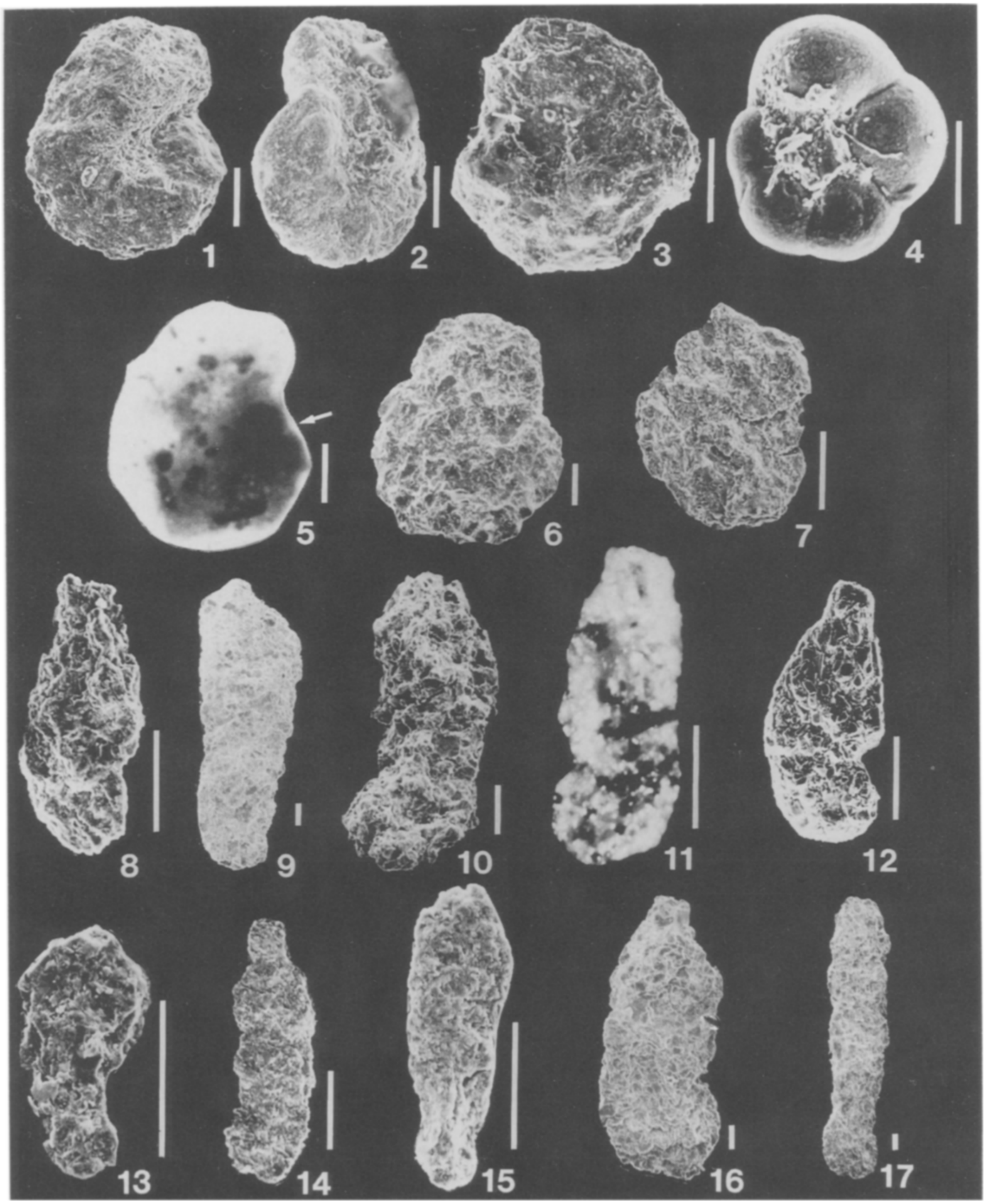
6, 7. *Trochammina* sp. 3, specimens agglutinated from medium grained silt. 6, dorsal view showing feint trace of trochispire. 7, ventral view. From the mixed assemblage overlying the Harbour coal seam, Boularderie Island.

8–10. *Ammotium* spp. Specimens from *Ammobaculites/Ammotium* assemblage. 8, agglutinated from medium-fine silt, showing coil with slightly depressed umbilicus. From split of upper Harbour seam and rider, Glace Bay. Compare with 12. 9, coarsely agglutinated (fine sand) specimen with small coil. From 27 m above Harbour seam, Glace Bay. 10, specimen agglutinated from medium–coarse silt, showing large coil. From midway between Bouthillier and Harbour seams, Glace Bay. Compare with 11.

11,12. *Ammotium salsum*. 11, Recent specimen from Chezetcook Inlet, N.S., photographed under Dynophot scanning light microscope, showing large coil and "salt and pepper" texture of felsic and mafic minerals incorporated into the test. 12, Recent specimen from saline marsh in the Mississippi Delta. Compare with 8.

13–17. *Ammobaculites* spp. Specimens from *Ammobaculites/Ammotium* assemblage. 13, agglutinated from medium-fine silt, showing small coil, broadly flaring test and thickened rim around the aperture. From split of upper Harbour seam and rider, Glace Bay. 14, agglutinated from medium-fine silt, showing well-preserved detail of the coil, chambers in the uncoiled portion, and an extended apertural neck. From split of upper Harbour seam and rider, Glace Bay. 15, agglutinated from medium-fine silt, showing well-preserved coil. From split of upper Harbour seam and rider, Glace Bay. 16, agglutinated from fine sand, showing good test outline, but indistinct sutures. The aperture has an extended neck. From 27 m above Harbour seam, Glace Bay. 17, agglutinated from fine sand, showing good test outline and well-preserved coil. A slender form with five chambers in the uncoiled portion. Note the slight constrictions between the chambers. From 27 m above Harbour seam, Glace Bay.

PLATE I



Two types of agglutinated "tubes" have also been identified in this assemblage from fine-grained shaley facies, and x-ray analysis has shown one type to be composed of lead sulphide (possibly galena) and the other of calcium carbonate. The affinities of the tubes are not known, although they resemble the tubular foraminifera *Hyperammina* or *Dendrophrya*.

Examples of the *Ammobaculites–Ammotium* assemblage composed of coarsely agglutinated, large specimens were found 2 m below the Emery seam and midway between the Phalen and Backpit seams in the Dominion Beach section. Coarse, large specimens also occur in this assemblage approximately 80 cm above the lower Bouthillier seam, midway between the upper Bouthillier and lower Harbour seams, and midway between the upper Harbour and Hub seams in southern limb of the Glace Bay syncline. In the same area, an organic-rich shale in a split between the uppermost Harbour seam and a rider seam 3.5 m above contains a rich example of the *Ammobaculites–Ammotium* assemblage with well-preserved, finely agglutinated, small (0.06–0.6 mm) specimens. Several distinct morphogroups of *Ammotium* and *Ammobaculites* occur in this assemblage, and an unusual feature of many *Ammobaculites* specimens is the presence of an elongate apertural neck. One form of *Ammotium* closely resembles the modern species *A. salsum* and also the Cretaceous forms illustrated by Wall (1986) and Scott et al. (1983).

The mixed assemblage (Trochammina–Ammobaculites–Ammotium)

A mixed *Trochammina–Ammobaculites–Ammotium*-dominated assemblage is associated with medium- to fine-grained siltstone and clayey siltstone facies. Degree of preservation is moderate and specimens are usually compressed, with limited relief but good outlines. Surficial features can usually be seen with a very low angle of incidence from the light source, but fine details (aperture and sutures) are rarely seen. Specimens are typically less than 1 mm in size. *Trochammina* is generally dominant, comprising as much as 75% of the specimens in these assemblages. Uncoiled forms assigned to *Ammotium* and *Ammobaculites* are common. Poorly preserved material that has been identified primarily on the basis of shape are placed within this assemblage, although such material may include other coiled genera, for example *Haplophragmoides*, and uncoiled genera such as *Ammomarginulina*, *Reophax*, or *Spiroplectammina*.

The mixed assemblage is common in strata from both the eastern (Glace Bay area) and western (Boularderie Island) areas of the Sydney Basin. In the Dominion Beach section the assemblage is found in samples 2 m below and 5 m above the Backpit seam. On the southern limb of the Glace Bay syncline, this assemblage also occurs within splits of the Bouthillier seam, and in samples from 1 m above and below the Hub seam. In the Boularderie Island section, the mixed assemblage is found in strata immediately overlying the Backpit and upper Bouthillier seams. In strata within a seam split of the middle Harbour seam, the assemblage is associated with strata containing numerous in-situ upright tree trunks. Samples taken from beds adjacent to the Bonar seam and above the Point Aconi seam also contain this assemblage.

The Trochammina *assemblage*

The *Trochammina*-dominated assemblage is found in fine-grained siltstone and silty claystone facies. This assemblage typically consists of 90–100% *Trochammina*, with uncoiled morphogroups and, locally, thecamoebians making up the remainder of the fauna. Specimens are generally finely agglutinated from translucent siliceous material, and have low relief, probably due to compression. Examination of these assemblages is often easier under lower magnification whereby a low angled incidence of light creates shadows that emphasize depressions between adjacent chambers. Well-preserved examples immersed in glycerin and examined with transmitted light display the trochispiral coil and chamber outlines. Under high magnification (80 ×), careful manipulation of the glycerin surface allows light to be refracted in such a way that different portions of the test can be examined in detail, and in this manner, fine sutures have been observed. Individuals are usually less than 0.4 mm in diameter, and closely resemble the

Cretaceous forms illustrated by Wightman (1990a,b).

We have encountered this assemblage in both the Glace Bay and Boularderie Island sections, although it is more common in the latter area. In Glace Bay, the *Trochammina* assemblage is found immediately beneath the Emery seam, and in the seam split within the Harbour seam, 1 m below the *Ammobaculites–Ammotium* assemblage reported above. In the Boularderie Island section, a specimen-rich example occurs in the underclay ("seat earth") beneath the Point Aconi and Hub seams. Other examples of the assemblage are found in beds immediately underlying the Bonar, middle and lower Bouthillier seams, and immediately above the Backpit, upper Bouthillier and upper Harbour seams.

The thecamoebian assemblage

The thecamoebian assemblage (Plate II) is found in very fine siltstones and silty claystones, particularly in the Boularderie Island section. Specimens are exceptionally well preserved and, with the exception of a few *Trochammina* specimens, the assemblage is composed entirely of thecamoebians.

The typical specimen is spherical, 0.06–0.6 mm in diameter and green-grey or red (iron-stained) in colour. Specimens are easily misinterpreted as sideritic nodules, however, numerous specimens have been examined in thin sections, and all show the presence of an outer xenogenous (agglutinated) wall, and an internal cyst structure. The cyst wall is roughly twice the thickness of the test wall, and is also agglutinated. Many sections show an irregular mass of sulphide at the cyst centre, which likely represents the fossilized remnants of the original cell cytoplasm. A few specimens have been found with the exterior wall partially broken away, revealing the internal cyst and surrounding void. The apertures in all specimens are sealed by diaphragms, as is typical of encysted thecamoebians today. The inner margins of the apertures are frequently lobate, and many specimens show thin remnants of apertural rims. The spherical form appears similar to the modern genus *Difflugia*, and several variants are recognized, based on the type of aperture and associated structures. Another less common type bears one or two spines, similar to the modern form *Centropyxis*. A third, rarer, morphotype has a flattened flask-shaped test that is compressed and draped over an internal cyst. The cyst has remained inflated, probably because the cyst was full of cytoplasm, whereas the test was empty at the time of burial. The outer wall appears to be xenogenous, although it is constructed of finer particles than the spherical, *Difflugia*-like forms. The aperture, also sealed by a diaphragm, appears as a loop at the narrow end of the test. Morphologically, this form is similar to the modern genus *Nebela*.

The thecamoebian assemblage is common in strata in the Boularderie Island section, particularly in samples taken from the lower part of the section up to about 10 m below the Backpit seam. Specimen-rich examples are found in strata containing upright tree trunks 10 m above the Hub seam, and in the "seat earth" immediately beneath the Point Aconi seam. In the latter case, detailed sampling shows that thecamoebian and *Trochammina* assemblages alternate on a decimeter scale. In the Glace Bay area, sparse thecamoebians are found 5 m above the Emery seam and 2 m above the Bouthillier seam in the Dominion Beach section.

Discussion

Paleoecology and paleoenvironments of agglutinated foraminifera and thecamoebian assemblages

Considerable information exists on the distribution of agglutinated foraminifera within modern marginal marine environments, against which we can compare the assemblages found in the Sydney Basin. Shallow-water agglutinated foraminifera have been reported from marshes, tidal channels and interdistributary bays in Canada (e.g. Scott and Medioli, 1980; Scott et al., 1981; Scott and Martini, 1982), the Gulf Coast (Phleger, 1966; Haman, 1983; Scott et al., 1991) and South America (Scott et al., 1990) at latitudes of up to 54°. Foraminiferal species in such marginal marine environments lie within narrow vertical zones related to tidal range (Table 1), allowing clear faunal divisions to be made between the assem-

PLATE II

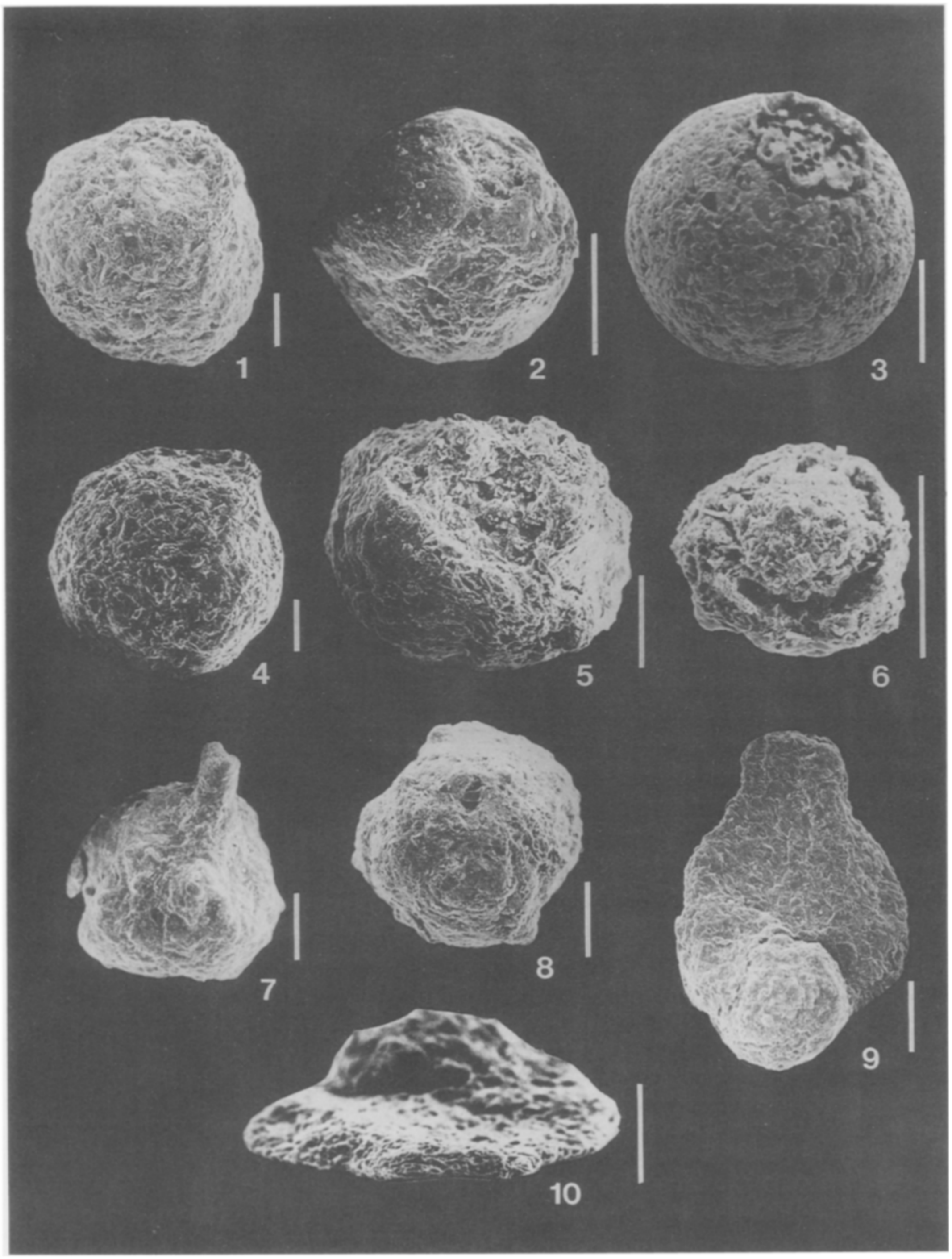


TABLE 1

Agglutinated foraminifera and thecamoebians characteristic of modern estuaries, salt and freshwater marshes[1]

	Environment			
	Estuary	Lower salt marsh	Upper salt marsh	Freshwater marsh
Tidal range:	Sub/inter tidal	0–70 cm above MSL	70–110 cm above MSL	N/A
Salinity (‰):	1–35	15–32	1–25	0
Fauna:	Agglutinated foraminifera	Agglutinated foraminifera	Agglutinated foraminifera	Thecamoebians
	Miliammina fusca	*Ammotium salsum*	*Trochammina inflata*	*C. constricta*
	Ammotium salsum	*Miliammina fusca*	*T. macrescens*	*Nebela collaris*
	Ammobaculites spp.	*Ammobaculites* spp.	*Tiphotrocha comprimata*	*Centropyxix aculeata*
	Eggerella advena		*Haplophragmoides* spp.	*Difflugia* spp.[2]
	Reophax spp.			

[1] The faunal successions represent species typical of most latitudes, although additional species may be present at some latitudes. Estuaries and marshes vary considerably depending on tidal range, freshwater discharge, seasonality, geology and physiography, and the tidal range and salinity data presented here are generalizations only.

[2] Also endemic to floating marsh environment.

blages found in freshwater and brackish marshes, upper and lower saline marshes, estuaries and open-marine settings (Scott and Medioli, 1978, 1980, 1986; Scott et al., 1990, 1991).

Estuarine and salt marsh environments vary considerably, depending on tidal range, freshwater discharge, seasonality, physiography, and the resultant mixing of freshwater and sea water. Consequently the tidal range and salinity data presented in Table 1 represent generalizations only. Our concept of an estuary, for the purpose of paleoenvironmental considerations, is a semi-enclosed coastal body of water significantly diluted by freshwater runoff and where tidal effects are evident. This broad definition includes river mouths, bays and inlets ("lower estuarine"), and the terrestrial extremities of marine (tidal) influences which may extend inland 100 km or more ("upper estuarine"). Salt marshes represent the most terrestrial extreme of the marine environ-

PLATE II

Scale bar 100 μm. Specimens photographed under SEM. Specimens (except 3) from the thecamoebian assemblage in the seat earth underlying the Point Aconi seam.

1, 4. Thecamoebian, spherical form, with large aperture (top right quarter) drawn out slightly beyond the confines of the sphere. Note agglutinated difflugid wall structure.

2, 5. Thecamoebian, spherical form, with large aperture (top right quarter 2, centre 5) within the confines of the sphere. Note the lobate inner margins of the apertures (compare with 3). The diaphragm sealing the aperture in 5 is perforated at the centre. Note agglutinated difflugid wall structure.

3. *Cucurbitella tricuspis* Carter, clonal culture of a living difflugid grown at Dalhousie University, showing spherical test and large aperture (top right quarter). Note the lobate apertural margin and surrounding rim (compare with 2 and 5).

6. Thecamoebian, spherical form with outer wall broken away to reveal central cyst and surrounding void.

7. Thecamoebian, spherical form with a spine. Specimen mounted with aperture down in order to examine spine. Comparable to modern *Centropyxis*.

8. Thecamoebian, spherical form with small aperture (just above centre).

9, 10. Thecamoebian, flask-shaped form. 9, side view showing outer test wall draped over inner cyst located at the base of the test. Fractures, outlining the shape of the cyst, indicate compaction of the outer wall around the robust cyst. The aperture is located terminally at the narrow (top) end of the test. 10, apertural view of same specimen, showing the constricted apertural end of the test in the closest field of view. The aperture appears as a "u"-shaped loop in the left half of the close field of view. Comparable to modern *Nebela*.

ment, and, with few exceptions, for example, the Bay of Fundy in Atlantic Canada, occupy the narrow zone between higher high water (HHW) and mean sea level (MSL) (Wells and Hirvonen, 1988). Although within marshes the salinity, floral diversity, channel morphology and marsh gradient vary considerably, related to tidal range, geographic setting and geology, almost all marshes may be divided into lower, middle and upper sections on the basis of the plant successions (Wells and Hirvonen, 1988). The faunal successions in Table 1 are well established, and represent forms that are typical of most latitudes, although additional agglutinated forms may be present at some latitudes (Scott et al., 1990). In addition to agglutinated foraminifera, a number of calcareous species also characterize estuaries and marshes, although these generally undergo post mortem dissolution and are not relevant to this paper. Species diversity generally declines from estuarine, through lower, to upper marsh environments where one or two species of *Trochammina* may dominate in high abundances (Scott et al., 1990). Freshwater marshes, within the context of a coastal setting, include fluvial marshes developed in oxbow lakes, subject to seasonal flooding, deposition of silt and local desiccation, and floating marshes developed in lower delta areas such as those in the lower Mississippi Delta.

The association of *Ammobaculites* with *Ammotium* in siltstone facies in the Glace Bay area suggests an estuarine paleoenvironment, based on present-day distribution of these foraminiferal groups. Species of *Ammobaculites* are well documented as infaunal inhabitants of modern estuaries (Ellison, 1972), often living at depths of 10–15 cm below the sediment surface and probably tolerant of reduced oxygen levels (Buzas, 1974). *Ammotium* is also typical of modern nearshore (estuarine-marsh) environments. *Ammotium salsum* is restricted to upper estuarine environments, where it is associated with species of *Ammobaculites*, and salt marsh environments, where it co-dominates with *Miliammina fusca* and other agglutinants (Scott et al., 1983, 1990). *Trochammina* is a minor component in our *Ammobaculites–Ammotium* assemblage, suggesting an upper estuarine, rather than salt marsh, paleoenvironment.

Poag (1978) recognized two distinct ecophenotypes of *Ammotium salsum*, living in Gulf Coast estuaries, that have distributions directly correlated with temperature and substrate. One ecophenotype has a smaller test, smaller chambers and a finer-grained wall, whereas the other has a larger test, larger chambers and a coarser-grained wall. The smaller type is correlated with lower salinities and finer substrates, and the larger type with higher salinities and coarser substrates. Poag (1978) suggested that the smaller ecophenotype is characteristic of near optimum environments for the species, whereas the larger form is typical of marginally tolerable environments. Relating Poag's (1978) findings to the Sydney Basin *Ammobaculites–Ammotium* assemblage, the coarser-grained, larger specimens such as those recovered from between the Harbour and Hub seams probably inhabited lower mudflats and estuaries, whereas the fine-grained, smaller specimens from the Harbour seam split probably lived in upper mudflats. Wightman (1990a,b) described *Ammobaculites* assemblages from the Lower Cretaceous of Portugal, and reached similar conclusions. The assemblage from the Harbour seam split probably reflects development of optimum environmental conditions for the associated species as the observed fauna was abundant, well preserved, small and finely agglutinated. Uncoiled lituolid foraminifera generally live infaunally and feed on detritus (Jones and Charnock, 1985), a life position and feeding strategy that suggests high ambient suspended particulate matter concentrations associated with ponding of ebb and flood tides in estuarine and estuarine transition zones.

A mixed assemblage of agglutinated foraminifera with co-dominance of *Trochammina*, *Miliammina*, *Ammotium* and *Ammobaculites* is typical of modern lower marsh environments (Scott et al., 1983, 1991). Faunal composition in lower marshes may be influenced by local conditions, for example, laterally adjacent estuarine facies, which can result in mixing of faunas (Scott et al., 1991). Specimens from the Sydney Basin mixed assemblage generally have medium-grained walls, and grain size within each population tends to be unimodal, suggesting that reworking or mixing was minimal. Those assemblages richer in

Trochammina may have been subject to slight reworking. The association of a mixed assemblage with vertical tree trunks in a split of the Harbour seam in Boularderie Island indicates inundation of a former terrestrial environment, and subsequent marsh development.

Modern brackish high marsh environments are generally dominated by one or two species of *Trochammina*, and are distinguished from higher-salinity lower marshes by the absence of *Ammotium salsum* and other agglutinants (Scott et al., 1991). Low numbers of thecamoebians, a freshwater group, may also occur in brackish marshes depending on how far landward the marsh lies within the brackish system (Scott et al., 1991). The *Trochammina*-dominated assemblage of the Sydney Basin probably represents a high marsh setting. Thecamoebians occur in low numbers in some of our samples, indicating proximity to a freshwater system. The fine-grained tests, small size and abundance of *Trochammina* in our assemblages suggests optimum environmental conditions for the group.

Living trochamminids are epifaunal and herbivorous, and live attached to aquatic plants (Jones and Charnock, 1985). We have not established relationships between the Sydney Basin *Trochammina* faunas and the floral assemblages, although we are confident that an aquatic flora inhabited low-salinity environments equivalent in many aspects to modern mangrove marshes. The association of *Trochammina* assemblages with strata immediately below or above several of the coal seams suggests that the peats formed immediately adjacent to marine-influenced marshes.

Thecamoebians, as already stated, are a predominantly freshwater group today, inhabiting virtually all terrestrial freshwater niches (Medioli and Scott, 1983). A few exceptions to this are reported by Bartlett (1966) who recognized four species living in the upper estuarine zone of the Miramichi River, New Brunswick, where salinities were as high as 20‰. Within the freshwater areas of coastal wetlands, dense thecamoebian populations occur in both freshwater and floating marshes (Scott et al., 1991). The presence of a rich thecamoebian assemblage a few centimeters above a *Trochammina* assemblage in the "seat earth" immediately below the Point Aconi coal seam in Boularderie Island suggests that the two groups occupied adjacent environments in the Carboniferous as they do today: high marsh (*Trochammina* assemblage) and freshwater (thecamoebian assemblage).

Substrate composition is recognized as a significant environmental limitation on thecamoebian populations (Scott et al., 1991). The agglutinated thecamoebians, which include the difflugids, require mineral grains for test construction and are associated with mineralic substrates. This relationship is clear in the Sydney Basin difflugid assemblage which is found in fine silty facies. Organic substrates with low mineralic content support thecamoebian populations with little or no agglutinated components in their tests, for example, *Nebela*. Scott et al. (1991) also recognized that two thecamoebian populations, one agglutinated and the other with a secreted organic wall, may co-exist where a floating marsh (organic substrate) is underlain by a mineralic substrate; limited exchange between the peat and the lake bottom allows the faunal differences between the two environments to be preserved. Although we have not yet found significant populations of organic-walled thecamoebians in our material, such assemblages could help establish whether floating marshes, or equivalent environments, existed during the Carboniferous.

During adverse environmental changes, such as desiccation or changes in salinity, thecamoebian populations generally encyst, and remain dormant until conditions return to "normal" (Medioli and Scott, 1983). Consequently, thecamoebians may live and reproduce rapidly in ephemeral aquatic environments. The encysted nature of thecamoebian assemblages in the Sydney Basin indicates that the local environments were rapidly changing. The assemblage in the "seat earth" below the Point Aconi seam, and the presence of the *Trochammina* assemblage a few centimeters below, suggests that salinity decreased from brackish to freshwater, allowing thecamoebians to become established. A rapid return to brackish conditions within the lifespan of the initial colony of thecamoebians is indicated by the encystment of the entire population.

Paleogeographic implications

Observed distributions of agglutinated foraminifera and thecamoebians in the Sydney Basin indicate that deposition took place on an extensive coastal platform. The Glace Bay area was more proximal to open-marine conditions, and the Boularderie Island area was transitional to terrestrial environments as suggested by the distribution of the four assemblages.

The *Ammotium–Ammobaculites* assemblage predominates in the Glace Bay area (Fig. 6), and indicates that estuarine conditions prevailed in the eastern part of the basin. The mixed (*Trochammina–Ammobaculites–Ammotium*) assemblage which is also found in the Glace Bay area signifies that vegetated substrates, analogous to modern salt marshes, flanked the estuaries, perhaps some distance upstream. The general paucity of thecamoebians in this area suggests that there were few freshwater habitats, although there were perhaps periods of increased freshwater input that resulted in transportation of thecamoebian tests from farther upstream.

The Boularderie Island area contrasts with the eastern part of the basin by the absence of estuarine and the dominance of freshwater and high "marsh" faunas (Fig. 6). The western part of the basin was distal to marine influences and affected by the upper part of the tidal range. Vegetated substrates equivalent to marshes flanked the river systems, and were colonized either by thecamoebians, *Trochammina* or mixed assemblages, depending on local tidal range. Environmental changes were likely to have been particularly rapid in the transition zone between freshwater and brackish environments, depending on many factors that we may never be able to quantify, including slope of the coastal platform, tidal range, climate and local tectonic effects.

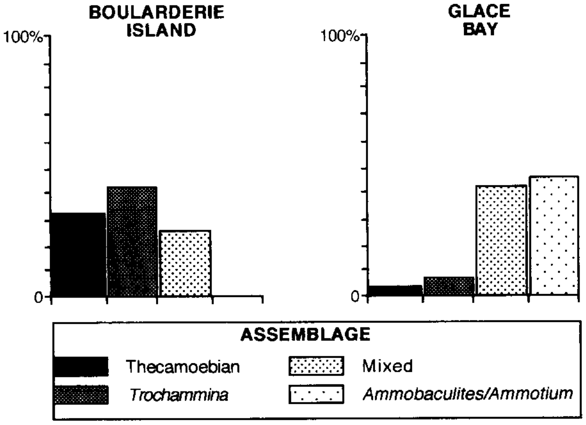


Fig. 6. Histograms showing percentage of samples falling into each assemblage at Glace Bay and Boularderie Island.

Conclusions

The distribution of agglutinated foraminiferal and thecamoebian assemblages is documented for the first time in strata of Westphalian D to Stephanian age in the Sydney Basin of Nova Scotia. A thecamoebian assemblage and three foraminiferal assemblages (*Ammobaculites–Ammotium*, mixed and *Trochammina* dominated) are identified in strata associated with all the economic coal seams, indicating varying levels of marine influence during deposition.

An *Ammobaculites–Ammotium* assemblage is found in the Glace Bay area in the eastern part of the basin, and indicates estuarine deposition. Relationships between test size, size of grain used in the test wall, and substrate suggest that assemblages of small, finely agglutinated individuals characterize lower-salinity, upper estuarine subfacies whereas large, coarsely agglutinated assemblages signify higher-salinity, lower estuarine environments.

A mixed assemblage dominated by *Trochammina*, *Ammobaculites* and *Ammotium* occurs in the eastern and western parts of the basin, and probably represent vegetated substrates, analogous to present-day lower marshes, that formed in still waters, flanking, and affected by, tidal estuaries.

Thecamoebian and *Trochammina* assemblages predominate in the western part of the basin, and indicate freshwater conditions and environments equivalent to modern high marshes. Occurrence of the *Trochammina*, followed by the thecamoebian, assemblage in two successive samples from a seat earth indicates a change from brackish to freshwater environments. Encystment of the thecamoebians indicates a rapid decline in the quality of their environment.

The assemblages are remarkably similar to those occurring in modern coastal wetlands. The lateral succession of assemblages from estuarine through lower to upper marsh and freshwater environments today apparently mirrors the succession of Carboniferous assemblages and suggests that marginal marine agglutinated foraminiferal faunas have evolved little, if at all, during the past 300 m.y. Although the flora that existed in Carboniferous marginal marine environments differs substantially from that of today's marsh zones, the relationships between foraminiferal test morphology, life habitat and feeding strategy appear to have changed little.

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