Article

"Foraminiferal Distribution in the Central and Western Parts of the Late Pleistocene Champlain Sea Basin, Eastern Canada"

Jean-Pierre Guilbault
Géographie physique et Quaternaire, vol. 43, n° 1, 1989, p. 3-26.

FORAMINIFERAL DISTRIBUTION IN THE CENTRAL AND WESTERN PARTS OF THE LATE PLEISTOCENE CHAMPLAIN SEA BASIN, EASTERN CANADA

Jean-Pierre GUILBAULT, Département de géologie, Université de Montréal, C.P. 6128, Succursale «A», Montréal, Québec H3C 3J7.

ABSTRACT Marine sediments from the late-glacial Champlain Sea have been sampled at 20 localities representing the deeper part of the basin, between Ottawa and the Rivière St-François, Québec. Foraminiferal assemblages have been extracted and a sequence of three deep water and two shallow water ecozones recognized. The lowermost zone (A) is characterized by *Cassidulina reniforme*, *Islandiella helenae* and *I. norcrossi* and represents a paleosalinity of 25 to 30‰. The overlying zone B is dominated by *Elphidium excavatum*. It represents salinities decreasing from 25 to as low as 10‰. The uppermost zone (C) contains only a sparse assemblage of a morphotype of *E. excavatum*. It suggests a paleosalinity of no more than 10‰. A mostly unfossiliferous silt and clay layer of variable thickness (post-C) occurs above zone C. It is probably lacustrine. Below zone A and above the Late Wisconsinan till there is a pre-A interval whose variable assemblages represent hyposaline environments east of Montréal, predominantly lacustrine conditions west of Montréal and alternating hyposaline/lacustrine environments near and south of Montréal. Bottom water temperatures were probably "Arctic" (within a few degrees of 0°) from the pre-A interval up to zone B inclusively. The data from zone C are too poor to estimate temperatures. The shallow water zones indicate environments with high (zone EH) or low (zone EA) salinities but of shallower depths than the deep water zones. The existence of two sequences is interpreted as the result of (probably seasonal) water stratification. The data does not allow to determine the depth of the limit between the shallow and deep waters.

RÉSUMÉ *La distribution des foraminifères dans les parties centrale et occidentale du bassin du Pléistocène supérieur de la Mer de Champlain, est du Canada.* Des dépôts marins tardiglaciaires de la Mer de Champlain ont été échantillonnés à 20 sites entre Ottawa et la rivière Saint-François, représentant la partie profonde du bassin. Les assemblages de foraminifères ont permis de reconnaître une séquence de trois écozones d'eau profonde et une autre séquence de deux écozones d'eau peu profonde. La zone inférieure de la première séquence (A) est caractérisée par *Cassidulina reniforme, Islandiella helenae* et *I. norcrossi,* et indique une paléosalinité de 25 à 30 ‰. La zone suivante (B) est dominée par *Elphidium excavatum* et représente un déclin des salinités, variant de 25 à aussi peu que 10 ‰. La zone supérieure (C) ne contient qu'un nombre réduit d'un morphotype d'*E. excavatum* indiquant une paléosalinité n'excédant pas 10 ‰. La zone C est recouverte par une épaisseur variable d'argile et de silt en général stérile et probablement lacustre (post-C). Entre la zone A et le till du Wisconsinien supérieur, il existe un intervalle pré-A dont les assemblages variables indiquent des milieux hyposalins à l'est et principalement lacustres à l'ouest de Montréal. Près de Montréal et au sud, on observe une alternance de conditions hyposalines et lacustres. La température des eaux profondes était probablement «arctique» (à près de 0°C) de l'intervalle pré-A jusqu'à la zone B inclusivement. Les zones d'eau peu profonde indiquent des milieux de salinité élevée (zone EH) ou réduite (zone EA), mais de bathymétrie plus faible que les zones d'eau profonde. L'existence de deux séquences distinctes semble être le produit d'une stratification (probablement saisonnière) des eaux. Les données ne permettent pas de déterminer la bathymétrie de la limite entre les eaux profondes et peu profondes.

ZUSAMMENFASSUNG *Verteilung der Foraminifera in den zentralen und westlichen Teilen des Spät-Pleistozän Champlain-Meer-Beckens, Ost-Kanada.* Zwischen Ottawa und dem Fluss St-François, Québec, wurden an 20 Fundorten im tieferen Teil des Beckens Proben von Sedimenten aus dem spätglazialen Champlain-Meer entnommen. Foraminifera-Verbindungen wurden herausgelöst und eine Folge von drei Tiefwasser- und zwei Seichtwasser-Ökozonen festgestellt. Die unterste Zone (A) ist gekennzeichnet durch *Cassidulina reniforme, Islandiella helenae* und *I. norcrossi* und hat einen Paläosalzgehalt von 25 bis 30‰. Die darüberliegende Zone B wird von *Elphidium excavatum* beherrscht. Sie repräsentiert abnehmenden Salzgehalt von 25 bis so niedrig wie 10‰. Die oberste Zone (C) enthält nur eine geringe Menge eines Morphotypus von *E. excavatum*. Sie lässt vermuten, dass der Salzgehalt 10‰ nicht überschreitet. Über der Zone C befindet sich eine vorwiegend nichtfossilhaltige Schlamm- und Lehmschicht unterschiedlicher Dicke (post-C). Sie stammt möglicherweise von einem See. Unter der Zone A und über der Grundmoräne aus dem späten Wisconsin befindet sich ein Prä-A-Intervall, dessen verschiedene Verbindungen östlich von Montréal eine hyposaline Umgebung, westlich von Montréal vor allem See-Bedingungen und abwechselnd hyposaline/See-Bedingungen bei und südlich von Montréal repräsentieren. Die Temperatur auf dem Wassergrund waren wahrscheinlich "arktisch" (nahe bei O°) von dem Prä-A-Intervall bis einschliesslich der B-Zone. Die Daten von der C-Zone sind zu spärlich, um Temperaturen zu schätzen. Die Niedrigwasserzonen weisen auf Umwelten mit hohem (EH-Zone) oder niedrigem (EA-Zone) Salzgehalt aber niedrigeren Tiefen als die Tiefwasserzonen. Die Existenz zweier Folgen scheint das Ergebnis von (wahrscheinlich saisonbedingter) Wasserschichtung zu sein. Die Daten erlauben nicht die Tiefe der Grenze zwischen niedrigem und tiefem Wasser zu bestimmen.

INTRODUCTION

The purpose of this paper is to describe a sequence of foraminiferal biofacies from a series of borings and exposed sections in the Champlain Sea sediments between Ottawa in the west and the Rivière St-François in the east (Fig. 1). These biofacies always occur in the same stratigraphical order; they represent ecozones (hereafter referred to simply as "zones") in the sense of Feyling-Hanssen (1964). These zones have no chronological meaning. They are laterally correlatable *layers of sediment, each representing a particular set of en-vironmental conditions.*

Following the usage of Dionne (1972), the "Champlain *Sea" refers to the late Pleistocene postglacial glacio-isostatic* body of water which flooded the St. Lawrence/Ottawa River lowlands west of Québec City, while the areas to the east are designated "Goldthwait Sea". Radiocarbon age deter-minations on marine shells indicate that the marine phase lasted from 12.8 to 9.8 ka BP (Occhietti and Hillaire-Marcel, 1977). Figure 1 shows the marine limit following Elson (1969a), *Gadd et al. (1972) and MacClintock and Stewart (1965) and* the St-Narcisse-St-Faustin ice frontal position which according to LaSalle and Elson (1975) is associated with a cold climatic event occurring between 11.0 and 10.6 ka BP.

Sections from the area near the St-Narcisse Moraine and near Québec are not discussed in this article. They present special difficulties of their own and shall be discussed in future publications. The set of 22 localities described here yields a homogeneous record and, taken as a whole, can serve as a Champlain Sea reference section to which more marginal or problematic sections could be compared. Most localities are situated within the low-lying middle parts of the basin, which makes them less influenced by nearshore factors. They can thus give a general ideal of the history of paleosalinities and hence of the history of the basin's connection to the open sea.

During the past 150 years, many authors have investigated the marine macro- and microfossils of the Champlain Sea. Summaries of previous paleontological studies can be found in Wagner (1967, 1970), Cronin (1977a and 1979), Guilbault (1980) and Rodrigues and Richard (1986). The majority of these studies were based on surface material usually rep-resenting shallow-water environments from poorly known stratigraphical context. Works emphasizing the stratigraphical *sequence are the following: Fillion and Hunt (1974), Gunther* and Hunt (1977), Corliss *et al.* (1982) and Rodrigues and Gadd (1987). The first 3 studies were made on cores from modern Lake Champlain where a piston corer was used and where a freshwater — saltwater — freshwater sequence was recovered. The work of Rodrigues and Gadd (1987) was made on sections exposed at the surface in the western *Champlain Sea Basin in Ontario.*

MATERIAL

The present material comes primarily from 12 borings carried out by the Québec Department of Natural Resources in the
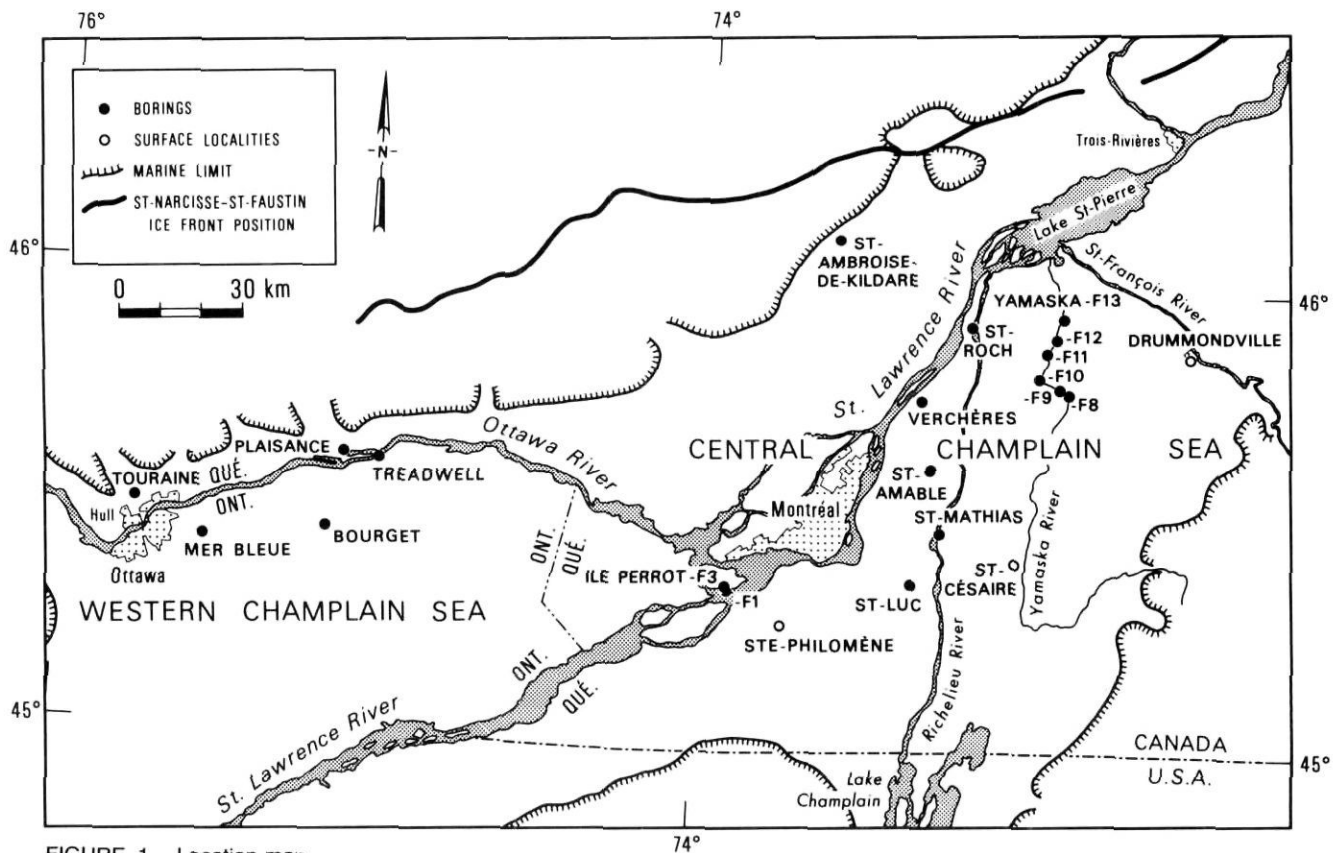

FIGURE 1.   Location map.

Carte de localisation.

St. Lawrence River Lowland and from 5 other boreholes drilled by the Geological Survey of Canada in the Ottawa River Lowland. In addition, the results from three surface sections sampled by the author are included (Fig. 1 and Table I). The subsurface sedimentologic data reported herein comes mostly from the two above-mentioned organizations.

The Québec cores were drilled with equipment used for collecting geotechnical samples. The Shelby tubes (coring pipes) were 60 cm long and, as there was usually only one paleontological sample taken per tube, the sampling interval was in most instances greater than 60 cm. The usual interval between the tops of successive Shelby tubes was 1.5 or 3 m. This was rather large, but considering the thickness of the sequence (commonly 20 to 30 m, up to 45 m), it was adequate to discern broad trends in faunal composition.

The Geological Survey cores have been described lithologically by Gadd (1986). The interval between paleontological samples varied considerably. At Mer Bleue, 45 samples were analyzed over a stratigraphic thickness of 45 m. Elsewhere, sampling was much less tight and in one instance (the upper part of Treadwell hole), there is nearly 20 m between two samples. The Bourget foraminifera have been the object of an unpublished Geological Survey of Canada note from F. E. Cole of Atlantic Geoscience Centre to Nelson Gadd. The data reported here is a re-analysis of the samples previously analyzed by Cole.

The surface exposures at St-Césaire, Ste-Philomène and Drummondville largely represent shallow water environments. Their main interest reside in the fact that they help in delineating the area and altitude of occurrence of zones B and C. The sampling interval varied considerably but was generally closer than in the core material. As much as possible, every lithofacies present was sampled.

The material discussed here includes 262 samples, of which 100 contained more than 50 foraminifera and 104, less than 50. Fifty-eight were totally barren. Fifty-one samples from the present collection as well as from other Champlain Sea localities were sent (after processing) to T. M. Cronin of the U.S. Geological Survey in Reston, Virginia, for ostracodal study. His results will be referred to later in the article. A list of foraminiferal species mentioned in this paper is given in Table II.

METHODS

The amount of sediment processed varied from 50 to 100 g according to sample size. Disaggregation was obtained with either tap water, or a detergent solution (Calgon) or a solution of hydrogen peroxide (H_2O_2). Sieving was carried out with either a 100 μm or a 106 μm screen, mostly the former. A 63 μm screen was used at five localities: Mer Bleue, Bourget, St-Luc, St-Mathias and St-Césaire. This resulted in a slightly higher percentage of smaller species such as *Cassidulina reniforme* but because of the sharp contrast in composition between the zones, the correlations are not affected. Concentration was done by flotation in a heavy liquid of density 1.8 g/ml (mixture of dibromoethane and ethyl alcohol). Whenever possible, up to 300 foraminifer specimens were picked and identified. These data were used in establishing the per-

TABLE I

Altitude and UTM coordinates of localities (altitudes are for tops of sections or boreholes)

Locality	Altitude	UTM coordinates
Drummondville, Rivière Noire section	75	18 T XF 938 824
Yamaska boreholes:		
borehole F8	30	18 T XF 656 724
F9	26	18 T XF 631 741
F10	34	18 T XF 580 773
F11	26	18 T XF 598 813
F12	23	18 T XF 612 858
F13	20	18 T XF 629 916
St-Ambroise-de-Kildare	100	18 T XC 087 066
St-Roch-de-Richelieu	15	18 T XF 420 880
Verchères	18	18 T XF 298 699
St-Amable	40	18 T XF 332 523
St-Mathias	13	18 T XF 636 038
St-Luc	35	18 T XF 630 025
St-Césaire	48	18 T XF 653.5 029.5
Ste-Philomène	45	18 T WF 990 140
Île Perrot boreholes:		
borehole F1	43	18 T WF 853 224
F3	43	18 T WF 874 226
Treadwell	53	18 T VF 990 490
Plaisance	47	18 T VF 918 503
Bourget	61	18 T VF 879 302
Mer Bleue	77	18 T VF 561 283
Touraine	95	18 T VF 430 360

centages of the species present. When the populations were significantly larger than 300, the total number of specimens was estimated by extrapolating from the counted fraction. The uncounted part of the sample was scanned in order to find species that might not be present in the counted fraction.

RESULTS

A sequence of three well-defined biofacies emerges clearly from the data, corresponding to three correlatable zones designated respectively, from bottom to top, zone A, B and C (Table III and Fig. 2, inset). Marine assemblages are present below zone A, but no consistent biofacies (and hence, zone) can be defined. Instead, they are referred to collectively as "pre-A levels". The essentially barren levels above zone C were labelled "post-C".

Various indicators of faunal diversity are used in this article. They are Walton's faunal diversity (Walton, 1964), Fisher's α index (Fisher *et al.*, 1943) and the faunal dominance (percentage of the most abundant species). Diversity indicators are designed to express the level of diversity within a fauna independently of the number of specimens present. High values of dominance and lower values of Walton's faunal diversity and Fisher's α-index are usually associated with more unstable conditions. In a marine environment, that could mean reduced or variable salinities or temperatures.

TABLE II

List of foraminiferal species mentioned in the text and distribution charts and their original designation (the name is not repeated when it is the same as the original designation)

Astrononion gallowayi LOEBLICH and TAPPAN, 1953.

Buccella frigida (CUSHMAN): *Pulvinulina frigida* CUSHMAN, 1922.

Cassidulina reniforme NØRVANG: *Cassidulina crassa* d'Orbigny, var. *reniforme* NØRVANG, 1945.

Cibicides lobatulus (WALKER and JACOB): *Nautilus lobatulus* WALKER and JACOB, 1798.

Elphidium albiumbilicatum (WEISS): *Nonion pauciloculum albiumbilicatum* WEISS, 1954.

Elphidium bartletti CUSHMAN, 1933.

Elphidium excavatum TERQUEM: *Polystomella excavata* TERQUEM, 1876.

Elphidium excavatum forma *clavata* CUSHMAN: *Elphidium incertum* (WILLIAMSON) var. *clavatum* CUSHMAN, 1930.

Elphidium excavatum forma *excavata* TERQUEM: *Polystomella excavata* TERQUEM, 1876.

Elphidium hallandense BROTZEN, 1943.

Elphidium incertum (WILLIAMSON): *Polystomella umbilicatula* var. *incerta* WILLIAMSON, 1858.

Elphidium magellanicum HERON-ALLEN and EARLAND, 1932.

Eoeponidella pulchella (PARKER): *Pninaella pulchella* PARKER, 1952.

Epistominella vitrea PARKER, 1953.

Fissurina laevigata REUSS, 1850.

Fissurina marginata (MONTAGU): *Vermiculum marginatum* MONTAGU, 1803.

Haynesina orbiculare (BRADY): *Nonionina orbicularis* BRADY, 1881.

Islandiella helenae FEYLING-HANSSEN and BUZAS, 1976.

Islandiella norcrossi (CUSHMAN): *Cassidulina norcrossi* CUSHMAN, 1933.

Miliolinella subrotunda (MONTAGU): *Vermiculum subrotundum* MONTAGU, 1803.

Nonion labradoricum DAWSON, 1860.

Proteonina difflugiformis (BRADY): *Reophax difflugiformis* BRADY, 1879.

Pyrgo williamsoni (SILVESTRI): *Biloculina williamsoni* SILVESTRI, 1923.

Quinqueloculina seminulum (LINNÉ): *Serpula seminulum* LINNÉ, 1758.

Recurvoides turbinatus (BRADY): *Haplophragmium turbinatum* BRADY, 1881.

Reophax subfusiformis EARLAND, 1933.

Scutuloris tegminis LOEBLICH and TAPPAN, 1953.

Silicosigmoilina groenlandica CUSHMAN: *Quinqueloculina fusca* Brady, var. *groenlandica* CUSHMAN, 1933.

Spiroplectammina biformis (PARKER and JONES): *Textularia agglutinans* d'Orbigny var. *biformis* PARKER and JONES, 1865.

Triloculina oblonga (MONTAGU): *Vermiculum oblongum* MONTAGU, 1803.

Triloculina trihedra LOEBLICH and TAPPAN, 1953.

Virgulina concava HÖGLUND, 1947.

Virgulina schreibersiana CZJZEK, 1848.

PRE-A LEVELS

Under this designation are included all the marine or lacustrine assemblages that have been observed between the Late Wisconsinan till and the overlying zone A. As such, this

TABLE III

Summary of Champlain Sea foraminiferal assemblages from top to bottom

Zone	Assemblage
a) Deepwater sequence:	
Post-C	Post-Champlain Sea. Usually unfossiliferous or containing at most a few specimens redeposited from zones A or B. Lacustrine or extremely hyposaline.
C	Small numbers of *Elphidium excavatum* some of which are large and belong to a morphotype characteristic of this zone. Other species are rare.
B	*E. excavatum* (ca 85% or more). Small amounts of *Haynesina orbiculare* and *Cassidulina reniforme*. Faunal diversities: low to very low.
A	In order of abundance: *Cassidulina reniforme*. *Islandiella helenae* and *I. norcrossi*. Variable amounts of *Elphidium excavatum*. Faunal diversities: from low to high.
Pre-A	Poor and undiversified. Dominated either by *Elphidium excavatum* or *Cassidulina reniforme*. Oligohaline ostracodes common, and at times the only microfossils present.
b) Shallow water sequence:	
Lampsilis	Deposits with the freshwater mollusk *Lampsilis*. Not investigated micropaleontologically.
EA	*E. excavatum*, *H. orbiculare* and *Elphidium albiumbilicatum*. Faunal diversities: moderate to low.
EH	*E. excavatum*, *H. orbiculare*, *Elphidium hallandense* and *Elphidium incertum*. Variable proportion of *Islandiella* spp. Faunal diversities: high.
transitional	Elphidiids, haynesinids and oligohaline ostracodes. Faunal diversities: low. Reported by Cronin (1977a, 1979) from the Lake Champlain area. *Not found in present material*.

is not a zone nor a biofacies, but an heterogeneous group: it includes assemblages which vary considerably from one area to the other and are thus uncorrelatable. On the average however, pre-A assemblages exhibit low diversities and low abundances. In the western part of the basin, that is, in the Ottawa Lowland and area west of Montréal, pre-A levels are commonly composed of freshwater to oligohaline ostracodes of the genus *Candona*, either predominantly or exclusively (recorded by the present author and by Cronin, 1980, pers. comm.). At Île Perrot (Figs. 3,4), near Montréal, pre-A levels are represented in two different boreholes by samples containing *Candona* and/or poor foraminiferal assemblages. The dominant foraminiferal form is *Elphidium excavatum*, followed by *Cassidulina reniforme* and *Haynesina orbiculare*. In one

of the boreholes (Île Perrot F3), one sample with such an assemblage was found stratigraphically *below* an other one containing exclusively *Candona*, itself superseded by zone A, thus indicating shifting fresh/marine conditions in the early Champlain Sea (see Paleoenvironmental Discussion).

In an exposed section in Drummondville (Fig. 5), zone A is underlain by a complex sequence of lithofacies including clay, silt, varved sediment and clay breccia. Most of these strata are either barren or contain only a few scattered foraminifer specimens, mostly *E. excavatum*, but also some *C. reniforme* and one *Islandiella helenae*. One clay layer, with sand laminations, yielded a more abundant *Cassidulina reniforme*-dominated assemblage (sample 13). It differs from the A-type assemblages by the absence of the genus *Islandiella*. However, all the specimens are very small and of equal size, suggesting post-mortem redeposition and sorting.

Further up the Drummondville section (between 1.85 and 2.30 m), zone A is underlain by a transition layer attributable to pre-A where a quantitatively very poor but presumably *in situ* assemblage was found. The dominant forms were *E. excavatum* and Polymorphinidae. Within that layer, there is a centimetre-thick, *Portlandia arctica*-rich sub-layer covering the upper surface of a boulder (sample 18) where an assemblage comparable to those assigned to zone A occurs. Seven percent of the foraminiferal assemblage is *Islandiella*. This locality illustrates the wide variations in composition of the assemblages included under the pre-A designation. It also shows that at the time when the earliest pre-A strata exposed here were laid down, some marine influence was being felt, it not at the site of the Drummondville section, then at least in neighbouring parts of the Champlain Sea basin.

North of the St. Lawrence River, at St-Ambroise-de-Kildare (Fig. 6), the pre-A interval consists in a *Cassidulina reniforme*-dominated facies containing a few percent of *Triloculina* cf. *oblonga*. This last species is rare elsewhere in the Champlain Sea and has been found only at localities situated eastward from this point (unpublished data of Guilbault, 1980).

In summary, the assemblages occurring below zone A may change drastically from one area to the other and even within the same section. There are nevertheless two general trends obvious throughout the pre-A levels. First, pre-A assemblages consistently show less abundance and diversity than those of the overlying zone A and they rarely contain *Islandiella helenae*. Second, foraminiferal populations and diversities decrease from east to west, with a concomitant increase in oligohaline ostracode numbers.

Lithologically, pre-A assemblages are commonly associated with rhythmic sedimentation, in the form of thin beds or laminations of silt, fine sand and clay corresponding to Unit II of Gadd (1986) from the Ottawa Lowland. That author reports that at most localities, the rhythmites "have the appearance of typical varves (ditactic) comprising coarse to fine silt and silty clay". Rhythmites are present at Mer Bleue (Fig. 7), Touraine, Île Perrot, St-Luc, St-Mathias and in parts of the pre-A strata at Drummondville. Thin beds and laminations of fine sand are present at Île Perrot, interspersed among the pseudo-varves, as well as in the St-Césaire (Fig. 8), St-Am-
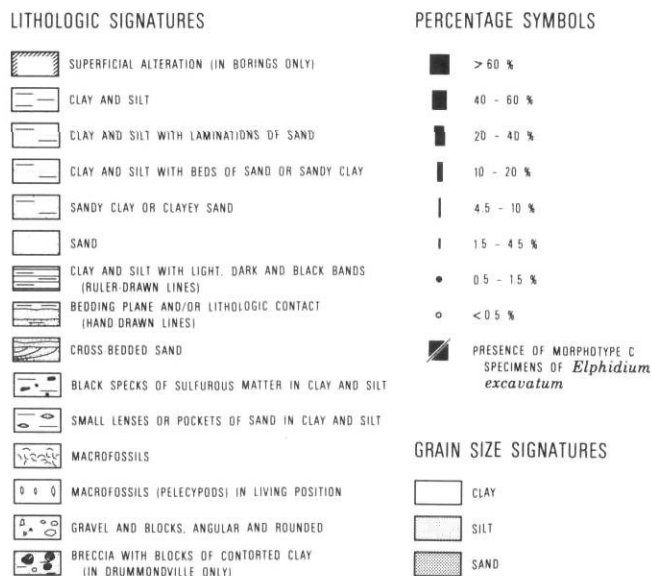
LITHOLOGIC SIGNATURES

- SUPERFICIAL ALTERATION (IN BORINGS ONLY)
- CLAY AND SILT
- CLAY AND SILT WITH LAMINATIONS OF SAND
- CLAY AND SILT WITH BEDS OF SAND OR SANDY CLAY
- SANDY CLAY OR CLAYEY SAND
- SAND
- CLAY AND SILT WITH LIGHT, DARK AND BLACK BANDS (RULER-DRAWN LINES)
- BEDDING PLANE AND/OR LITHOLOGIC CONTACT (HAND DRAWN LINES)
- CROSS-BEDDED SAND
- BLACK SPECKS OF SULFUROUS MATTER IN CLAY AND SILT
- SMALL LENSES OR POCKETS OF SAND IN CLAY AND SILT
- MACROFOSSILS
- MACROFOSSILS (PELECYPODS) IN LIVING POSITION
- GRAVEL AND BLOCKS, ANGULAR AND ROUNDED
- BRECCIA WITH BLOCKS OF CONTORTED CLAY (IN DRUMMONDVILLE ONLY)

PERCENTAGE SYMBOLS

- > 60 %
- 40 - 60 %
- 20 - 40 %
- 10 - 20 %
- 4.5 - 10 %
- 1.5 - 4.5 %
- 0.5 - 1.5 %
- < 0.5 %
- PRESENCE OF MORPHOTYPE C SPECIMENS OF *Elphidium excavatum*

GRAIN SIZE SIGNATURES

- CLAY
- SILT
- SAND

FIGURE 3. Explanation of symbols for distribution charts.
Légende des diagrammes de distribution.

broise and Drummondville sections. Soft, sticky and featureless clay has been found at Ste-Philomène (Fig. 9) and Drummondville. Finally, silty clay similar to that of zone A is present in the upper part of the pre-A interval at St-Césaire and Drummondville.

ZONE A

Zone A (observed in 21 samples and 13 localities) is characterized by the abundance of *Cassidulina reniforme*, *Islandiella helenae* and *I. norcrossi*, the last two species being the most significant. *Cassidulina reniforme* is usually the most frequent form, representing between 20 and 85% of the assemblage, the average being 59%. There is one exceptional case with a 99% occurrence of *C. reniforme* (at Mer Bleue). In some samples, *Islandiella helenae* dominates (up to 63%, although the average is only 19% and the minimum, 4%). *Islandiella norcrossi* is widespread and locally it may be more abundant (up to 26%) than *I. helenae*, especially in the southern part of the region, at Ste-Philomène, St-Luc and St-Césaire, and also at Bourget. In most other samples, *I. norcrossi* is either rare or totally absent. Its average occurrence is 10%. *Elphidium excavatum* varies in zone A from 1% up to 23%, with an average of 5%. Morphologically, all the *E. excavatum* observed in zone A belong to forma *clavata*.

Among the less common rotaline species, the most commonly occurring are *Haynesina orbiculare*, *Virgulina concava*, *V. schreibersiana* and *Astrononion gallowayi*. *Haynesina orbiculare* may exceptionally represent up to 11% of the assemblage but on the average, its proportion lies around 1% and the specimens are rather small and globular. This species and *V. concava* (maximum occurrence, 3%) are the only rare species to be present in nearly all zone A samples.

Few specimens of the Textulariina have been recorded and at some localities only, principally St-Ambroise-de-Kildare,

8
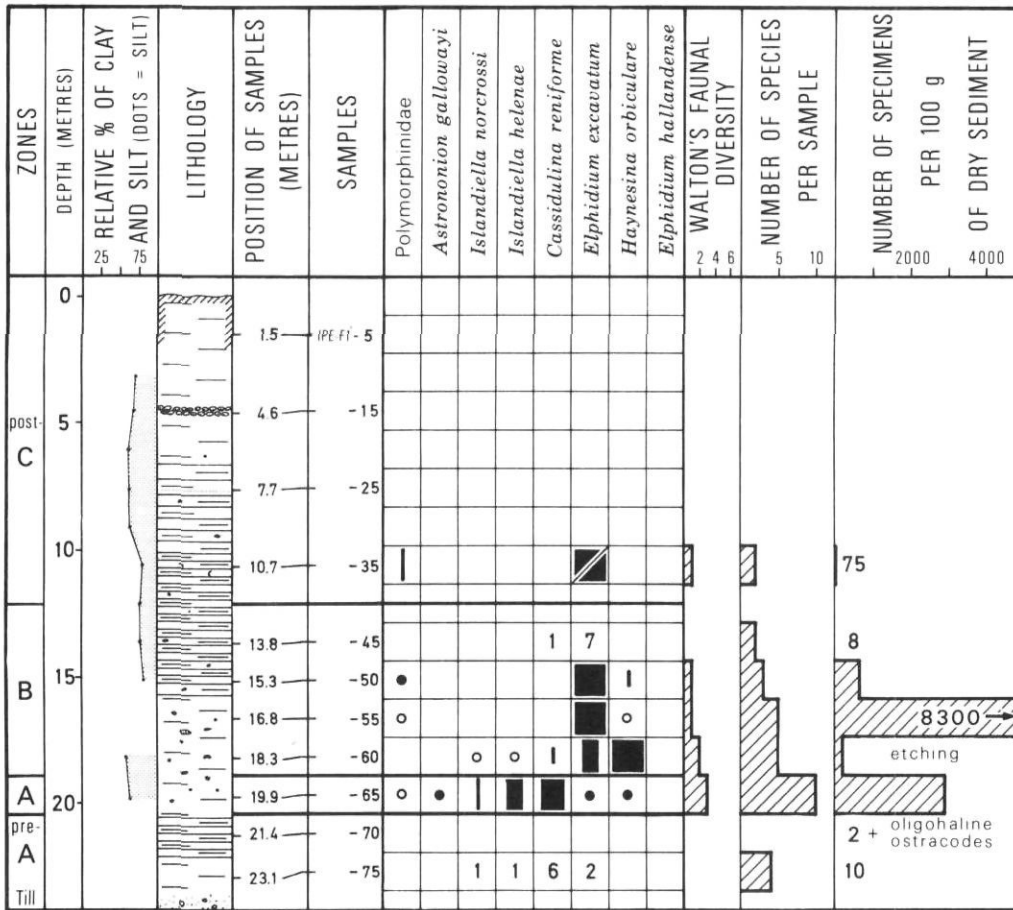
ILE PERROT F1

ILE PERROT F3
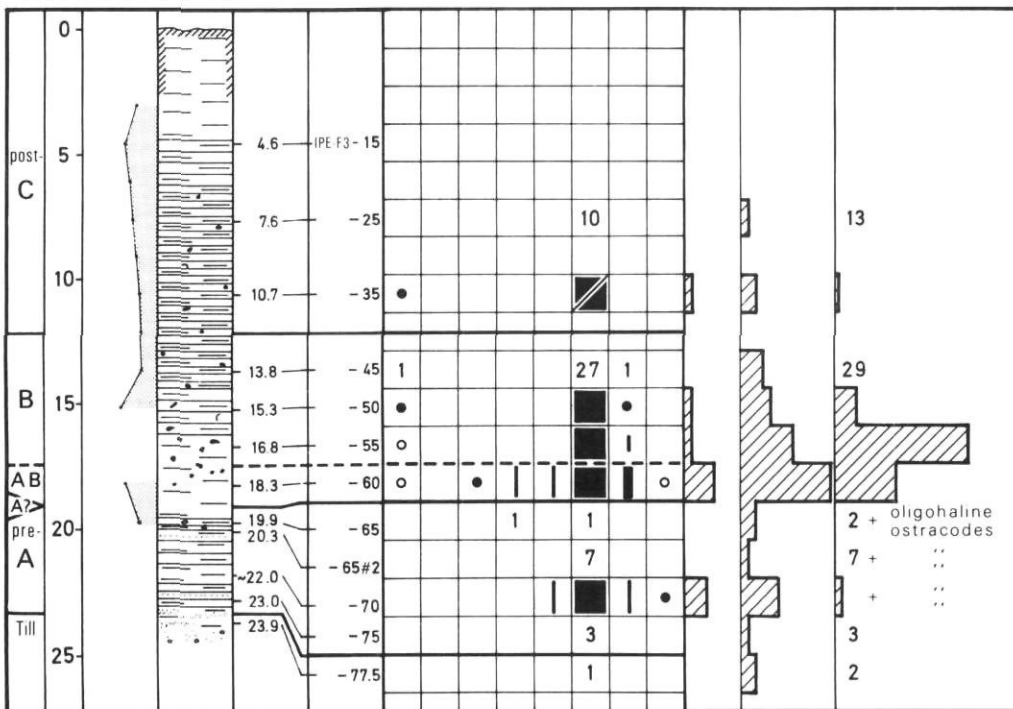
FIGURE 4. Distribution charts for the Île Perrot boreholes. When the total number of specimens in a sample is less than 50, percentage symbols are replaced by the total number of individuals of each species. Number of specimens in 100 g of dry sediment is given in numbers (instead of a bar) when it is less than 100. These remarks apply to all distribution charts.

Diagrammes de distribution des forages à l'île Perrot. Quand le nombre de spécimens dans un échantillon est inférieur à 50, les symboles de pourcentage sont remplacés par le nombre total d'individus de chaque espèce. Le nombre de spécimens par 100 g de sédiment sec est indiqué par un nombre (au lieu d'un symbole) lorsqu'il est inférieur à 100. Ces remarques s'appliquent à tous les diagrammes de distribution.
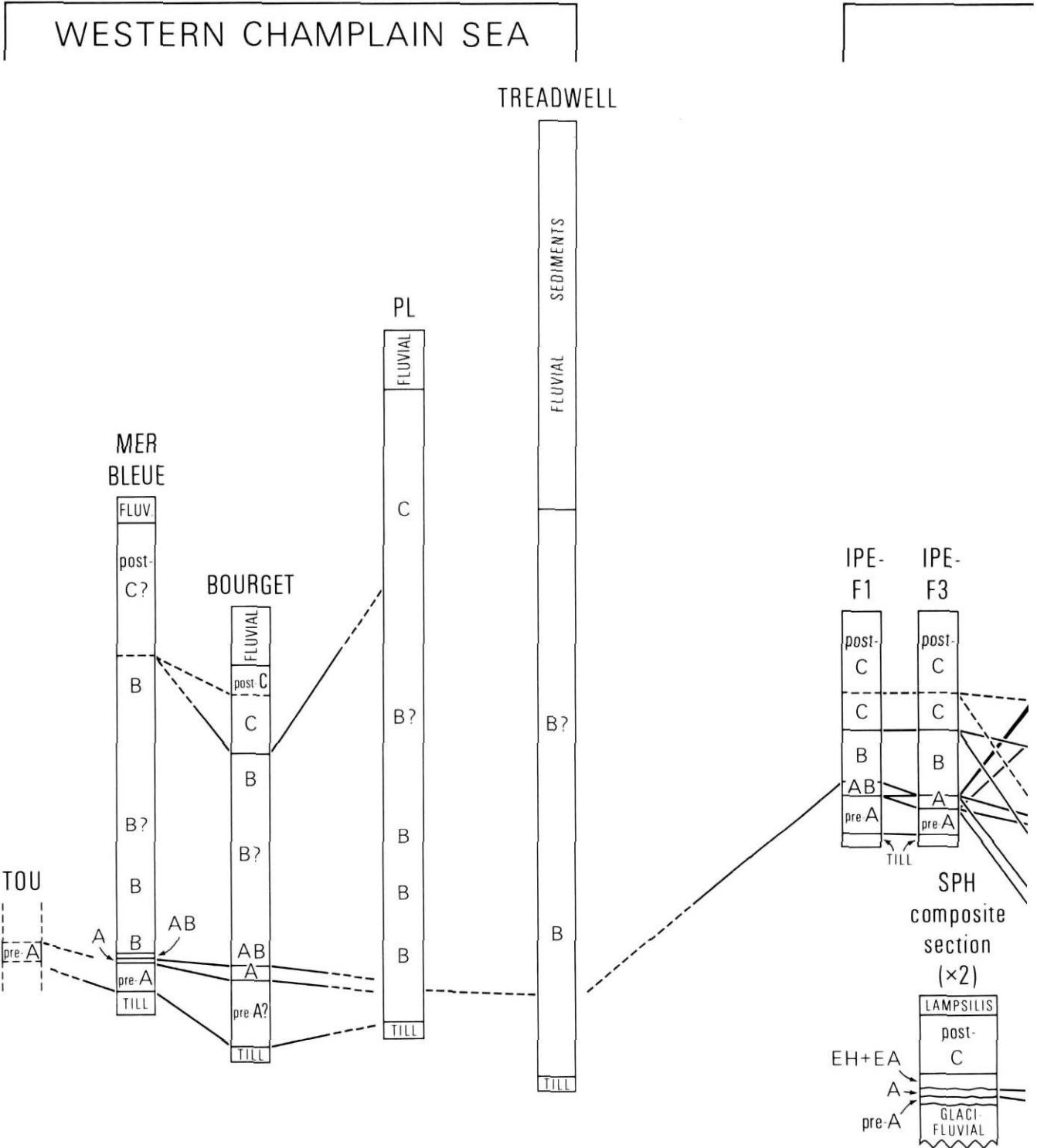
FIGURE 2. General correlation chart, designed as a fence diagram with sections placed according to their geographic position, the north being at the back. To improve clarity, SPH, CES and DRN sections are reproduced at twice the scale of the rest of the figure. Information on tills and fluvial sediments: in the western Champlain Sea, following Gadd (1986); in the central Champlain Sea, personal communication from J. Lebuis, ministère de l'Énergie et des Ressources, Québec.

Diagramme général de corrélation; les coupes sont disposées se, leur position géographique, le nord étant à l'arrière. Pour plus clarté, l'échelle des coupes SPH, CES et DRN a été doublée. Donne sur les tills et les sédiments fluviatiles: dans la partie ouest de Mer de Champlain, d'après Gadd (1986); dans la partie centra communiquées par J. Lebuis, du ministère de l'Énergie et des R sources du Québec.

CENTRAL CHAMPLAIN SEA

SAK

post-C?

?

?

B

AB

A

pre-A

SR

FLUVIAL SANDS

post-C

C

B

AB

A

TILL

CES	:	ST-CÉSAIRE	SPH	:	STE-PHILOMÈNE
DRN	:	DRUMMONDVILLE	SR	:	ST-ROCH
IPE	:	ILE PERROT	TOU	:	TOURAINE
LUC	:	ST-LUC	VER	:	VERCHÈRES
MAT	:	ST-MATHIAS	YAM	:	YAMASKA
PL	:	PLAISANCE			
SA	:	ST-AMABLE	F1	:	Borehole number
SAK	:	ST-AMBROISE-			
		DE-KILDARE			

SA

post-C

C

B

?? TILL

VER

post-C

C

B

AB

A

YAM-F13

post-C

C

B

TILL

YAM-F12

post-C

C

B

TILL

YAM-F11

post-C

C

B

A

TILL

YAM-F10

C

TILL

YAM-F9

post-C

C

B

A

TILL ?

YAM-F8

C

B

A

DRN (×2)

EH+EA

A

pre-A

0

10

20 m

LUC

post-C

C?

B

A

pre-A

TILL

MAT

post-C

B

pre-A

CES (×2)

EH+EA

A

pre-A

GENERAL CORRELATION CHART

DRUMMONDVILLE
Rivière Noire

METRES ABOVE BASE OF SECTION

ZONES

LITHOLOGY

POSITION OF SAMPLES (METRES)

SAMPLES

Reophax subfusiformis
Recurvoides cf *turbinatus*
Spiroplectammina biformis
Other arenaceous forms
Polymorphinids
Fissurina spp.
Cibicides lobatulus
Buccella frigida
Astrononion gallowayi
Virgulina concava
Virgulina schreibersiana
Islandiella norcrossi
Islandiella helenae
Cassidulina reniforme
Elphidium excavatum
Haynesina orbiculare
Elphidium incertum
Elphidium hallandense
Elphidium albiumbilicatum

WALTON'S FAUNAL DIVERSITY
5

NUMBER OF SPECIES PER SAMPLE
10 20 30

NUMBER OF SPECIMENS PER 100 g OF DRY SEDIMENT
2000 4000 6000

EA?
EA
EH
A
pre-A + A
pre-A

Lacustrine (?)
Glacial (?)
?

4.36, 4.19, 4.12, 3.99, 3.78, 3.54, 3.28, 3.05, 2.93, 2.84, 2.54, 2.38, 2.17, 1.93, 1.64, 1.46, 1.40, 1.31, 1.22, 1.12, 1.04, 0.95, 0.77, 0.69, 0.58, ~0.39, 0.24, 0.18, 0.08

30, 31, 29, 28, 27, 26, 25, 24, 23, 23a, 22, 21, 20, 19, 18, 17, 16, 15, 14, 14a, 13, 12, 11, 10, 9, 8, 7, 6, 5, 4, 3, 2, 1

Probably totally decalcified

FIGURE 5. Distribution chart for Drummondville, Rivière Noire section. *Diagramme de distribution de la coupe de la rivière Noire, à Drummondville.*
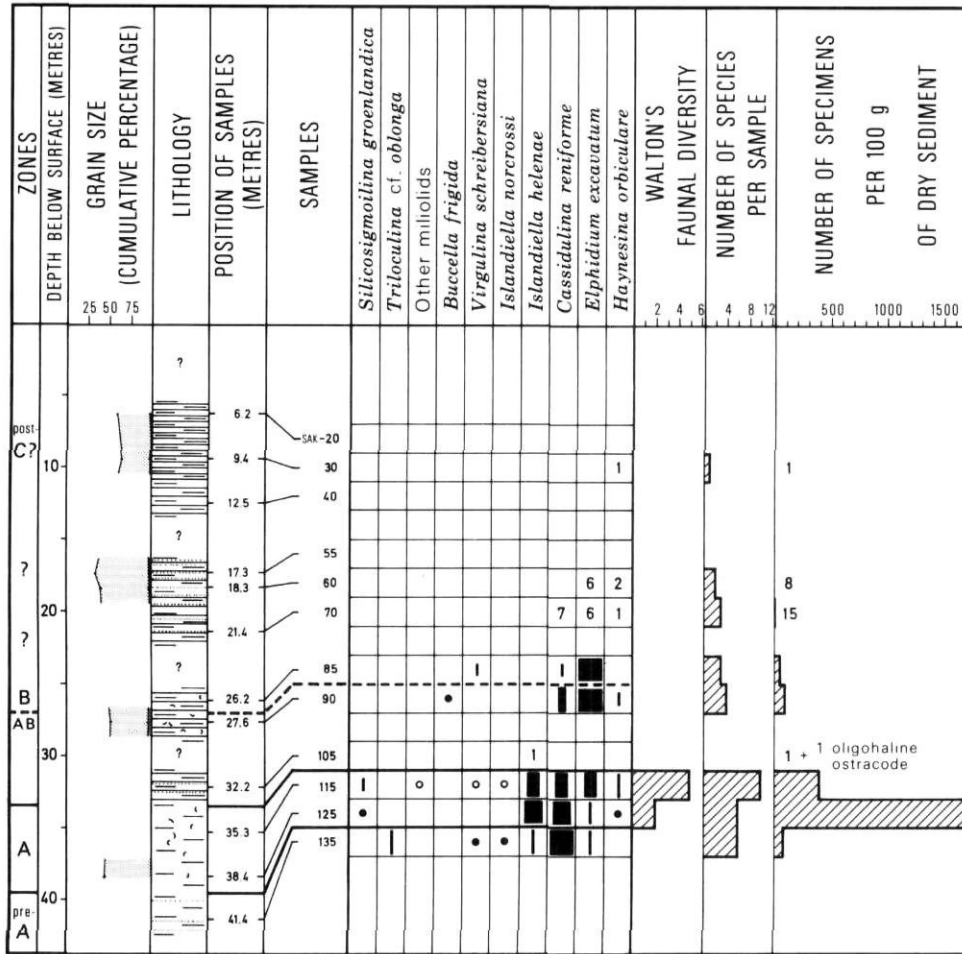
ST-AMBROISE-DE-KILDARE

FIGURE 6. Distribution chart for the St-Ambroise-de-Kildare borehole.

Diagramme de distribution du forage de Saint-Ambroise-de-Kildare.

Drummondville and the Yamaska boreholes. The main species present are *Silicosigmoilina groenlandica*, *Spiroplectammina biformis*, *Recurvoides turbinatus*, *Proteonina difflugiformis* and *Reophax subfusiformis*. Their total proportion in any given sample never exceeds 5%. Where present they may be observed in more than one zone. For instance, in Drummondville, they are seen in zones A, EH and EA. This suggests that their presence or absence is determined not only by ecological factors but also by local conditions of preservation (except possibly for *S. groenlandica*).

Miliolids are rare in zone A, the main species present being *Quinqueloculina seminulum*, *Pyrgo williamsoni*, *Triloculina trihedra* and *Miliolinella subrotunda*. The quality of their preservation is irregular.

Shallow water species such as *Elphidium albiumbilicatum*, *E. hallandense* and *E. incertum* occur in zone A only in very small numbers. Furthermore, they are usually small and their features are poorly developed, making them difficult to differentiate at the species level.

Valves of *Candona* are present in zone A at St-Césaire and Ste-Philomène. Considering the overwhelming abundance and diversity of material of marine origin, the environment is considered marine and the *Candona* specimens are assumed
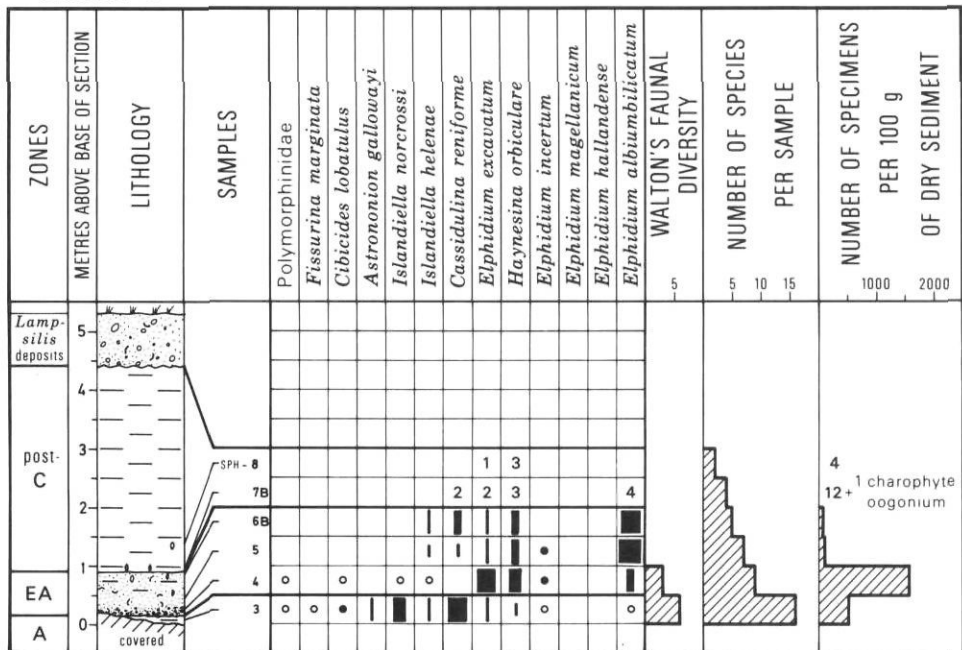
to have been transported into the Champlain Sea by rivers or streams or to have been redeposited from earlier (pre-A?) strata. Sample 105 at St-Ambroise-de-Kildare resembles pre-A paleontologically and lithologically (contains sandy laminations). It is completely anomalous and could be the result of redeposition, possibly by ice-rafting.

The assemblages of zone-A show a broad range of variation in terms of abundance of specimens, number of species per sample, faunal dominance, Walton's faunal diversity and Fisher's α-index. The number of specimens per 100 g of dry sediment varies from 400 to 24,000. The number of species per sample may be as low as 6 or as high as 37 and the faunal dominance may range from 85% to 32% with one extreme case at 99%. Walton's faunal diversity varies from 1 to 8 and Fisher's α-index from less than 1 to approximately 3.5 (Fig. 10). Zone A assemblages rarely contain more than a few species representing 1% or more of the population. Therefore, in samples containing a "large" number of species — 20, for example — most of the recorded elements are extremely minor.

Thickness variations in zone A

Zone thicknesses can be determined accurately only from exposed sections, such as St-Césaire (0.4 to 0.7 m) and
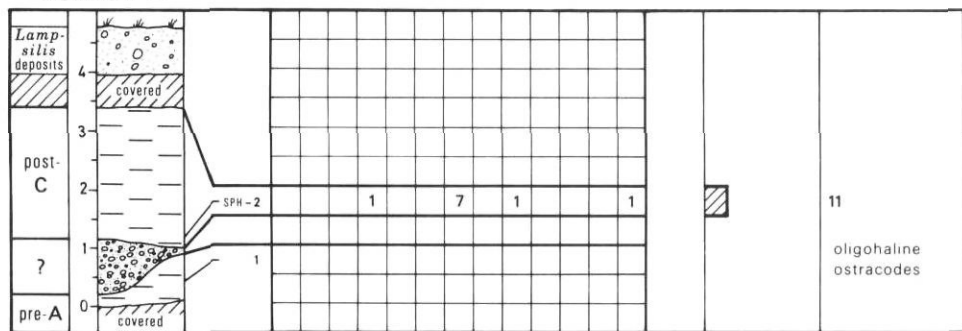
MER BLEUE

FIGURE 7. Distribution chart for the Mer Bleue borehole. *Diagramme de distribution du forage de Mer Bleue.*

ST-CÉSAIRE

FIGURE 8. Distribution chart for the St-Césaire section. This section is also discussed in LaSalle et al. (1982, p. 16-17 and Fig. 12).

Diagramme de distribution de la coupe de Saint-Césaire. Cette coupe est également commentée dans LaSalle et al. (1982, p. 16-17 et fig. 12).

Drummondville (0.6 m). At borehole localities, the knowledge of zone thicknesses is dependant on the resolution allowed by the sampling interval. The thicknesses shown on Figure 2 are assumed as the zonal limits are placed halfway between the last sample of one zone and the first sample of the next; the values used in Figure 2 are thus intermediate between the maximum and minimum allowable values. When a zone is represented by only one sample, which is frequent in zone A, there is always the possibility that the thickness is minimal. When a zone is absent, it may have been missed because the sampling interval was too wide. It is the repetition of the sequence at many localities that gives support to the thickness values adopted in Figure 2.

In the central Champlain Sea, the thickness of zone A is generally less than 3 m but probably more than 1.5 m, ranging from exceptionally thin — tens of centimetres — at outcrop localities south of the St. Lawrence River (Drummondville and St-Césaire) to exceptionally thick — 6 to 9 m — on the north side (St-Ambroise-de-Kildare). At Île Perrot and in the western Champlain Sea, zone A is definitely thinner than 1.5 m.

At Mer Bleue, zone A consists in two successive samples that were adjacent within the core (sample 81A and 81B). It is not known which is stratigraphically above which. Since the core was considerably stretched upon extrusion (Gadd, 1986), it is possible the bedding has been distorted. Nevertheless, sample 81A was found to consist of 99% of *Cassidulina reniforme*, which is atypical of zone A. Sample 81B, on the contrary, yielded an assemblage with 85% of *C. reniforme* and 6% of *Islandiella* spp., which is representative of zone A. As both samples were adjacent and as there were no grounds to create a new zone, sample 81A was included in

zone A. However, such a strong faunal change in such a short interval indicates important environmental variations during zone A at Mer Bleue. At other locations where there are more than one sample of zone A, no similar shifts are observed.

The fact that zone A appears thin on the south margin of the central basin can be explained by the higher altitudes (75 and 48 m) of the sites where it is observed in exposed sections. These higher altitudes may have resulted in a shorter period of deposition for the deep-water zone A and in an early replacement by the shallow water conditions of zone EH. In addition, there is at least one halt in sedimentation visible within zone A at the Drummondville section.

The greater thickness at St-Ambroise-de-Kildare could be the result of the longer persistence of deep conditions north of the St. Lawrence due to the northward isostatic tilt that existed in the Champlain Sea area at the time of deglaciation. It could also be the consequence of higher sedimentation rates due to the closeness of the St-Narcisse-St-Faustin ice front.

Lithologically, zone A is rather uniform. It consists mostly in silty clay without visible bedding except on rare occasions where it is underlined by dark bands of hydrotroilite (data about presence or absence of hydrotroilite comes from Québec Government borings only, *i.e.* from the central Champlain Sea). Dark specks of hydrotroilite, on the other hand, are common. Sand grains and granules are present but scattered.

ZONE B

Zone B occurs immediately above zone A throughout the low parts of the central Champlain Sea. A thin interval with

STE-PHILOMÈNE
Section 3

Column headers: ZONES | METRES ABOVE BASE OF SECTION | LITHOLOGY | SAMPLES | Polymorphinidae | Fissurina marginata | Cibicides lobatulus | Astrononion gallowayi | Islandiella norcrossi | Islandiella helenae | Cassidulina reniforme | Elphidium excavatum | Haynesina orbiculare | Elphidium incertum | Elphidium magellanicum | Elphidium hallandense | Elphidium albiumbilicatum | WALTON'S FAUNAL DIVERSITY | NUMBER OF SPECIES PER SAMPLE | NUMBER OF SPECIMENS PER 100 g OF DRY SEDIMENT

Section 2

FIGURE 9. Distribution charts for sections 2 and 3 at Ste-Philomène. Seven sections were described at this locality. Zone EH occurs in section 5 only.

Diagrammes de distribution des coupes nᵒˢ 2 et 3 de Sainte-Philomène. Sept coupes ont été élevées à cet endroit. La zone EH est présente à la coupe nᵒ 5 seulement.

assemblages transitional between A and B is locally observed; considering the size of the sampling interval (1.5 to 3 m), it is probable that the AB transition has been "missed" in many borings. Also, there are 14 samples containing less than 50 specimens which can nevertheless be considered close to B (labeled "B?") because of their stratigraphic position and their dominance in *E. excavatum*. Thirty-eight zone B (excluding B?) and 6 AB samples coming from 17 localities have been analyzed.

Zone B is characterized by the dominance of a single species: *Elphidium excavatum*. Its average proportion is 95.4% and is never lower than 81%. In some samples, *E. excavatum* is the only species observed. This dominance is diagnostic of both zones B and C, the difference between both zones being made on the basis of the morphology of *Elphidium excavatum*. The representatives of this species in zone B all belong to forma *clavata*.

Among the other species found in zone B, *Haynesina orbiculare* is the most widespread. It is present in 27 out of 35 samples, usually as the second most abundant species.

Its average proportion for zone B is 2.9%; it varies from 0 to 15%.

Cassidulina reniforme occurs in 18 out of 35 zone B samples and its maximum frequency reaches 8%. Its average is only 0.9%. The percentage of *C. reniforme* varies vertically within zone B. It is usually more frequent in the lower part, where it may be the second most abundant species. Further up in zone B, it is very rare and commonly absent.

Islandiella helenae is either absent or extremely rare. *Elphidium albiumbilicatum* is present in zone B, within the area of study, at the average rate of less than 1% although further east, Guilbault (1980) has reported it to be locally as high as 25%. Polymorphinidae are a common occurrence in zone B (up to 3%, usually 1% or less); their distribution is irregular.

The existence, between zones A and B, of assemblages of intermediate composition implies that the passage from one zone to the next is transitional. These assemblages show a higher percentage of *Elphidium excavatum* than zone A but their cassidulinid content is lower. They may contain *Cassidulina reniforme* and *Islandiella* spp. or only *C. reniforme*.
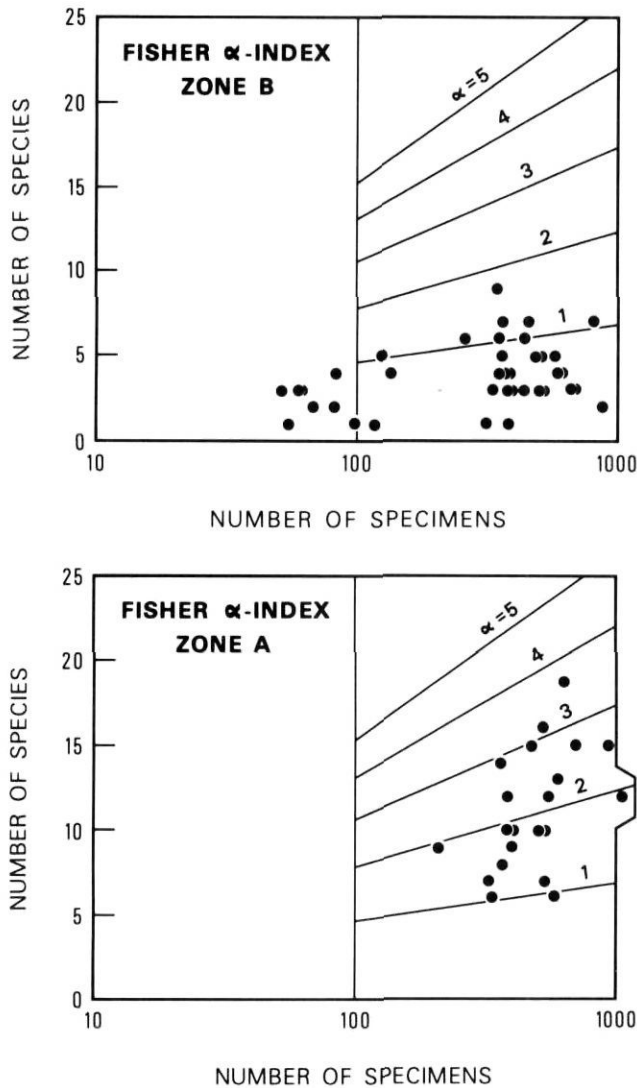
FIGURE 10.   Fisher α-index diagrams for zones A and B. Transitional A-B samples have been excluded.

Diagrammes de l'index α de Fisher pour les zones A et B. Les échantillons de transition A-B ont été exclus.

In Figure 2 and in the distribution charts, transitional assemblages are treated as a subzone and labeled "AB". The limit between AB and B has been arbitrarily set at 10% of *C. reniforme* and 1% of *Islandiella* spp., lower percentages indicating zone B. The limit between A and AB has been set at 50% of *Elphidium excavatum*, lower percentages being representative of zone A. The A to B transition is best illustrated by the Verchères borehole (Fig. 11) where the sampling interval is only 75 cm.

The number of specimens per 100 g of dry sediment reaches a maximum of 11,500. The number of species per sample varies from 1 to 8, with an average of 6. Walton's faunal diversity is never higher than 3 and in most cases, only 1 or 2. Similarly, Fisher's α-index may reach 2, but usually stays around or below 1 (Fig. 10). The faunal dominance is identical with the percentage of *E. excavatum* and varies from 81 to

100 with an average of 95.4. Within the transitional AB interval, the number of species per sample varies from 4 to 15, the faunal dominance, from 62% to 84%, Walton's faunal diversity, from 2 to 4 and the Fisher α-index, from 1 to 2.

Thickness and variations of zone B

Zone B has been observed from Ottawa (Mer Bleue) in the west to St-Ambroise-de-Kildare in the east (Fig. 1). Guilbault (1980) recorded it further to the east; these occurrences will be discussed in a later publication.

Thickness estimations meet with the same kind of problem as with zone A. However, being generally thicker than zone A, zone B is represented by more than one sample at most of the sites where it occurs. This allows the setting of a lower limiting value to its thickness. Within the central Champlain Sea, zone B tends to be everywhere thicker than 3 m. The maximum possible thickness varies from 5.6 to 9.2 m, the actual thickness being probably rarely more than 6 m. The small number of occurrences of the transitional AB assemblages suggests that the AB interval is rather thin, definitely thinner than zone A.

The only place where zone B might be significantly thicker than 6 m is St-Ambroise-de-Kildare where however the absence of a recognizable zone C makes it impossible to set an upper limit. Instead, zone B grades upward into a sequence of silts and laminae of fine sand yielding only scattered foraminifera and probably representing the St-Félix-de-Valois Delta (Elson, 1962).

Zone B is absent from localities situated at higher altitudes on the south side of the central Champlain Sea. At Drummondville, St-Césaire and Ste-Philomène, zone A is directly overlain by shallow water facies. The top of zone A is at an altitude greater than 45 m at all three places. By contrast, zone B is omnipresent in boreholes drilled in low-lying areas, wherever the top of zone A is below 30 m above present-day sea level. On the north side of the central Champlain Sea, the latter observations do not hold as, for instance, zone B occurs at an altitude of 75 m at St-Ambroise-de-Kildare. This site being much closer to the ice front, it is likely that the greater isostatic downwarping has resulted in zone B now occurring at higher altitudes.

In the western Champlain Sea, zone B is everywhere much thicker than in the St. Lawrence Lowland. Minimum values are in the 20-metre range. These very thick occurrences of zone B coincide with a coarsening-upward deltaic sequence described by Gadd (1986). At Mer Bleue and Treadwell, the upper limit is unknown because zone C is absent and zone B grades progressively upward into B? levels. An important proportion of the B? samples may be the product of redeposition. There is no similar thick deltaic sequence in the central Champlain Sea near Montréal and thus it is not possible to correlate the upper part of the fossil sequence between Montréal and Ottawa.

Zone B occurs in two different lithologic settings. In the central Champlain Sea, it is found in silty clays similar to those of zone A except for the presence of dark bands of hydrotroilite parallel to the bedding plane, giving to the sequence
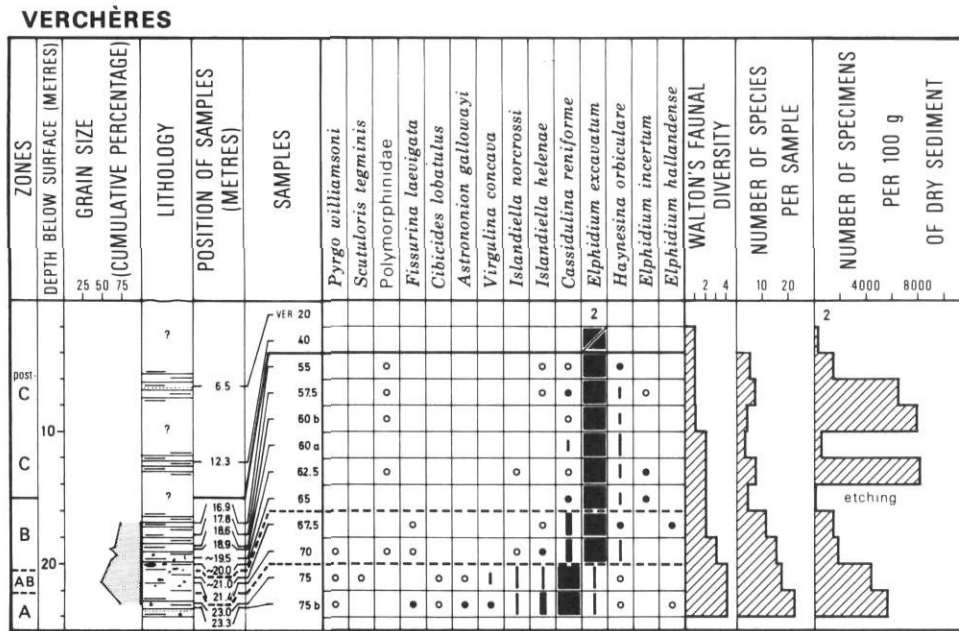
VERCHÈRES

FIGURE 11. Distribution chart for the Verchères borehole

Diagramme de distribution du forage de Verchères.

Distribution chart columns (left to right): ZONES; DEPTH BELOW SURFACE (METRES); GRAIN SIZE (CUMULATIVE PERCENTAGE) 25 50 75; LITHOLOGY; POSITION OF SAMPLES (METRES); SAMPLES; *Pyrgo williamsoni*; *Scutuloris tegminis*; Polymorphinidae; *Fissurina laevigata*; *Cibicides lobatulus*; *Astrononion gallowayi*; *Virgulina concava*; *Islandiella norcrossi*; *Islandiella helenae*; *Cassidulina reniforme*; *Elphidium excavatum*; *Haynesina orbiculare*; *Elphidium incertum*; *Elphidium hallandense*; WALTON'S FAUNAL DIVERSITY 2 4; NUMBER OF SPECIES PER SAMPLE 10 20; NUMBER OF SPECIMENS PER 100 g OF DRY SEDIMENT 4000 8000.

Zones (top to bottom): post-C, C, B, A-B, A. Sample positions (metres): 6.5, 10, 12.3, 16.9, 17.8, 18.6, 18.9, ~19.5, ~20.0, 21.0, 21.4, 23.0, 23.3. Samples (top to bottom): VER 20, 40, 55, 57.5, 60 b, 60 a, 62.5, 65, 67.5, 70, 75, 75 b. Note: "etching" marked in the specimens-per-100 g column.

a rhythmic aspect. The earliest dark bands may be found as low as the top of zone A to as high as middle or upper zone B. Sand grains and granules are exceptional. In the western Champlain Sea, zone B occurs in the coarsening upward deltaic sequence mentioned above (units 4 and 5 of Gadd, 1986) with a concentration in the basal, finer-grained part.

ZONE C

Twenty zone C samples (14 localities) have been analyzed, 6 of which yielded more than 50 foraminifera. Like zone B, this zone is found at lower altitudes in the central parts of the St. Lawrence and Ottawa Lowlands. It does not occur at higher elevations on the south margin of the central basin such as at Drummondville, St-Césaire and Ste-Philomène. Zone C has never been found in direct contact (*i.e.* underlying or overlying) with EH or EA. It is thus not possible to say how it correlates with the shallow-water facies.

In most samples of zone C, the only foraminifer species present is *Elphidium excavatum*. Zone C can be set apart from zone B by using variations in the morphology of *E. excavatum*. Since the variants recorded in zone C are found nowhere else in the underlying strata, their presence cannot be attributed to redeposition and must have been characteristic of that stage in the basin's evolution. Therefore, the presence of only a few of those variants (hereafter referred to as "morphotype C" specimens of *E. excavatum*) identifies zone C. Guilbault (1980) labeled those forms "well-developed specimens of *Elphidium excavatum*".

In contrast to specimens from earlier zones, individuals belonging to morphotype C of *E. excavatum* are large but laterally flattened, have either a small central boss or none at all and a very small umbilical area. The sutures may be strongly bent backward and the sutural area may or may not open into the umbilical area. The periphery may vary from smooth to quite strongly lobate. The most striking feature, along with the lateral compression, are the many long sutural

bridges which are not observed in zones A, B or in the pre-A interval. Plate I illustrates the difference between the morphotype C specimens and other, simpler morphotypes.

The system of formae proposed by Feyling-Hanssen (1972) and Miller *et al.* (1982), which is based on umbilical characters, can be applied to morphotype C specimens but the transition between these morphotypes and those of earlier zones does not coincide with the transition between forma *clavata* and forma *excavata*. Some morphotype C specimens are referable to forma *clavata* while others belong to forma *excavata*. The author intends to elaborate further on the variants of *E. excavatum* in a later publication.

In the 6 samples containing more than 50 specimens, *E. excavatum* accounts for between 95 and 100% of the assemblage. In the other samples, most if not all specimens are *E. excavatum*. Although some morphotype C forms are always present (in accordance with the definition of zone C) a strong proportion of the recorded specimens are similar to those found in zone B. The morphotype C forms do not appear suddenly without transition at the base of zone B but instead gradually. The *E. excavatum* of zone B are clearly somewhat more complex, on the average, than those of zone A. This is particularly visible in the upper part of zone B. The base of zone C corresponds to a point where the most complex specimens in a sample reach a higher, arbitrarily set level of complexity labeled "morphotype C" (the impression of "complexity" comes mostly from the many, long sutural bridges).

Other species occur in small numbers in zone C. The most common are *Haynesina orbiculare*, *Cassidulina reniforme* and undifferentiated Polymorphinidae.

Abundances are low, rarely more than 200 specimens per 100 g. In most samples, only a few specimens are found and the populations are too small to allow the use of diversity indices. In the few cases where they can be used, the results are the same as with zone B.

Thickness and extent of zone C

The thickness of zone C varies between 3 and 10 m but more commonly does not exceed 6 m. Plaisance (Figs. 1 and 2) is the only locality where the greatest allowable thickness is higher (27.5 m) but this figure probably reflects the extremely wide sampling interval in that part of the core.

Zone C occurs at most localities where zone B is present. It is however absent from two of the four Ottawa Valley borings (Treadwell and Mer Bleue) and from St-Ambroise-de-Kildare. It is likely that at these localities, rapid deltaic sedimentation resulted in a strong dilution of the assemblages even near the base of zone B.

Guilbault (1980) did not observe zone C further east than Ste-Monique-de-Nicolet (locality 117 of Gadd, 1971). In contrast, he recognized zone B as far east as Rivière Ste-Anne (section reported by Occhietti, 1977). It seems therefore that zone C does not extend as far east as zone B.

Lithologically, zone C and the overlying post-C beds are a continuation of zone B, with the same dark bands of hydrotroilite. At a point that may be situated in zone C or in post-C, thin beds and laminations as well as small pockets of sand begin to appear, although the sequence remains essentially clayey and silty. The dark bands commonly vanish a few metres before the surface.

POST-C LEVELS

The uppermost samples of zone C are frequently overlaid by a more or less thick layer of unfossiliferous or very poorly fossiliferous clayey sediment which is usually included under the designation "Champlain Sea clay". The designation "post-C" has been applied collectively to all these deposits because the data they yielded, if any, were not correlatable. The limit between C and post-C is difficult to set with certainty and on the general correlation chart (Fig. 2), it is represented by a dashed line.

The foraminiferal tests present at post-C levels constitute a representative sampling of the commonest Champlain Sea species. They are mostly *Elphidium excavatum* (not the morphotype C type) and *Cassidulina reniforme* with occasional *Haynesina orbiculare* and *Islandiella helenae*. There are rarely more than 5 or 10 specimens in one sample, more commonly 1 or 2 and usually none at all. Oligohaline ostracodes and charophyte oogonia have been recorded on rare occasions.

Sedimentation remains remarkably similar as one goes up above zone C. Fine sandy layers may appear in the upper part of the section but it is not related to any zone limit and their occurrence and level of appearance may vary considerably from locality to locality.

SHALLOW WATER ZONES

These zones are not discussed in as much detail as the deep water sequence. They have already been studied elsewhere (Cronin, 1977a) and their interest lies mainly in the contrast they offer with the deep water sequence and their implications for the paleoceanography (see Paleoenvironmental Discussion).

The shallow water zones have been designated respectively EH and EA. Both zones are distinguished from the deep water zones (pre-A, A, B, C and post-C) by the relatively high proportion of the following species, which will be considered shallow water indicators for the rest of this paper: *Elphidium albiumbilicatum*, *E. hallandense*, *E. incertum* and *Haynesina orbiculare*. Collectively, they represent, on the average, 57% of the shallow water samples at Drummondville, Ste-Philomène and St-Césaire, with a minimum of 31% and a maximum of 96%. By contrast, they represent an average of only 3% of zones A and B and a maximum of 14% of zone A. Furthermore, the only one of the 4 shallow water indicators to occur in significant numbers in zones A and B is *H. orbiculare*.

The shallow water zones tend to occur in coarser sediment than the deeper water zones. They are usually found in sandy clays, clayey sands and loose sands. They occur one above the other, EA being at the top. They are distinct in their occurrence from the deep water sequence in the sense that one may find sections containing either the sequence from pre-A to post-C or the EH-EA sequence but no interstratification of both. Apart from the passage from the deep water sequence to the shallow water sequence commonly observed at one point only in a given section (for example, after zone A at Drummondville), the two sequences occur separately.

ZONE EH

The most commonly occurring species in zone EH is *Elphidium excavatum*. *Islandiella helenae* may be as important as in zone A, or nearly absent. The small species *Eoeponidella pulchella* is frequent at St-Césaire where a 63 μm sieve was used. Among the shallow water indicators mentioned above, *E. albiumbilicatum* is rare or absent, whereas the three others are common. The most important forms for distinguishing zone EH from zone EA are *Elphidium hallandense* and *E. albiumbilicatum*, the first being more frequent than the second in zone EH and the reverse being true in zone EA.

In zone EH, the values for Walton's faunal diversity vary from 5 to 8, the number of species per sample from 17 to 27 and the dominance, from 29 to 58%. Fisher's α-index ranges from 3 to 7 and the number of specimens per 100 g of sediment, from 1100 to 4000. The diversity values are comparable to those of zone A, the smaller range of variation being probably due to the small number of samples.

ZONE EA

This zone is composed predominantly of varying proportions of *Elphidium excavatum*, *E. albiumbilicatum* and *Haynesina orbiculare*. *E. hallandense* is rare or absent. *Islandiella* spp. may be common, but not as much as in zone EH and frequently in the form of damaged (redeposited?) specimens.

The number of specimens per 100 g of sediment varies from 80 to 5100 and the number of species per sample from 5 to 16. Walton's faunal diversity ranges from 2 to 7, Fisher's α-index from 1 to 2.5 and the dominance, from 36 to 92%. Diversities are thus generally inferior to those of zones EH and A, but superior to those of zone B.

In addition to the three localities reported here, the EH-EA sequence has been reported by Guilbault (1980) at Rang Ste-Germaine near St-Joseph-du-Lac, ca. 30 km west of Montréal (lithologic description and location in Hillaire-Marcel et al., 1974) and in two boreholes at St-Alban, north of the St. Lawrence River, between Trois-Rivières and Québec (details in Guilbault, 1980).

COMPARISONS WITH OTHER STUDIES

In the Ottawa Lowland, interesting comparisons can be made with the results of Rodrigues and Gadd (1987). An *H. orbiculare* peak, accompanied by a small peak in *Elphidium incertum* and designated "ecozone F2", has been reported by these authors from a section at Navan, Ontario, between their ecozones F1 (present zone A) and F3 (probably zone B). A similar ecozone ("FC") is reported in the same paper in one sample of a section situated at Bearbrook, Ontario. No such peak appears in the Ottawa Lowland boreholes discussed here nor in the central Champlain Sea. The altitude of occurrence of the tops of ecozones F1 and FB at Navan and Bearbrook are respectively 95 and 67 m, which is much higher than the top of zone A at Mer Bleue and Bourget (30 m and 24 m). The *H. orbiculare* peak could represent a short period of shallower waters (resulting from low sea levels) followed by a temporary return to deeper water. It would have affected only the higher localities. Elson (1968b) proposed a similar oscillation of relative sea levels to explain the stratigraphy of the Ste-Philomène section but there is no evidence to suggest that both events, if real, are correlative. The presence of an assemblage resembling zone B at 95 m at Navan (much higher than in the region of Montréal) is probably not due to greater isostatic downwarping in the Ottawa Valley. Instead, it may be the result of an earlier A to B transition, resulting from the influx of fresh water in the upper Ottawa Valley. Ecozone F4 at Navan seems to be the same as the present zone EA, and *Elphidium* sp. (illustrated by Rodrigues and Richard, 1986) is probably *Elphidium albiumbilicatum*.

Rodrigues and Gadd (1987) found strata correlatable with the present pre-A levels at Casselman, Ontario. They saw, underneath zone A-type assemblages, a fully lacustrine layer followed by a short brackish interval while at Bearbrook, the brackish phase was 1 m thick and no lacustrine phase was detected. At Sparrowhawk Point, New York, there is a lacustrine-brackish sequence but the full marine phase is not present (Rodrigues, 1987).

Anderson (1987) reports on the palynology of the Mer Bleue core and of a few other localities in eastern Ontario. The early lacustrine phase (pre-A interval of this paper) corresponds to his pollen zone 9 (herb-shrub) whereas the rest of the core, from the base of the marine sequence up to a core depth of 20 m, corresponds to pollen zone 7 (*Picea*); pollen zone 8 (*Populus*) is totally lacking. In their regional stratigraphy, zone 8 corresponds to an interval extending from 11,000 to 10,200 a BP. Although Anderson does not comment on it, this apparent hiatus might explain the relative thinness of zone A at Mer Bleue as well as the sharp passage from lacustrine to marine facies.

The percentages observed in the Verchères borehole are consistent with the vertical distribution reported by Corliss et al. (1982) in their Lake Champlain cores, where *Islandella* spp. peaks simultaneously with *C. reniforme* but where this last species declines more slowly than *Islandiella* spp. concurrently with an increase in *E. excavatum*. In the Lake Champlain cores however, a peak in *Haynesina orbiculare* precedes the *E. excavatum* maximum, a feature not observed in the present set of samples.

The present author has made a qualitative investigation of the Lake Champlain Cores 13 and 14 of Fillon and Hunt (1974) and can compare them with his own zonal scheme (Table IV). The composition of the zones is sufficiently contrasted that a quick examination is sufficient to determine which species is dominant, without having to do an extensive count. At the bottom of core 13, two samples were found that were assignable to pre-A levels; Fillon and Hunt did not examine them. The lower sample contained *Candona* and the other, the brackish ostracode *Cytheromorpha macchesneyi*. Both samples yielded foraminifera and therefore were not fully lacustrine. Overlying this are Fillon and Hunt's assemblages V and W, characterized by different proportions of *Cassidulina reniforme* (they refer to it as *Islandiella islandica*) and *Islandiella helenae* (*I. teretis*). Both correspond to this paper's concept of zone A.

Fillon and Hunt's assemblage X, with its dominance of *Haynesina orbiculare* (*Protelphidium orbiculare*) and *Elphidium bartletti* (this species was not confirmed by the present author's investigation) has no clear equivalent in the present stratigraphy. However, it is similar in position and content to the *H. orbiculare* peak of Corliss et al. (1982) and to ecozones F2 and FB of Navan and Bearbrook (Rodrigues and Gadd, 1987), and could be similarly explained by postulating a low water phase. The present-day altitude of the Lake Champlain cores is very low but if one takes into account the northward isostatic gradient that must have existed in late-glacial time, then it seems possible for water depth in that area to have been rather reduced.

TABLE IV

Lake Champlain cores C-13 and C-14 according to Fillon and Hunt (1974) and following the present zonal scheme

Fillon and Hunt (1974)	This paper
FW	post-C
Z Y	B
X	absent from the central St. Lawrence Lowland
W V	A
not investigated	pre-A
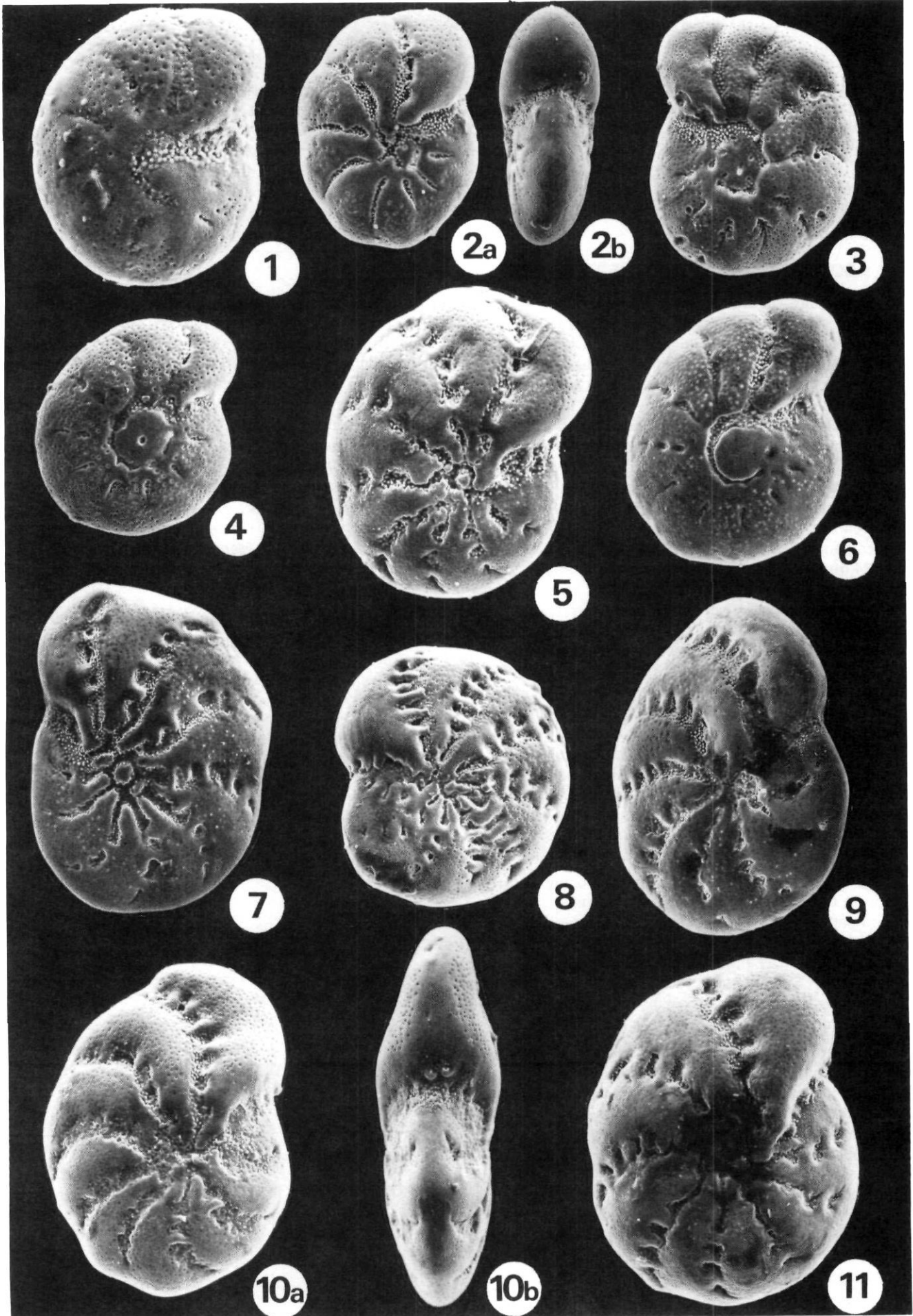
The only place within the present material where a peak in *H. orbiculare* can be suspected is one single sample in one of the holes of Île Perrot (sample IPE-F1-60). This small assemblage of deeply etched tests, situated between zones A and B, contains 66% of *H. orbiculare*. It is situated between zone A and zone B. Its foraminiferal assemblage has been deeply etched and dissolved by groundwater and it should not be considered quantitatively representative.

Assemblages Y and Z consist in an increasing proportion of *E. excavatum* and a decreasing proportion of *Haynesina orbiculare*. Both are assignable to zone B. No morphotype C specimens of *E. excavatum*, typical of zone C, have been discovered in Lake Champlain cores. Finally, the FW deposits with their diatoms are fresh-water and belong to early Lake Champlain. They may be considered "post-C" but they are difficult to compare with the St. Lawrence Lowland's post-C deposits, which did not yield any diatom.

The shallow water zones EH and EA correspond respectively to Cronin's (1977a) concept of *Hiatella* and *Mya* phases for the Lake Champlain area, both in terms of species composition and diversity. In the Montréal region, zone EA is present in *Mya arenaria* beds at Ste-Philomène and at Rang Ste-Germaine. At both localities, zone EH is found in the underlying *Hiatella*-rich, *M. arenaria*-free deposits. At Rang Ste-Germaine, there is a certain thickness of EA beds underlying the earliest occurrence of *M. arenaria*. The transitional hyposaline phase of Cronin (1977a and b) has not been recognized in the shallow water facies of the present material, but it may be considered equivalent to the pre-A interval of the deep water sequence.

PALEOENVIRONMENTAL DISCUSSION

PRE-A LEVELS

The samples collected at pre-A levels represent environments that vary from moderately hyposaline to fully lacustrine. However, the presently available data — in particular because of the large sampling intervals — do not allow a clear recognition of both an earlier basinwide lacustrine phase and a subsequent hyposaline phase. The most reasonable interpretation of the deepwater pre-A assemblages is that they represent, on the average, less marine (*i.e.* less saline) conditions than the overlying zone A.

A critical evidence in the interpretation of pre-A assemblages is the occurrence of the freshwater ostracode genus *Candona*. Any sample containing *only* this genus may be considered lacustrine, unless there is a good reason to believe it has been redeposited. There are such lacustrine samples near Ottawa, at Mer Bleue and Touraine and further east, at Ste-Philomène and Île Perrot.

At the Mer Bleue site, in a part of the basin where Gadd (1986) reports the extensive occurrence of rhythmic or varved deposits at the top of the Late Wisconsinan till, the lacustrine phase seems to have persisted up to the base of zone A, when high salinity water abruptly came in. This apparent abruptness could be due to a hiatus (see earlier comments about Anderson, 1987). At Touraine, the pre-A phase is represented by only one sample and it is *Candona*-bearing lacustrine. Rodrigues and Gadd (1987) report a lacustrine-brackish-marine sequence at Casselman. At Île Perrot and St-Césaire, lacustrine layers are intercalated with other assemblages consisting of *Candona* plus a few foraminifera, indicating shifting marine/non-marine conditions. At Drummondville and St-Ambroise-de-Kildare, there is no evidence of lacustrine conditions in the pre-A interval save for a few varves at the first locality. The influence of salt water manifests itself already in the earliest sampled beds. As the underlying glacial deposits were not observed at any of both localities, an early lacustrine phase remains possible.

In the Lake Champlain area, the existence of a transitional brackish phase has been established by Cronin (1977a and b) for shallow water environments while in the deep water material, the cores of Fillon and Hunt sampled only hyposaline pre-A beds but no fully lacustrine deposits.

In summary, western Champlain Sea data contain much evidence of fully lacustrine environments, plus evidence of a transitional hyposaline phase. Going eastward, fully lacustrine environments become more and more scarce while hyposaline conditions become predominant even though they contain lacustrine intercalations.

PLATE I. *Elphidium excavatum* (Terquem)

Figures 1-4, 6: Smaller morphotypes, found in all zones. 1) Forma *clavata*, Verchères, sample 75b, zone A, ×250; 2) Forma *clavata*, Yamaska F-13, sample 70, zone B. Figure 2a: lateral view, ×150; 2b: apertural view, ×150; 3) Forma *clavata*, Île Perrot F-3, sample 50, zone B, ×150; 4) Forma *clavata*, St-Roch-de-Richelieu, sample 140b, zone B, ×150; 6) Forma *clavata*, St-Roch-de-Richelieu, sample 140b, zone B, ×150.

Figure 5: Transitional morphotype. Forma *clavata*, St-Roch-de-Richelieu, sample 120, zone C, ×150.

Figures 7-11: Morphotype C, present only in zone C: 7) Forma *clavata*. St-Roch-de-Richelieu, sample 110, zone C, ×120; 8) Forma *clavata?*, St-Roch-de-Richelieu, sample 110, zone C, ×120; 9) Forma *excavata*, St-Roch-de-Richelieu, sample 120, zone C, ×120; 10) Forma *excavata*, St-Roch-de-Richelieu, sample 120, zone C: 10a) lateral view, ×120; 10b) apertural view, ×133; 11) Forma *excavata?*, Yamaska F-13, sample 60, zone C, ×120.

PLANCHE I. Elphidium excavatum (*Terquem*)

Figures 1-4, 6: Petits morphotypes, présents dans toutes les zones: 1) Forma clavata, *Verchères, échantillon 75b, zone A, ×250; 2) Forma* clavata, *Yamaska F-13, échantillon 70, zone B. Figure 2a) vue latérale, ×150; 2b) vue frontale, ×150; 3) Forma* clavata, *île Perrot F-3, échantillon 50, zone B, ×150; 4) Forma* clavata, *St-Roch-de-Richelieu, échantillon 140b, zone B, ×150; 6) Forma* clavata, *St-Roch-de-Richelieu, échantillon 140b, zone B, ×150;*

Figure 5: Morphotype de transition. Forma clavata, *St-Roch-de-Richelieu, échantillon 120, zone C, ×150.*

Figures 7-11: Morphotype C, présent seulement en zone C: 7) Forma clavata, *St-Roch-de-Richelieu, échantillon 110, zone C, ×120. 8) Forma* clavata?, *St-Roch-de-Richelieu, échantillon 110, zone C, ×120; 9) Forma* excavata, *St-Roch-de-Richelieu, échantillon 120, zone C, ×120; 10) Forma* excavata, *St-Roch-de-Richelieu, échantillon 120, zone C: 10a) vue latérale, ×120; 10b) vue frontale, ×133; 11) Forma* excavata?, *Yamaska F-13, échantillon 60, zone C, ×120.*

ZONE A

Zone A assemblages are comparable in their species composition to those of other Pleistocene-Holocene glacial seas, *i.e.* seas that bordered retreating continental ice sheets. Although the species proportion may vary from basin to basin, the main species are *Elphidium excavatum, Cassidulina reniforme, Islandiella helenae, I. norcrossi, Buccella frigida, Haynesina orbiculare* and *Nonion labradoricum*. In North America, such assemblages have been reported in late-glacial sediments of the Scotian Shelf by Vilks and Rashid (1976), on the Labrador Shelf by Vilks *et al.* (1982) and in Lake Melville by Vilks *et al.* (1987). Similar assemblages have been reported in a core from Hudson Bay by Leslie (1965) and in many cores from the Beaufort Shelf by Vilks *et al.* (1979), as well as in the Prudhoe Bay cores of McDougall *et al.* (1986). On land in Eastern Canada, these assemblages have been reported in the Goldthwait and Tyrrell seas, as reported by Wagner (1968). Similar assemblages have been reported from Norway, Denmark and Western Sweden (Feyling-Hanssen, 1964; Feyling-Hanssen *et al.*, 1971 and Knudsen, 1982); these are rich in *Nonion labradoricum* and poor in *Islandiella helenae*. Usually, localities showing reduced diversities and a strong dominance of *E. excavatum* have been considered hyposaline while those with high diversity values and a dominance of *Islandiella* spp. and/or *Nonion labradoricum* have been interpreted as more saline and open-marine.

Paleoenvironments are usually interpreted by making comparisons with equivalent living assemblages and their occurrences. Unfortunately, comparisons between zone A and modern cold-water shelf-depth faunas are difficult as many of the latter are dominated by arenaceous species while the Champlain Sea's (including zone A) and other glacial clay assemblages characteristically contain few or no arenaceous forms. It is not our purpose here to discuss the reasons — whether environmental or diagenetic — for this relative poorness in arenaceous forms, but just to indicate that it makes it difficult to find a good modern equivalent. A good modern equivalent for zone A might be the shallow waters of the Beaufort Sea; however the only study on that area (Vilks *et al.* 1979) does not give information on the distribution of living foraminifera. Elverhø *et al.* (1980) report living calcareous glacial faunas in Spitsbergen but as they contain few *Islandiella* and a strong proportion of *N. labradoricum*, they are difficult to compare with zone A.

Based on the salinities and bathymetries reported by various authors for living faunas whose calcareous component, regardless of the number of arenaceous specimens, is similar in composition to zone A, Guilbault (1980) suggested that zone A-like assemblages were living at depths usually exceeding 20 m with salinities in the range of 27 to 33‰. That interpretation was based on data reported by the following authors: Leslie (1965), Vilks (1968), Sen Gupta (1971), Hooper (1975), Aasgaard (1978) and on recent samples from Kejser Fanz Josef Fjord in eastern Greenland supplied to the author by Peter Konradi of the Geological Survey of Denmark. Additional information not included in Guilbault (1980) concerning

zone A-like assemblages and more specifically the salinity requirements of *Islandiella helenae* and *I. norcrossi* can be found in Rodrigues and Hooper (1982) (30.7 to 34.3‰ for their associations 1 to 4 which contain a high proportion of these two species). Also, Mudie *et al.* (1984) discovered the existence, in the Labrador Sea and Lake Melville, of a salinity-sensitive *Islandiella helenae* "factor" (designated F5) whereas the F1 "factor" (*Elphidium excavatum*) shows little relation to salinity.

The range of salinities reported by the above-mentioned references for *I. helenae-I. norcrossi*-dominated faunas suggests that fossil assemblages with a strong percentage of these species, such as zone A, did not live in areas where salinities reached below 25‰.

Such a salinity is too low to be called normal or stenohaline. It does not represent deep, open shelf conditions. The term polyhaline may be more appropriate. It is nevertheless the highest salinity recorded in the Champlain Sea basin and for the rest of the paper will be considered "high".

There are two approaches to the paleobathymetric interpretation of the Champlain Sea zones. One consists in comparing the present altitude of occurrence of an assemblage that is dated or whose age can be estimated with the altitude of the nearest dated shoreline, taking into consideration, where necessary, the regional isostatic tilt. For example, at St-Roch (Figs. 1 and 2), zone A occurs in one sample situated at 31 m below present sea level. Considering that the highest marine beaches on Mont St-Hilaire and Mont Royal are at approximately 170 m (LaSalle, 1966; Prest and Hode-Keyser, 1975), the greatest possible paleodepth for that sample is *ca.* 200 m, assuming that the sample represents a very early marine phase. Since datings suggest zone A to be somewhat younger (see "chronology" section), a more reduced depth is likely. On the other hand, the maximum altitude of *ca.* 60 m that has been found for the post-Champlain *Lampsilis* deposits (Elson, 1969a and b; Terasmae, 1960). Assuming that Champlain Sea water levels have never been lower than those of Lake Lampsilis, depth must have been more than 90 m even during the latest Champlain Sea phases. If we allow a certain time for the deposition of zones B and C before the return of lacustrine conditions, a paleodepth of the order of 150 m appears reasonable for zone A at St-Roch.

An other way of studying Champlain Sea paleobathymetry is to rely on the information supplied by the foraminifer assemblages. Foraminifera are not affected by depth alone, *i.e.* by hydrostatic pressure, but rather react to varying temperature and salinity conditions which may be related with depth within a given area. An idea of the contrast between shallow bay and deep offshore faunas can be obtained by comparing, for example, the results of Bartlett (1966) for Tracadie Bay or Buzas (1965) for Long Island Sound with those of Rodrigues and Hooper (1982) from the deeper parts of the Gulf of St. Lawrence or Williamson *et al.* (1984) for the deep Scotian Shelf.

In the Champlain Sea, there exists a contrast between two sequences, one that suggests shallow water (EH, EA) and the other, deep water (pre-A, A, B, C, post-C). The former

is characterized by the relative abundance of four species (*E. albiumbilicatum*, *E. hallandense*, *E. incertum* and *H. orbiculare*) that reach their maximum concentration in the shallowest waters where seasonal variations in salinity are the strongest. The deeper water zones of the Champlain Sea contain very few of these shallow water species and more of *Islandiella* spp. which is less tolerant to salinity variations and therefore suggestive of deeper waters. It is not possible however to assign an actual depth figure to each assemblage: In a fjord-like situation such as the Champlain Sea, a low salinity surface layer probably developed every summer. A similar situation is documented in the Gulf of St. Lawrence (Canadian Oceanographic Data Centre quoted by Rodrigues and Hooper, 1982) and in Lake Melville and the neighbouring shallow parts of the Labrador Sea (Vilks *et al.* 1982, 1987). It is likely that the shallow water assemblages of the Champlain Sea correspond to the occurrence of the shallow brackish layer whereas the deep water assemblages lived in the deeper, stable water. The bathymetric limit between these water masses may vary from basin to basin and within the same basin depending on the influx of freshwater and the distance from its source. In Lake Melville, Vilks *et al.* (1982, 1987) found the base of the halocline (or reduced salinity layer) to lie at a depth of 25 m, coinciding with a summer salinity of 20‰ while in Groswater Bay (open Labrador Sea) it is situated at *ca*. 40 m and summer salinities of 32‰.

In the Champlain Sea, especially in the western part, the limit may have been deeper and in the later part of the basin's history the runoff from the accelerated melting of the Laurentide Ice Sheet may have been such as to create brackish conditions possibly over the whole water column (an alternative cause could be a change in the drainage pattern along the receding ice front which would have caused large amounts of meltwater to be diverted from the Great Lakes area towards the St. Lawrence Basin). The faunal change from zone A to zone B might be due to such an invasion by hyposaline water. However, as shallow water assemblages are found at all stages of Champlain Sea evolution, EA substituting for EH in later times, there has to be shallow water equivalent facies to zones B and C even though it is not known how both sequences correlate. Thus we have to admit that however strong the influx of freshwater, some form of differentiation persisted between deep and shallow water until the end of the marine invasion.

The presence of a sizable proportion of *Islandiella helenae* in some samples of zone EH, in particular at Drummondville, implies, if the above line of thinking is right, that the salinity at or slightly above the base of the halocline was superior to 25‰. This is lower than in the Labrador Sea but higher than in Lake Melville (Vilks *et al.*, 1982). This is not surprising since in the Champlain Sea, even though the freshwater input may have been much greater than in Lake Melville, the basin was larger and the connection with the open sea undoubtably broader except in the late phases.

As to the actual thickness of the seasonal layer in the Champlain Sea during the deposition of zone A, the solution to the problem, potentially interesting paleoceanographically,

will come only by comparing altitudes of dated occurrences of zone A with dated shorelines.

In terms of temperature, zone A is typically "arctic". The phrase "arctic foraminifera" is not formally defined but can be used to designate species that can live in polar waters or waters of polar origin, where the temperature stays below approximately 3°C year round. Most species recorded in the Champlain Sea are either cosmopolitan or at least are not restricted to polar waters but all of them can be found in polar waters.

In addition to cold-tolerant cosmopolitan forms, there are a few species whose distribution seems restricted to cold seas. Sejrup and Guilbault (1980) concluded from a search of the literature and from field evidence in Western Norway that *Cassidulina reniforme* lived only in arctic waters. Guilbault (1980) reached the same conclusion concerning *Islandiella helenae* by compiling the literature. Those two species are the most common in zone A and clearly point to a cold water environment. No species limited to even slightly warmer conditions has ever been found in zone A. Assemblages reported by other authors (Fillon and Hunt, 1974; Cronin, 1977a and b, 1979; Corliss *et al.*, 1982; Rodrigues and Gadd, 1987) from equivalent biofacies similarly indicate cold water. The same paleotemperature discussion applies to zones B and C.

Arctic waters are found today in the Gulf of St. Lawrence at intermediate depths, *i.e.* between 60 and 125 m, where temperatures stay between $-2°$ and $+1°C$ year-round (Canadian Oceanographic Data Centre quoted by Rodrigues and Hooper, 1982). Therefore, despite the postglacial climatic improvement, some parts of the Gulf of St. Lawrence remain essentially as cold as the Champlain Sea; it follows that air temperatures (*i.e.* climate) may well have improved during Champlain Sea time while having no effect on bottom water temperatures except in the shallowest areas, such as the *Mya arenaria* beds (Elson and Elson, 1959; Cronin, 1977a).

The ostracodes occurring in zone A (whether in the present area or further east) belong predominantly to the genus *Cytheropteron*. According to Cronin (1980, pers. comm.), the species recorded (mostly *Cytheropteron pseudomontrosiense*, *C. champlainum* and *C. paralatissimum*) suggest offshore conditions and relatively deeper water. The salinity would be included between 35‰ and less than 25‰, possibly as low as 15‰ (Cronin, 1987, pers. comm.). This does not conflict with the foraminifer results.

ZONE B

This zone is dominated by one species, *Elphidium excavatum*, which is very tolerant to salinity variations and can be found living at salinities as low as 10, possibly 7.25‰ (Miller *et al.*, 1982, p. 125). The forma *clavata*, which is the only variant form (forma) occurring in zone B, can be found at all depths on the continental shelf and even on the slope (Schafer and Cole, 1982). The second most common form, *Haynesina orbiculare*, is about as tolerant as *excavatum* to changes in salinity. Both *E. excavatum* and *H. orbiculare* are cosmopolitan, living in many climatic zone. *Cassidulina ren-*

iforme may be less salinity tolerant than the preceeding species, but it occurs in the lower part of the zone where the salinity can be expected to be higher.

The very low diversities of zone B, the strong dominances of forms that are among the most salinity tolerant and the near-total absence of salinity-sensitive forms suggest low and/ or variable salinities, probably between 10 and 20‰.

The paleobathymetric interpretation of zone B poses the same problems as that of zone A. The only foraminiferal evidence is negative: it is the low percentage of typically shallow water species relatively to zones EH and EA. This implies, despite the general hyposalinity of the basin, that water stratification was persisting and that zone B assemblages were inhabiting the deeper waters, although it gives no indication as to the depth of the transition between deep and shallow assemblages.

By relying on shorelines and proceeding in the same way as zone A, it is possible to reach an approximation of the depths at which zone B assemblages flourished. We know on one hand that zone B occurs only in the lowest parts of the basin, below 30 m above present sea level (at least on the southern side of the St. Lawrence River) and on the other hand, that the highest shorelines of Lake Lampsilis seem to have been situated at up to 60 m, at least in the same general area. Thus, even in the latest phase of the Champlain Sea, water depth at all zone B sites would have been no less than 30 m, locally more than 60 m. In view of the fact that the basin did not turn lacustrine until after the deposition of zone C, it seems likely that the paleobathymetry of zone B would be closer to that of zone A than to that of Lake Lampsilis, possibly up to 100 m in the deepest parts.

According to the ostracode results supplied by Cronin (1980, pers. comm.), zone B samples were split between three ostracodal biofacies. Two of these were composed mostly of nearshore, euryhaline genera, in particular *Sarsicytheridea*, *Heterocyprideis* and *Cytheromorpha* while the third was *Cytheropteron*-dominated and identical to the ostracode biofacies found in zone A. This last biofacies occurred in samples coming rather from the lower part of zone B whereas the others came from the upper part. The paleosalinity values for the *Cytheropteron* biofacies would have been higher (15-20‰ and up to 35‰) than for both other assemblages (5 to 25‰).

The sequence of faunal events recorded in the central Champlain Sea during the deposition of zone B may then be interpreted simply in terms of a gradual reduction in paleosalinity. When salinities dropped below 25‰, zone A was gradually replaced by the more tolerant zone B and as salinities dropped even further, possibly below 20 or 15‰, the ostracode assemblages also changed.

At some point in the basin's history, following isostatic uplift which restricted the inflow of saltwater from the Québec area, and also because of increased inflow of meltwater when the ice receded northward from the St-Narcisse-St-Faustin position, there must have been a phase when conditions became strongly hyposaline over the whole basin including the deeper

parts, before turning entirely fresh. It seems likely that the reduction in salinity witnessed by zone B and the subsequent zone C coincides with that phase.

ZONE C

In terms of species composition and number of specimens, zone C looks as a natural continuation of the trends begun in zone B, *i.e.*, gradual reduction in diversity and foraminiferal numbers and greater percentage of *E. excavatum*. There is also a continuous gradation between the smaller morphotypes of *E. excavatum* of earlier zones and the morphotype C specimens of zone C. There is therefore no doubt that both belong to the same species, the morphologic change being probably the result of environmental changes.

Few references have been made in the literature to variants of *E. excavatum* such as those occurring in zone C. Brodniewicz (1972) reported similar forms (her *E. clavatum* "morphotype 3") in a Quaternary deposit in Poland. They occur in layers where the other major foraminifer species is *E. albiumbilicatum*, and disappear when the diversity increases. She interprets the assemblage as representing arctic climatic conditions, but does not comment on the salinity. However, the faunal association she reports suggests it was low.

Nagy (1965 and pers. comm.) reported from a Spitsbergen fjord (Van Keulenfjorden) some poor *E. excavatum* assemblages without illustrating the specimens. He graciously lent some of his material to the present writer who found a few of the specimens to be nearly identical to his own morphotype C forms while most others were smaller and simpler. The part of the fjord they came from was shallow (2.5 m or less). No salinity data was given but because of the presence of a nearby melting ice front, it is probable that the surface waters were nearly fresh during the warmer part of the year.

Wang and Lutze (1986) discovered that various foraminiferal groups including elphidiids, when living in low salinities, tend to develop inflated chambers. In addition, elphidiids acquire longer sutural bridges and umbilici with papillae. There is some resemblance between these observations and the present material. However, zone C specimens are laterally flattened and their outline may vary from lobate (rather than inflated) to completely smooth.

On the basis of the disappearance of less salinity-tolerant forms before the base of zone C and by referring to the results of Brodniewicz (1972), Nagy (1965 and pers. comm.) and Wang and Lutze (1986), it seems probable that the salinity in zone C was very low, as low as 7.25‰ which the lowest value found by Miller *et al.* (1982) in their review of *E. excavatum*. Even lower values cannot be excluded for short periods of time. That is consistent with the concept of the late Champlain Sea as a basin progressively turning to fresh water.

The paleobathymetric discussion of zone B applies also to zone C. By reasoning on the basis of shorelines, as with zone B, it is possible to conclude that depths were everywhere greater than 30 m, and probably superior to 60 m in the deepest part of the basin.

The only sample of zone C sent to Cronin yielded an assemblage having *Cytheromorpha macchesneyi* as a predominant species. It suggests a salinity range of 5 to 15‰. The present author recorded rare occurrences of *Candona* sp. in zone C.

POST-C DEPOSITS

The post-C levels represent the last phase of submergence in the St. Lawrence Lowlands. They may correspond to the Lake Lampsilis phase but there is no definite evidence that the environment was either marine or lacustrine. The rare foraminifera may be considered redeposited from zones A or B when marine regression exposed them to erosion. This appears likely considering that the foraminiferal tests present at post-C levels constitute a representative sampling of the commonest Champlain Sea species and that their distribution is irregular.

In order for the post-C specimens (especially those of *Islandiella* spp.) to be *in situ*, it would be necessary to admit the existence of a late saline phase of the Champlain Sea, more saline than zone C for example. This is possible (see Elson, 1969a and b) but highly unlikely. On the basis of the gradual reduction in salinity down to near zero between zone A and the top of zone C and taking into account the context of the Champlain Sea which is that of a regressing marine basin progressively turning into a lake, the author assumes that post-C deposits indeed coincide with a late lacustrine or near-lacustrine phase and that their scattered foraminifera are redeposited, at least as long as well-preserved and laterally correlatable fossil occurrences have not been reported.

CHRONOLOGY

Many radiocarbon age determinations have been carried out on marine shells from Champlain Sea sediments but the majority of them were from shallow water facies. There are very few dates on foraminiferally investigated deep water material. Two dated samples reported by Occhietti (1976) from a section on Rivière Ste-Anne, between Trois-Rivières and Québec, were studied for their foraminiferal content by Guilbault (1980). One of them was found to belong to zone A (10,600 ± 160 a BP, GSC-2090, *Balanus hameri*) and the other to zone B (10,200 ± 90 a BP, GSC-2150, *Macoma calcarea*). At Pointe-St-Nicolas, near Québec City, LaSalle *et al.* (1977) reported an age of 11,200 ± 170 a BP (GSC-1476, *Balanus hameri*) from a deposit found by Guilbault (1980) to contain a zone A assemblage. At Rivière-des-Chutes, in the sediment of the St-Narcisse Moraine, Gadd *et al.* (1972) reported an age of 11,500 ± 630 a BP (GSC-1526) on a collection of foraminifera studied for them by professor Hooper of Carleton University. It probably represents zone A, considering its high *Islandiella teretis* (probably *I. helenae*) content (95%).

The last three localities are situated to the east of the area studied in the present paper. It may be assumed that the Champlain Sea zones are diachronous and that the high-salinity zone A was briefer at more westerly localities. None of the deep water localities reported here have been dated,

but Rodrigues and Gadd (1987) report an age of 11,000 ± 90 a BP (GSC-3706, *Balanus hameri*) on their ecozone F1 (equivalent to zone A) at Navan, Ontario, and ages of 10,700 ± 100 and 10,800 ± 90 a BP (GSC-3743, *Macoma balthica*) on ecozone F4 (equivalent to zone EA) at the top of the same section. Ecozone F3 (zone B) occurs between these two dated samples. At the Bearbrook site, they found ages of 10,700 ± 130 and 10,800 ± 90 a BP (GSC-3983, *Balanus hameri*) for ecozone FB (zone A) and 10,200 ± 90 and 10,200 ± 110 a BP (GSC-3907, *Hiatella arctica*) for a late shallow phase not correlatable with the present material. At Sparrowhawk Point, New York, Rodrigues (1987) found brackish (post-*Candona*) pre-A deposits yielding ages of 11,900 ± 100 (GSC-3767, *Portlandia arctica*) and 11,900 ± 140 a BP (GSC-4044, *Portlandia arctica*). The earliest age reported for any Champlain Sea marine shell is 12,800 ± 100 a BP (GSC-2151, *Macoma balthica*; Richard, 1978).

No other ^{14}C datings are available on positively identified Champlain Sea foraminiferal biofacies. However, some indirect information exists. At St-Césaire, *Hiatella arctica* shells probably collected in the shallow water part of the section have been dated at 10,500 ± 90 a BP (GSC-2861; Lowdon and Blake, 1979) and 10,500 ± 140 a BP (QU-1059; LaSalle *et al.*, 1982). This puts a lower limit to the age of zone A at that locality. Corliss *et al.* (1982) conclude to an age of 10,850 a BP for a break in their ^{18}O curve which, they believe, coincides with Cronin's (1977b) estimate for the beginning of the *Mya arenaria* phase in the Lake Champlain area. The break in the ^{18}O curve takes place in the middle of the present zone B, above their *Haynesina orbiculare* peak.

The above data indicate that zone A assemblages were living in all major areas of the Champlain Sea around 11,000 a BP. The transition from A to B must have occurred later in the east, at the Rivière Ste-Anne section (between 10,600 and 10,200 a BP), but earlier in the west, at Navan and/or Bearbrook (around 10,700 to 10,800 a BP). This would agree with the idea that the advent of zone B is due to an influx of fresh water coming into the upper Ottawa Valley. However, the results from Navan imply a transition from zone A through an *H. orbiculare* phase, zone B and into zone EA in no more than 300 years, which seems surprisingly short. Many additional dates will be needed before a clear pattern emerges.

The transition from pre-A to A does not seem to have taken place earlier than 11,900 a BP in the Upper St. Lawrence area or later than 11,200 a BP near Québec. Assuming it took place earlier in the east than in the west, there remains a broad range of possibilities.

CONCLUSIONS

The Champlain Sea sediments are subdividable into correlatable biostratigraphic units. Paleoenvironmentally, it can be concluded that the marine waters that flooded the St. Lawrence and Ottawa lowlands in late-glacial times were at best of polyhaline nature and reached a salinity of 25 to possibly 30‰. This result is quite close to the conclusions of other authors (Wagner, 1970; Cronin 1979, 1981). During the polyhaline phase, waters from the Goldthwait Sea proceeded

freely into the Champlain Sea and so did most of the fauna. Salinities were only slightly reduced as compared to the Goldthwait Sea.

The polyhaline phase is preceeded by a freshwater to hyposaline interval that is highly variable both in thickness and composition. It is followed by a long phase of decreasing salinities that begins with polyhaline conditions and finishes with oligohaline or fresh waters. The last phase represented by the St. Lawrence Lowland clays contains no certain *in situ* marine fossils and is believed to represent oligohaline to freshwater conditions.

The few age determinations available allow only a rough estimate of the ages of the zones and the correlation with the abundantly dated shallow water deposits remains difficult. However, it seems that the high-salinity phase must have begun between 12,000 and 11,000 and ended between 11,000 and 10,000 a BP. The end seems to have occurred in the west earlier than in the east.

The A-to-B transition must have corresponded to an important environmental change in the Champlain Sea and it probably had an equivalent in the shallow water sequence. The advent of zone EA and of the subsequent *Mya arenaria* phase may be that equivalent.

ACKNOWLEDGMENTS

REFERENCES

Aasgaard, K., 1978. Foraminiferfaunaen i Kongsfjorden, Svalbard. Hovedsfagsoppgave. M. Sc. Thesis, Institut for marin biologi og limnologi, Universitetet i Oslo, 133 p.

Anderson, T. W., 1987. Terrestrial environments and age of the Champlain Sea, based on pollen stratigraphy of the Ottawa Valley-Lake Ontario region, p. 31-42. *In* R. J. Fulton, ed., Quaternary Geology of the Ottawa Region, Ontario and Québec. Geological Survey of Canada, Paper 86-23.

Bartlett, G. A., 1966. Foraminifera distribution in Tracadie Bay, Prince Edward Island. Geological Survey of Canada, Paper 66-20.

Brodniewicz, I., 1972. Pleistocene foraminifers of the area of the lower Vistula River (Northern Poland). Acta Paleontologica Polonica, 17(4): 423-525.

Buzas, M. A., 1965. The distribution and abundance of foraminifera in Long Island Sound. Smithsonian Miscellaneous Collection, 149 (1), 88 p.

Corliss, B. H., Hunt, A. L. and Keigwin, L. D., 1982. Benthonic foraminiferal faunal and isotopic data for the postglacial evolution of the Champlain Sea. Quaternary Research, 17(3): 325-338.

Cronin, T. M., 1977a. Champlain Sea Foraminifera and Ostracoda: a systematic and paleoecological synthesis. Géographie physique et Quaternaire, 31(1-2): 107-122.

———— 1977b. Late-Wisconsin Marine Environments of the Champlain Valley (New York, Quebec). Quaternary Research, 7(2): 238-253.

———— 1979. Late Pleistocene benthic foraminifers from the St. Lawrence Lowlands. Journal of Paleontology, 53(4): 781-814.

———— 1981. Paleoclimatic implications of Late Pleistocene marine ostracodes from the St. Lawrence Lowlands. Micropaleontology, 27(4): 384-418.

Dionne, J.-C., 1972. La dénomination des mers du post-glaciaire du Québec. Cahiers de géographie de Québec, 16 (39): 483-487.

Elson, J. A. and Elson, J., 1959. Phases of the Champlain Sea indicated by littoral mollusks. Geological Society of America Bulletin, 70(12), part 2: 1596 (abstract).

———— 1969a. Late Quaternary marine submergence of Québec. Revue de Géographie de Montréal, 23(3): 247-258.

———— 1969b. Radiocarbon dates, *Mya arenaria* phase of the Champlain Sea. Canadian Journal of Earth Science, 6(3): 367-372.

Elson, J. A. and Elson, J., 1959. Phases of the Champlain Sea indicated by littoral mollusks. Geological Society of America Bulletin, 70(2), part 2: 1596 (abstract).

Elverhøi, A., Liestøl, J. and Nagy, J., 1980. Glacial erosion, sedimentation and microfauna in the inner part of Kongsfjorden, Spitsbergen. Norsk Polarinstitutt Skrifter, 172: 33-61.

Feyling-Hanssen, R. W., 1964. Foraminifera in Late Quaternary deposits from the Oslofjord area. Norsk Geologisk Undersøkelse, 225, 383 p.

———— 1972. The foraminifer *Elphidium excavatum* (Terquem) and its variant forms. Micropaleontology, 18(3): 337-354.

Feyling-Hanssen, R. W., Jørgensen, J. A., Knudsen, K. L. and Lykke Andersen, A.-L. 1971. Late Quaternary Foraminifera from Vendsyssel, Denmark and Sandnes, Norway. Bulletin of the Geological Society of Denmark, 21: 67-317.

Fillon, R. H. and Hunt, A. L., 1974. Late Pleistocene benthic Foraminifera of the southern Champlain Sea: Paleotemperatures and paleosalinity indicators. Maritime Sediments, 10(1): 14-18.

Fisher, R. A., Corbet, A. S. and Williams, C. B., 1943. The relation between the number of species and the number of individuals in a random sample of an animal population. Journal of Animal Ecology, 12: 42-58.

Gadd, N. R., 1971. Pleistocene geology of the central St. Lawrence Lowland. Geological Survey of Canada, Memoir 359, 153 p.

———— 1986. Lithofacies of Leda Clay in the Ottawa Basin of the Champlain Sea. Geological Survey of Canada, Paper 85-21, 44 p.

Gadd, N. R., LaSalle, P., Dionne, J.-C., Shilts, W. W. and McDonald, B. C., 1972. Quaternary Geology and Geomorphology, Southern Québec. Guidebook, field Excursions A44-C44, XXIV International Geological Congress, Montréal.

Guilbault, J.-P., 1980. A stratigraphic approach to the study of the Late-Glacial Champlain Sea deposits with the use of foraminifera. Licentiat Thesis, Aarhus University, Denmark, 294 p. University microfilms no. 82-27, 762.

Gunther, F. and Hunt, A., 1977. Paleoecology of marine and freshwater Holocene ostracodes from Lake Champlain, Nearctic North America. Proceedings of the Sixth International Ostracode Symposium, Saalfelden, p. 327-334.

Hillaire-Marcel, C., Prichonnet, G. and Boutray, B. de, 1974. Le faciès du Pléistocène marin des collines d'Oka, Québec. Naturaliste canadien, 101 : 781-802.

Hooper, K., 1975. Foraminiferal ecology and associated sediments of the lower St. Lawrence Estuary. Journal of Foraminiferal Research, 5(3) : 218-238.

Knudsen, K. L., 1982. Foraminifers, p. 148-177. In E. Olausson, ed., The Pleistocene/Holocene Boundary in South-Western Sweden, Sveriges Geologiska Undersökning, Ser. C, no. 794.

LaSalle, P., 1966. Late Quaternary vegetation and glacial history in the St. Lawrence Lowlands, Canada. Leidse Geologische Mededelingen, 38 : 91-128.

LaSalle, P., David, P. P. and Bouchard, M. A., eds., 1982. Guidebook of the 45th Annual Meeting of the friends of the Pleistocene, Drummondville-St-Hyacinthe, Québec, Canada. Université de Montréal, 60 p.

LaSalle, P. and Elson, J. A., 1975. Emplacement of the St-Narcisse Moraine as a Climatic Event in Eastern Canada. Quaternary Research, 5 : 621-625.

LaSalle, P., Martineau, G. and Chauvin, L., 1977. Morphologie, stratigraphie et déglaciation dans la région de Beauce — Monts Notre-Dame — Parc des Laurentides. Ministère des Richesses naturelles du Québec, Exploration géologique, DPV-516.

Leslie, R. J., 1965. Ecology and paleoecology of Hudson Bay Foraminifera. Bedford Institute of Oceanography Report 65-6 (unpublished). 192 p.

Lowdon, J. A. and Blake, W., 1979. Geological Survey of Canada radiocarbon dates XIX. Geological Survey of Canada, Paper 79-7, 58 p.

MacClintock, P. and Stewart, D. P., 1965. Pleistocene Geology of the St. Lawrence Lowland. New York State Museum Bulletin 394, 152 p.

McDougall, K., Brouwers, E. and Smith, P., 1986. Micropaleontology and sedimentology of the BP Boreholes series, Prudhoe Bay, Alaska. U.S. Geological Survey Bulletin 1598, 62 p., 14 pl.

Miller, A. A. L., Scott, D. B. and Medioli, F. S., 1982. Elphidium excavatum (Terquem): Ecophenotypic versus subspecific variation. Journal of Foraminiferal Research, 12(2) : 116-144.

Mudie, P. J., Keen, C. E., Hardy, I. A. and Vilks, G., 1984. Multivariate analysis and quantitative paleoecology of benthic foraminifera in surface and Late Quaternary sediments, northern Canada. Marine Micropaleontology, 8 (4) : 283-314.

Nagy, J., 1965. Foraminifera in some bottom samples from shallow waters in Vestspitsbergen. Norsk Polarinstitutt, Årbok 1963 : 109-128.

Occhietti, S. and C. Hillaire-Marcel, 1977. Chronologie ^{14}C des événements paléogéographiques du Québec depuis 14 000 ans. Géographie physique et Quaternaire, 31 (1-2) : 123-133.

——— 1977. Stratigraphie du Wisconsinien de la région de Trois-Rivières — Shawinigan, Québec. Géographie physique et Quaternaire, 31 (3-4) : 307-322.

Occhietti, S. and C. Hillaire-Marcel, 1977. Chronologie ^{14}C des événements paléogéographiques du Québec depuis 14 000 ans. Géographie physique et Quaternaire, 21 (1-2) : 123-133.

Prest, V. K. and Hode-Keyser, J. 1975. Geology and engineering characteristics of surficial deposits, Montreal Island and Vicinity, Quebec. Geological Survey of Canada, Paper 75-27.

Rodrigues, C. G., 1987. Late Pleistocene invertebrate macrofossils, microfossils and depositional environments of the Western Basin of the Champlain Sea, p. 16-23. In R. J. Fulton, ed., Quaternary geology of the Ottawa region, Ontario and Quebec, Geological Survey of Canada, Paper 86-23.

Rodrigues, C. G. and Gadd, N. R., 1987. Day 2: Stops 2-1 to 2-5, p. 16-25. In R. J. Fulton, ed., 1986. Quaternary Geology of the Western Basin of the Champlain Sea. Geological Association of Canada, Mineralogical Association of Canada, Canadian Geophysical Union, Joint Annual Meeting, Ottawa '86, Field Trip 7: Guidebook, 35 p.

Rodrigues, C. G. and Hooper, K., 1982. Recent benthonic foraminiferal associations from offshore environments in the Gulf of St. Lawrence. Journal of Foraminiferal Research, 12 (4) : 327-352.

Rodrigues, C. G. and Richard, S. H. 1986. An ecostratigraphic study of Late Pleistocene Sediments of the Western Champlain Sea Basin, Ontario and Quebec. Geological Survey of Canada, Paper 85-22, 33 p.

Schafer, C. T. and Cole, F. E., 1982. Living benthic foraminifera distributions on the continental slope and rise east of Newfoundland, Canada. Geological Society of America Bulletin, 93 : 207-217.

Sejrup, H. P. and Guilbault, J.-P., 1980. Cassidulina reniforme and C. obtusa (foraminifera), taxonomy, distribution and ecology. SARSIA, 65 : 79-85.

Sen Gupta, B. K., 1971. The benthonic foraminifera of the Tail of the Grand Banks. Micropaleontology, 17 (1) : 69-98.

Terasmae, J., 1960. Surficial geology of the Cornwall map-area, Ontario and Quebec. Geological Survey of Canada, Paper 60-28 : 4 p.

Vilks, G., 1968. Foraminiferal Study of the Magdalen Shallows, Gulf of St. Lawrence. Maritime Sediments, 4 (1) : 14-21.

Vilks, G., Deonarine, B., Wagner, F. J. and Winters, G. V., 1982. Foraminifera and Mollusca in surface sediments of southeastern Labrador Shelf and Lake Melville, Canada. Geological Society of America Bulletin, 93 : 225-238.

Vilks, G., Deonarine, B. and Winters, G. V., 1987. Late Quaternary marine geology of Lake Melville, Labrador. Geological Survey of Canada, Paper 87-22.

Vilks, G. and Rashid, M. A., 1976. Post-glacial paleo-oceanography of Emerald Basin, Scotian Shelf. Canadian Journal of Earth Science, 13(9) : 1256-1267.

Vilks, G., Wagner, F. J. E. and Pelletier, B. R., 1979. The Holocene marine environment of the Beaufort Shelf. Geological Survey of Canada, Bulletin 303, p. 1-43 plus microfilm.

Wagner, F. J. E., 1967. Published references to Champlain Sea faunas 1837-1966 and list of fossils. Geological Survey of Canada, Paper 67-16.

———— 1968. Faunal study, Hudson Bay and Tyrrell Sea, p. 7-48. *In* P. J. Hood, ed., Earth Science Symposium on Hudson Bay. Geological Survey of Canada, Paper 68-53.

———— 1970. Faunas of the Pleistocene Champlain Sea. Geological Survey of Canada, Bulletin 181, 104 p.

Walton, W. R., 1964. Recent foraminiferal ecology and paleoecology, p. 151-237. *In* J. Imbrie and N. D. Newell, eds., Approaches to Paleoecology. Wiley and Sons, New York.

Wang, P. and Lutze, G. F., 1986. Inflated later chambers: ontogenic changes of some recent hyaline benthic foraminifera. Journal of Foraminiferal Research, 16(1): 48-62.

Williamson, M. A., Keen, C. E. and Mudie, P. J., 1984. Foraminiferal distribution on the continental margin off Nova Scotia. Marine Micropaleontology, 9: 219-239.