

## Champlain Sea Foraminifera and Ostracoda: a systematic and paleoecological synthesis

## Foraminifères et Ostracodes de la mer de Champlain : synthèse systématique et paléoécologique

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Résumé de l'article

Certains dépôts de la mer de Champlain, au Québec, en Ontario et aux États-Unis ont fourni plus de 40 espèces d'Ostracodes et 60 espèces de Foraminifères benthiques. Les tendances géographiques de la diversité des espèces de Foraminifères, telles que mesurées par la fonction d'information de Shannon-Wiener, H(S), montrent les plus fortes diversités (H(S) : 1,6-1,7) dans la partie ouest de la mer de Champlain, en Ontario, et dans le sud du Québec, alors qu'une faune moins diversifiée (HS) : 1,0) habitait le bassin du lac Champlain. On a reconnu trois phases marines, écologiquement distinctes, en se basant sur la distribution des espèces d'Ostracodes dans le bassin du lac Champlain et le sud du Québec. Une première période se distingue par la présence d'eau douce et d'espèces marines euryhalines, et représente la phase de transition entre l'eau douce et l'eau salée. Par la suite, des conditions climatiques glaciales à très froides et des conditions aquatiques polyhalines et euhalines ont prévalu. En dernier lieu, entre 11 000 et 10 600 ans BP, on présume qu'il y a eu baisse de la salinité et augmentation de la température à partir de l'observation d'espèces d'Ostracodes mésohalines de climat tempéré froid. Les valeurs moyennes de la diversité des espèces de Foraminifères, respectivement de 1,0, 1,5 et 1,2 pour les trois phases, sont des preuves supplémentaires de la variation de la salinité dans le temps.

# CHAMPLAIN SEA FORAMINIFERA AND OSTRACODA: A SYSTEMATIC AND PALEOECOLOGICAL SYNTHESIS

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**ABSTRACT** Champlain Sea deposits from Québec, Ontario and the United States yielded over 40 ostracode and 60 benthonic foraminiferal species. Geographical trends in foraminiferal species diversity as measured by the Shannon-Wiener Information Function,  $H(S)$ , show highest diversities ( $H(S) = 1.6-1.7$ ) in the western Champlain Sea of Ontario, southern Québec and near Québec City, while a significantly less diverse fauna ( $H(S) = 1.0$ ) inhabited the Champlain Valley. Three environmentally distinct phases of the sea based on ostracode species distribution were recognized in the Champlain Valley and southern Québec. An early period, characterized by fresh water and euryhaline marine species, represents a lacustrine-marine transition. Subsequently, frigid to subfrigid, polyhaline to euhaline conditions prevailed. Finally, some time between 11,000 and 10,600 yr BP a salinity decrease and a water temperature increase is inferred from the dominance of mesohaline, cold temperate ostracode species. Additional evidence for temporal salinity variation are mean foraminiferal species diversity values which are 1.0, 1.5 and 1.2 respectively for the three phases.

**RÉSUMÉ** *Foraminifères et Ostracodes de la mer de Champlain: synthèse systématique et paléocéologique.* Certains dépôts de la mer de Champlain, au Québec, en Ontario et aux États-Unis ont fourni plus de 40 espèces d'Ostracodes et 60 espèces de Foraminifères benthiques. Les tendances géographiques de la diversité des espèces de Foraminifères, telles que mesurées par la fonction d'information de Shannon-Wiener,  $H(S)$ , montrent les plus fortes diversités ( $H(S): 1,6-1,7$ ) dans la partie ouest de la mer de Champlain, en Ontario, et dans le sud du Québec, alors qu'une faune moins diversifiée ( $H(S): 1,0$ ) habitait le bassin du lac Champlain. On a reconnu trois phases marines, écologiquement distinctes, en se basant sur la distribution des espèces d'Ostracodes dans le bassin du lac Champlain et le sud du Québec. Une première période se distingue par la présence d'eau douce et d'espèces marines euryhalines, et représente la phase de transition entre l'eau douce et l'eau salée. Par la suite, des conditions climatiques glaciales à très froides et des conditions aquatiques polyhalines et euhalines ont prévalu. En dernier lieu, entre 11 000 et 10 600 ans BP, on présume qu'il y a eu baisse de la salinité et augmentation de la température à partir de l'observation d'espèces d'Ostracodes mésohalines de climat tempéré froid. Les valeurs moyennes de la diversité des espèces de Foraminifères, respectivement de 1,0, 1,5 et 1,2 pour les trois phases, sont des preuves supplémentaires de la variation de la salinité dans le temps.

**РЕЗЮМЕ** ФОРАМИНИФЕРА И ОСТРАКОДА МОРЯ ШАМПЛЭН-СИСТЕМАТИЧЕСКИЙ И ПАЛЕОЭКОЛОГИЧЕСКИЙ АНАЛИЗ. Отложения моря Шамплэн от Квебека, Онтарио и Соединенных Штатов дали больше чем 40 остракодных и 60 бентонных фораминиферических образцов. Географические тенденции в разнородности фораминиферических породах или видах оцениваются математической функцией информации имени Шаннон-Винер  $X(C)$ . Эти тенденции проявляют самые большие разнообразия ( $X(C) =$  от 1.6 до 1.7) в западной части море Шамплэн в Онтарио, в южном Квебеке и в районе недалеко от города Квебека. В то же время, значительно менее разнообразная фауна обитала в долине Шамплэн (где  $X(C) = 1.0$ ). Три фазы моря, различные по окружающей среде, основаны на разнородности остракодных видов, были обнаружены в долине Шамплэн и в южном Квебеке. Более ранний период, который характеризуется видами пресной воды и эвригалинными морскими видами, представляет озерно-морской переход. Впоследствии преобладали холодные-очень холодные и солоноватые - мезо-халинные условия. Третья фаза, относящаяся к периоду между 11 000 и 10 600 лет тому назад, дает возможность подразумевать что преобладание мезо-халинных, холодных, умеренных, остракодных видов способствовало убыванию солености и повышению температуры воды. Добавочные данные которые подтверждают временное изменение солености это есть средние значения разнородности фораминиферических видов. Приводятся эти значения, соответствующие трем фазам: 1.0/1.5/1.2.

## INTRODUCTION

Champlain Sea fossils have long been the subject of paleoecological investigation. The intriguing situation of a post-glacial inland inundation of the St. Lawrence Lowlands (Fig. 1) has attracted the attention of paleontologists and glacial geologists alike for over 100 years. Studies of Champlain Sea macrofaunas, particularly molluscs, are numerous, most notably those of GOLD-RING (1922), WAGNER (1970), ELSON (1969) and HIL-LAIRE-MARCEL (1972, 1974). WAGNER (1967) lists published references up to 1967. Nevertheless, Champlain Sea Foraminifera and Ostracoda have been all but neglected. This paper summarizes the results of a recently completed study of these microfossils from various parts of the Champlain Sea. More detailed accounts can be found in CRONIN (1976a, 1977, in prep.). The purpose of this paper is sixfold:

1) to discuss the distribution and abundance of microfossils in various Champlain Sea lithologies;

2) to provide species lists of Foraminifera and Ostracoda and scanning electron photomicrographs of characteristic species;

3) to analyze temporal and geographical variation in foraminiferal species diversity;

4) to summarize paleoenvironmental conditions at various stages in the sea's history in the Champlain Valley and Québec;

5) to discuss faunal changes in light of deglaciation history;

6) to briefly discuss the potential of microfossils for paleoenvironmental study of the Champlain Sea.

## MATERIALS AND METHOD

Sediment and fossil samples were collected by the author from about 60 localities from Ontario, southern Québec, New York and Vermont. Additional samples from the central St. Lawrence Lowlands near Trois-Rivières and Québec City were provided by Professors Serge Occhietti, Pierre Lasalle and Joseph Hazel. Figure 1 shows the four primary areas of study.

After washing from 25-200 gm of sediment through a 200 mesh wire sieve, ostracode valves and carapaces (2 valves articulated) were hand-picked from the sediment. Foraminifera were separated by floatation of tests in carbon tetrachloride, a method which usually assures large sample size of tests of all sizes.

## PREVIOUS STUDIES

WAGNER (1970) studied Champlain Sea faunas from Canada but emphasized molluscs, and recognized relatively few Foraminifera and Ostracoda, primarily the

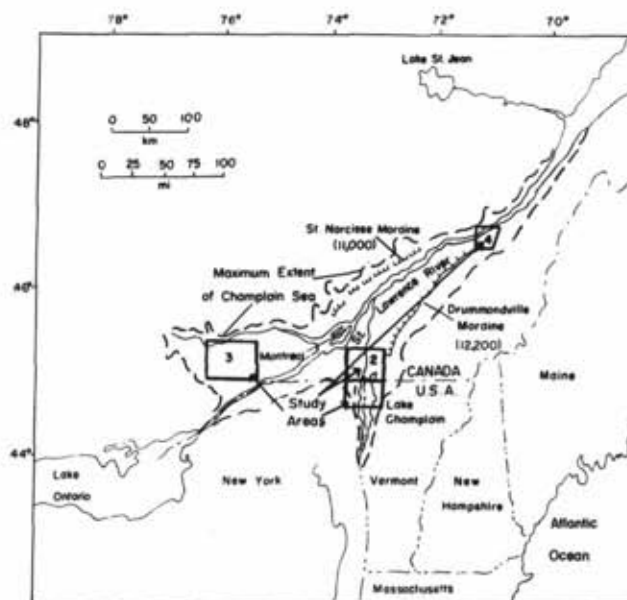


FIGURE 1. Region inundated by the Champlain Sea and areas from which microfossils were studied.

*Extension de la mer de Champlain et régions d'où les microfossiles ont été étudiés.*

most abundant taxa *Elphidium* and *Islandiella*. A list of Pleistocene microfossils from Québec, compiled by WAGNER (1968) from the literature reveals the paucity of data on the Champlain Sea microfauna. The little information on the ostracodes comes from a study by BRADY and CROSSKEY (1871), who recognized 12 species.

More recently, several reports, preliminary in nature, have provided additional data on the microfauna from the United States. FILLON and HUNT (1974) and CRONIN (1976b) list Foraminifera species from the Champlain Valley and infer changing paleoenvironmental conditions throughout the sea's history. Several ostracode species have also been recognized from sediment cores taken from the Lake Champlain basin (GUNTHER and HUNT, 1976).

Otherwise, most references to Champlain Sea microfossils consist of short species lists accompanying studies of surficial and glacial geology of the region of inundation (DENNY, 1972; MACCLINTOCK and STEWART, 1965; GADD, 1971). Thus, this paper is the first attempt to consider both Foraminifera and Ostracoda from the Champlain Sea of the United States and Canada.

## DISTRIBUTION AND ABUNDANCE

Both groups of microfossils are widely distributed throughout the entire region of marine inundation. As

a rule, they are more common in deposits which also yield abundant macrofossils. Moreover, Foraminifera are generally numerically more abundant and present at more localities than ostracodes. Several exceptions were found in which Foraminifera are absent, yet ostracodes are very abundant.

Numerous factors are responsible for the variable distribution and abundance of microfossils in Champlain Sea sediments. Most important are rates of sedimentation, diagenetic activity, post depositional winnowing of finer material, and the actual environment of deposition, including factors such as, temperature and salinity. The effects of these, as well as other factors, are reflected in the different microfossil abundances in various Champlain Sea lithologies. Although there is great variability even within one type of sediment, *Portlandia arctica* clays for example, several generalizations can be made. Table I lists four broad divisions of Champlain Sea lithologies and the associated occurrence of microfossils for each. Gravels and sands with the mollusc *Hiatella arctica* usually yield large numbers of well-preserved Foraminifera and Ostracoda. This facies is found throughout most of the region of inundation. Microfossils are also present in reworked glacial deposits, such as tills and eskers, but often finer grain sizes have been winnowed out, leaving a biased sample of larger tests. Care must be taken to obtain a sample with a wide range of grain sizes.

Beach and deltaic sands and gravels which often contain *Macoma balthica* are rare to absent in microfossils, probably due to a rapid sedimentation rate and extremely harsh environmental conditions.

Clays containing scarce but well-preserved valves of the bivalve *Portlandia arctica* are particularly common along the central St. Lawrence Lowlands but often lack

microfossils. Yet in lenses of coarser sediments with accumulations of broken *Portlandia* shells, both ostracodes and Foraminifera can be found.

With such great variability, obtaining an adequate, representative sample can be a problem. To illustrate this, Figure 2 shows the number of species (S) versus the number of specimens of Foraminifera for each locality. Clearly, the smallest sample size generally also yielded fewer species, as might be expected. It is, therefore, advisable to obtain samples of at least 100 tests preferably 200-500, in order to obtain an accurate representation of the fauna.

**SYSTEMATIC SYNTHESIS**

Foraminifera and ostracode species from the Champlain Sea are listed in Tables II and III respectively. Plates 1-4 illustrate the more common species. A formal systematic treatment is near completion. Without question, congeners of *Elphidium* and *Protelphidium orbiculare* are the dominant taxa in sands, gravelly sands and silty sands, while *Islandiella* and *Cassidulina crassa* characterize clays and silty clays. With few exceptions, species of *Oolina*, *Fissurina*, *Dentalina*, *Lagena Quinqueloculina* and others are extremely rare, each species constituting less than one percent of a particular sample. Many rare species (*Nonion labradoricum*, *Trifarina fluens*, *Pyrgo williamsoni*, *Patellina corrugata*, *Lagena gracillima*) have been found at a small percentage of all the localities studied.

Several Foraminifera are present at many localities but in very low numbers. These include *Cibicides lobatulus*, *Buccella frigida* and the various polymorphinid

TABLE I  
Occurrence of Foraminifera and Ostracoda in Champlain Sea sediments  
*Fréquence des Foraminifères et des Ostracodes dans les dépôts de la mer de Champlain*

Lithology	Foraminifera	Ostracoda
Sands and Gravels with <i>Hiatella arctica</i>	Abundant	Common-Abundant
Reworked glacial deposits (tills, eskers, etc.)	Common (Large tests only)	Rare (Large shells only)
Beach and deltaic sands with <i>Macoma balthica</i>	Rare-absent	Common-absent
Clays and silts with <i>Portlandia arctica</i>	Common-absent	Rare-Abundant

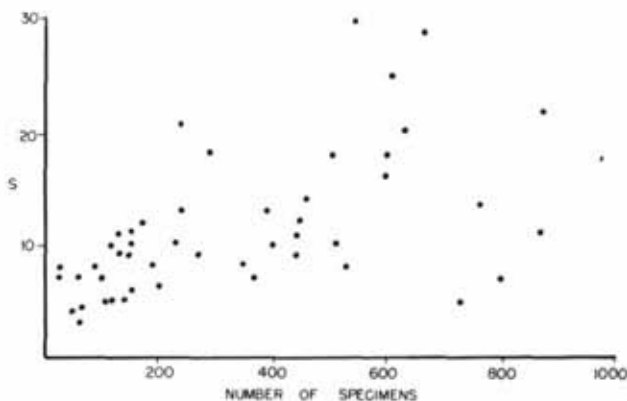


FIGURE 2. Number of foraminiferal species (S) versus number of specimens for each locality. A locality from Kars, Ontario, not shown on this plot, yielded 45 species and 1,250 specimens.

*Nombre d'espèces de Foraminifères en regard du nombre de spécimens par site. Un site, près de Kars, Ontario (non indiqué sur la figure) a fourni 45 espèces et 1 250 spécimens.*

TABLE II

Champlain Sea Foraminifera  
*Les Foraminifères de la mer de Champlain*

*Elphidium incertum* (Williamson)  
*Elphidium excavatum* forma *clavatum* Cushman  
*Elphidium bartletti* Cushman  
*Elphidium albiumbilicatum* (Weiss)  
*Elphidium subarcticum* Cushman  
*Elphidium asklundi* Brotzen  
*Protelphidium orbiculare* (Brady)  
*Protelphidium* cf. *P. anglicum* Murray  
*Elphidiella arctica* (Parker and Jones)  
*Islandiella helenae* Feyling-Hanssen and Buzas  
*Islandiella islandica* Norvang  
*Islandiella norcrossi* (Cushman)  
*Cassidulina crassa* d'Orbigny  
*Pseudopolymorphina novangliae* (Cushman)  
*Pseudopolymorphina suboblongata* Cushman and Ozawa  
*Pseudopolymorphina soldani* (d'Orbigny)  
*Guttulina lactea* (Walker and Jacob)  
*Guttulina glacialis* (Cushman and Ozawa)  
*Guttulina dawsoni* Cushman and Ozawa  
*Guttulina austriaca* d'Orbigny  
*Guttulina problema* d'Orbigny  
*Pyrulina cylindroides* (Roemer)  
*Glandulina laevigata* d'Orbigny  
*Eosyrinx curta* (Cushman and Ozawa)  
*Laryngosigma hyalascidea* Loeblich and Tappan  
*Laryngosigma williamsoni* (Terquem)  
*Dentalina ittai* Loeblich and Tappan  
*Dentalina pauperata* d'Orbigny  
*Dentalina frobischerensis* Loeblich and Tappan  
*Dentalina baggi* Galloway and Wissler  
*Dentalina melvillensis* Loeblich and Tappan  
*Oolina melo* d'Orbigny  
*Oolina* cf. *O. laevigata* d'Orbigny  
*Oolina* cf. *O. hispida* Reuss  
*Oolina hexagona* (Williamson)  
*Oolina williamsoni* (Alcock)  
*Oolina lineata* (Williamson)  
*Oolina caudigera* (Wiesner)  
*Oolina acuticosta* (Reuss)  
*Oolina squamosa-sulcata* (Heron-Allen and Earland)  
*Lagena semilineata* Wright  
*Lagena gracillima* (Sequenza)  
*Fissurina marginata* (Montagu)  
*Fissurina serrata* (Schlumberger)  
*Fissurina ventricosa* (Wiesner)  
*Fissurina cucurbitasema* Loeblich and Tappan  
*Fissurina* sp. 1  
*Fissurina* sp. 2  
*Quinqueloculina seminulum* (Linne)  
*Quinqueloculina* cf. *Q. akneriana* d'Orbigny  
*Quinqueloculina* sp.  
*Quinqueloculina agglutinata* Cushman  
*Triloculina trihedra* Loeblich and Tappan  
*Pyrgo williamsoni* (Silvestri)  
*Silicosigmollina groenlandica* (Cushman)

*Pateoris hauerinoides* (Rhumbler)  
*Virgulina schreibersiana* Czjzek  
*Virgulina loeblichii* Feyling-Hanssen  
*Buccella frigida* (Cushman)  
*Pattellina corrugata* Williamson  
*Cibicides lobatulus* (Walker and Jacob)  
*Astacolus hyalaculus* Loeblich and Tappan  
*Nonion labradoricum* Dawson  
*Trifarina fluens* (Todd)  
*Astrononion gallowayi* Loeblich and Tappan  
*Bolivina subaenariensis* Cushman  
*Bolivina* sp.  
*Bulimina* cf. *B. marginata* d'Orbigny

TABLE III

Champlain Sea Ostracoda  
*Les Ostracodes de la mer de Champlain*

*Cytheromorpha macchesneyi* (Brady and Crosskey)  
*Cytheromorpha fuscata* (Brady)  
*Leptocythere castanea* (Sars)  
*Baffinicythere emarginata* (Sars)  
*Finmarchinella curvicosta* Neale  
*Roundstomia globulifera* (Brady)  
*Eucytheridea bradii* (Norman)  
*Eucytheridea macrolaminata* (Elofson)  
*Eucytheridea punctillata* (Brady)  
*Heterocyprideis sorbyana* (Jones)  
*Palmanella limicola* (Norman)  
*Eucythere declivis* (Norman)  
*Cythere lutea* O. F. Muller  
*Acanthocythereis dunelmensis* (Norman)  
*Cytherura gibba* (O. F. Muller)  
*Semicytherura* cf. *S. atra* (Sars)  
*Semicytherura* sp.  
*Cytheropteron inflatum* Brady, Crosskey and Robertson  
*Cytheropteron latissimum* (Norman)  
*Cytheropteron nodosum* Brady  
*Cytheropteron montrosiense* Brady, Crosskey and Robertson,  
 form 1  
*Cytheropteron montrosiense* Brady, Crosskey and Robertson,  
 form 2  
*Cytheropteron paralatissimum* Swain  
*Cytheropteron arcuatum* Brady, Crosskey and Robertson  
*Cytheropteron* cf. *C. alatum* Sars  
*Sclerochilus contortus* (Norman)  
*Cyprideis* cf. *torosa* (Jones)  
*Cyprinotus* cf. *salinus* (Brady)  
*Ilyocypris gibba* (Ramdohr)  
*Candona subtriangulata* Benson and MacDonald  
*Jonesia simplex* (Norman)  
*Candona* sp.

species of *Guttulina* and *Pseudopolymorphina*. Collectively, the foraminiferal fauna resembles recent assemblages from arctic to subarctic habitats. No planktonic species of Foraminifera were found, and only one agglutinated species was encountered. The fauna consists of calcareous, benthonic species, although the lack of arenaceous forms may be due to preservational bias.

The ostracodes in Table III present a curious mixture of marine, brackish and fresh water species from several families. Never, however, were they all found together and their temporal distribution in the Champlain Sea provides the basis for delineating the environmentally distinct periods in the sea's history. This will be discussed below.

The most common species are *Cytheromorpha machesneyi*, *Heterocyprideis sorbyana*, *Eucytheridea punctillata*, *Eucytheridea bradii*, *Baffinicythere emarginata*, *Finmarchinella curvicosta*, *Cytherura gibba* and *Cytheromorpha fuscata*. These are usually abundant in coarser grained deposits, while species of *Cytherop-teron* are rare in sandy sediments but usually are found in silts and clays. Rare species constituting a small proportion of an assemblage are *Eucythere declivis*, *Cythere lutea*, *Roundstomia globulifera*, *Jonesia simplex*, *Acanthocythereis dunelmensis* and several *Cytherop-teron* species.

Trends in the distribution of Champlain Sea Foraminifera are best seen through a study of their temporal and geographical variation in species diversity. However, because of the more limited nature of the ostracode fauna and, more importantly, the recent ecological data available for individual species, the temporal distribution of ostracodes in the Champlain Sea was analysed to infer changing environmental conditions. Foraminiferal species diversity will be considered first.

#### FORAMINIFERAL SPECIES DIVERSITY

GIBSON and BUZAS (1973) have shown that, with some exceptions, foraminiferal species diversity increases with depth and decreases with latitude. However, since the Champlain Sea was relatively shallow and most samples studied come from shallow water deposits (paleodepth < 100 m, usually < 10-20 m), depth probably had little effect on diversity. Moreover, arctic and subarctic foraminiferal assemblages, similar to Champlain Sea assemblages, do not show increased diversity with depth (GIBSON and BUZAS, 1973). The most important single factor controlling foraminiferal diversity in the Champlain Sea was probably salinity. Foraminifera are primarily marine organisms and the number of species decreases as salinity decreases (REMANE and SCHLIEPER, 1971), a trend commonly observed in marine organisms. Thus, the analysis of

foraminiferal species diversity may reveal trends in paleosalinity of the Champlain Sea.

Three values were determined for each locality: S, H(S), and E. S is simply the number of species. Species diversity was calculated using the Shannon-Wiener Information Function expressed in the equation  $H(S) = - \sum p_i \ln p_i$ , where H(S) is species diversity, and  $p_i$  is the proportion of the  $i^{\text{th}}$  species (see GIBSON and BUZAS, 1973 for a discussion). The value H(S) is strongly dependent on the proportions of different species, as well as the total number of species. Finally a measure of the equitability of each sample was made using the equation  $E = \frac{e^{H(S)}}{S}$ . This value measures how evenly distributed the species are. When the proportions of all species in a sample are equal,  $E = 1$ .

Table IV summarizes the results. To assess the geographical variation in diversity, the region of inundation was divided into four broad areas, the western Champlain Sea of Ontario, southern Québec, the Québec City area and the Champlain Valley of New York and Vermont.

Figure 3 shows the geographical distribution of S and H(S) throughout the Champlain Sea. The H(S) values for the three Canadian regions are clearly similar, between 1.5 and 1.7, while the H(S) value for the Champlain Valley averaged less than 1.1. A Mann-Whitney-Wilcoxon was used to test for statistical difference. Values of H(S) for each locality were ranked, two areas at a time (the Champlain Valley and Ontario, for example), and the resulting statistic T was found in tables from SNEDECOR and COCHRAN (1967). At the .05 probability level, none of the 3 Canadian areas show any statistical difference from one another in H(S), yet, all three are statistically different from the Champlain Valley. Thus, the Champlain Valley was generally a region of low foraminiferal species diversity compared to more northerly and western areas of the sea. These results confirm those of GOLDRING (1922) who found the lowest macrofaunal diversities in this part of the sea. Apparently, the great distance from the marine water source, as well as the somewhat isolated nature of this region caused low salinities and therefore lower foraminiferal species diversities. Interesting to note are the high values of S and H(S) for the western Champlain Sea, where diverse foraminiferal assemblages flourished, despite the great distance from the marine water source.

Little is revealed by the values of E (Table IV), except that equitability in the Québec City area was slightly higher than in other areas, indicating a more equal distribution of species, less dominance by relatively few species and perhaps, therefore, less rigorous environmental conditions.

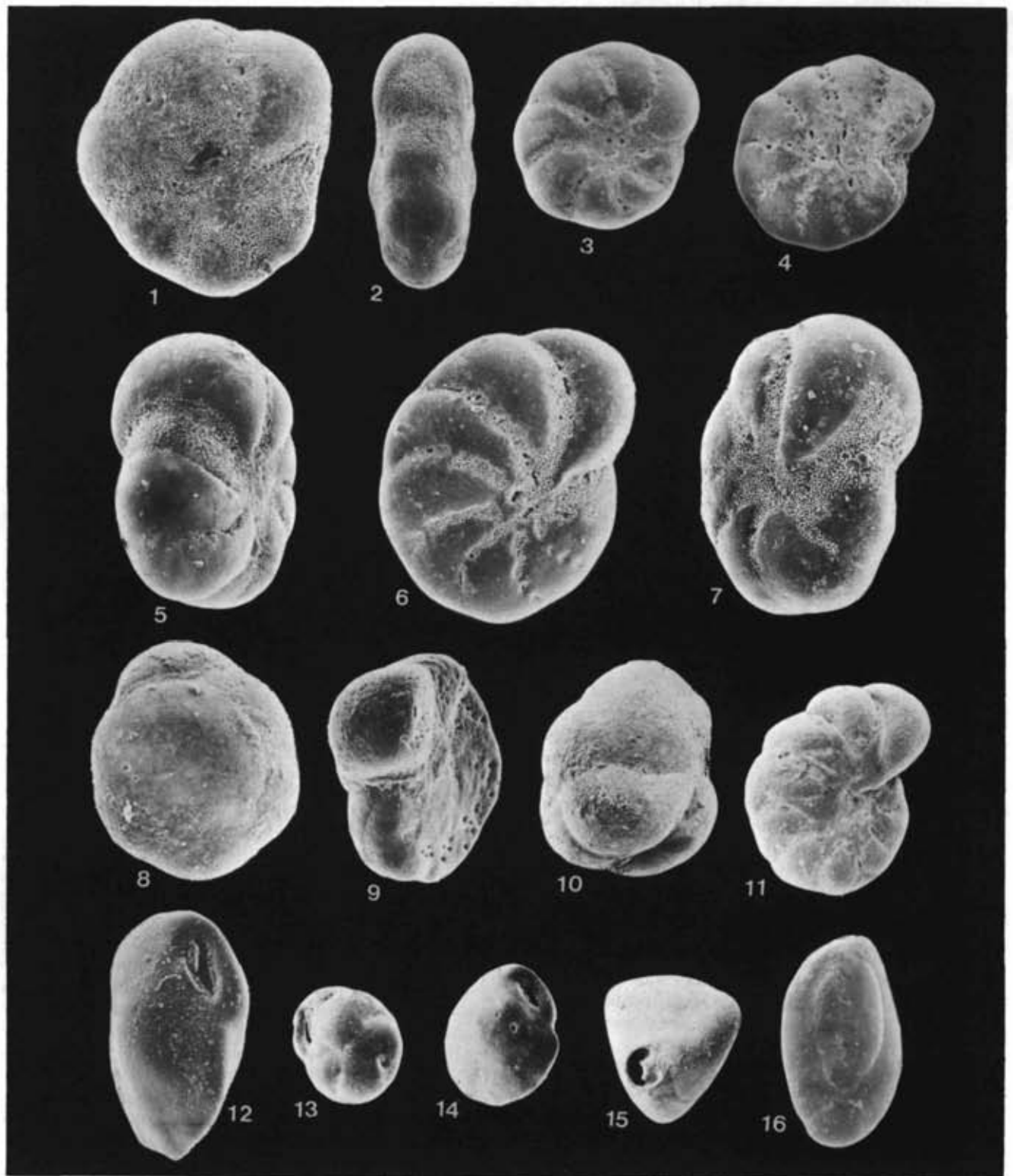


TABLE IV

Geographical variation in foraminiferal species diversities.  
(means and observed ranges of S, H(S) and E; N = number of samples)

Variations dans le temps et dans l'espace de la diversité des espèces de Foraminifères.

Area	N	S		H(S)		E		
		Mean	O.R.	Mean	O.R.	Mean	O.R.	
1. Champlain Valley (New York, Vermont)	23	11.5	4-18	1.064	.502-1.788	.307	.162-.760	
2. Southern Québec	11	18.1	9-30	1.570	1.147-1.987	.295	.198-.429	
3. Ontario	7	20.3	9-44	1.693	1.073-2.479	.314	.209-.500	
4. Québec City Region	4	11.8	8-15	1.688	1.411-2.049	.497	.273-.668	
Phase of the sea								
5. Transitional	7	10.1	6-17	.991	.685-1.409	.287	.197-.375	
6. <i>Hiatella arctica</i>	14	15.6	7-30	1.508	.954-1.987	.298	.162-.429	
7. <i>Mya arenaria</i>	9	14.4	4-29	1.238	.667-1.787	.312	.178-.760	

Environments of the Champlain Sea, however, were not constant during its brief history, but rather they changed significantly as the result of glacial and climatic events which influenced the hydrological conditions of the sea. Invertebrate faunas have been used to document environmentally distinct phases of the sea. ELSON (1969) recognized an early *Hiatella arctica* Phase and a late *Mya arenaria* Phase in Canada based on the characteristic molluscan species. In New York and Vermont correlative phases have been recognized, in addition to an initial period of inundation called the Transitional Phase (CRONIN, 1977, and below).

Foraminiferal species diversities for each phase suggest that temporal environmental changes occurred in the Champlain Sea. Figure 4, modified from CRONIN (1977) shows H(S) values for each phase of the sea and Table IV summarizes the results for S, H(S) and E. Transitional Phase (about 12,500 to 11,600 yr BP) mean H(S) is extremely low whereas diversity increased during the *Hiatella* Phase (about 11,600 to 11,000 to 10,600 yr BP). A decrease in diversity is recorded for the *Mya* Phase (11,000-10,600 to 10,000 yr BP). The Mann-Whitney-

Wilcoxon test showed that diversities from both the Transitional and *Mya* phases were significantly lower than those during the *Hiatella* Phase, but were not significantly different from one another. These results suggest an early period of low salinity, more saline conditions during the *Hiatella* Phase, and again low salinity during the *Mya* Phase. The distribution of ostracodes confirms this and permits more accurate estimates of Champlain Sea paleoenvironments.

PLATE I. Champlain Sea Foraminifera. *Les Foraminifères de la mer de Champlain*. Figures 1-2) *Elphidium subarcticum* Cushman, side and edge views,  $\times 115$ . Figure 3) *Elphidium cf. E. bartletti* Cushman,  $\times 60$ . Figure 4) *Elphidiella arctica* (Parker and Jones),  $\times 60$ . Figure 5) *Protelphidium orbiculare* (Brady),  $\times 115$ . Figures 6-7) *Elphidium incertum* (Williamson), side and apertural views,  $\times 115$ . Figure 8) *Buccella frigida* (Cushman),  $\times 115$ .

Figure 9) *Cibicides lobatulus* (Walker and Jacob),  $\times 115$ . Figure 10) *Islandiella islandica* Norvang,  $\times 84$ . Figure 11) *Astrononion gallowayi* Loeblich and Tappan,  $\times 84$ . Figure 12) *Islandiella teretis* Tappan,  $\times 115$ . Figure 13) *Cassidulina crassa* d'Orbigny,  $\times 72$ . Figure 14) *Islandiella norcrossi* (Cushman),  $\times 50$ . Figure 15) *Triloculina trihedra* Loeblich and Tappan,  $\times 70$ . Figure 16) *Quinqueloculina seminulum* (Linne),  $\times 115$ .

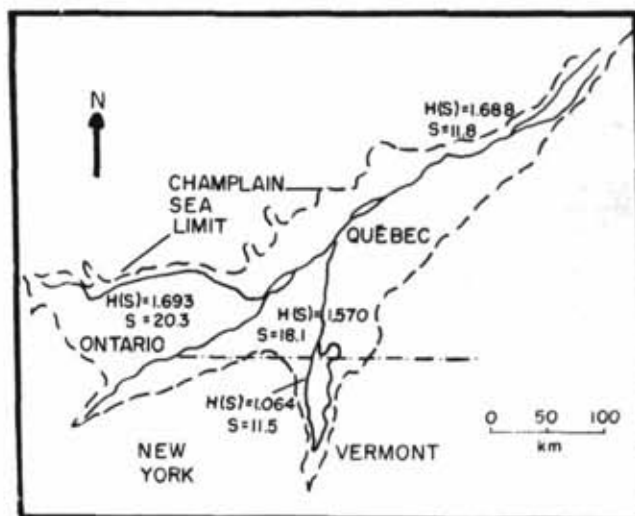
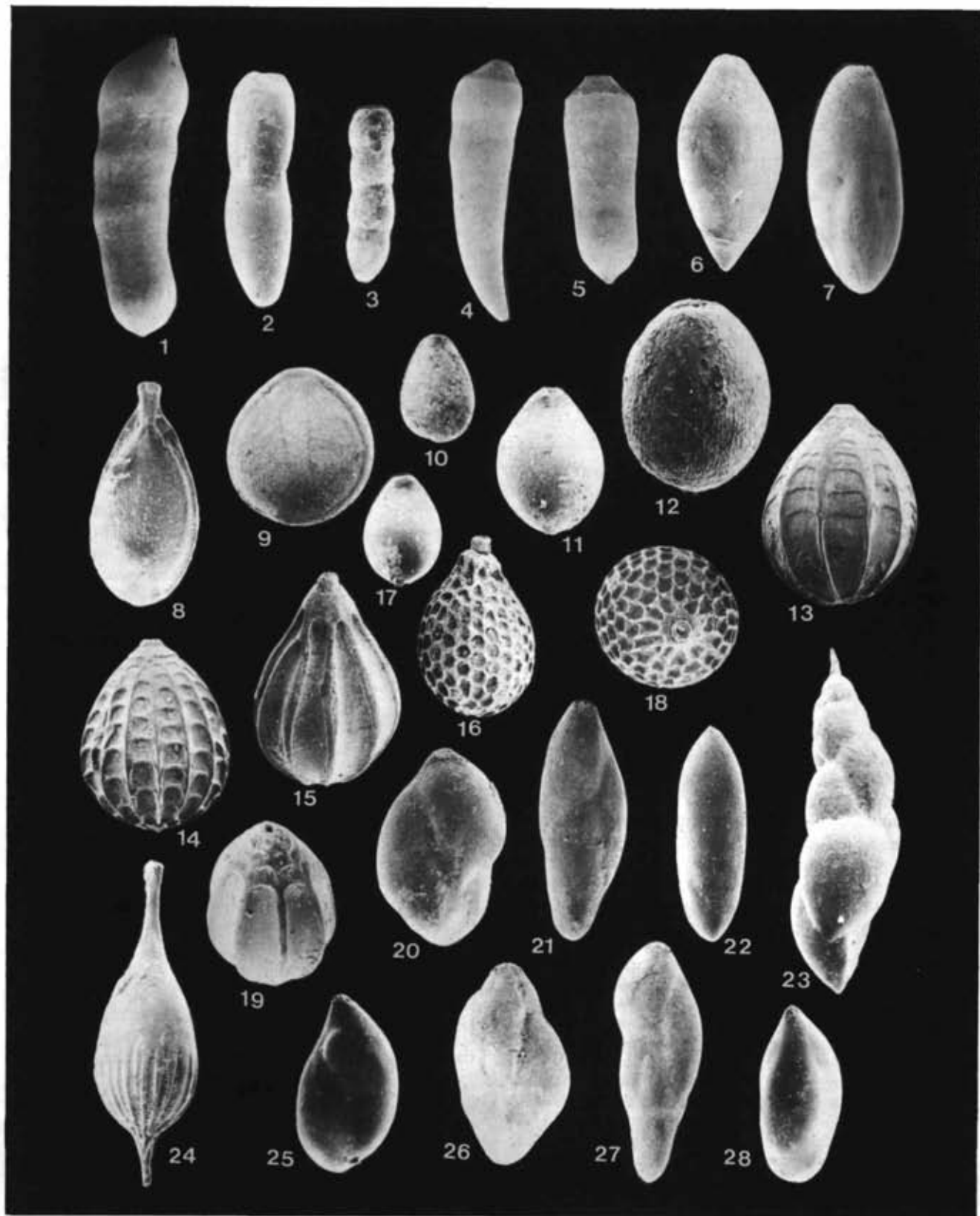


FIGURE 3. Geographical variations in foraminiferal species diversity. The means of the Shannon-Wiener Information Function (H(S)) and the mean number of species per locality (S) are shown for the four study areas.

Variation géographique de la diversité des espèces de Foraminifères. Les moyennes de la fonction d'information de Shannon-Wiener (H(S)) et le nombre moyen d'espèces par site (S) sont indiqués pour les 4 régions à l'étude.





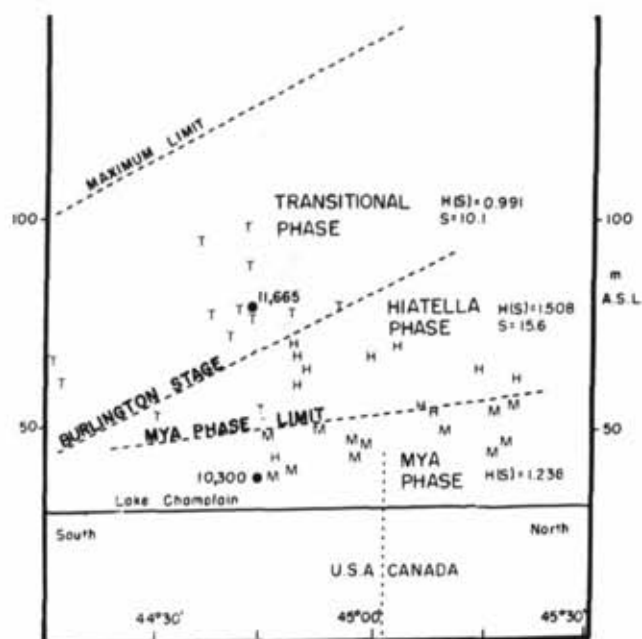


FIGURE 4. Latitudinal and altitudinal distribution of fossiliferous localities from southern Québec, New York and Vermont. T, H and M, represent localities yielding Transitional, *Hiatella arctica* and *Mya arenaria* Phase faunas respectively. Also shown are mean H(S) values from different phases of the sea. Burlington Stage is a near synchronous reference time plane determined by Chapman (1937) on the basis of parallel alignment of tilted shoreline features. Mya Phase limit shows the level above which *Mya arenaria* phase deposits have not been found. See text for discussion.

Distributions en latitude et en altitude des sites fossilifères du sud du Québec et des États de New York et du Vermont. T, H et M localisent les sites qui ont fourni les faunes des phases de transition, de *Hiatella arctica* et de *Mya arenaria*, respectivement. On indique également les valeurs moyennes de H(S) des différentes phases marines. Le stade de Burlington, référence chronologique presque synchrone, a été déterminé par CHAPMAN (1937) en se basant sur l'alignement parallèle des constructions littorales soulevées. La phase de *Mya* indique le niveau au-dessus duquel on n'a plus retrouvé de dépôts de la phase de *Mya arenaria*.

### OSTRACODA AND CHAMPLAIN SEA PALEOENVIRONMENTS

Figure 4 plots the elevation (ASL) and latitude of fossiliferous localities in areas 1 and 2. Also shown are the maximum limit of inundation and the level of the Burlington Stage of CHAPMAN (1937). These reference time planes were determined by Chapman on the basis of parallel alignment of shoreline features, and are tilted due to differential isostatic rebound. It is well documented that, following an initial maximum transgression, the Champlain Sea gradually regressed to lower elevations due to crustal rebound (CHAPMAN, 1937; WAGNER, 1972; DENNY, 1974). Thus, littoral deposits at higher elevations are generally older than those at lower altitudes. Figure 4 shows the position of 2 Queens College radiocarbon shell dates, QC 199 (10,300 ± 180 yr BP) and QC 200 (11,665 ± 175 yr BP), which generally confirm this relationship. Note that the following environmental inferences apply only to the region indicated.

Characteristic species of each phase of the sea are listed in Table V. The Transitional Phase was characterized by the fresh water *Candona subtriangulata* and the marine *Cytheromorpha macchesneyi*, both found at every locality above Chapman's Burlington Stage. Several new immigrants entered the sea during the *Hiatella arctica* Phase, but *Candona subtriangulata* is absent. The *Mya arenaria* Phase shows an entirely different assemblage of ostracodes from earlier periods. Several species which inhabited all phases of the sea are also listed. What do these faunal changes reveal about Champlain Sea paleoenvironments?

The recent temperature and salinity tolerances of many Champlain Sea ostracodes are discussed by CRONIN (1977) and are shown in Figures 5 and 6. *Hiatella* and *Mya* Phase species, as well as those surviving all phases of the sea, are shown. The paleosalinities during the Transitional Phase must have been very low, and probably extremely variable, as indicated by the mixed association of fresh and marine water species. *Candona subtriangulata* is known from fresh water Holocene deposits near Lake Erie, while *Cytheromorpha macchesneyi* inhabits marine environments.

PLATE II. Champlain Sea Foraminifera. Les Foraminifères de la mer de Champlain. Figure 1) *Dentalina pauperata* d'Orbigny, × 23. Figure 2) *Dentalina ittal* Loeblich and Tappan, × 77. Figure 3) *Dentalina melvillensis* Loeblich and Tappan, × 104. Figure 4) *Dentalina frobischensis* Loeblich and Tappan, × 23. Figure 5) *Dentalina* sp., × 23. Figure 6) *Glandulina laevigata* d'Orbigny, × 60. Figure 7) *Laryngosigma hyalascidea* Loeblich and Tappan, × 48. Figure 8) *Fissurina serrata* (Schlumberger), × 115. Figure 9) *Fissurina marginata* (Montagu), × 120. Figure 10) *Fissurina cucurbitasma* Loeblich and Tappan, × 90. Figures 11, 17) *Fissurina ventricosa* (Weisner), × 90. Figure 12) *Oolina lineata* (Williamson), × 80. Figure 13) *Oolina squa-*

*mosa-sulcata* (Heron-Allen and Earland), × 80. Figure 14) *Oolina melo* d'Orbigny, × 80. Figure 15) *Oolina acuticosta* (Reuss), × 115. Figures 16, 18) *Oolina hexagona* (Williamson), × 80 and × 115. Figure 19) *Oolina williamsoni* (Alcock), × 96. Figure 20) *Eosyrinx curta* (Cushman and Ozawa), × 60. Figure 21) *Pseudopolymorphina novangliae* (Cushman), × 45. Figure 22) *Pyrulina cylindroides* (Roemer), × 65. Figure 23) *Virgulina loeblichii* Feyling-Hanssen, × 95. Figure 24) *Lagena semilineata* Wright, × 115. Figure 25) *Guttulina glacialis* Cushman and Ozawa, × 50. Figure 26) *Guttulina austriaca* d'Orbigny, × 50. Figure 27) *Guttulina dawsoni* Cushman and Ozawa, × 50. Figure 28) *Guttulina lactea* (Walker and Jacob), × 60.

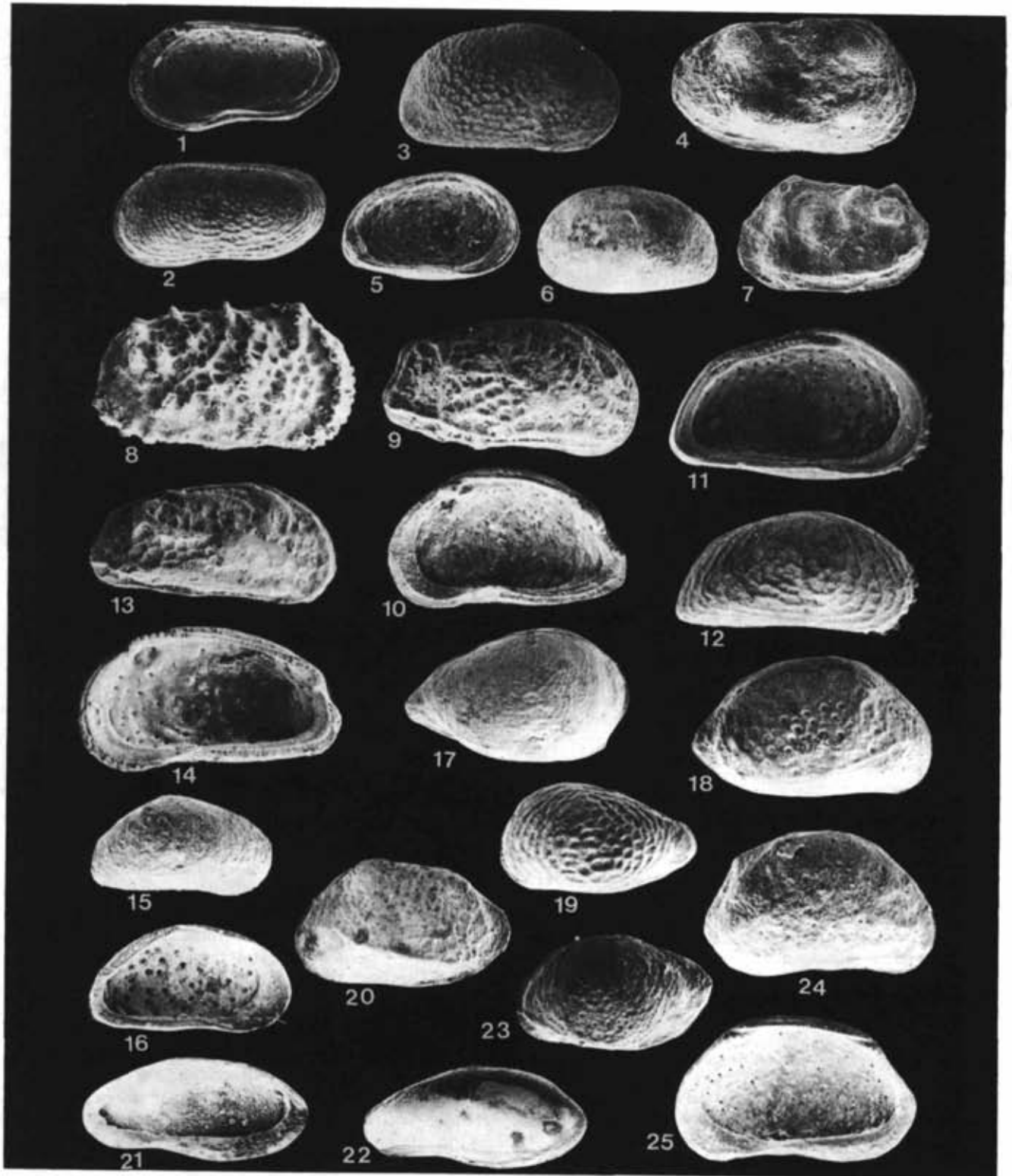


TABLE V

Characteristic ostracodes of phases of the Champlain Sea  
*Ostracodes typiques des phases de la mer de Champlain*

TRANSITIONAL PHASE	MYA ARENARIA PHASE
<i>Candona subtriangulata</i>	<i>Cytherura gibba</i>
<i>Cytheromorpha macchesneyi</i>	<i>Cytheromorpha fuscata</i>
<i>Ilyocypris gibba</i> (rare)	<i>Leptocythere castanea</i>
	<i>Cyprinotus cf salinus</i>
	<i>Cyprideis cf torosa</i>
	<i>Ilyocypris gibba</i>
HIATELLA ARCTICA PHASE	ALL PHASES
<i>Finmarchinella curvicosta</i>	<i>Heterocyprideis sorbyana</i>
<i>Baffinicythere emarginata</i>	<i>Eucytheridea punctillata</i>
<i>Cythere lutea</i>	<i>Eucytheridea bradli</i>
<i>Palmanella limicola</i>	<i>Cytheroanomia latissimum</i>
<i>Acanthocythereis dunelmensis</i> (rare)	<i>Cythere declivis</i>
<i>Jonesia simplex</i> (rare)	
<i>Cytheromorpha macchesneyi</i>	
<i>Cytheroanomia nodosum</i>	
<i>Cytheroanomia arcuatum</i>	
<i>Cytheroanomia inflatum</i>	
<i>Cytheroanomia montrosiense</i>	
<i>Cytheroanomia paralatissimum</i>	
<i>Eucytheridea bradli</i>	

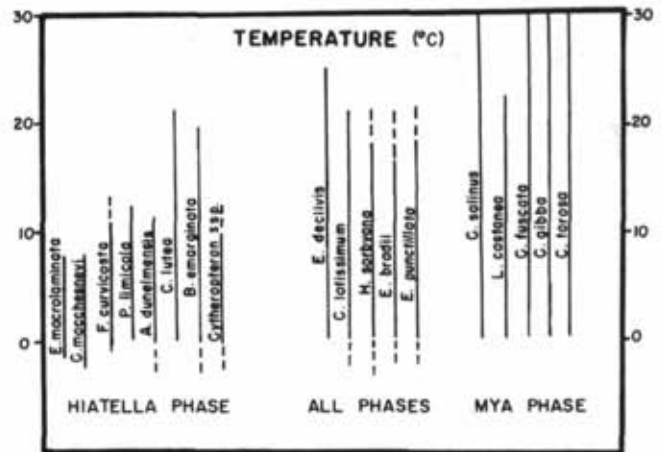


FIGURE 5. Recent salinity tolerances of Champlain Sea Ostracoda. Those species under "All phases" were found in Transitional *Hiatella arctica* and *Mya arenaria* phase deposits.

*Les taux de tolérance des Ostracodes de la mer de Champlain à la salinité. Les espèces indiquées sous la rubrique "All phases" ont été retrouvées dans les dépôts des phases de transition, de Hiatella arctica et de Mya arenaria.*

PLATE III. Champlain Sea Ostracoda. *Les Ostracodes de la mer de Champlain*. Figures 1-2) *Cytheromorpha macchesneyi* (Brady and Crosskey); 1, female, right valve, internal view; 2, female, left valve, lateral view, × 60. Figure 3) *Eucytheridea punctillata* (Brady); female, right valve, lateral view, × 50. Figure 4) *Roundstomia globulifera* (Brady); right valve, lateral view, × 80. Figures 5-6) *Eucytheridea macrolaminata* (Elofson); 5, female, left valve, internal view; 6, female, left valve, lateral view, × 44. Figure 7) *Palmanella limicola* (Norman); left valve, lateral view, × 53. Figure 8) *Acanthocythereis dunelmensis* (Norman); female, right valve, lateral view, × 44. Figures 9-10) *Baffinicythere emarginata* (Sars); 9, right valve, lateral view; 10, female, right valve, internal view, × 55. Figures 11-12) *Heterocyprideis sorbyana* (Jones); 11, female, left valve, internal view; 12, male, left valve, lateral view, × 38. Figures 13-14) *Finmarchi-*

*nella curvicosta* Neale; 13, male, right valve, lateral view; 14, female, left valve, internal view, × 55. Figures 15-16) *Eucythere declivis* (Norman); 15, right valve, lateral view, × 40; 16, left valve, internal view, × 50. Figure 17) *Cytheroanomia montrosiense* Brady, Crosskey and Robertson form 2, right valve, lateral view, × 70. Figure 18) *Cytheroanomia latissimum* (Norman); right valve, lateral view, × 70. Figure 19) *Cytheroanomia montrosiense* Brady, Crosskey and Robertson, form 1, left valve, lateral view, × 70. Figure 20) *Cytheroanomia nodosum* Brady, left valve, lateral view, × 70. Figures 21-22) *Schlerochilus contortus* (Norman); 21, right valve, internal view; 22, left valve, lateral view, × 45. Figure 23) *Cytheroanomia inflatum* Brady, Crosskey and Robertson, left valve, lateral view, × 52. Figure 24-25) *Cythere lutea* O. F. Muller; 24, right valve, lateral view; 25, right valve, internal view, × 52.

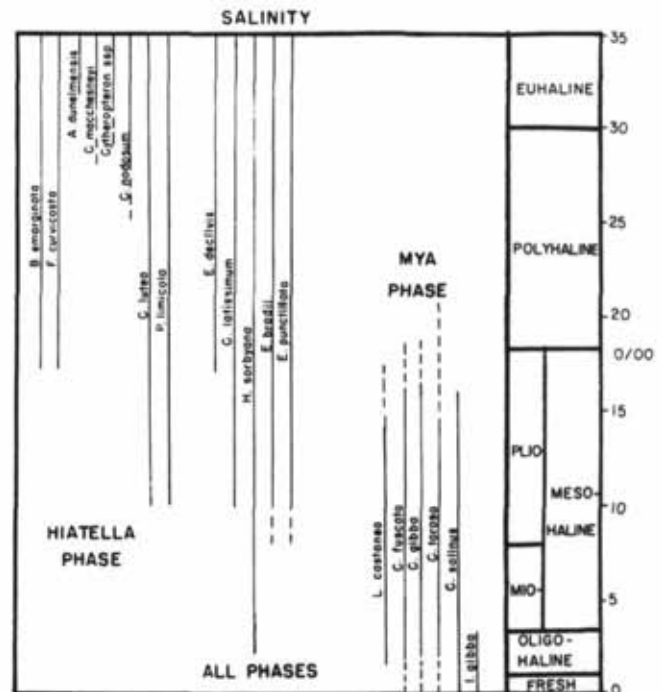
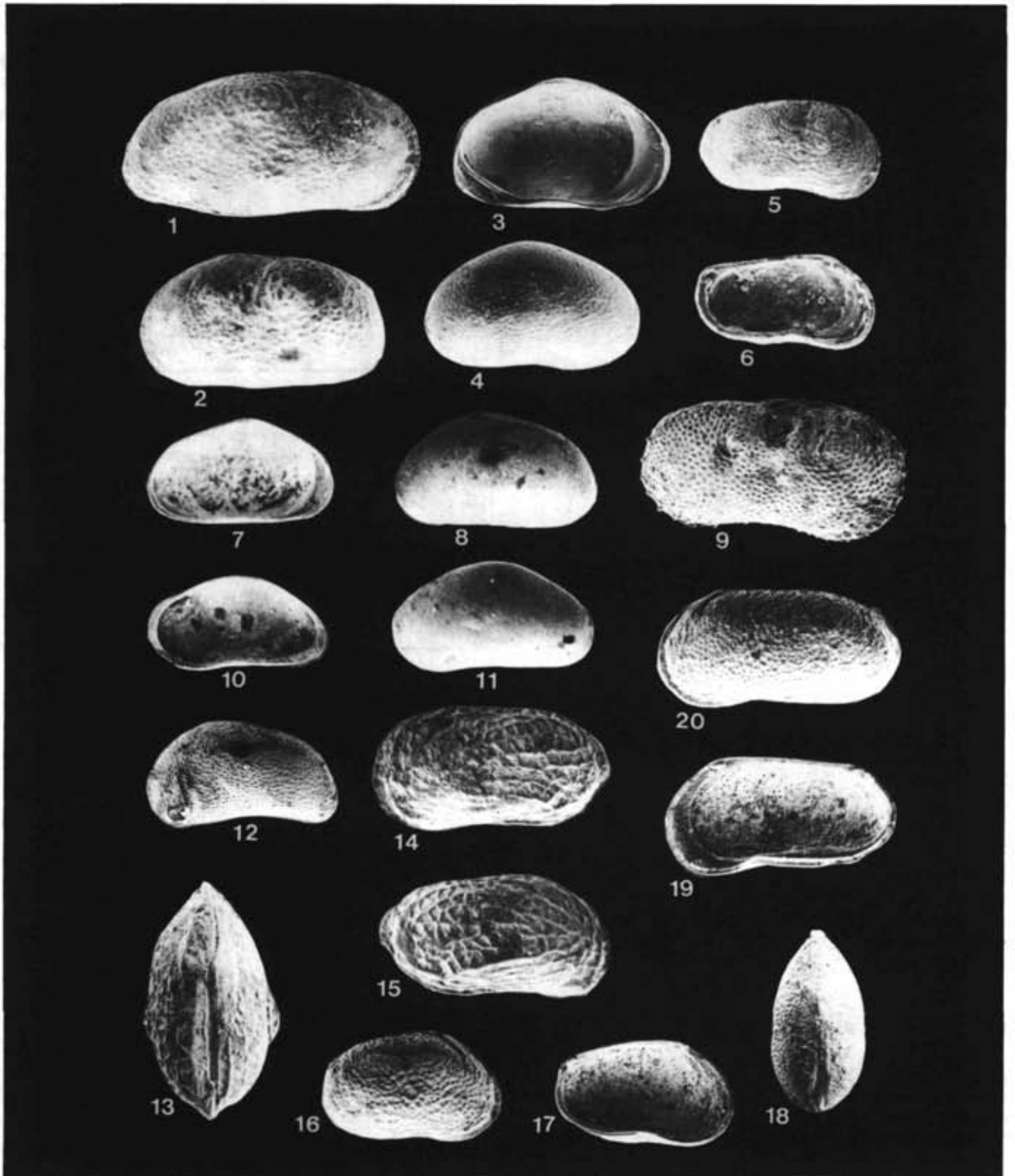


FIGURE 6. Recent temperature tolerances of Champlain Sea Ostracoda.

*Tolérances des Ostracodes de la mer de Champlain à la température.*



Both species are indicative of arctic-like conditions. Thus, the earliest phase of the Champlain Sea appears to have had frigid environments, and fluctuating salinities. Such rigorous habitats are also suggested by the extremely low foraminiferal species diversity.

Water temperature during the *Hiatella* Phase increased only slightly and rarely exceeded 12°C during the warmest months (Fig. 5). However, a drastic change in salinity, already suggested by the increased foraminiferal diversities, is apparent from the ostracode assemblage. Figure 6 shows that species restricted to the *Hiatella* Phase inhabit polyhaline-euhaline water (18‰ – 35‰). Since most *Hiatella* Phase ostracodes are euhaline to various degrees, normal marine conditions rarely if ever were reached in this part of the sea for extended periods of time. The polyhaline, near normal marine environments, however, were considerably more saline than either the Transitional or *Mya* Phase environments.

Between 11,000-10,600 yr BP, the Champlain Sea was colonized by the *Mya* Phase fauna, an assemblage indicative of higher water temperatures, and substantially lower salinities (Fig. 5 and 6). Rather than frigid-subfrigid conditions of earlier phases, *Mya* Phase ostracodes suggest a cold temperate climatic zone similar to Norwegian and Caledonian zoogeographical provinces of Europe (HAZEL, 1967). Characteristic ostracodes of this final phase of the sea tolerate waters as high as 30°C, although it is doubtful that late Champlain Sea temperatures were more than 20-22°C. Moreover, these species are unknown from climatic zones north of cold temperate regions; that is, they do not tolerate frigid and subfrigid conditions.

Salinity conditions during the *Mya* Phase were clearly mesohaline (3 – 18‰) as indicated by the association of euhaline fresh and strictly brackish water species

(Fig. 6). Low foraminiferal species diversities during the *Mya* Phase are consistent with this interpretation.

## DEGLACIATION AND CHAMPLAIN SEA MICROFOSSILS

The significant temporal environmental changes suggested by microfaunal data on foraminiferal species diversity and ostracode distribution require an explanation in light of the deglaciation of the St. Lawrence Lowlands. Of course, the existence of the Champlain Sea itself resulted from two factors — the crustal depression from the ice sheet, and the subsequent northward retreat of the ice margin near Québec City, an event which permitted marine water to enter the St. Lawrence Lowlands. The fauna of the Transitional Phase indicates continued glacial influence during the earliest period of the sea. The mixed association of marine and fresh water ostracodes, and the extremely low foraminiferal species diversity suggests a period of mixing between fresh waters of proglacial Lake Vermont (and Lake Sherbrooke?) with the earliest influx of marine water. Moreover, the fluctuating salinities during this time probably resulted from continued influx of melt-water from remnant glaciers in the Adirondack and Green Mountains, as well as the Laurentide Ice Sheet itself. Similarly, glacial influence is in evidence from the frigid climatic conditions of this period. Thus, late Wisconsin ice appeared to have a profound influence on early Champlain Sea environments.

Frigid to subfrigid environments persisted during the *Hiatella* Phase, but the more saline conditions reflect a continual influx of marine water, and probably a lessening influence of meltwater.

The most significant Champlain Sea faunal change occurred between 11,000 and 10,600 yr BP, when the sea was colonized by a mesohaline, cold-temperate ostracode assemblage, an event contemporaneous with decreasing foraminiferal diversities. Several factors appear responsible for these changes. Decreasing salinities suggest the influx of significant volumes of fresh water causing dilution of the Champlain Sea. One source of this water may have been the Laurentide Ice Sheet itself. Rapid deglaciation following the building of the St. Narcisse Moraine (post 11,000 yr BP) may have discharged large amounts of meltwater into the sea, contributing to its dilution. Although a precise chronology of events is not yet established due to problems associated with radiocarbon shell dates (MANGERUD, 1972; OCCHIETTI and HILLAIRES-MARCEL, 1977), the inception of a predominantly mesohaline fauna (11,000-10,600 yr BP) immediately follows the St. Narcisse event, suggesting the two events may be related.

A later, and better documented event that discharged fresh water into the Champlain Sea was the eastward

PLATE IV. Champlain Ostracoda. *Les Ostracodes de la mer de Champlain*. Figures 1-2) *Cyprideis cf. torosa* (Jones); 1, right valve, lateral view; 2, left valve, lateral view, × 39. Figures 3-4) unidentified Cypridae; 3, left valve, internal view; 4, right valve, lateral view, × 55. Figures 5-6) *Leptocythere castanea* (Sars); 5, right valve, lateral view; 6, left valve, internal view, ×. Figures 7-8) *Cyprinotus cf. salinus* (Brady); 7, left valve, internal view; 8, left valve, lateral view, × 30. Figure 9) *Ilyocypris gibba* (Ramdohr), right valve, lateral view, × 55. Figures 10-11) *Candona sub-*

*triangulata* Benson and Macdonald; 10, left valve, internal view; 11, left valve, lateral view, × 24. Figure 12) *Candona* sp. left valve, lateral view, × 55. Figures 13-15) *Cytherura gibba* (O. F. Muller); 13, female carapace, dorsal view; 14, female, left valve, lateral view; 15, female, right valve, lateral view, × 75. Figures 16-20) *Cytheromorpha fuscata* (Brady); 16, female, right valve, lateral view; 17, female, left valve, internal view; 18, female carapace, dorsal view; 19, male, right valve, internal view; 20, male, left valve, lateral view, × 52.

drainage of Lake Algonquin. KARROW *et al.* (1975) date this event at post 10,600 yr BP, probably about 10,400 yr BP in the Alliston region, and slightly later through the North Bay outlet (HARRISON, 1972). Mesohaline conditions of the late Champlain Sea reflect dilution of marine waters by fresh Lake Algonquin waters. Thus, the deglaciation and subsequent uplift in the eastern Great Lakes region which caused Lake Algonquin to drain, may have significantly affected Champlain Sea environments.

Finally, the cold temperate conditions of the *Mya* Phase suggest climatic amelioration and a diminishing glacial influence on water temperatures. Dominant ostracode and molluscan species of this period could not tolerate frigid glaciomarine conditions and their presence during the *Mya* Phase signifies the end of such conditions in the Champlain Valley. However, since these species were absent during the Transitional and *Hiatella* phases, they must have migrated into the sea from the Gulf of St. Lawrence, through the lower St. Lawrence River, a region very close to the retreating ice margin. CRONIN (1977) discusses the possibility that warm Gulf Stream water, the presence of which is well documented for the Gulf of St. Lawrence about 11,000 yr BP (BARTLETT and MOLINSKY, 1972), may have entered the Champlain Sea bringing with it a warmer water fauna. Although the cold Labrador Current was the major factor in determining maritime oceanographic conditions at this time, the data of Bartlett and Molinsky indicate periodic warm water incursions with temperatures possibly as high as 24° to 30°C. Once successful migration into the Champlain Sea occurred, the cold temperate fauna of the *Mya* Phase flourished in the Champlain Valley until the marine episode ended.

In other regions of the Champlain Sea, however, there is evidence for continued frigid-subfrigid environments relatively late in the sea's history. CRONIN (1976a) records an arctic foraminiferal assemblage from Ontario, associated with *Hiatella arctica* shells dated at 10,900 ± 100 yr BP (GSC 2312). The persistence of such conditions at this time suggests the influence of nearby glacial ice. In fact, this area was much closer to the ice margin than was the Champlain Valley.

Additional data is required to understand the complex history of the Champlain Sea. Yet as these data accumulate, it clearly must be interpreted in light of the deglaciation of eastern Canada. The faunal data presented above reflect an intimate relationship between Champlain Sea water temperatures and salinities and the regional chronology of glacial and geological events.

#### MICROFOSSILS AND CHAMPLAIN SEA

Champlain Sea microfossils can clearly be useful in future studies of temporal environmental changes

during the sea's brief history, as well as in deciphering the Wisconsin relationships between the Great Lakes and St. Lawrence Lowlands. Although ostracodes are not as common as Foraminifera, they, nevertheless, have more potential for indicating paleoenvironmental conditions. There are three reasons for this. First, the class Ostracoda is a taxon with marine, brackish and fresh water representatives. The complex paleo-oceanographical situation of the Champlain Sea, with its temporal and geographically variable salinities, was an ideal region for all types of species to inhabit. Furthermore, at a time of rapid climatic change, such as that of the late Wisconsin, the temperature regimes of the Champlain Sea would also be variable. Ostracodes have been used successfully to define recent zoogeographical provinces and climatic zones, and ostracode assemblages would, therefore, be expected to reflect changing climatic conditions.

Second, the data presented above show that Champlain Sea Ostracoda, for the most part, are well-studied species, whose recent ecological tolerances are known. Temperature and salinity ranges, as well as zoogeographical distribution, are known for most species, permitting relatively accurate paleoenvironmental reconstruction.

Finally, Champlain Sea ostracode species are more easily recognized than foraminiferal species which dominate the Champlain Sea. Diagnostic morphological features of ostracodes are usually clearly visible and consistent within a single species. The ubiquitous foraminiferal genus, *Elphidium*, however, is notorious for morphological variation and intergradation among several species. Other common taxa, members of the Polymorphinidae, in particular, are extremely difficult to identify. Furthermore, recent ecological preferences of Champlain Sea Foraminifera are known only in a broad sense. They are typical of marginal marine, often brackish water environments, yet, the ecological tolerances of most species are very broad, and poorly known.

Within the Champlain Valley of New York, Vermont and Québec, ostracodes can be used successfully to grossly define three environmentally distinct phases of the Champlain Sea and to correlate fossiliferous deposits in this region. Whether similar paleoenvironmental changes occurred throughout the entire sea, and whether such changes were nearly synchronous over the entire region of inundation is not yet known. Yet changing environments during the brief history of the Champlain Sea can be inferred if the relative age, and preferably the absolute age as well, of deposits can be determined. Strategically-placed sediment core sections, which sample a large temporal segment of the sea's history, would be ideal for this type of paleo-

ecological and stratigraphical study. Here, microfossils have the particular advantage of large abundances from relatively small sediment samples. The results of the present study confirm these advantages and reveal the potential of ostracodes, and to a lesser extent Foraminifera, for both local correlation, as well as regional, large-scale paleoclimatic inference.

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#### QUESTIONS AND COMMENTS

G. SAMSON:

"What are the implications of the paleo-zoological conditions of the Champlain Sea that you presented for larger marine fauna (seals, etc) and consequently human occupation? (Vegetative conditions presented by Richard suggest favorable conditions)."

T. M. CRONIN:

"During the late Champlain Sea (10,600-10,000) in the Champlain Valley I believe the marine environments were cold-temperate, water temperatures could have been as high as 20-24°C during the warmest month. Dominant molluscan species, *Mya arenaria* and *Mytilus edulis* were small (stunted) but common and could have been a food source. Of course fossil vertebrates have been reported in Champlain Sea sediments both in Ontario and Vermont. Thus, if the terrestrial environment was inhabitable, the shores of the Champlain Sea could have been occupied by humans in the Champlain Valley. Whales, and I think seals, could have probably inhabited the waters of low salinity of the late Champlain Sea. I think, therefore, a concentrated effort to search for evidence of human occupation in this area about 10,000 years ago would be worthwhile."