A GEOCHEMICAL AND PALEOCEANOGRAPHIC INVESTIGATION USING MARINE MOLLUSCS OF THE LATE QUATERNARY MARINE SUBMERGENCES

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This thesis is dedicated to

Margaret Linda Wassenaar

Were it not for her love, support and unfailing encouragement this work would not have been possible.

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General Abstract

Sediments deposited in the Late Quaternary marine submergences that followed the deglaciation of Ontario, Québec, and British Columbia often contain an abundant marine invertebrate macrofauna. The macrofauna, dominated by aragonitic pelecypods, is fully preserved in their original mineralogy and chemistry as determined by x-ray diffraction, scanning electron microscopy, trace and minor element analyses and stable isotopes.

The trace element and stable isotope geochemistry of chemically unaltered aragonitic molluscs can be used to determine paleotemperatures and paleosalinities. However, corrections need to be made when determining oxygen-isotope paleotemperatures due to the influence of isotopically light glacial meltwaters and reduced salinities. The eastern Laurentide Ice Sheet probably had an oxygen isotopic composition as low as -80 ^{o}/oo (SMOW). In addition, corrections need to be made to the carbon-isotope values, before salinity determinations are made, due to the reduction of the terrestrial carbon biomass during glacial maxima.

Using geochemical data from 537 marine macroinvertebrates from 72 localities in southeaster Ontario and southern Québec, it has been determined that the Late Quaternary Champlain Sea was density stratified along salinity and temperature gradients. The deep-waters of the Champlain Sea had salinities that ranged from 31 to 36 ppt, and temperatures of 0° to 5°C. Conversely, the shallow-water regime of the Champlain Sea had salinities that ranged from 24 to 33 ppt, with temperatures ranging from 5° to 15° C.

The major, minor, and trace element geochemical analysis of 155 marine invertebrates from 4 localities of the Late Quaternary Ft. Langley

Formation and Capilano Sediments, southwestern British Columbia, suggest, that the waters of the marine inundation that followed the retreating Cordilleran Ice Sheet had salinities ranging from 32 to 36 ppt.

General Introduction

The purpose of this thesis is to use recent developments in carbonate trace element and stable isotope geochemistry and apply them to a paleoecological problem using marine macrofossils from the Late Quaternary marine deposits of Ontario, Québec and British Columbia. More specifically, trace element analysis, isotopic analysis, x-ray diffraction, scanning electron microscopy, and the ecology of Recent molluscs, will be used to:

1. establish the degree of chemical, mineralogical, and microstructural integrity of marine macroinvertebrates from the Late Quaternary deposits,

2. determine quantitative paleosalinties for the marine environments of the Champlain Sea of Ontario and Québec, and the Ft. Langley Formation and Capilano Sediments of southwestern British Columbia,

3. determine the isotopic composition of the eastern Laurentide Ice Sheet, and,

4. determine oxygen-isotope paleotemperatures that have been corrected for salinity and isotopic meltwater effects for the Champlain Sea.

Chapter 1 of the thesis deals with the theory and techniques involved in this multi-faceted approach. Chapter 2 is devoted to the geochemistry of macroinvertebrates and paleoceanography of the Champlain Sea, Ontario and Québec, and the eastern Laurentide Ice Sheet, whereas, Chapter 3 deals with the geochemistry of macroinvertebrates and paleosalinities of the marine waters that inundated southwestern British Columbia.

Chapter 1

Methods, Procedures, and Preliminary Considerations

Methods and Procedure

Sampling

Marine pelecypods, gastropods, brachiopods, and cirripeds were collected from marine sediments exposed in sand and gravel pits, roadcuts, and excavations of the Champlain Sea deposits, Ontario and Québec, and the Ft. Langley Formation and Capilano Sediments, British Columbia. Some of the pelecypods collected from both study areas are well preserved with the periostracum commonly still intact. In addition, several localities (i.e., Wakefield, P.Q., Charet, P.Q.) contained fossil populations still preserved in their life position, indicating no transport after death. Marine pelecypods were the most abundant invertebrate (>90%) at all localities and are the primary data base for this study.

Stratigraphic interpretations were based on information obtained from published surficial and Quaternary geology maps and reports (Armstrong,1981; Clague,1981; Elson,1969a, 1969b; Gadd, 1960, 1963, 1971, 1983; Terasmae, 1965; Hillaire-Marcel,1974; Cronin,1977; Lowdon and Blake,1973,1979,1981; Blake,1983; Richard,1978; Rodrigues and Richard,1985; Sharpe,1979; Catto *et al.*, 1982). All samples were labelled in the field and stored in plastic bags.

In the laboratory mollusc valves, gastropod shells, and cirriped plates were identified, labelled, and manually cleaned of any adhering matrix. Samples were further cleaned by immersion in an ultrasonic bath of deionized water for 15 min. The samples were then leached in 15% HCl (v/v), rinsed in deionized water, and allowed to dry. Further handling of valves, plates, and shells was done wearing plastic gloves in order to eliminate Na contamination.

X-Ray Diffraction

A representative suite of fossils were analysed by x-ray diffraction (XRD) in order to determine mineralogy. XRD allows for the quantitative determination of mineralogy and the concentration of Mg in carbonates (Milliman,1974).

1. Dried and labelled samples were powdered using a mortar and pestle. Precautions were taken to avoid overgrinding, since prolonged grinding reduces the total aragonite and calcite peak intensity and can produce enough heat to transform aragonite into calcite (Milliman,1974). Molluscs with mixed mineralogies were separated into their aragonite and calcite portions prior to XRD analyses.

2. Powdered samples were applied to a clean glass slide coated with silicone grease.

3. Samples were run on a Picker 6238 x-ray diffractometer (using Cu-K alpha radiation), scanned over a 2 theta angle of 20° to 50°, and compared to an internal aragonite standard (Milliman,1974).

4. Diffractograms were examined and compared with the diagnostic 2 theta peaks for aragonite and calcite as recorded by Milliman (1974 p.22).

Scanning Electron Microscopy

A representative set of marine molluscs were examined by scanning electron microscopy (SEM) in order to determine the degree of preservation of skeletal microstructures. Fragments of shell material depicting a complete skeletal cross-section were leached briefly in 2% HCl (v/v) and dried prior to mounting on aluminum stubs. Each stub was coated with a thin layer of gold-palladium alloy. Samples were then examined using an

ISI SEM and photomicrographs were taken using a Polaroid photographic attachment. Microstructures were identified and compared with those listed in Carter (1980).

Atomic Absorption Spectrophotometry

Four hundred and ninety-three macroinvertebrates from the Champlain Sea sediments were analysed for ten elements (Ca, Mg, Sr, Na, Mn, Cu, Ni, Al, Fe, Zn) for a total of 4930 determinations. One hundred and fifty-five macroinvertebrates from the Ft. Langley Formation and Capilano Sediments were analysed for seven elements (Ca,Mg,Sr,Mn,Al,Fe,Na) for a total of 1085 determinations. In addition, 60 duplicate macroinvertebrates were analysed for an overall total of 6075 determinations. The following procedures were utilized;

1. Prior to use, all glassware, plastic storage bottles and lids were washed in warm, soapy water and rinsed with tap water. Wearing gloves and working in a fume hood, all glassware and bottles were filled with aqua regia (1 part concentrated nitric acid to 3 parts concentrated hydrochloric acid). After 15 minutes the aqua regia was poured back into the storage bottle. Bottle tops were placed in large beaker and filled with aqua regia. Following treatment with aqua regia, the bottles, glassware and tops were allowed to degas for 15 min and then rinsed thoroughly with deionized water. The equipment was then dried at 100° C.

2. Individual, previously cleaned, samples for AAS analysis were powdered using a mortar and pestle. The mortar and pestle were cleaned thoroughly between samples using 2% HCl (v/v) and deionized water. Powdered samples were stored in clean numbered plastic vials.

3. Preliminary calculations were performed in order to estimate the concentrations of major, minor, and trace elements in the samples. The average elemental concentrations for Recent molluscs (Milliman,1974, Tables 32 and 33) provided a basis for estimation. This allowed for the estimation of dilution factors needed to bring samples within the working range of the AAS for a particular element.

Cold acid digestion of carbonate samples

1. The powdered samples were placed in clean 50 ml beakers and oven dried at 150°C for 2-3 h.

2. Approximately 0.5 grams or 0.25 grams of each sample were weighed into clean 100 mL beakers using a Sartorius electronic balance which automatically recorded the weights to a Hewlett-Packard computer disk. The beakers were then covered with watch glasses.

3. Using a digital diluter, the 0.5 g samples were dissolved in 18 mL of 5% HCl (v/v) containing 5000 ppm K for 1 to 3 h. The 0.25 g samples were dissolved in 9 mL of 5% HCl (5000 ppm K). K was added to the solutions in order to reduce inter-elemental interference during analysis.

4. The dissolved 0.5 g samples were then filtered through Whatman No. 40 ashless filter paper into 50 mL volumetric flasks. Similarly, the 0.25 g samples were filtered into 25 mL volumetric flasks. Plastic gloves were worn to eliminate Na contamination during handling. Deionized water was then added to the flasks to make exactly 50 mL and 25 mL respectively. The samples were then

stored in clean, numbered, plastic vials at a final concentration of 2% HCl and 2500 ppm K.

5. The filter papers containing the insoluble portion of the carbonate sample were placed in pre-fired, pre-weighed Vitrocel crucibles and were then ashed in a muffle furnace at 800° C for 45 min. The insoluble residue (IR) in the crucibles represents the insoluble aluminosilicate portion of the sample.

6. The crucibles were cooled in a desiccator and weighed gravimetrically on the Sartorius balance. The difference in the weight between the empty and full crucible represents the IR, which was then automatically recorded on disk as a percentage of the total sample weight (Appendix I and II). The percentage of IR is used to recalculate the elemental concentrations to a 100% carbonate basis.

All samples were analysed on a Varian AA-1475 / HP 85 atomic absorption flame spectrophotometer for 10 or 7 elements. An additional dilution factor of 100 using 2% HCl (v/v) and 10 000 ppm La (to supress ionization) was applied to Ca and Mg samples. A dilution factor of 50 using 2500 K in 2% HCl (v/v) was applied to the Na and Sr samples. All other elements were analysed without further dilution. Al and Sr samples were analysed using an acetylene-nitrous oxide flame, whereas, all other elements were determined in an acetylene-air flame.

The Standard Curve method of AAS analysis was used by preparing 5 reference solutions spanning the optimum working range of the instrument for each element. The absorbances read by the Varian AAS for each sample, using the most sensitive spectral line, were automatically converted to concentrations and stored on disk. Blank samples containing the acids used

in digestion of the samples were analysed for purity and the elemental concentrations obtained were automatically subtracted from the sample value.

Reproducibility was obtained by running 60 duplicate samples. Accuracy was determined by using National Bureau of Standard rocks (NBS 633, NBS 634, NBS 636). Average reproducibility and accuracy was better than 5 to 10 relative percent for Ca, Mg, Sr, Na, Mn, Fe, and Zn, and better than 10 to 15 relative percent for Al, Cu, and Ni. IR reproducibility was better than 10 relative percent. All elemental data, on a 100% carbonate/insoluble residue free basis, is summarized in Appendix I and II, with the corresponding species and localities reported in Apppendix III and IV, resectively. All discussion in the text is also on a 100% carbonate basis.

The formula used for recalculating samples to a 100% carbonate basis is;

$$\text{ppm of element in sample} = \frac{DV * X * Y}{(wt - IR)} \qquad (1)$$

where

DV= original dissolution volume

X= concentration value from AA in ppm

Y= additional dilution factor

wt= original sample weight

IR= insoluble residue weight

Precision of duplicates was calculated by determining the absolute difference in concentrations between a sample and duplicate (Y),

calculating the mean between the sample and the duplicate (ã) and using the formula;

$$\% \text{ error} = \ddot{Y} / (\tilde{a} / 100). \tag{2}$$

Carbon and Oxygen Isotopes

Fourty-seven samples of skeletal carbonate from molluscs of the Champlain Sea were analysed for stable isotopes ^{13}C and ^{18}O. Five mg of powdered sample were roasted to remove any organic material and reacted with 100% phosphoric acid at 50°C for 30 min. The resulting stable CO_2 gas released was cleaned and analysed on a 602 VG Micromass Spectrophotometer at the University of Waterloo, Ontario. The $^{18}O/^{16}O$ and $^{13}C/^{12}C$ ratios determined from the samples were compared to the standard rock COWS (University of Waterloo, Ontario) and reported relative to the PDB standard in $^o/oo$. Both samples, standards and duplicates were treated identically, thus, average accuracy and reproducibility were $\partial^{18}O$ (0.10,4.2) and $\partial^{13}C$ (0.05,5.9) relative percent respectively. In addition, all samples were corrected for ^{17}O. The isotopic data presented in Appendix V is reported in the ∂ notation where:

$$\partial^{18}O = \{ (^{18}O/^{16}O_{sample}) / (^{18}O/^{16}O_{standard}) - 1 \} \tag{3}$$

and

$$\partial^{13}C = \{ (^{13}C/^{12}C_{sample}) / (^{13}C/^{12}C_{standard}) - 1 \} \tag{4}$$

and the standard is relative to PDB (Epstein *et al*, 1953).

Statistical Analyses

Statistical t-tests and Varimax rotated factor analyses of the chemical data (reported in Appendix VI and VII) were performed using the Statistical Package for the Social Sciences computer statistical program (Nie *et al*, 1975) on the Brock Universitiy Burroughs B7900 mainframe computer. Other statistical analyses of the data were performed using Statworks[TM] on an Apple Macintosh microcomputer.

Cathodoluminescence

Ten samples of thick shelled *Mya arenaria* from the Champlain Sea were examined by cathode luminesence to determine chemical variations within the skeletal carbonate due to chemical diagenesis (Fe, Mn), or dissolution and reprecipitation events. All samples, composed entirely of homogeneous aragonite, did not show any chemical variations of Mn or Fe, or dissolution features. This suggests that no chemical alteration had taken place and that *Mya arenaria* from the Champlain Sea deposits were preserved in their original state. No further experiments were performed using cathodoluminesence.

Preliminary Considerations

Geochemistry of Molluscan Carbonate

The skeletal carbonate of marine organisms may preserve chemical, structural, and morphological information that can be related to environmental parameters such as salinity, temperature, substrate, storms and pollution (Rhoads and Lutz,1981). In this study, the focus will be primarily on the chemical aspects of fossil molluscan carbonate as a record of environmental factors. Therefore, it is necessary to briefly review the role of trace elements and stable isotopes in molluscan shell formation. Since most studies in the literature deal with molluscan carbonate, the calcitic cirripeds and brachiopods will not be considered.

Shell Formation

Many invertebrates and most molluscs precipitate shells composed of rhombohedral calcite (6-fold coordination) and/or orthorhombic aragonite (A)(9-fold coordination). In addition, the shells may contain organic matter of usually less than 2-3% of the total weight (Milliman,1974). Calcitic skeletons have been further subdivided into three categories; Low-magnesian calcite (LMC) containing less than 5 mole% $MgCO_3$, high-magnesian calcite (HMC) containing 15-30 mole% $MgCO_3$, and intermediate-magnesian calcite (IMC) containing 12-13 mole% $MgCO_3$ (Milliman,1974).

Molluscan carbonate is precipitated from the extrapallial fluid which is enclosed between the outer mantle epithelium and the inner surface of the shell (Wilbur,1972). Mineral deposition takes place primarily near or at the shell margin (Wheeler and Wilbur,1977). The materials needed for shell growth, i.e., calcium, bicarbonate, and other minor and trace elements pass through the permeable inner and outer epithelium to become part of the

extrapallial fluid. These materials are ultimately derived from the water in which marine molluscs live (Crenshaw,1980).

Skeletal carbonate is precipitated from the extrapallial fluid and all components necessary for shell formation must pass through this fluid, although, the extrapallial fluid may contain materials that are not incorporated into the shell. The direct entry of seawater or freshwater into the pallial space is prohibited by a protective outer organic periostracum which covers the shell (Crenshaw,1972). Crenshaw (1972) has shown that during shell precipitation the extrapallial fluid is always saturated or super-saturated with respect to the mineral phase of the shell.

The nucleation of carbonate crystals from the extrapallial fluid has been little studied and is poorly understood. Weiner and Hood (1975) proposed that a small soluble portion of the organic matrix contains amino acids (ß-carboxyl group of aspartic acid) that can bind Ca so that the interatomic distances are similar to those of calcite or aragonite. Crenshaw and Ristedt (1975,1976), on the other hand, proposed that the soluble organic matrix induces carbonate crystallization by means of "ionotropy", where macromolecules induce ordered crystal formation. Other studies (Kitano *et al.*,1976) suggest that the organic matrix is not chemically interactive with the carbonate but rather functions as a protective covering from dissolution by physically coating the carbonate. This protective coating is especially evident and necessary for freshwater molluscan carbonate since A, HMC and IMC are metastable in the meteoric environment (Brand and Veizer,1980). Further studies are needed to clarify the role of the organic matrix in mineral nucleation. In order to eliminate the organic matrix factor in this study, all elemental concentrations from

the fossil carbonate were recalculated to a 100% carbonate/ organic residue free basis.

Shell Dissolution

It is well known that during unfavorable conditions intertidal molluscs can survive for periods of time without an oxygen supply. The energy needed for these times is supplied by the acid-producing process of anaerobic glycolysis. The acids produced are neutralized by dissolution of previously deposited shell material which functions as an alkali reserve (Crenshaw,1980). Molluscs may exhibit daily or seasonal dissolution events in their shells.

Minor and trace elements in carbonates

Skeletal and inorganic carbonate minerals tend to contain cations and anions within the lattice structure other than Ca^{2+} and CO_3^{2-}. Aragonite favors the incorporation of larger cations such as Sr^{2+}, Na^+, Ba^{2+}, Pb^{2+}, and K^+ into the larger orthorhombic structure (Okumura and Kitano, 1985), whereas, calcite favors smaller cations such as Mg^{2+}, Fe^{2+}, Mn^{2+}, Zn^{2+}, Cu^{2+}, Ni^{2+}, and Cd^{2+} (Milliman,1974) into the rhombohedral structure. Incorporation of cations in the carbonate mineral can occur in five ways (Veizer,1983a; Krauskopf,1967):

1) substitution for Ca^{2+} in the $CaCO_3$ structure,

2) interstitial substitution between planes,

3) substitution into lattice defects,

4) adsorption to satisfy unbalanced charges, and,

5) in non-carbonate inclusions.

Factors 2-5 are essentially random processes that are difficult to quantify. Factor 1 is fairly well understood, can be quantified, and is of much greater importance than Factors 2-5 (Veizer,1983b).

The incorporation of a particular trace element M_e^{2+} into a carbonate (c) may be expressed by the equation (Veizer, 1983b):

$$CaCO_{3\ (c)} + M_e^{2+}{}_{(aq)} = M_e^{2+} CO_3 + Ca^{2+}{}_{(aq)} \tag{5}$$
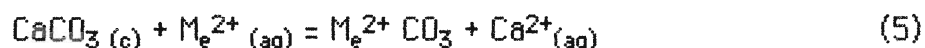
and is governed by the distribution coefficient (D)(McIntire, 1963):

$$D = (^mM_e / {}^mCa)_c / (^mM_e / {}^mCa)_l \tag{6}$$

where m indicates molar concentrations, M_e is the trace element, c is the carbonate phase, and l is the liquid from which the carbonate was precipitated. This relationship is only true when the system is in equilibrium, at constant temperature and pressure, and the solid carbonate phase does not show any elemental concentration gradients during precipitation (Veizer, 1983a).

Experimental distribution coefficients for selected minor and trace elements in carbonates are shown in Table 1. When D is less than unity, the precipitated carbonate mineral phase will contain, relative to Ca, lower M_e concentrations than the fluid with which the solid phase was in equilibrium. If D is greater than unity the solid phase will contain, relative to Ca, higher M_e concentrations than the fluid with which the solid is in equilibrium. The equilibrium situation applies only to conditions where the amount of precipitated solid is minor compared to the volume of fluid (Veizer, 1983a,b). This equilibrium situation also applies to the extrapallial fluid of molluscs since molluscs constantly replenish the pallial fluid to super-saturation during skeletal precipitation (Crenshaw, 1980). Molluscs, however, may exert biological control over the

Table 1. Partition coefficients (D) for trace elements in calcite and aragonite (adapted from Veizer,1983a)[t].

	Trace element	Reported D	Recommended D
Calcite			
	Sr	0.027-0.4(1.2)	0.13 (D.P.)
	Na	0.00002-0.00003	
	Mg	0.013-0.06 (0.0008-0.12)	
	Fe	$1 \leq x \leq 20$	
	Mn	5.4-30(1700)	6 (D.P.)
	Zn	5-20 (50)	
	Cu	25 (15-40)	
Aragonite			
	Sr	0.9-1.2 (1.6)	
	Na	$3-4 \times D^{Na}_{calcite}$	
	Mg	0.0006-0.005	
	Mn	$0.86 (1/3 - 1/2 \times D^{Mn}_{calcite})$	
	Zn	5	
	Cu	2.5 (1-10)	

D.P. – direct precipitation, [t]see Veizer (1983a,b) for references.

ionic composition of the extrapallial fluid as reflected in the shell chemistry. This process of biogenic fractionation by ionic regulation in molluscs may result in the enhancement, or reduction, of particular trace elements in the skeletal $CaCO_3$. For example, the biogenic discrimination against Mg in some marine organisms allows for the precipitation of LMC and A in the marine environment where only HMC should be the "equilibrium" phase (Veizer,1983a,b). Molluscs also show biogenic fractionation against equilibrium incorporation of Sr into aragonite skeletons (Dodd,1967; Milliman,1974; Brand,1981).

A simplified comparative summary of the pathways and processes for the incorporation of trace elements into biogenic and inorganic carbonates is shown in Fig. 1. Providing no chemical diagenesis and no biogenic fractionation has taken place, and equilibrium conditions existed during shell precipitation, it is possible to estimate the chemistry of the waters from which the carbonate was precipitated using the experimental distribution coefficient and partition equation (Brand and Veizer,1980). The majority of marine carbonates are biogenic in origin, and biogenic fractionation of trace elements often masks the true chemistry of the ambient waters. In addition, the rapid chemical alteration of metastable biogenic and inorganic carbonates when exposed to meteroic waters and deep burial brines makes paleo-environmental analyses of diagenetically altered carbonates extremely difficult (Brand and Veizer,1980; Baker *et al.*,1982).

Carbon and Oxygen Isotopes

The global natural abundance of carbon and oxygen isotopes are shown in Table 2. Although isotopes of an element may behave identically,

Fig. 1. Pathways for the incorporation of minor and trace elements into biogenic and inorganic carbonates.

Inorganic Carbonates
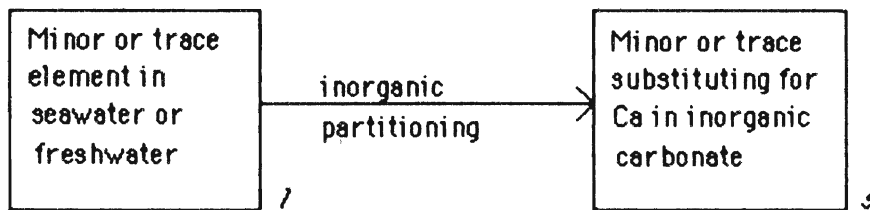
Biogenic Carbonates
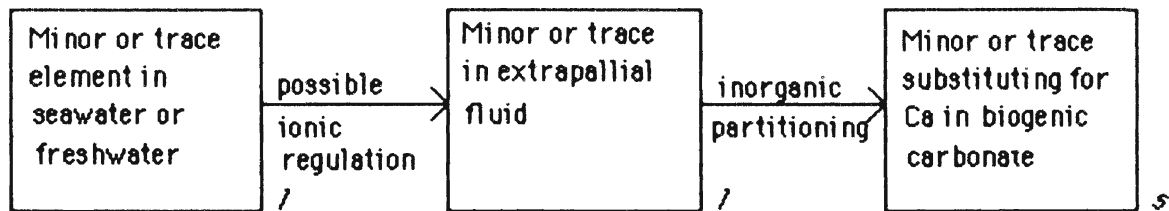
l = liquid   *s* = solid carbonate

Table 2. The global abundances of stable carbon and oxygen isotopes (from Hoefs, 1980).

Isotope	Relative abundance %
^{12}C	98.89
^{13}C	1.11
^{18}O	0.1905
^{16}O	99.763
^{17}O	0.0375

generally, they do not in many natural chemical, physical, and biological processes (Anderson and Arthur,1983). Moreover, the isotopic composition of a precipitated carbonate is related to the isotopic composition of the fluid (Urey,1947). Thus, knowledge of the distribution of stable isotopes within a carbonate can provide insight into the nature of the medium from which the carbonate was precipitated (Milliman,1974). Stable isotopes of carbon and oxygen are incorporated into carbonates by the following reactions:

$$H_2{}^{18}O_{(l)} + 1/3\ CaC^{16}O_{3(s)} = H_2{}^{16}O_{(l)} + 1/3\ CaC^{18}O_{3(s)} \qquad (7)$$

and

$$^{13}CO_3{}^={}_{(aq)} + {}^{12}CO_3{}^={}_{(s)} = {}^{12}CO_3{}^={}_{(aq)} + {}^{13}CO_3{}^={}_{(s)} \qquad (8)$$
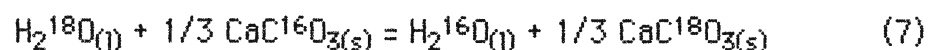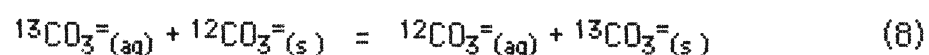
There are a number of factors, however, such as mineralogy, salinity, temperature, and biogenic fractionation that may influence the fractionation of stable isotopes in marine organic and inorganic carbonates.

Mineralogy

The formation of an inorganic carbonate mineral, or a calcareous skeleton, plays an important role in isotopic fractionation. For example, it has been shown that aragonite precipitated at 25° C contains 0.6 $^o/oo$ more ^{18}O than calcite precipitated under identical conditions (Sharma and Clayton,1965). This mineralogical difference led to the development of an independent aragonite paleotemperature equation by Grossman and Ku (1981).

Salinity

Salinity also affects the oxygen and carbon isotope composition of seawater, which is in turn reflected in the stable isotope composition of a

carbonate precipitated from that water. With an increace in salinity both ^{13}C and ^{18}O become more isotopically enriched (or positive). Ocean water with a salinity of 35 ppt has a mean $\partial^{18}O$ value of about 0 $^o/oo$ (SMOW). An increace in salinity will enrich the $\partial^{18}O$ composition of seawater, whereas, dilution of seawater by freshwater, such as in the nearshore or estuarine environment, will deplete the $\partial^{18}O$ values (Epstein and Mayeda,1953). Due to the removal of water from the oceans during the Pleistocene glaciations, the salinity of the oceans increased by about 3.5%, which corresponds to an estimated $\partial^{18}O$ enrichment of +1.6 $^o/oo$ (Broecker,1982).

Although isotopic variations in the ocean are small due to the enormous volume of seawater, the effects of salinity on the oxygen isotope composition of seawater have been shown to be;

$$\partial^{18}O_{sw} = -21.2 + 0.61\ (S) \qquad\qquad (9)$$

where $\partial^{18}O_{sw}$ is the final isotopic composition of the seawater with a measured salinity S, and the isotopic composition of the freshwater contaminant is about -22 $^o/oo$ (SMOW)(Faure,1977,p.333).

Biogenic Fractionation

Many molluscs do not precipitate their carbonate skeletons year-round (Epstein and Lowenstam, 1953) and some of them may discriminate against the isotopic equilibrium incorporation of carbon or oxygen into the skeletal carbonate (Lowenstam and Epstein,1954). In general, however, molluscs and brachiopods appear to secrete their carbonate in isotopic equilibrium with the ambient seawater (Epstein *et al*, 1953; Lowenstam,1961). Paleotemperatures derived from molluscs that do exhibit biogenic fractionation tend to be anomalous (Morrison and Brand, in press).

Oxygen Isotopes in the Water Cycle

Oxygen has three stable isotopes and hydrogen has two, thus, there are nine different isotopic configurations possible for a water molecule. The vapor pressures of each configuration are inversely proportional to their mass, therefore, water vapor derived from seawater is preferentially enriched in ^{16}O, while the remaining seawater becomes enriched in ^{18}O. The average oxygen isotopic composition of present seawater varies about 0 °/oo (SMOW) (Faure,1977).

During evaporation the lighter ^{16}O isotope species is preferentially extracted from the liquid by the diffusion-controlled stage of the evaporation process (Anderson and Arthur,1983). The vapor masses (or clouds) may move onto a continent where condensation and precipitation may occur. Again, because of differences in vapor pressures, the ^{18}O species is preferentially incorporated into the condensate. The removal of condensate from a vapor mass is analogous to a Rayleigh distillation cycle where the condensate is in instantaneous equilibrium with the vapor phase (Anderson and Arthur,1983). With further precipitation, the condensate becomes isotopically lighter. A range of variations in the oxygen isotopic composition of natural waters and ice is illustrated in Table 3.

In addition to these kinetic factors, the $\partial^{18}O$ composition of precipitation becomes isotopically depleted with increasing latitude, altitude, and decreasing temperature (Faure,1977). The effects of altitude, due to orographic uplift causes an isotopic depletion of about 0.15 to 0.5 °/oo of $\partial^{18}O$ / 100m (Gat,1980).

While continental precipitation is mostly consistent with a Rayleigh process a number of other factors must be considered (Gat,1980);

Table 3. The average isotopic composition of natural waters and ice. Data from Keith *et al.* (1964), Faure (1977), Broecker (1982), Anderson and Arthur (1983) and Lorius *et al.* (1985).

Waters and Ice	$\partial^{18}O$ (SMOW) $^0/_{00}$
Modern seawater	0.0
Quaternary seawater	+1.6
Freshwater lakes	-8.0
River water	-8.0 to -15.0
Glacial ice (Greenland)	-30.0 to -43.0
Glacial ice (Antarctica)	-55.0 to -63.0
Red Sea	+0.6 to +1.9

1) the actual pattern of air movement is not always consistent with `
a poleward movement of low latitude air masses,

2) the Rayleigh distillation cycle does not predict a straight line
process, especially in the final stages,

3) the distillation column is not a closed system, evaporation can
occur over high latitude oceans and continents as well, and finally,

4) the isotopic composition of precipitation is not only controlled
by the vapor mass since isotopic re-equilibration may occur due
to temperature changes.

Paleosalinities

Paleosalinities can be determined using the trace element and $\partial^{13}C$ content from chemically unaltered molluscan aragonite by means of two mutually independent methods. A brief summary of each salinity equation is necessary to clarify the theoretical background of each method.

Sr/Na Salinity Equation

Marine molluscs are isosmotic with respect to Na and Cl of the ambient seawater. All fluids, including the extrapallial fluid from which the skeletal carbonate is precipitated, have Na and Cl concentrations similar to seawater (Crenshaw,1972). As Na can substitute for Ca in the orthorhombic aragonite lattice (Okumura and Kitano,1985), Brand (1984) has shown that molluscs incorporate Na into shell aragonite in chemical equilibrium with the surrounding seawater.

It is well documented, on the other hand, that molluscs control the Sr content of their skeletal carbonate (Bathurst,1975; Lowenstam,1963). The control of Sr uptake is regulated by variations in body permeability, active excretion of ions, or uptake of ions through gill membranes (Prosser,1973).

Marine molluscs, in brackish water, lose Na and Cl to the surrounding medium. However, in order to maintain isosmotic equilibrium, the loss of Na and Cl must be compensated by the controlled uptake of specific ions and water (Prosser,1973). Brand (1984) has shown that for aragonitic molluscs, the loss of Na can be balanced by the uptake of Sr. Moreover, considering the laws for diadochic substitution (Henderson,1982), Brand (1984) and Okumura and Kitano (1985) have demonstrated that Sr and Na can substitute directly for Ca in the $CaCO_3$ lattice and that there is a covariant relationship between the Sr and Na content of mollucan aragonite that can be related to salinity with high statistical correlation ($r^2 = 0.982$). The covariant relationship of Sr and Na for Ca is confirmed by factor analyses of the chemical data for molluscan aragonite from the late Quaternary Seas (Appendix VII). As trace elements are log-normally distributed in carbonates, the relationship is given by;

$$Salinity\ (\pm\ 1.0\ ppt) = -4.010\ ln\ Sr/Na\ (wt) + 29.120 \qquad (10)$$

where Sr/Na is the chemical weight ratio of Sr and Na in the aragonitic mollusc shell and ln is the natural logarithm (Brand,1984). This method is extremely useful because it is independent of all environmental factors other than salinity. The optimum working range for equation 10 is from about 10.0 to 0.70 Sr/Na (wt), which esentially delimits the tolerance limits of the marine faunal realm (Gall,1983; Brand,1984). Moreover, possible variations in the Sr content of seawater will not affect the Sr/Na ratio since molluscs actively control the Sr content of their body fluids (Buchardt and Fritz,1978). Fossil molluscs used for this method must be composed of chemically unaltered aragonite. Slight variations in

determined salinity may occur between several species in a stratigraphic horizon and is likely due to seasonal/diurnal variations in salinity or differences in calcification times and life modes.

$\delta^{13}C$ Salinity Equation

Most aragonitic molluscs, except those that exhibit biological fractionation effects, precipitate their shell carbonate in $\delta^{13}C$ equilibrium with the total dissolved inorganic carbon (TDC) of the ambient seawater and is enriched in $\delta^{13}C$ by 1-2 $^0/oo$ relative to the $\delta^{13}C$ of the TDC of seawater (Anderson and Arthur,1983). The $\delta^{13}C$ of present seawater varies about 0 $^0/oo$ (PDB), whereas, the $\delta^{13}C$ of meteoric waters vary from -10 $^0/oo$ to -20 $^0/oo$ (PDB) (Strain and Tan, 1974). As there is only a negligible temperature effect on the fractionation of $\delta^{13}C$ (Emrich et al., 1970), chemically unaltered molluscan carbonate accurately reflects the $\delta^{13}C$ of the TDC of the ambient oceanic reservoir (Anderson and Arthur,1983). Thus, the decreasing $\delta^{13}C$ of seawater with decreasing salinity is reflected in the skeletal carbonate of aragonitic molluscs. On the basis of the $\delta^{13}C$-salinity relationship proposed by Mook (1971) for biogenic carbonates, Brand (1984) demonstrated, with high statistical correlation ($r^2 = 0.989$), a direct relationship between the $\delta^{13}C$ of Recent marine aragonitic molluscs and salinity. The relationship between $\delta^{13}C$ and salinity defines a linear expression;

$$\text{Salinity} (\pm 1.0 \text{ ppt}) = 1.904 \, \delta^{13}C \, (^0/oo, PDB) + 30.566 \qquad (11)$$

and $\delta^{13}C$ is the value from the unaltered fossil aragonitic mollusc (Brand,1984). However, not only must the requirements of no diagenetic

alteration be met, but the samples must also be corrected for secular variations in the $\partial^{13}C$ of seawater (Veizer *et al*, 1980).

Whereas the $\partial^{13}C$ content of marine molluscs can be related directly to the salinity of the ambient seawater, the $\partial^{13}C$ content of the TDC of seawater is intimately linked to the $\partial^{13}C$ of atmospheric CO_2. Recent studies have shown that there was a significant increase in atmospheric CO_2 during deglaciation (Delmas *et al*,1980; Neftel *et al*,1982) from about 200 pm to 300 ppm (Berger,1985). This change in atmospheric CO_2 has been partially linked to a decrease in the productivity of the ocean surface waters. In addition, it is related to changes in the $\partial^{13}C$ of the oceanic TDC due to changes in the continental carbon biomass reservoir, which is reflected in the $\partial^{13}C$ content of benthic and planktonic foraminifers (Broecker,1982; Keir and Berger,1983).

Paleotemperature Equations

The fractionation of stable isotopes of oxygen between carbonates and the liquid medium from which the carbonate was precipitated has been shown to be temperature dependant. On the basis of measurements from controlled systems the following paleotemperature equations were derived for calcite (Craig,1965):

$$T(°C) = 16.9 - 4.2 (\partial_c - \partial_w) + 0.13 (\partial_c - \partial_w)^2 \qquad (12)$$

and for aragonite (Grossman and Ku,1981):

$$T(°C) = 19.0 - 3.52 (\partial_A - \partial_w) + 0.03 (\partial_A - \partial_w)^2 \qquad (13)$$

where ∂_c or ∂_A is the $\partial^{18}O$ value of CO_2 generated from the carbonate sample at 25°C (relative to PDB) and ∂_w is the the $\partial^{18}O$ value of CO_2 generated for the ambient seawater at 25°C (relative to SMOW). Thus, in order to use the paleotemperature equation one needs to know the salinity of the ambient seawater and the isotopic composition of the ambient seawater (Rye and Sommer, 1981). In addition, the following criteria must be met when determining paleotemperatures using fossil molluscs (Rye and Sommer,1981; Veizer,1983a; Veizer *et al*, 1980) :

   1) the fossil must be chemically unaltered,

   2) the skeletal carbonate must have been precipitated in isotopic
      equilibrium with the ambient seawater,

   3) the isotopic composition of the ambient waters (∂_w) must be
       known, and,

   4) corrections must be made for the secular variation of ^{18}O for
      ancient seawater.

Only when conditions 1 to 4 are satisfied can $\partial^{18}O$ paleotemperatures be calculated with any degree of confidence using fossil invertebrates.

Ecology of Marine Invertebrates of Late Quaternary Seas

The spatial distribution of invertebrate macrofauna in a sea or estuary is related to a number of interrelated environmental factors such as salinity, temperature, substrate, food supply and water depth (Schopf,1980). A particular species may exhibit a wide or narrow range of environmental tolerances, thus in any paleooceanographic study the faunal assemblages can provide information about salinity, temperature, and water depth in a very general way. A major problem, however, is that fossil species or genera may not be extant and comparisons cannot be made with Recent fauna.

Late Quaternary deposits of North America contain an abundant and diverse macrofauna (Wagner,1959,1970) but only a few species of marine macro-invertebrates dominate the fauna; the majority (>90%) are pelecypods. The fossil populations of the Champlain Sea, Ft. Langley Fm and Capilano Sediments are dominated, generally, by one or more of the following pelecypods; *Macoma balthica*, *M. calcarea*, *Hiatella arctica*, *Mya arenaria*, *M. truncata*, *Nuculana pernula*, *Mytilus edulis*, the cirriped *Balanus*, and to a much lesser extent the gastropod *Neptunea despecta* and the brachiopod *Hemithiris psittacea* (Plate 1). All species live today off the coasts of North America and Europe. As all species are extant and the fossils are less than 15 000 years old, it is reasonable to assume that they have undergone little or no evolutionary change and therefore direct comparisons will be made with the life modes and chemistry of their Recent counterparts.

Plate 1

Dominant marine invertebrate macrofaunal species
from the Late Quaternary deposits of Ontario, Québec,
and British Columbia

A – *Macoma balthica* (Linné)

B – *Hiatella arctica* (Linné)

C – *Mya arenaria* Linné

D – *Mya truncata* Linné

E – *Macoma calcarea* (Gmelin)

F – *Balanus* sp. Bruguière

G – *Mytilus edulis* Linné

H – *Hemithiris psittacea* (Gmelin)

I – *Neptunea despecta* (Gould)

Macoma balthica (Linné)

Macoma balthica is an arctic-boreal, deposit and suspension feeder that burrows up to 10 cm in fine grained substratum (Beukema,1981; Stanley, 1970). *M. balthica* can be found in the intertidal to subtidal zones and is limited exclusively to coastal areas less than 25 m in depth (Beukema,1981). In the Beaufort Sea, *M. balthica* is found at a mean depth of 4 m. A euryhaline species, it can tolerate salinities ranging from normal marine to less than 10 ppt. However, below 23 ppt *M. balthica* individuals can be described as "impoverished", being small in size and thin shelled. At salinities below 10 ppt, *M. balthica* is usually extremely fragile though abundant due to lack of competition for food (Michaelis,1981; Remane and Schlieper,1971). The growth period is late spring, with a minimum water temperature of 5°C and a maximum water temperature of 15°C (Beukema,1981; Hillaire-Marcel,1980). Juvenile forms of *M. balthica* need summer temperatures of at least 10°C in order to survive (Hillaire-Marcel,1980).

In the Champlain Sea, *M. balthica* is one of the most prolific invertebrate macrofossils, but it was not found in the Ft. Langley Fm or Capilano sediments. The plurimodal aspect of histograms of heights and lengths of thin shelled Champlain Sea *M. balthica* populations indicate that a lack of larval development may have occurred when optimum water temperatures for growth (10°C) were occasionally not reached (Hillaire-Marcel,1980,p.15).

Macoma calcarea (Gmelin)

The bivalve, *M. calcarea* is unlike *M. balthica*; the former is an arctic species that prefers the stable deeper water environment (60m-140m), where the temperature varies little about 0°C (Thorsen,1933) and requires

salinities greater than 30 ppt (Hillaire-Marcel,1980). *M. calcarea* prefers to settle vertically in a fine-grained substrate such as clay or silt. In the Champlain Sea basin *M. calcarea* population histograms are relatively homogeneous, an indication of small thermal or salinity variations (Hillaire-Marcel,1980). In many *M. calcarea* populations up to a third of the valves are perforated, indicating that *M. calcarea* was a frequent prey of gastropods (Hillaire-Marcel,1980).

Mya arenaria Linné

The sandgaper, *Mya arenaria* is a boreal amphi-atlantic pelecypod that is typically found burrowing in sandy, silty, or clayey shallow water sediments (Kühl,1981; Hillaire-Marcel,1980). *M. arenaria* is predominantly a suspension feeder but may occasionally feed on detrital material. *M. arenaria* requires water temperatures during the summer greater than 5°C, and, temperatures greater than 10°-15°C are required for larval development. Spawning occurs from May to June; the main growth period for *M. arenaria* being June to October (Kühl,1981). The optimal depth for *M. arenaria* is less than 6 m to intertidal (Laursen,1966). On the Atlantic seaboard, *M. arenaria* is presently found at an average depth of 4 m (Wagner,1984). *M. arenaria* can survive in salinities as low as 5 ppt, however, the lower salinity limit averages about 15 ppt. When unfavorable salinities occur, such as in the intertidal zone, *M. arenaria* closes its shell and becomes anaerobic (Kühl,1981).

In the Champlain Sea basin, *M. arenaria* population histograms indicate that for some years the water temperature did not exceed 10°C to 15°C resulting in larval decimation (Hillaire-Marcel,1980). The presence of *M. arenaria* in late Champlain Sea sediments may indicate summer

temperatures as high as 20°C (Elson,1969a). *M. arenaria* was probably introduced to the Pacific in the late 1800's (Wagner,1959).

Mya truncata Linné

The bivalve *M. truncata*, unlike *M. arenaria*, is an arctic species that prefers very cold waters. The depth at which *M. truncata* occurs depends primarily on temperature. In the Beaufort Sea, *M. truncata* is found at a mean depth of 41 m (Vilks *et al*,1979). *M. truncata* prefers to settle in the silts and clays of the relatively deeper waters, and requires salinities greater than 30 ppt (Hillaire-Marcel,1980).

Mytilus edulis Linné and *M. californianus* Linné

The bivalve *Mytilus* is a sessile suspension feeder commonly found in beds on tidal flats or in less than 10 m of water (Wagner,1984; Michaelis,1981). *Mytilus* have slow filtration rates which restricts their distribution in the offshore direction due to lack of food. In addition, they are limited by water levels, tides, and substrate (Michaelis,1981).

Mytilus is primarily limited in its distribution by water temperature and substrate type (Fradette and Bourget,1980). Although it can tolerate temperatures as low as 5°C, optimum growth conditions occur at 10° to 15°C in high food supply areas water temperatures become lethal at or above 26°C to 27°C (Michaelis,1981; Verwey, 1981). *Mytilus* , being sessile, requires a hard or coarse substrate for fixation and, generally, does not occur in sandy or unstable conditions.

Mytilus is unique in that it can very rapidly colonize areas during favorable conditions and build up large populations, but disappears as rapidly during unfavorable conditions. Although *Mytilus* can adapt to low salinities, it is generally found in salinities above 28 ppt. With lower

salinities, *Mytilus* closes its shell and becomes anaerobic (Michaelis,1981).

In the Champlain Sea basin *M. edulis* populations are high in number, but widely distributed. The fossil specimens are generally smaller than Recent counterparts. Population histograms also indicate some years of unfavorable conditions for larval development (Hillaire-Marcel,1980). *M. californianus* was found at one locality in the southwestern British Columbia study area.

Hiatella arctica (Linné)

The bivalve *H. arctica* is an arctic filter feeder, but it is distributed worldwide and can be found as far south as South Carolina. *H. arctica* adapts to a variety of substrates by boring, attaching, or settling in firm sediments. It grows large shells in cold water, especially at 2° to 3°C, while decreasing in size in warmer waters (Strauch,1968). *H. arctica* is an ultrahaline species, requiring salinities greater than 26 ppt. Although it thrives in frigid waters, larval development requires a minimum summer water temperature between 10° and 12° C (Hunter,1949). A deeper water species, *H. arctica* in the Beaufort Sea is found at a mean depth of 41 m and has been found as deep as 2000 m (Vilks *et al,*1979).

In the Champlain Sea, Ft. Langley Fm, and Capilano Sediments, *H. arctica* is abundant indicating favorable deeper water conditions for development. In the Montreal area of the Champlain Sea basin, larger *Hiatella* occur at higher elevations. This trend of decreasing shell size with decreasing elevation and age may be an indicator of an increase in water temperature and/or a reduction in salinity (Elson and Elson,1959; Elson,1969a).

Other Species

Bivalves, *Nuculana pernula* (Müller) and *Clinocardium ciliatum* (Fabricus) are arctic to sub-arctic species that require normal salinities greater than 30 ppt. *N. pernula* and *C. ciliatum* are found at average depths of 120 m and 50 m, respectively (Vilks *et al*, 1979). Both species were found only in the Ft. Langley Fm and Capilano Sediments of British Columbia.

The cirriped *Balanus* (Bruguiere) is the dominant barnacle of the post-glacial seas. Although fossil fragments can be difficult to identify, *Balanus* is found in sediments throughout the Champlain Sea basin. It requires a hard subtrate and thrives in a high energy environment, such as the intertidal zone. Barnacles are made up of calcitic skeletal plates surrounded by an inner circle of opercular plates, which easily become disarticulated after death (Hillaire-Marcel,1980; Milliman,1974).

The brachiopod *Hemithiris psittacea* (Gmelin) was found at only one locality in the eastern Champlain Sea basin. Along with the predatory gastropod *Neptunea despecta*, *Hemithiris psittacea* is likely an indicator of near normal marine conditions of a sheltered embayment (Hillaire-Marcel,1980).

Discussion

The distribution of invertebrates in a sea or estuary depends on several environmental factors such as temperature, salinity, and depth. The ranges of salinity, temperature, and depth for selected pelecypod of the Late Quaternary Seas are summarized in Figures 2 and 3.

The classical theory on species distribution in estuaries postulates a decreasing species richness with decreasing salinity until a freshwater association occurs (Dittmer,1981). The decreasing species richness which occurs to the south and west in the Champlain Sea basin has often been
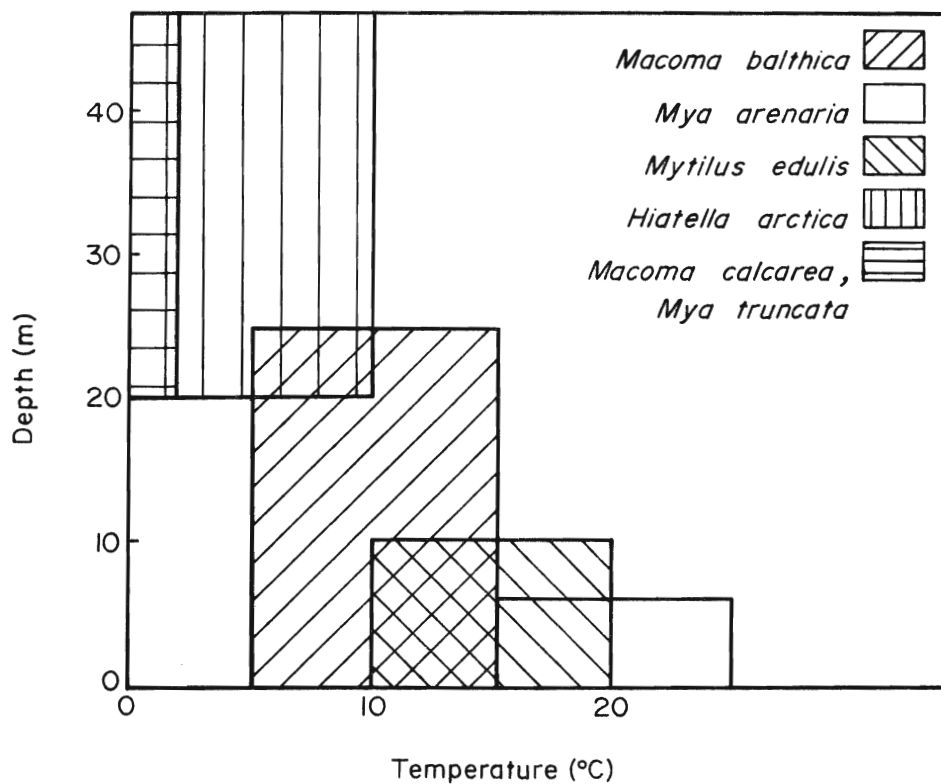
Fig. 2. Temperature and depth ranges for selected pelecypods from late Quaternary seas. See pages 26 - 35 in text for refernces.
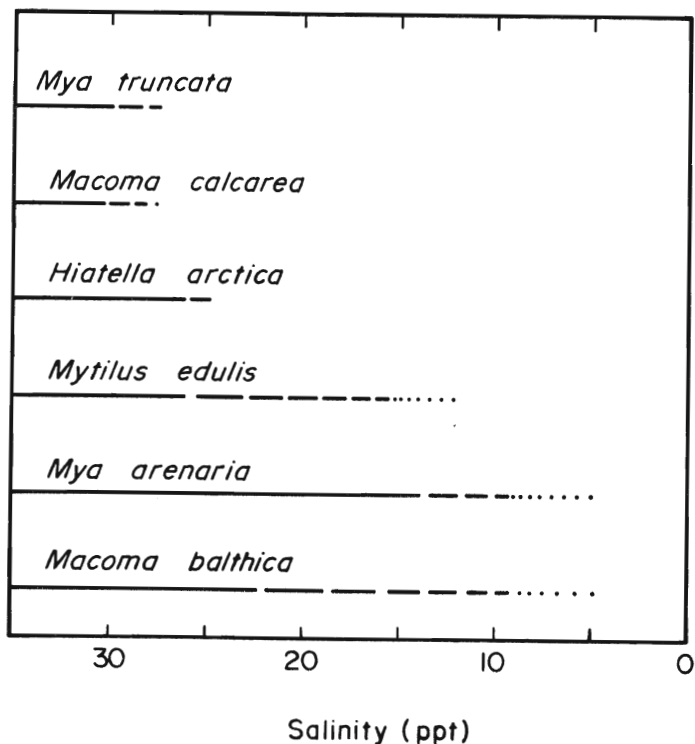
Fig. 3. Salinity ranges for selected pelecypods from late Quaternary seas. References as in Fig. 2.

attributed to decreasing salinity (Goldring,1922; Elson,1969a). Decreasing salinity indeed may present ecological barriers. In many estuaries, a faunal break occurs at about 23 ppt salinity, below which impoverished euryhaline species exist. A second ecological threshold occurs at about 14 ppt salinity where an increase in muddy and silty sediments concurs with a decrease in sea-grasses and microalgae (Michaelis,1981; Wolff,1981). However, in the late Quaternary post-glacial seas it appears that changes in temperature and, in part, salinity, sea level changes, and violent storms are the primary delimiting factors for macroinvertebrates (Hillaire-Marcel,1980). Other factors such as food supply, however, cannot be measured and are of unknown importance.

Chapter 2

Geochemistry and Paleoceanography using Molluscs

of the Late Quaternary Champlain Sea,

Ontario and Québec

Abstract

Four-hundred and ninety-three fossil macroinvertebrates were collected at twenty-eight localities in southeastern Ontario and southern Québec from raised beach deposits, deeper-water sediments, and wave winnowed ridges of the Late Quaternary Champlain Sea. All macroinvertebrates were analysed for their major, minor, and trace element composition. In addition, a representative set of 47 macroinvertebrates were analysed for their $\partial^{18}O$ and $\partial^{13}C$ contents. All marine macroinvertebrates were determined to be chemically, mineralogically, and microstructurally unaltered after 10 to 13 ka of burial.

The $\partial^{13}C$ values for the aragonitic molluscs range from +1.36 to -2.66 $^0/oo$ (PDB). Differences in calculated salinities between trace element techniques and $\partial^{13}C$ can be corrected, and are related to a reduction in the terrestrial biomass during glaciation which resulted, relative to present, in the enrichment of isotopically light CO_2 in the $\partial^{13}C$ of oceanic total dissolved-carbon. The data indicate that the Champlain Sea was density stratified along salinity gradients. Salinities of the shallow waters of the Champlain Sea ranged from 24 to 33 ppt, whereas, those of the deeper waters ranged between 31 and 36 ppt.

The $\partial^{18}O$ compositions of the molluscs range from -13.0 to +1.0 $^0/oo$ (PDB). Water temperatures calculated with these values rarely represent realistic post-glacial environmental conditions. These unrealistic temperatures persist even after a $\partial^{18}O$ correction for Quaternary meteoric water is applied.

Glaciomarine environments are strongly influenced by the input of isotopically-light glacial meltwater. The data indicates that meltwater of

the eastern Laurentide Ice Sheet probably had $\partial^{18}O$ compositions ranging as low as -80 to -70 $^o/oo$ (SMOW). These negative values are related to variations in temperature, altitude, latitude and longitude, increased albedo, extremely low temperatures, and a general Rayleigh distillation process for continental precipitation. The $\partial^{18}O$ composition of this ice mass upon melting, mixes with the $\partial^{18}O$ of marine waters, as was the case for the Champlain Sea. After the $\partial^{18}O$ composition of the marine molluscs has been corrected for the isotopic and salinity influence of glacial meltwater, only then are computed paleotemperatures reasonable for the post-glacial inland sea. Summer water temperatures calculated using Champlain Sea aragonitic molluscs average 12.4 °C for the shallow waters and 4.5 °C for the deeper waters.

Introduction

Paleosalinities and paleotemperatures can be determined from chemically unaltered molluscan aragonite using trace elements and the stable isotopes of carbon and oxygen. However, for metastable carbonates, such as molluscan aragonite, it must be established beyond a reasonable doubt that no chemical or isotopic alteration has taken place. Chemical diagenesis of metastable carbonates in the meteoric environment will result in the the gain or loss of certain trace elements (Brand and Veizer,1980), and lead to a depletion in the $\delta^{18}O$ and $\delta^{13}C$ compositions with increasing diagenetic alteration (Brand and Veizer,1981). It follows, then, that paleoenvironmental interpretations using chemically altered fossils will inevitably lead to anomalous results. Moreover, one must always consider the possibility of osmotic regulation and various fractionation effects for trace elements and stable isotopes. A careful consideration of all these factors is essential before paleoenvironmental reconstructions can be made.

The $\delta^{18}O$-paleotemperature equation of Epstein *et al* (1953), which first enabled the quantification of sea water temperatures from brachiopod and molluscan calcite, was soon beset by a number of problems. It was recognized that the original $\delta^{18}O$ composition of fossils was influenced not only by temperature, but also by salinity (Epstein and Mayeda,1953), mineralogy (Sharma and Clayton,1965; Grossman and Ku, 1981), and possibly biological fractionation. Moreover, the secular variation of the $\delta^{18}O$ of seawater in the past should also be considered (Veizer *et al*,1980). Finally, the likelihood of chemical diagenesis for mineralogically metastable fossils in the meteoric or deep burial environments could lead

to aberrant paleotemperatures (Brand and Veizer,1980,1981; Baker *et al*, 1982).

Mook (1971) recognized that the $\partial^{13}C$ content of molluscan skeletal carbonate is directly dependent upon the salinity of the ambient waters, but independent of temperature (Emrich *et al*, 1970). This fact led to the development of a $\partial^{13}C$ paleosalinity equation that has been successfully applied to chemically unaltered aragonitic molluscs as old as Carboniferous (Brand,1984). As with the paleotemperature equation, the $\partial^{13}C$ paleosalinity equation must take into account the secular variation in the $\partial^{13}C$ of ancient seawater as well as the diagenetic condition of the fossils. In addition, since the $\partial^{13}C$ of seawater is intimately related to the $\partial^{13}C$ of atmospheric CO_2, variations in the $\partial^{13}C$ of atmospheric CO_2 during glacial events (Broecker,1982; Berger,1985) will lead to variations in the $\partial 13C$ content of glacial seawater. Thus, paleosalinities calculated with the isotopic chemistry of Quaternary aragonitic molluscs may not reflect the true salinity.

A review of the literature indicates that most of the studies which have successfully used stable isotopes are from fossil molluscs, brachiopods, and cephalopods for paleoenvironmental interpretations from Holocene or non-glacial deposits (Lowenstam,1961; Brand, 1982; Morrison *et al*,1985). The use of stable isotopes for Quaternary paleoenvironmental reconstructions, on the other hand, tends to focus on the benthic and planktonic foraminifera of the open sea, even though an abundance of macrofossils can be found in Quaternary glaciomarine, periglacial, and estuarine sediments (Wagner,1959,1970; Hillaire-Marcel,1980). Moreover, only sparse isotopic data are available for marine invertebrate macrofossils from present-day Arctic regions (Andrews,1973).

The Late Quaternary Champlain Sea with its abundant molluscan fauna, and ease of accessibility, provides a unique opportunity for a comprehensive basin-wide geochemical-paleoceanographic study. Previously, paleosalinities and paleotemperatures of the Champlain Sea have been estimated on the basis of macrofaunal and foraminiferal assemblages (Goldring, 1922 ; Elson, 1969a; Fillon and Hunt,1974; Cronin, 1976, 1977, 1979, 1981; Hillaire-Marcel, 1980; Corliss *et al*, 1982; Richard and Rodrigues, 1983,1985). Moreover, attempts to establish quantitative paleotemperatures for Champlain Sea waters using the $\partial^{18}O$ paleotemperature equation (Epstein and Mayeda,1953), resulted in anomalous temperatures (-5.8°C to 52.7°C)(Wagner,1970; Hillaire-Marcel,1977). This is because of the lack of control on salinity and isotopic variations in the Champlain Sea that are due to the effects of isotopically light glacial meltwaters mixing with normal seawater.

The purpose of this study is to report on the chemical, structural and isotopic integrity of skeletal carbonate using the data from 493 marine molluscs, cirripeds, and brachiopods of the Late Quaternary Champlain Sea. Moreover, quantitative paleosalinities will be established for the Champlain Sea on the basis of the trace element chemistry of chemically-unaltered aragonitic molluscs. Finally, an attempt will be made to try to resolve some of the difficulties that arise when attempting to determine paleosalinities and paleotemperatures using the $\partial^{13}C$ and $\partial^{18}O$ of marine invertebrates from the glacially influenced Champlain Sea environment.

General Geology

The Champlain Sea (Fig. 4) refers to the Late Quaternary marine inundation that occupied the Ottawa-St. Lawrence Lowlands and Lake Champlain Valley (Elson,1969b). The Champlain Sea was first named by
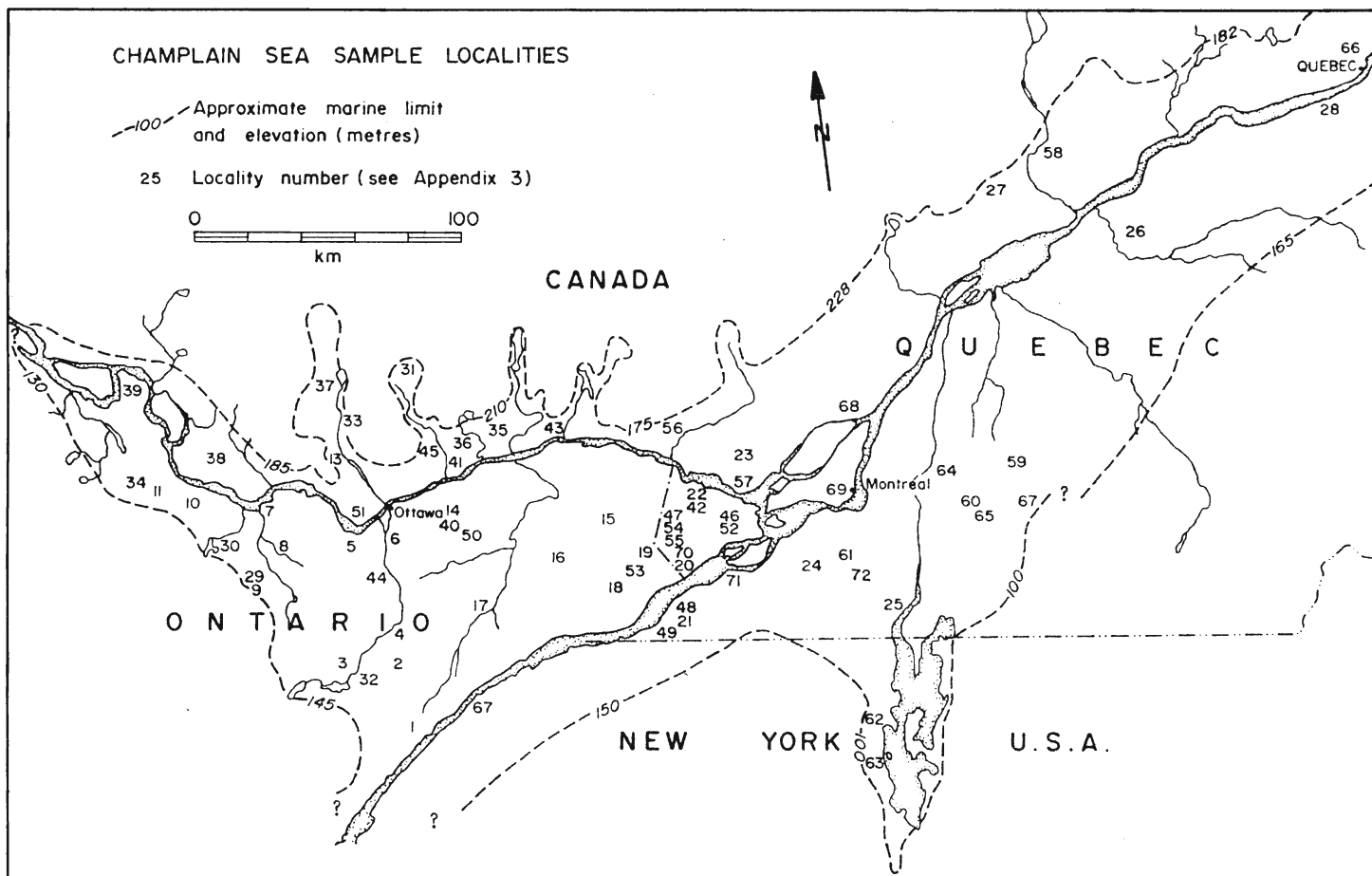
Fig. 4. Map showing sample and data localities from Champlain Sea deposits, Ontario and Quebec. Site descriptions in Appendix IV. Refernces for marine limit on page 71.

Hitchcock (1861) following studies in the Champlain Valley. Marine deposits of the Champlain Sea were studied by Logan (1864), Dawson (1893), Stansfield (1915), Johnston (1917), and Goldwaith (1933). The fauna of the Champlain Sea have also been the subject of numerous studies by various authors (e.g., Goldring, 1922; Wagner, 1967, 1970; Cronin, 1976, 1977, 1981; Hillaire-Marcel, 1980).

Bedrock Geology

The Quaternary deposits of the Ottawa-St. Lawrence Lowlands are underlain primarily by gently folded and faulted Ordovician strata (Wilson,1946) which are separated from the coeval strata of southwestern Ontario by the igneous and metamorphic rocks of the Precambrian Frontenac Arch. To the north and west of the Lowlands, the Ordovician rocks are in fault contact with the Precambrian Canadian Shield, which rises abruptly to form the Laurentian highlands. The Ordovician of southeastern Québec is bordered on the east by thrust faults of the Appalachians. The Ordovician rocks range in thickness from 910m to nearly 3000m (Poole *et al*,1970).

Champlain Sea Deposits

The Champlain Sea sediments in the Ottawa-St. Lawrence Lowlands represent a wide variety of depositional environments. In general, the sedimentary sequence records a transgressive marine event and fluvial or lacustrine conditions. Although a complete suite representing the transgressive-regressive cycle may not occur at a particular locality, a number of sedimentary facies were identified by Gadd (1977),where,

    1) at the base of the sequence, commonly overlying till, a varved clay facies, similar to those of freshwater glacial lakes, grades into

    2) a deep water marine facies composed of blue-gray clay and silty clay, typical of a quiescent marine basin or prodelta environment

(maximum salinity conditions). This facies often contains a deeper water marine fauna and grades upward into,

3) a red and gray banded, coarse , silty clay representing the bottom set facies of a prograding delta, grades into,

4) a sand and clay facies which exhibits structures typical of an upper delta facies of a prograding delta.

Champlain Sea deposits are in some regions overlain by extensive fluvial, lacustrine or eolian deposits, indicating the complete transition to freshwater or subaerial conditions. Large delta complexes are found east and west of Ottawa, Ontario (Catto *et al*,1981; Sharpe,1979), and near Shawinigan, Québec (Gadd,1971). The thickness of the Champlain sea deposits is highly variable throughout the basin (Gadd,1976) and is controlled by the bedrock and the distribution of glacial sediments (Sharpe,1979). Thickness may vary up to 60 m.

The Leda Clay, a marine clay of the Champlain sea, has been the focus of many geotechnical studies due to its highly unstable nature (Karrow,1961; Brydon and Patry,1961; Laventure and Warkentin,1965; Donovan and Lajoie,1979; Quigley *et al*,,1983). These studies indicate that the main source of the Champlain Sea sediments is the igneous and metamorphic rocks of the Canadian Shield. The clays are composed of glacially ground-up primary minerals such as mica, chlorite, and smaller amounts of amphibole, quartz and feldspar (Laventure and Warkentin,1965).

Champlain Sea beaches, bars and spits can be found throughout the Ottawa-St. Lawrence Lowlands between 60 and 200 m above present sea level. Their distribution and prominence is controlled by the amount and degree of consolidation of sediment, the direction of the prevailing wind, and the duration of sea level at a particular elevation (Sharpe,1979;

Gadd,1971). Highly fossiliferous beach and bar deposits may contain a wide variety of macro-invertebrates, commonly the pelecypods *Macoma balthica*, *Mya arenaria*, *Mytilus edulis* and the cirriped *Balanus*.

Late Quaternary Chronology

An understanding of the Champlain Sea episode must be accompanied by an account of the events during that time as interpreted by stratigraphic and geochronologic work. A number of problems still exist in the reconstruction of deglaciation history and the invasion of the Champlain Sea into Ontario and Québec as a result of conflicting radiocarbon dates (marine shell vs wood) and lack of stratigraphic detail (Terasmae,1980). Nevertheless, the sequence of events for the Late Quaternary in southern Québec and southeastern Ontario is fairly well known. A generalized stratigraphic sequence for the central St. Lawrence Lowlands is shown in Fig. 5.

Early-Mid Wisconsinan

The first glacial advance in Early Wisconsin time is documented by the emplacement of the Bécancour Till (Fig. 5). Glacial retreat, occuring sometime prior to 65ka, is represented by the St. Pierre Interstadial deposits. This was followed by another ice advance, which remained in the Ottawa-St. Lawrence Lowlands until Late Wisconsin time, depositing the Gentilly Till (Dreimanis and Karrow,1972). Thus, glacial ice occupied the St. Lawrence Lowlands from Early Wisconsin time on.

Two Creeks Interstade

The Two Creeks Interstade was a period of widespread deglaciation in the Lake Ontario, Lake Huron, and Georgian Bay basins. Raised shorelines document falling lake levels in the Great Lakes region (Karrow,1984). By 12ka, glacial Lake Iroquois had formed in the Lake Ontario basin, draining

Central St. Lawrence Lowlands	
Holocene	Early St. Lawrence River
	Lampsilis Lake Sediments
Wisconsin	Champlain Sea Sediments
	Varved Sediments
	Gentilly Till
	Deschaillons Formation
	St. Pierre Sediments
	Pierreville Varves
	Bécancour Till
	Varves

Fig. 5. Generalized stratigraphic sequence in the central St. Lawrence Lowlands. Modified from LaSalle (1984)

southward through New York State near Rome (Karrow,1969). Although a major raised shoreline feature developed, glacial Lake Iroquois lasted only several hundred years. Eastward drainage through the St. Lawrence was prevented by an ice dam abutting the Adirondacks near Covey Hill (Terasmae,1965). In southeastern Québec field evidence suggests that remnant ice flowed downslope into the St. Lawrence Lowlands from the east. This northwest ice flow may have been the result of a calving bay in the Lowlands (Gadd,1976,1980).

The conventional scenario for deglaciation in the upper St. Lawrence valley (Prest,1970; Karrow,1984) has ice retreating from the northern flank of the Adirondacks in New York State, allowing for progressive drops in lake levels in the Lake Ontario basin, eventually coalescing with lakes in the Lake Champlain basin. A series of glacial lakes (LaSalle,1981; LaSalle *et al*, 1982) or a large proglacial lake (Anderson et al.,1985) developed south of the retreating ice margin in the Ottawa-St. Lawrence Lowlands and the Lake Champlain valley as indicated by freshwater ostracodes in rhythmically laminated, fine grained, sediments underlying Champlain Sea deposits.

Further ice retreat near Québec City allowed the sea to enter and flood the isostatically depressed Lowlands, creating the inland Champlain Sea. At its maximum extent, Champlain Sea deposits are found in the Lake Champlain basin (Cronin,1977), in the Ottawa Valley up to Chalk River (Catto *et al*,1981) and may have extended into the Lake Ontario basin (Sharpe,1979). Coalescence of Lake Ontario waters with the Champlain Sea occurred after the end of glacial Lake Iroquois (12ka), although radiocarbon dates for Champlain Sea molluscs (12ka), which overlap with dates for Lake Iroquois wood (Karrow,1984), seem to contradict this assertion.

To account for the overlapping radiocarbon dates of the Champlain Sea and Lake Iroquois, Gadd (1980) proposed that glacial ice, by rapidly calving westward, allowed the Champlain Sea to flood the central St. Lawrence Lowlands by about 12.5 ka (Champlain Sea shell dates), while ice remained in the south St. Lawrence Lowlands, damming up glacial Lake Iroquois until after about 12ka (date on Lake Iroquois wood). The reliability of the radiocarbon dating method, however, has been questioned recently due to the possible efffects of "old carbon" (Olsson,1979), indicating that the apparent ages on mollusc shells may be older than their true age by several hundred years (Hillaire-Marcel,1977). In any case, with the opening of the St. Lawrence valley, Lake Ontario was established. Since the initial outlet was isostatically depressed, lake levels then, were much lower than at present (Karrow,1984).

Greatlakean Stade

This stade is associated with an ice advance in the Lake Michigan basin (Burgis and Eschman,1981). The ice margin extended across southern Georgian Bay in the direction of Montreal and although the Champlain Sea existed at this time, no ice advance has been documented in the St. Lawrence Lowlands (Karrow,1984). Although the St. Narcisse moraine (LaSalle and Elson,1975) and the Drummondville moraine (Dreimanis,1977) have been proposed as correlative with that advance, the St. Narcisse is likely younger and the Drummondville is as yet undated (Karrow, 1984). Isostatic uplift at this time ended the drainage through the Trent valley system to Lake Ontario, forming glacial Lake Algonquin in the Lake Huron, Lake Michigan, and Georgian Bay basins (Karrow *et al*,1975).

North Bay Interstade to Present

This time is characterized by ice retreat leading to further deglaciation of the Lake Huron and Georgian Bay basins. As ice retreated onto the Canadian Shield, glacial Lake Algonquin expanded into the Sudbury basin (Burwasser,1979). Sometime between 10.5 ka and 10 ka, Lake Algonquin changed its drainage exit through an outlet at North Bay (Karrow *et al.*,1975). Through a series of channels crossing the highlands, Lake Algonquin drained to a level far below that of present Lake Huron, creating Lake Hough in the Georgian Bay basin and Lake Stanley in the Lake Huron basin (Harrison,1972).

In the Ottawa-St. Lawrence Lowlands, further ice retreat led to full deglaciation, however, a small readvance or possible glacial re-equilibration event (Occhietti,1980), shortly after 11 ka, established the St. Narcisse moraine on the north shore of the Champlain Sea (Gadd,1971; Occhietti,1980). As the ice retreated further into the Laurentian highlands the Champlain sea followed, depositing a complex sequence of glaciomarine deposits (Karrow,1961). Remnant ice masses, however, appear to have remained in the highlands south of the St. Lawrence Lowlands until the late phase of the Champlain Sea (minimum 10.8 ka)(Gadd,1983).

Between 10.5 ka and 10 ka, the North Bay outlet opened, draining Lake Algonquin into the proto-Ottawa river and Champlain Sea until about 5 ka (Catto *et al.*,1982). While transgression of the early phase of the Champlain Sea was due to isostatic depression relative to sea level, post-glacial rebound caused the sea to withdraw, to be replaced by fluvial environments and freshwater "Lampsilis Lake" (Elson and Elson, 1959) in the St. Lawrence Lowlands. By 6 ka, the St. Lawrence River probably occupied its present channel (Elson,1982). Since then, differential uplift due to isostatic

rebound has raised the beaches and marine deposits delimiting the Champlain Sea marine limit on the north side of the Ottawa-St. Lawrence Lowlands to much higher elevations on the north side than the south side.

Previous Work

Two studies have attempted to establish quantitative paleotemperatures for the Champlain Sea, using the $\partial^{18}O$ of marine molluscs, by Wagner (1970) and by Hillaire-Marcel (1977,1981). They were largely unsuccessful in determining realistic Champlain Sea water temperatures (-5.8° to 52.7°C) for several reasons. Firstly, they did not consider the differences in isotopic fractionation between calcite and aragonite. Aragonite is enriched in ^{18}O with respect to calcite by about 1 $^{o}/oo$ at 0°C and 0.5 $^{o}/oo$ at 20°C (Grossman and Ku,1981). Secondly, the effects of salinity (Craig and Gordon,1965), were not considered by the authors due to lack of quantitative data for the salinity of the Champlain Sea at each locality. Thirdly, the degree of mixing of isotopically-light glacial meltwater with isotopically-heavy seawater could not be established because of the lack of quantitative salinities. Finally, they assumed an average glacial ice oxygen-18 isotopic composition of about -30 $^{o}/oo$ to -22 $^{o}/oo$ (SMOW). The resulting unrealistic paleotemperatures were correctly attributed by Hillaire-Marcel (1977) to the masking effects of glacial meltwater and continental waters.

On the basis of a thorough faunal analysis, Hillaire-Marcel (1980), using *Mya arenaria* and *Macoma balthica* adult size histograms from several Champlain Sea localities in southern Québec, was able to qualitatively demonstrate that the shallow waters of the early Champlain Sea often did not reach 10°C, which represents the minimum summer temperature required for larval development. This temperature range was

confirmed by studies on Champlain Sea benthic foraminiferal assemblages by Fillon and Hunt (1974), Cronin (1976, 1977, 1979, 1981) and Corless *et al.* (1982), who concluded that the deeper waters of the western Champlain Sea varied about 0° to 5°C. Moreover, the prolific abundance of the pelecypod *M. balthica*, which requires a minimum summer growth temperature of 5°C (Beukema,1981), suggests that the shallow water temperatures of the early Champlain Sea probably ranged between 5° and 10°C. The presence of the boreal pelecypod, *M. arenaria* , in eastern Champlain Sea sediments indicates a slight warming trend in shallow water summer temperatures to about 12° or 15°C (Elson,1969a).

Salinities for the Champlain Sea have been inferred by faunal associations. The deeper water pelecypods *Hiatella arctica* and *Macoma calcarea* generally require salinities greater than about 30 ppt to survive (Hillaire-Marcel,1980). The shallow water pelecypods such as *M. balthica* and *M. arenaria*, however, can adapt to lower and more variable salinities (Beukema,1981; Kühl,1981). Moreover, foraminiferal assemblages from the western Champlain Sea have indicated salinities as high as 35 ppt (Cronin,1976,1977). Thus, on the basis of faunal associations it has previously been concluded that the Champlain Sea was brackish to marine and stratified along salinity gradients (cf. Hillaire-Marcel,1980; Rodrigues and Richard,1985).

Results and Discussion

Diagenetic Evaluation

The use of trace element techniques, stable isotope analyses, and mineralogical and microstructural analyses of biogenic carbonates allow for the establishment of a comprehensive diagenetic evaluation of the data (Brand and Veizer,1980;1981; Brand,1983). In addition, since all the

species from the Champlain Sea are extant, direct chemical comparisons can be made with the abundant chemical data for Recent marine invertebrates (Milliman,1974; Morrison and Brand,in press). However, since the chemical and isotopic composition of biogenic carbonates may be influenced by a number of environmental factors such as salinity, temperature , glacial meltwater, and disequilibrium factors such as kinetic and biological fractionation, secular isotopic variations in seawater chemistry, and elemental partitioning (Brand and Veizer,1980; Veizer *et al*,1980; Brand,1983), it is the trends and ranges of the chemical data that are important rather than absolute concentrations.

The results of XRD analysis, shown in Table 4, indicate that the pelecypods *Hiatella arctica, Macoma balthica, M. calcares, Mya truncata, M. arenaria,* and the gastropod *Neptunea despecta* are preserved in their original aragonitic mineralogy (cf. Milliman,1974; Morrison and Brand, in press). *Mytilus edulis* is also mineralogically preserved with its outer calcitic and inner aragonitic shell layers. XRD also indicates that the cirriped *Balanus* and the brachiopod *Hemithiris psittacea* are mineralogically preserved in their original low-Mg calcite skeleton (cf. Lowenstam,1961; Milliman,1974).

The preservation of original mineralogy in the Champlain Sea invertebrate macroinvertebrates is also supported by SEM data. Aragonite rapidly alters to diagenetic low-Mg calcite in the meteoric environment and loses its microstructural integrity (Brand,1983). All the molluscs of the Champlain Sea in this study, however, exhibit excellent original aragonitic homogeneous, crossed-lamellar, prismatic, and nacreous microstructures (Table 5; Plate 2, A-F; Plate 3, G-H; cf. Carter,1980), an indication that no structural diagenesis has occurred.

Table 4. Primary X-ray diffraction peaks for marine invertebrate macrofossils from the Late Quaternary Seas.

Species	2∅ degrees	No. of samples	Mineralogy
Pelecypods			
Hiatella arctica	26.25	3	aragonite
Macoma balthica	26.23	3	aragonite
Macoma calcarea	26.25	3	aragonite
Mya truncata	26.40	3	aragonite
Mya arenaria	26.25	3	aragonite
Mytilus edulis (inner)	26.23	2	aragonite
Mytilus edulis (outer)	29.48	2	calcite
Nuculana pernula	26.23	1	aragonite
Pecten sp.	29.50	1	calcite
Gastropod			
Neptunea despecta	26.22	1	aragonite
Cirriped			
Balanus	29.47	2	calcite
Brachiopod			
Hemithiris psittacea	29.50	1	calcite
Aragonite standard	26.27	3	aragonite

Table 5. Summary of microstructures of selected molluscs of the Late Quaternary Seas as determined by scanning electron microscopy (cf. Carter, 1980).

Species	Microstructures
Macoma balthica	−entirely cone complex crossed lamellar aragonite
Macoma calcarea	−outer simple prismatic layer, aragonite −inner crossed lamellar layer, aragonite
Mya truncata	−entirely homogeneous *sensu stricto* aragonite
Mya arenaria	−entirely granular homogeneous aragonite
Hiatella arctica	−inner and outer layers of granular homogeneous aragonite
Mytilus edulis	−outer fibrous calcite layer −inner tabular nacreous aragonite layer

Plate 2

Scanning electron micrographs of skeletal microstructures of selected molluscs from the Late Quaternary deposits, Ontario, Québec, and British Columbia (cf. Carter, 1981)

A - *Macoma balthica*, cone complex crossed lamellar aragonite.

B - *Macoma calcarea*, simple prism (left) and crossed lamellar (right) aragonite.

C - *Hiatella arctica*, inner layer (right) and outer (left) of homogeneous aragonite.

D - *Hiatella arctica*, inner granular homogeneous aragonite.

E - *Mya truncata*, homogeneous aragonite.

F - *Mya arenaria*, granular homogeneous aragonite.

A 20 µm

B 20 µm

C 25 µm

D 10 µm

E 10 µm

F 10 µm
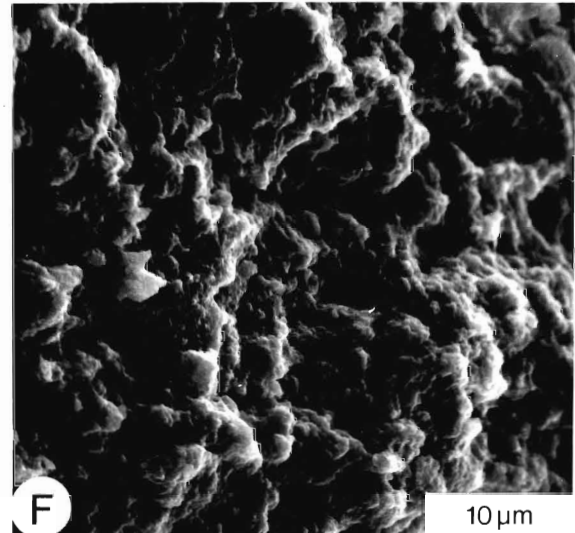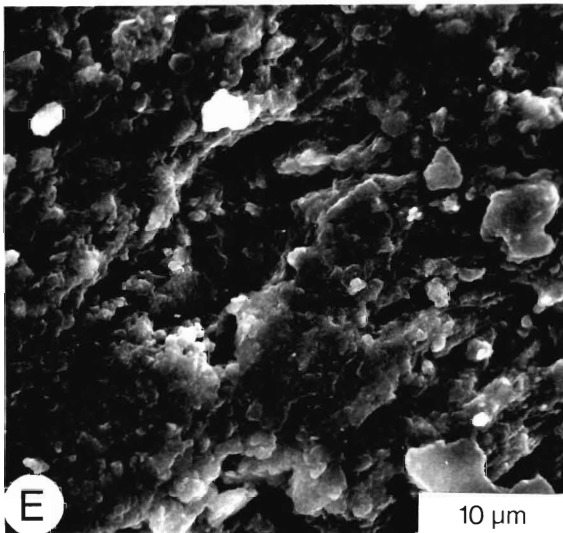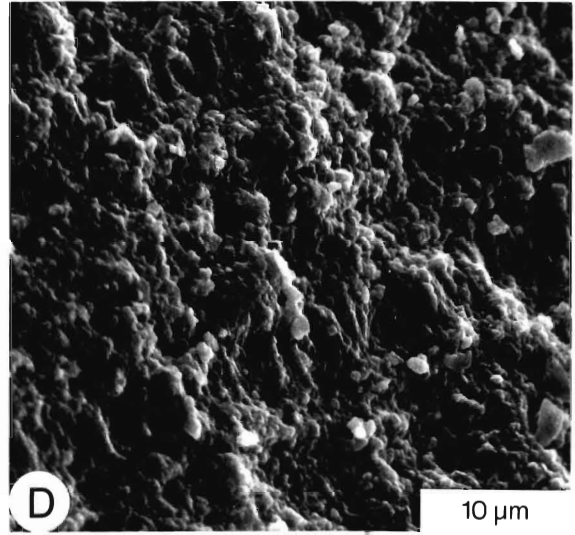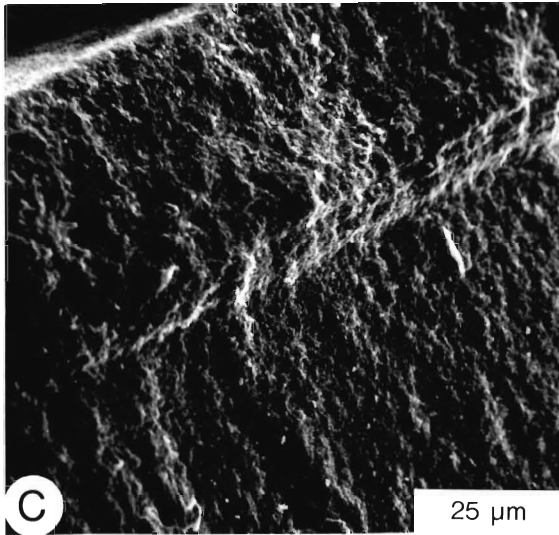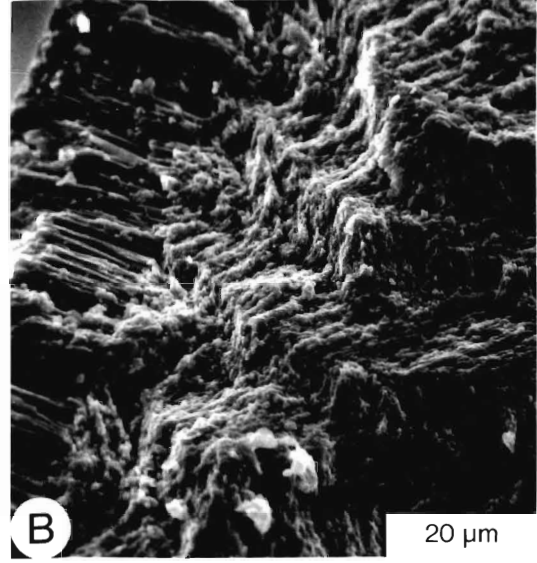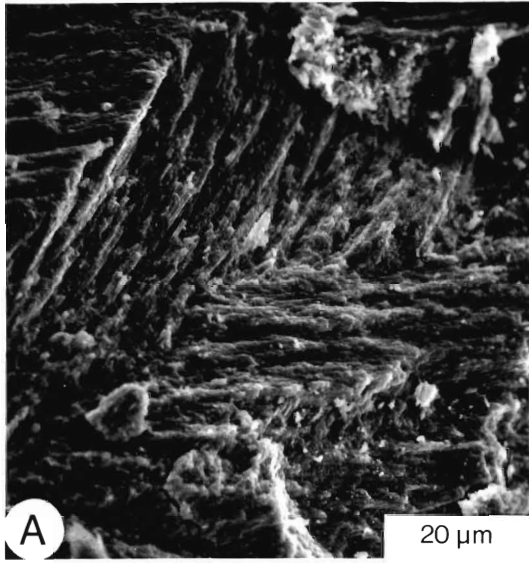
Plate 3

Scanning electron micrographs of skeletal microstructures of selected molluscs from the Late Quaternary deposits, Ontario, Québec, and British Columbia (cf. Carter, 1981)

G - *Mytilus edulis*, fibrous calcitic-outer layer.

H - *Mytilus edulis*, nacreous aragonite-inner layer.

G   10 μm

H   20 μm
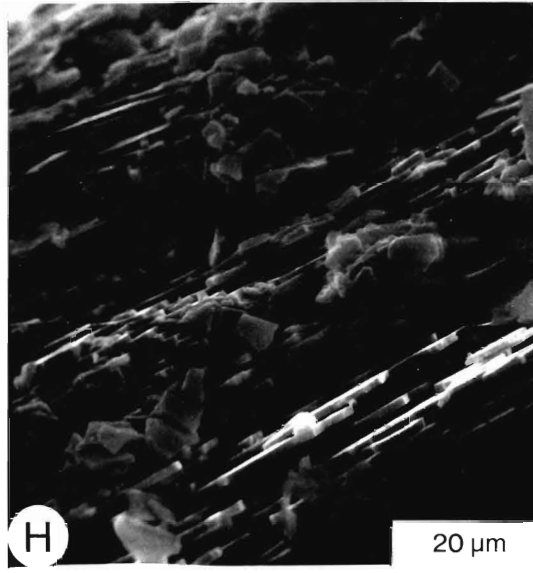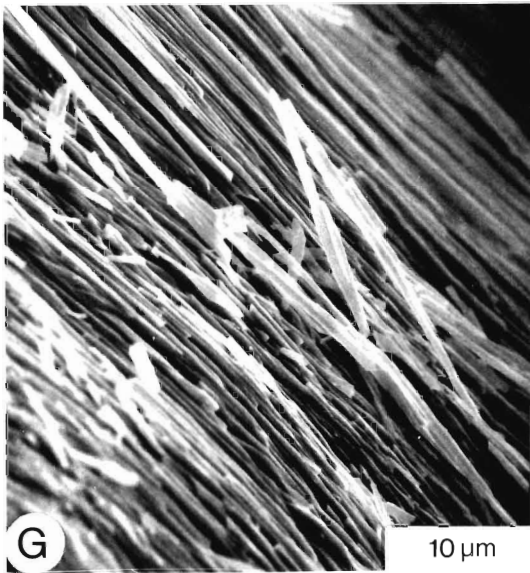
The minor and trace element content of the skeletal carbonate of the Champlain Sea fauna, summarized in Table 6, indicate that no chemical diagenesis has occurred. The Sr and Mg contents of the aragonitic molluscs range from 180-4090 ppm (Fig. 6) and 20-890 ppm (Fig. 7), respectively, which fall within the ranges for Recent marine molluscs (Milliman,1974; Morrison and Brand, in press). Similarly for Mn (Fig. 8), the aragonitic molluscs exhibit no diagenetic trends (Brand and Veizer,1980), and the data falls within the range for their Recent counterparts. If chemical alteration had occurred, the data would indicate a covariant decrease in Sr with and increase in Mn (Brand and Veizer,1980). The calcitic brachipods and calcitic portion of the molluscs (Fig. 9) also show Mn and Sr content similar to their Recent counterparts. *Balanus*, like Recent cirripeds, incorporates more Sr into their skeletons than molluscs or brachiopods (Milliman,1974; Brand *et al*, submitted). The Na content of all the calcitic molluscs also does not indicate any trends when plotted against Sr or Mg (Figs. 10 and 11), and all values lie within the range for Recent data.

It can be concluded then, on the basis of XRD, SEM, and trace element analyses, that the marine invertebrate macrofossils used in this study from the Champlain Sea have undergone no diagenetic alteration after 10 ka of burial in the meteoric environment.

The stable isotope contents of the Champlain Sea fauna, along with isotopic data for Champlain Sea aragonitic molluscs from Hillaire-Marcel (1977,1981) are plotted in Fig. 12. The isotopic data at first appear to show the diagenetic trend of decreasing $\partial^{13}C$ and $\partial^{18}O$ for diagenetic stabilization with meteoric waters (Brand and Veizer,1981). However, considering the previous analyses, it is apparent that the negative $\partial^{18}O$ and $\partial^{13}C$ content of the fauna are original. Moreover, it is apparent from Fig 12

Table 6. Means of major, minor, and trace element content of skeletal carbonate from marine fauna of the Champlain Sea. (ranges in parentheses).

Species	Ca %	Mg ppm	Sr	Na	Mn	Al	Fe	Zn	Ni	Cu	Mineralogy
Macoma balthica	35.4 (19-46)	104 (20-570)	2224 (180-3470)	3482 (160-5980)	18 (0-130)	111 (0-1200)	54 (0-180)	7 (1-170)	41 (0-80)	6 (0-20)	A
Mya arenaria	29.9 (26-37)	88 (40-150)	2419 (2040-3630)	3568 (2670-4210)	20 (10-40)	27 (4-40)	49 (30-80)	5 (2-7)	41 (30-50)	5 (2-9)	A
Mytilus edulis (outer)	30.3 (30-36)	467 (370-540)	1117 (910-1440)	1464 (1160-1790)	135 (50-200)	44 (20-80)	254 (170-380)	9 (3-6)	61 (60-80)	3 (1-4)	LMC
Mytilus edulis (inner)	32.4 (29-36)	68 (50-100)	2709 (1600-4090)	4083 (3090-5100)	19 (10-30)	26 (0-70)	65 (50-80)	4 (3-5)	67 (50-80)	3 (2-4)	A
Hiatella arctica	34.2 (24-42)	191 (100-890)	1668 (550-3050)	3978 (2600-5660)	28 (0-1630)	49 (0-550)	53 (0-940)	6 (0-50)	40 (0-80)	4 (0-20)	A
Mya truncata	34.2 (29-41)	141 (80-210)	2155 (1330-3020)	3987 (3160-4760)	23 (10-30)	41 (10-80)	53 (40-80)	4 (1-7)	42 (20-70)	4 (0-7)	A
Macoma calcarea	32.8 (23-38)	116 (70-180)	2611 (1860-3920)	3676 (2840-4330)	23 (10-50)	70 (0-170)	64 (10-100)	5 (3-10)	38 (1-70)	5 (0-10)	A
Balanus crenatus	32.9 (26-37)	1997 (1670-2930)	3208 (2890-4210)	3600 (3230-4450)	237 (130-350)	98 (60-180)	197 (70-300)	7 (4-10)	45 (30-70)	4 (0-10)	LMC
Hemithiris psittacea	35.9 (31-39)	732 (620-810)	1043 (930-1110)	2093 (1860-2260)	37 (20-70)	178 (40-450)	97 (30-190)	24 (4-60)	62 (50-70)	1 (0-2)	LMC
Neptunea despecta tornata	32.0 (29-35)	530 (150-710)	1680 (1540-1820)	3130 (2640-3930)	60 (20-90)	63 (50-80)	93 (70-110)	4 (2-7)	47 (40-50)	4 (3-6)	A

A-aragonite LMC-Low-Mg calcite
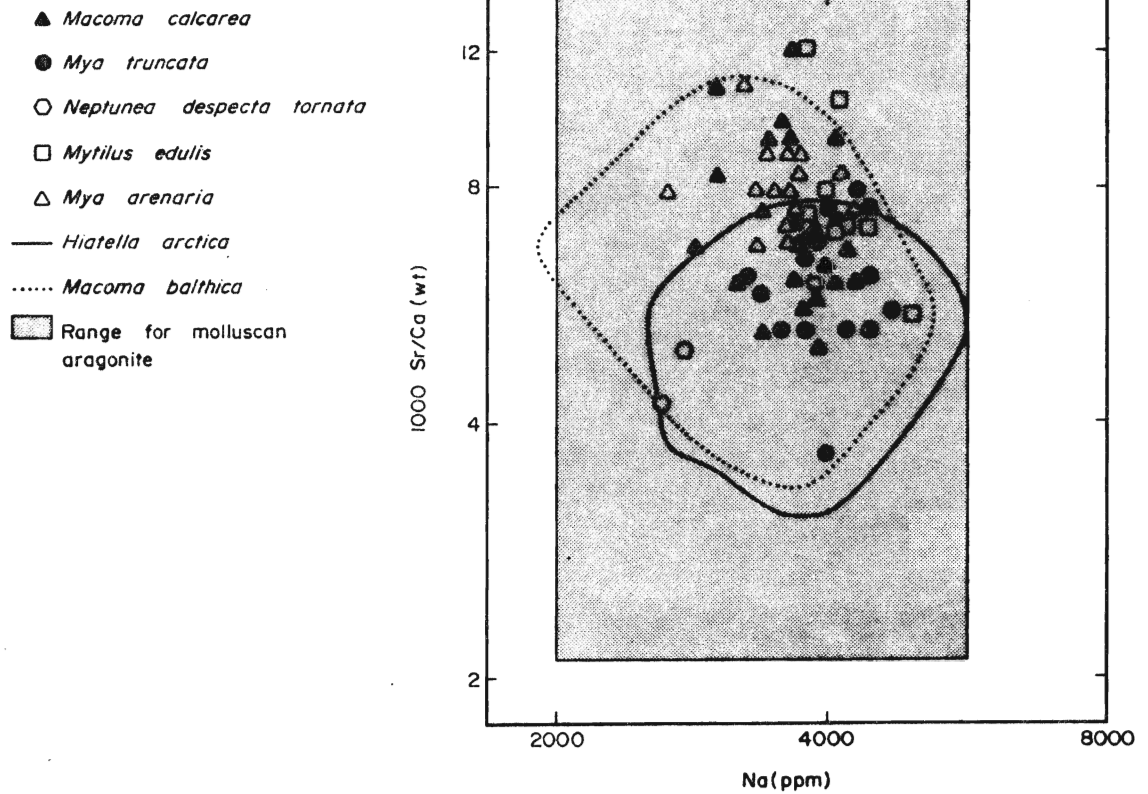
Fig. 6. Scattergram of 1000 Sr/Na vs Na for aragonitic molluscs from Champlain Sea deposits. Range for aragonite from Morrison and Brand (in press). Dotted line denotes 200 samples of Macoma balthica, solid line denotes 197 samples of Hiatella arctica. Ordinates are logarithmic.
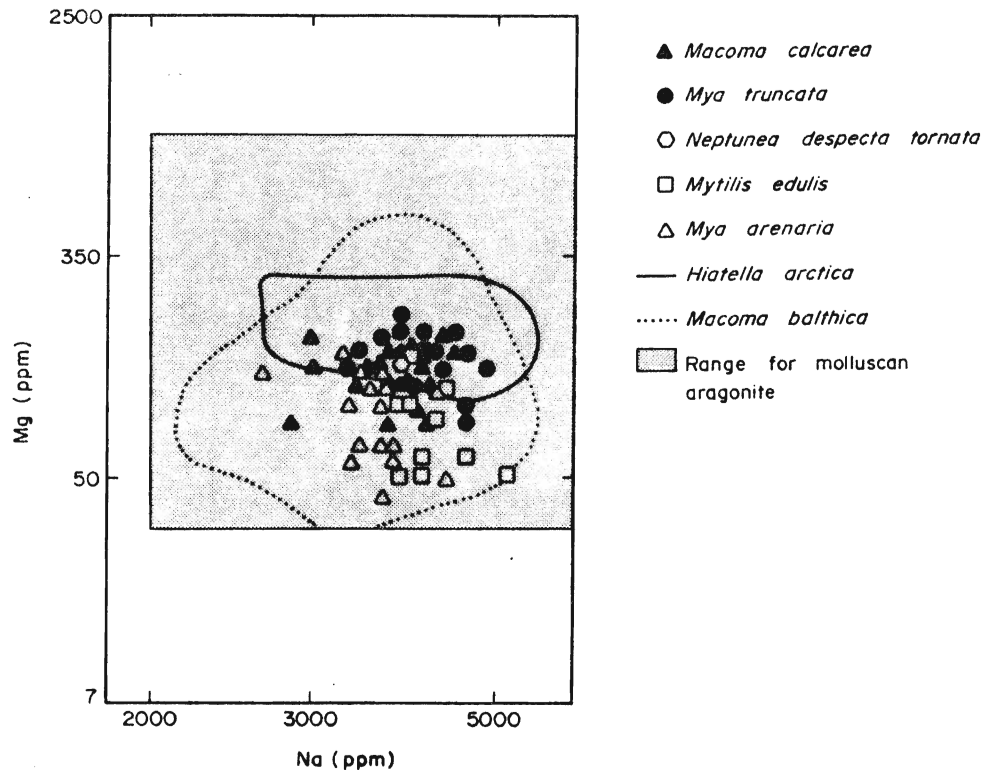
Fig. 7. Scattergram of Mg vs Na
for aragonitic molluscs from
Champlain Sea deposits. Data
source as in Fig. 6.
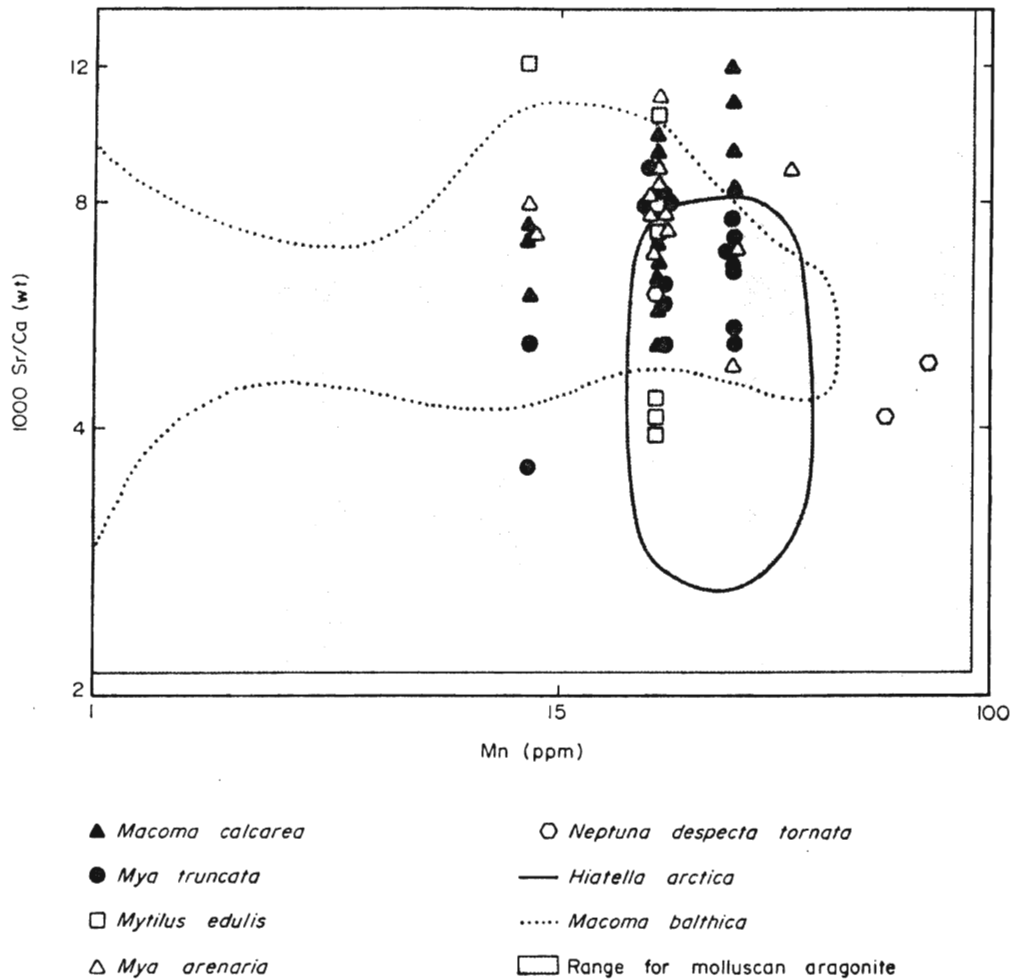
Fig. 8. Scattergram of 1000 Sr/Ca vs Mn for aragonitic molluscs from Champlain Sea deposits. Data source as in Fig. 6.
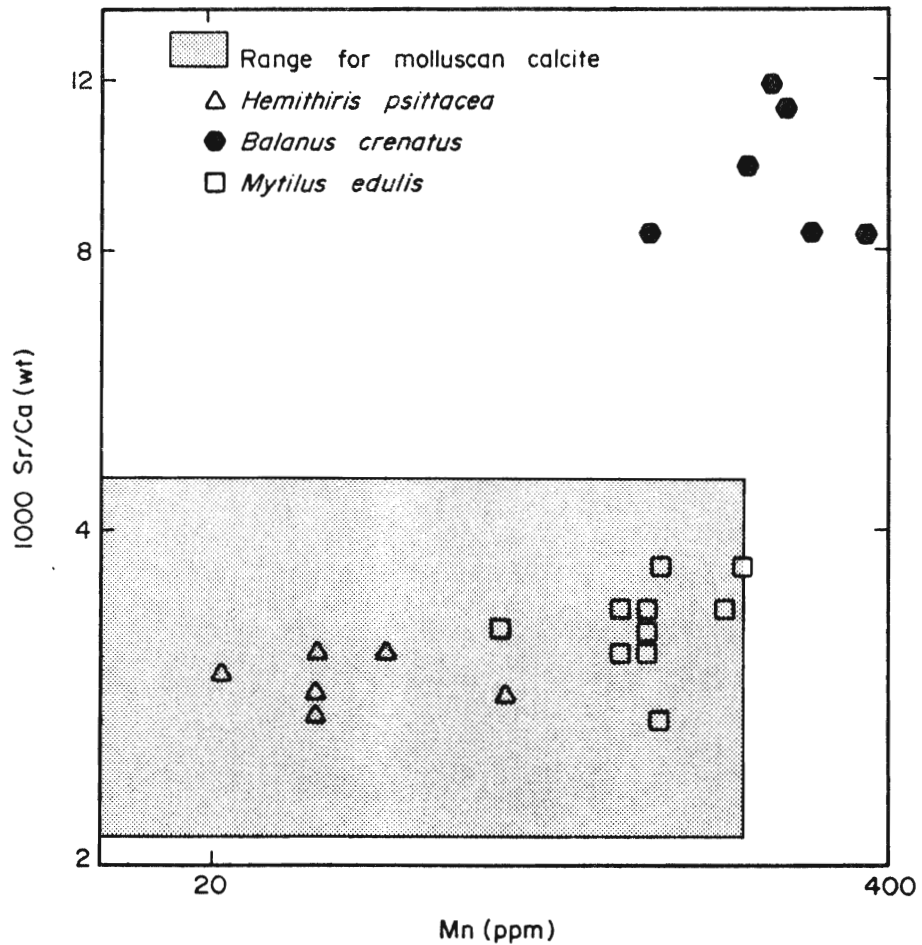
Fig. 9. Scattergram of 1000 Sr/Ca vs Mn
for calcitic macroinvertebrates from
Champlain Sea deposits. Range for calcite
from Morrison and Brand (in press). Ordinates
are logarithmic.
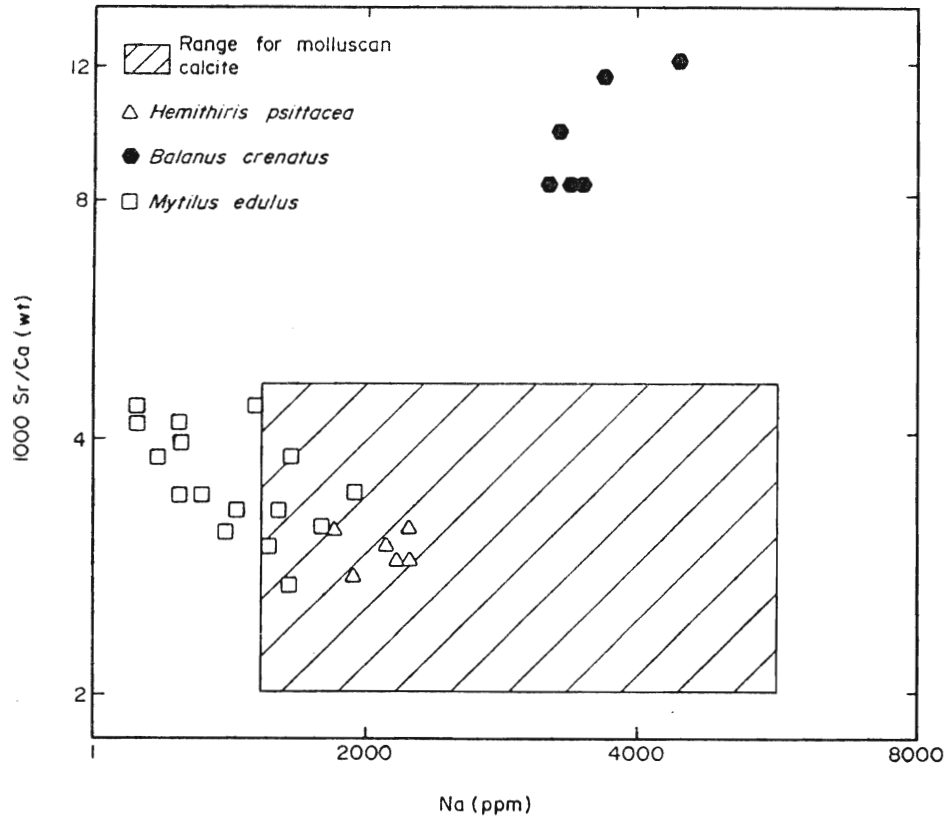
Fig. 10. Scattergram of 1000 Sr/Ca vs Na for calcitic macroinvertebrates from Champlain Sea deposits. Sources as in Fig. 9.
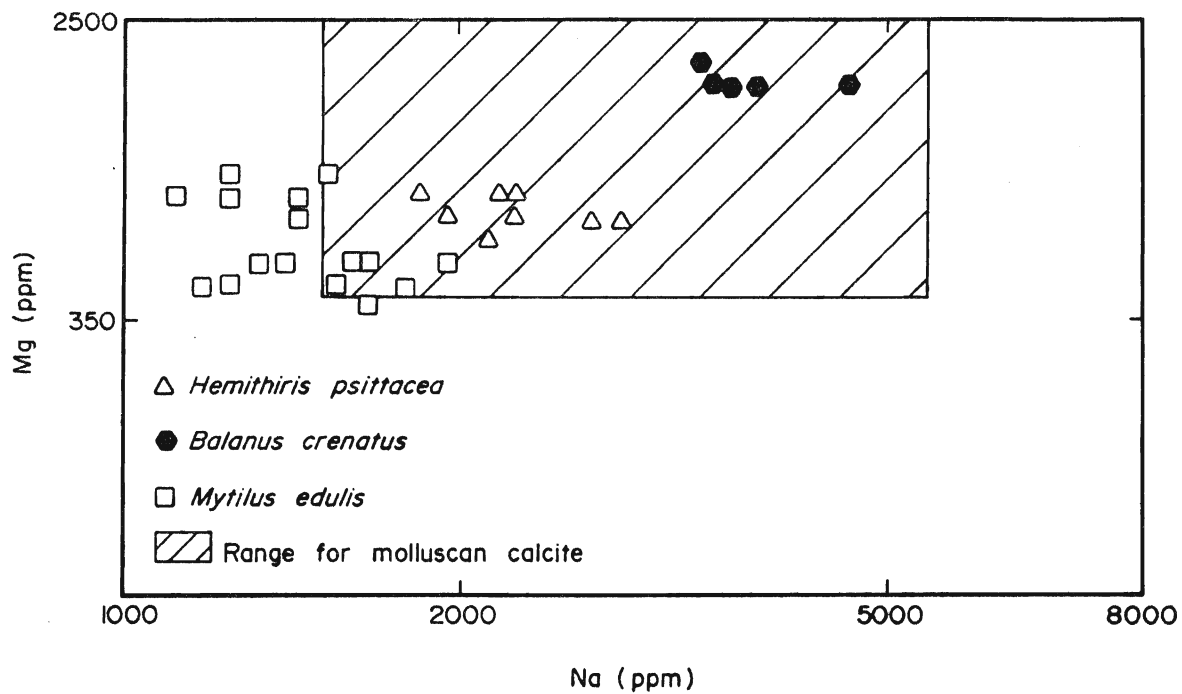
Fig. 11. Scattergram of Mg vs Na for calcitic macroinvertebrates from Champlain Sea deposits. Sources as in Fig. 9.
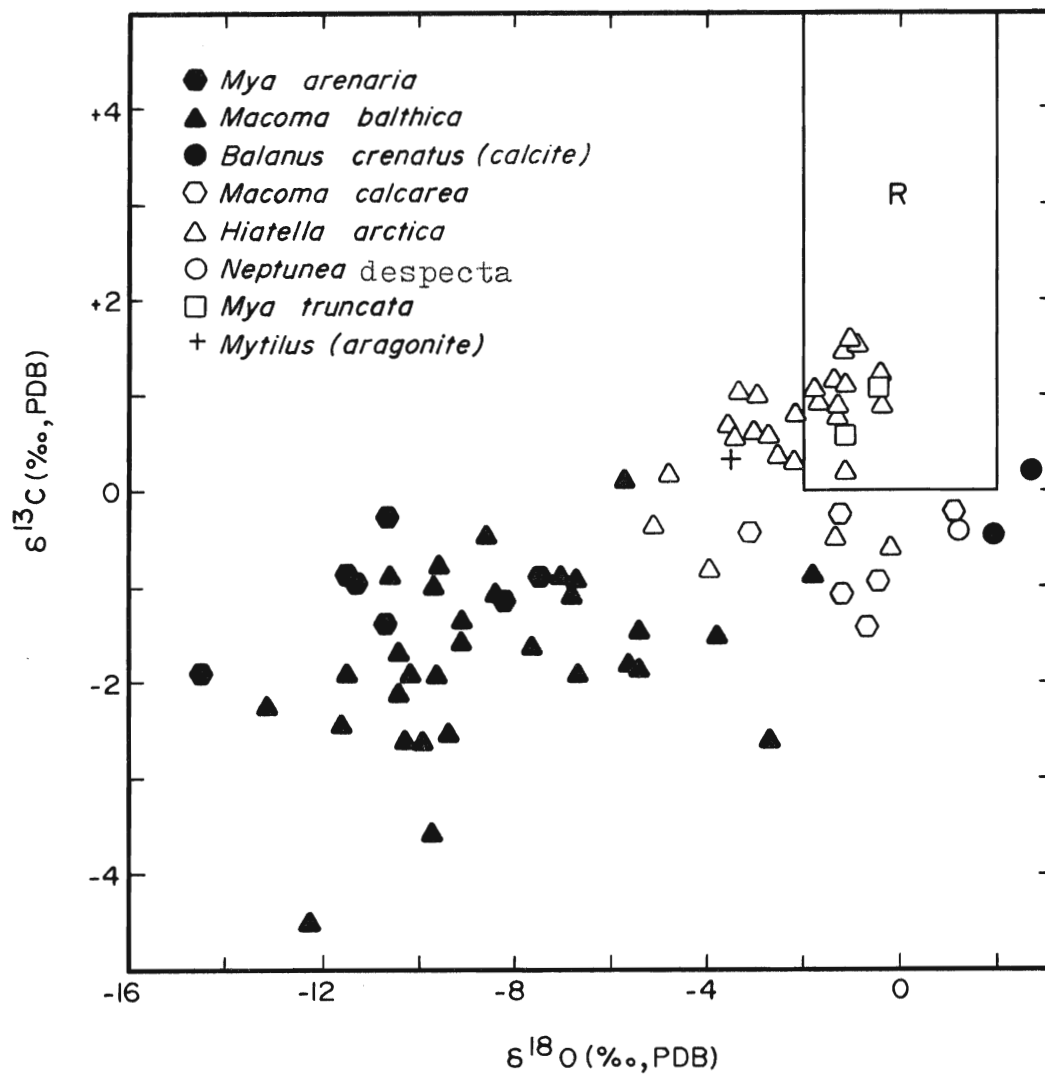
Fig. 12. Scattergram of ^{13}C vs ^{18}O data from marine macrofossils from Champlain Sea deposits. Includes data from Hillaire-Marcel (1977). R denotes range for Recent (Brand and Veizer, 1981).

that the $\partial^{13}C$ and $\partial^{18}O$ composition of the Champlain Sea fauna is much more negative than that of their Recent counterparts (R, Fig. 12; Milliman,1974; Morrison and Brand, in press).

Closer evaluation of the data for the aragonitic molluscs also indicates statistically significant ($p > 0.05$, unpaired t-test) geochemical differences between that of shallow water molluscs, *Mya arenaria, Macoma balthica, Mytilus edulis*; and the deeper water molluscs, *Macoma calcarea, Mya truncata,* and *Hiatella arctica* (Appendix VI). The deeper water aragonitic molluscs (solid and dotted symbols, Fig. 6, Fig. 7) have Mg, Na, and Sr concentrations that tend to cluster within a smaller field than the shallow water molluscs (open and dashed symbols, Fig. 6, Fig. 7). These variations can be attributed to salinity/density stratification of the Champlain Sea.

Similarly, the isotopic data (Fig. 12) also indicate that there is a statistically significant difference ($p > 0.05$, unpaired t-test) between the mean carbon- and oxygen-isotopic composition of the shallow water aragonitic invertebrates (filled symbols) and the mean carbon and oxygen isotopic composition of the deeper water aragonitic marine invertebrates (open symbols). This can be attributed to density stratification of the Champlain Sea along salinity and temperature gradients, with the shallow waters of the Champlain Sea being less saline and warmer than the deeper waters.

A variety of problems arise when attempting to quantify the environmental parameters by means of the empirical $\partial^{18}O$ aragonite-paleotemperature equation (Grossman and Ku,1981) and $\partial^{13}C$-paleosalinity equation (Brand,1984). As the majority of the data are based on aragonitic

molluscs, further discussion and argument will be related to the isotopic content of aragonitic molluscs.

Paleoceanography of the Champlain Sea

Paleosalinities

A frequency histogram for paleosalinities of the Champlain Sea, using the Sr/Na content of aragonitic molluscs and Equation 10, is shown in Fig. 13. Mean of Sr/Na salinities for molluscs at each locality are summarized in Table 7. The differences in salinity determined between deeper water aragonitic molluscs and shallow water aragonitic molluscs accounts for the two ranges for Sr and Na in Fig. 6. In addition, Fig. 6 indicates by the degree of scatter, that the shallow waters were less saline and more variable than the deeper waters. The data also quantitatively demonstrates that the inland Champlain Sea was density stratified along salinity gradients.

The deeper water pelecypod *Macoma calcarea*, however, indicates significantly lower salinities than other deeper water pelecypods (Table 7). It is suggested that perhaps *M. calcarea* controls the chemistry of its skeletal carbonate as is suggested for stable isotopes (see below). However, more data and studies of modern *Macoma calcarea* are needed to substantiate the postulate.

The use of the $\partial^{13}C$ data and equation 11, however, presents a problem. The means of salinities determined by the Sr/Na salinometer and the $\partial^{13}C$ method are statistically dissimilar ($p > 0.05$, unpaired t-test; Table 7, Salinity vs uncorrected salinity) at the 95% confidence level. Considering the effects of a reduction in the terrestrial biomass during glaciation, and the consequent enrichment in isotopically light CO_2 in the $\partial^{13}C$ of oceanic TDC, salinities determined with $\partial^{13}C$ and Equation 11 would be lower than expected. The salinities determined from $\partial^{13}C$ and Equation 11 for the
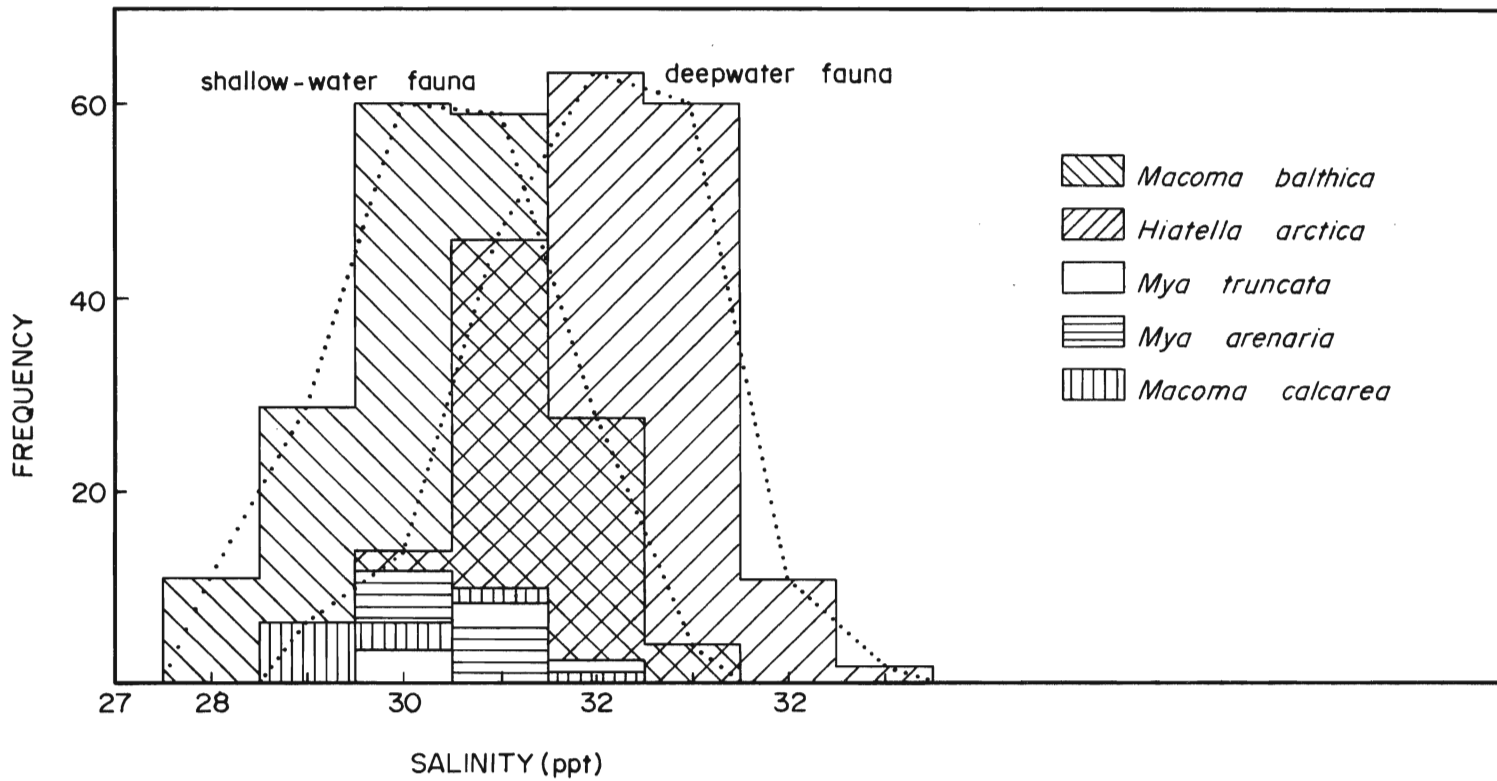
Fig. 13. Frequency histogram showing salinity distribution and stratification of Champlain Seawaters using aragonitic molluscs (N = 493).

Table 7. The $\delta^{18}O$ and $\delta^{13}C$ isotopic composition, mineralogy, paleosalinities and paleotemperatures using skeletal carbonate from marine invertebrates of the Late Quaternary Champlain Sea.

Locality	Species	Mineralogy	Salinity[1]	$\delta^{13}C$	Salinity[2]	Salinity[3]	$\delta^{18}O$	Paleotemperatures (°C)			
			ppt	o/oo	ppt		o/oo	A	B	C	D[4]
1 Prescott, ON	*M. balthica*	A	31.2	-1.98	26.8	30.3	-5.32	35.5	42.8	38.1	3.8
2 Oxford Mills, ON	*M. balthica*	A	31.2	-1.82	27.1	30.6	-5.68	39.9	43.8	39.4	5.0
3 Kilmarnock, ON	*M. balthica*	A	32.2	-0.82	29.0	32.5	-7.14	45.6	49.6	46.2	17.2
4 Kemptville, ON	*M. balthica*	A	30.6	-1.50	27.7	31.2	-5.44	39.0	42.9	37.9	0.8
5 Richmond, ON	*M. balthica*	A	32.7	-1.07	28.5	32.0	-6.78	44.2	48.2	45.4	19.7
6 Ottawa, ON	*M. calcarea*	A	31.4	-1.06	28.6	29.5	-0.37	20.3	24.2	22.5	-10.2
	M. balthica	A	32.6	-1.05	28.6	32.1	-6.86	44.6	49.0	45.6	19.3
7 Galetta, ON	*M. balthica*	A	31.9	-1.21	28.3	31.8	-8.30	50.2	54.7	50.6	19.0
	H. arctica	A	33.6	+0.40	31.2	32.3	-4.97	37.2	41.4	39.4	20.2
8 Hwy 17, ON	*M. balthica*	A	31.9	-1.33	28.0	31.6	-9.19	53.8	58.4	54.1	22.2
9 Clayton, ON	*M. balthica*	A	32.2	-0.57	29.5	33.0	-9.62	55.6	60.1	56.3	26.0
10 Goshen, ON	*M. balthica*	A	30.1	-1.89	26.7	30.5	-9.64	55.7	60.2	53.8	10.3
11 Renfrew, ON	*M. balthica*	A	31.1	-2.68	25.5	29.0	-10.02	57.2	61.8	56.6	19.0
13 Wakefield, PQ	*M. balthica*	A	30.7	-1.80	27.1	30.7	-6.68	43.8	48.2	42.7	4.7
	H. arctica	A	31.8	+0.73	32.0	33.0	-3.65	32.2	36.4	32.4	2.6
14 Bearbrook, ON	*H. arctica*	A	31.4	+1.38	33.2	34.2	+0.31	17.9	21.8	17.6	-12.2
	B. crenatus	LMC	-	+0.29	-	-	+3.13	4.3	8.7	-	-
15 Dunvegan, ON	*H. arctica*	A	32.3	+1.52	33.5	34.5	-0.60	21.1	25.0	21.7	-3.6
16 Warina, ON	*H. arctica*	A	33.3	+0.98	32.4	33.4	-2.63	28.5	32.5	30.2	9.9
	M. balthica	A	30.7	-1.47	27.8	31.3	-3.78	32.7	36.9	31.7	-4.5
17 Chesterville, ON	*H. arctica*	A	32.0	+0.59	31.7	32.7	-3.05	30.0	34.1	30.4	2.0
18 Martintown, ON	*M. balthica*	A	29.2	-0.85	29.0	32.5	-10.61	49.7	64.3	56.8	7.0
19 Alexandria, ON	*H. arctica*	A	32.4	+1.00	32.5	33.5	-3.45	31.5	35.6	32.3	6.1
	M. balthica	A	30.5	-1.89	27.0	30.5	-11.86	64.9	69.7	63.6	20.9
21 Lee's Corners, PQ	*H. arctica*	A	33.7	+1.09	32.6	33.6	-1.94	25.9	30.0	28.0	10.4
22 Rigaud, PQ	*H. arctica*	A	33.3	+1.22	32.9	33.9	+1.42	24.0	28.1	25.8	3.2
23 St Joseph, PQ -du-Lac	*H. arctica*	A	33.3	+1.23	32.9	33.9	-1.39	23.9	28.0	25.7	5.7
	M. calcarea	A	30.9	-1.81	27.1	28.1	-10.24	58.2	62.8	57.3	18.2
24 St. Martine, PQ	*M. arenaria*	A	30.6	-1.47	27.8	31.3	-10.87	60.8	65.4	59.5	18.2
	M. truncata	A	30.4	-1.73	27.3	28.3	-11.42	63.1	67.8	61.6	18.6
	B. crenatus	LMC	-	-0.54	-	-	+1.94	8.5	13.3	-	-
	M. balthica	A	28.9	-2.66	25.5	29.0	-10.09	57.6	62.1	54.3	3.2
25 Lacolle, PQ	*M. balthica*	A	29.8	-1.62	27.5	31.0	-10.30	58.5	63.0	56.2	10.3
	H. arctica	A	31.4	+0.72	31.9	32.9	-2.02	26.3	30.3	26.0	-5.2
	B. crenatus	LMC	-	+0.88	-	-	+3.68	2.5	6.7	-	-
	M. calcarea	A	29.3	-1.10	28.5	29.5	-1.28	23.5	27.5	21.1	-20.6
26 St. Gertrude, PQ	*H. arctica*	A	32.5	+0.19	30.9	31.9	-1.16	23.1	27.1	23.9	0.0
	M. truncata	A	32.0	+1.01	32.5	33.5	+0.65	16.7	20.6	17.0	-9.0
	Neptunea sp.	A	31.6	-0.42	29.8	30.8	+1.36	14.2	18.1	14.2	-14.0
27 Charet, PQ	*H. arctica*	A	33.4	+0.27	31.1	32.1	-2.22	26.9	31.0	28.8	9.2
	M. balthica	A	30.3	-2.24	26.3	29.8	-10.52	59.3	64.0	57.7	14.7
	M. arenaria	A	30.7	-0.92	28.8	32.3	-11.31	62.6	67.3	61.5	20.5
28 St. Nicolas, PQ	*H. arctica*	A	32.3	+0.64	31.8	32.8	-3.40	31.3	35.4	32.0	5.3
	M. truncata	A	32.7	+0.53	31.6	32.6	-1.18	23.2	27.1	24.7	0.9
	M. calcarea	A	30.7	-1.51	27.7	28.7	-0.77	21.7	25.6	20.7	-13.5
	M. edulis	A	30.8	+0.31	31.2	33.5	-3.66	32.2	36.4	32.8	-4.1
	M. edulis	LMC	-	-2.18	-	-	-4.64	36.0	46.1	-	-

Mineralogy: A= aragonite LMC= low Mg calcite

A - uncorrected temperature, using present seawater ($\delta^{18}O = 0$ o/oo, salinity = 35.5 ppt) and Equation 13.

B - partial correction, using Quaternary seawater ($\delta^{18}O = +1.6$ o/oo, salinity = 35.5ppt) and Equation 13.

C - partial correction, using Quaternary seawater ($\delta^{18}O = +1.6$ o/oo, and Sr/Na salinity[1]) and Equation 13 and 9.

D[4] - full correction, using late Quaternary seawater ($\delta^{18}O = +0.8$ o/oo, and true salinity[1]), and a correction for mixing with glacial meltwater having a mean $\delta^{18}O$ composition of -77 o/oo. In order for all the temperatures to be within the proper temperature tolerance the glacial meltwater must have had a $\delta^{18}O$ ranging from -75 o/oo to -80 o/oo. Thus the standard deviation of ±8°C. Equation 13 and 15.

[1] from Sr/Na and Equation 10.

[2] using $\delta^{13}C$ and Equation 11.

[3] adjusted, +3.5 ppt for shallow water species, +1.0 ppt deeper water species, using $\delta^{13}C$ and Equation 11.

shallow water molluscs are in fact, consistently lower than expected by 3.5±0.8 ppt, whereas, the salinities for the deeper water molluscs from $\partial^{13}C$ and Equation 11 are consistently lower than expected salinity by 1.0±0.8 ppt. Since the Sr/Na determined salinities are unaffected by factors other than salinity, salinity correction factors, due to secular variations in oceanic ^{13}C, for aragonitic molluscs of the Champlain Sea can be made by adding 3.5 ppt to the $\partial^{13}C$ salinity determined for the shallow water species, and adding 1.0 ppt to the $\partial^{13}C$ salinity determined for the deeper water species. After adjustments have been made, the corrected $\partial^{13}C$ salinites, with an inherent error margin of ±2 ppt, are statistically similar at the 95% confidence level or better (unpaired t-test; Table 7).

Using the salinity data calculated from the Sr/Na of the aragonitic molluscs and corrected $\partial^{13}C$ content of aragonitic molluscs of the Champlain Sea (Table 7), it is possible to reconstruct a paleoceanographic scenario. The early Champlain Sea is, in this study, is defined to be the period from 13 to 11 ka, whereas, the late Champlain Sea is defined to be the period from 11 to 10 ka. To provide a more complete picture, I have used additional corrected $\partial^{13}C$ data for aragonitic molluscs of the Champlain Sea from Hillaire-Marcel (1977), Lowdon and Blake (1979, GSC-2586, GSC-2195, GSC-2338, GSC-2366), Blake (1983, GSC-3539, GSC-3574, GSC-3770), and Rodrigues and Richard (1985). Thus, with a total salinity data base of 704 aragonitic mollusc samples from 72 localities in the Champlain Sea basin (Appendix V), four preliminary paleosalinity maps are produced for the shallow waters and deeper waters of the early Champlain Sea (13-11ka) and late Champlain Sea (11-10ka). The paleogeography, required for paleoceanographic reconstructions (Schopf,1980), and data for the maps was delimited on the basis of

elevations, radiocarbon dates, and surficial geology maps and reports (Gadd, 1960, 1963, 1971, 1983; Terasmae, 1965; Hillaire-Marcel, 1974; Cronin,1976, 1977; Lowdon and Blake, 1973,1979, 1981; Blake,1983; Richard, 1978; Sharpe, 1979; Catto *et al*, 1982). The isohalines produced are based on the rules for topographic contouring and probably represent summer conditions, since most molluscs calcify during the summer months (Epstein and Lowenstam, 1953). Where no data was available, no isohalines were plotted. It must be emphasized that these maps are prelimininary, and that additional data may alter the location of isohalines.

Early Champlain Sea

The deeper waters of the early Champlain Sea (13-11 ka) (Fig. 14) had salinities that ranged from 31 up to 36 ppt in the central part of the basin. Lower salinities occur primarily near marginal localities where a dilution by freshwater can be expected. The data also indicate that the water salinity of the greater part of the basin remained relatively stable and varied about 33 ppt.

The data indicate that the shallow waters of this period (Fig. 15) had more variable salinities ranging from 24-33 ppt due to the influx of glacial meltwaters and incomplete mixing with deeper marine waters. The isohalines also indicate the influence of freshwaters (arrows) primarily from ablating glacial ice in the north and southeast. The lack of a brackish water molluscan fauna may support the hypothesis of a rapid marine inundation that may have been accomplished by a calving bay (Gadd,1983).

Late Champlain Sea

By 11 to 10 ka, the Champlain Sea was regressing due to the effects of post-glacial rebound (Elson,1969b). The marine limit for this time was estimated on the basis of radiocarbon dates and marine beaches as obtained
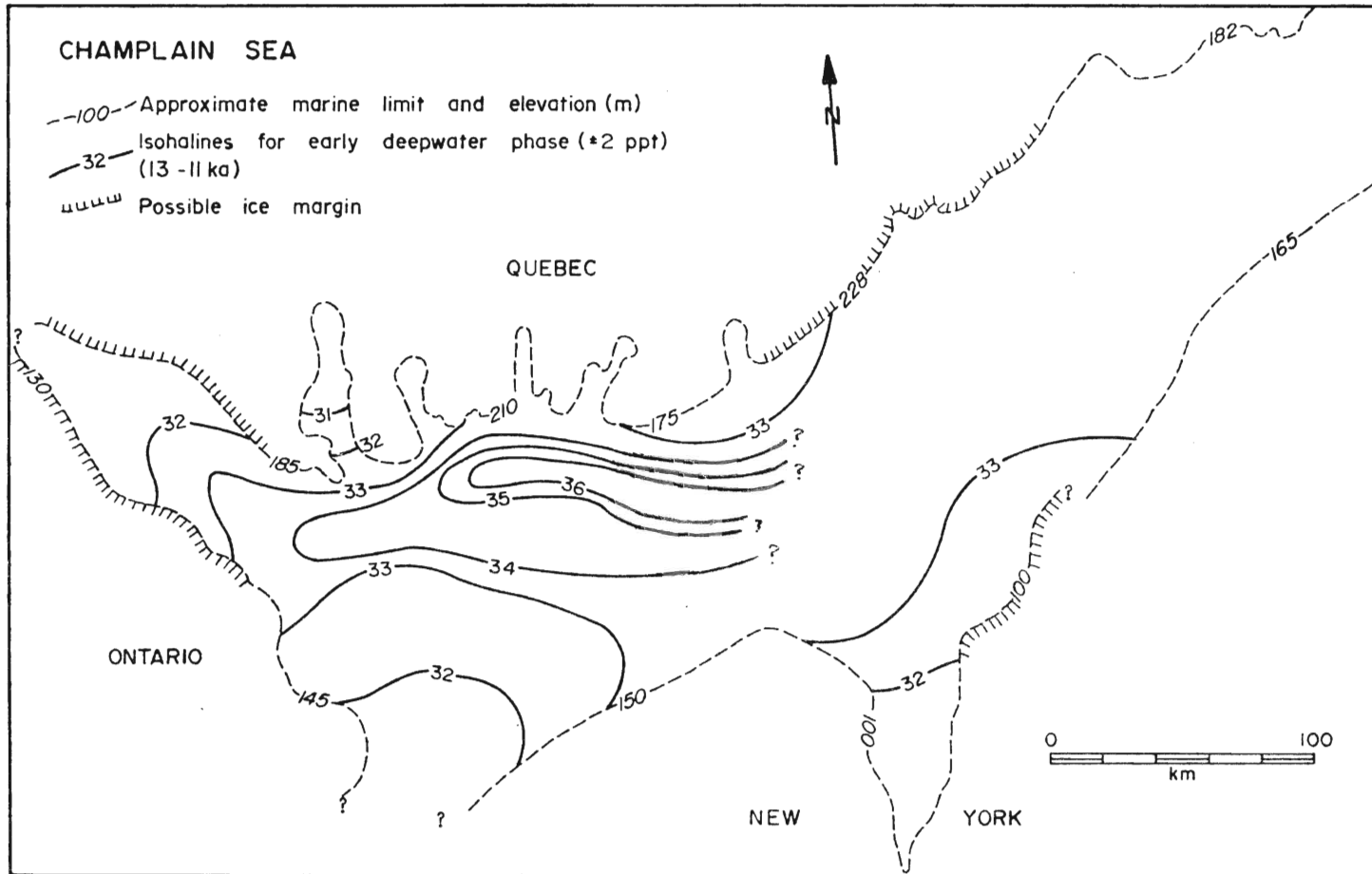
Fig. 14. Isohalines for the deeper waters of the early Champlain Sea (13-11 ka). Based on geochemical data from this study, Hillaire-Marcel (1977) and Rodrigues and Richard (1985). ? denotes lack of data.
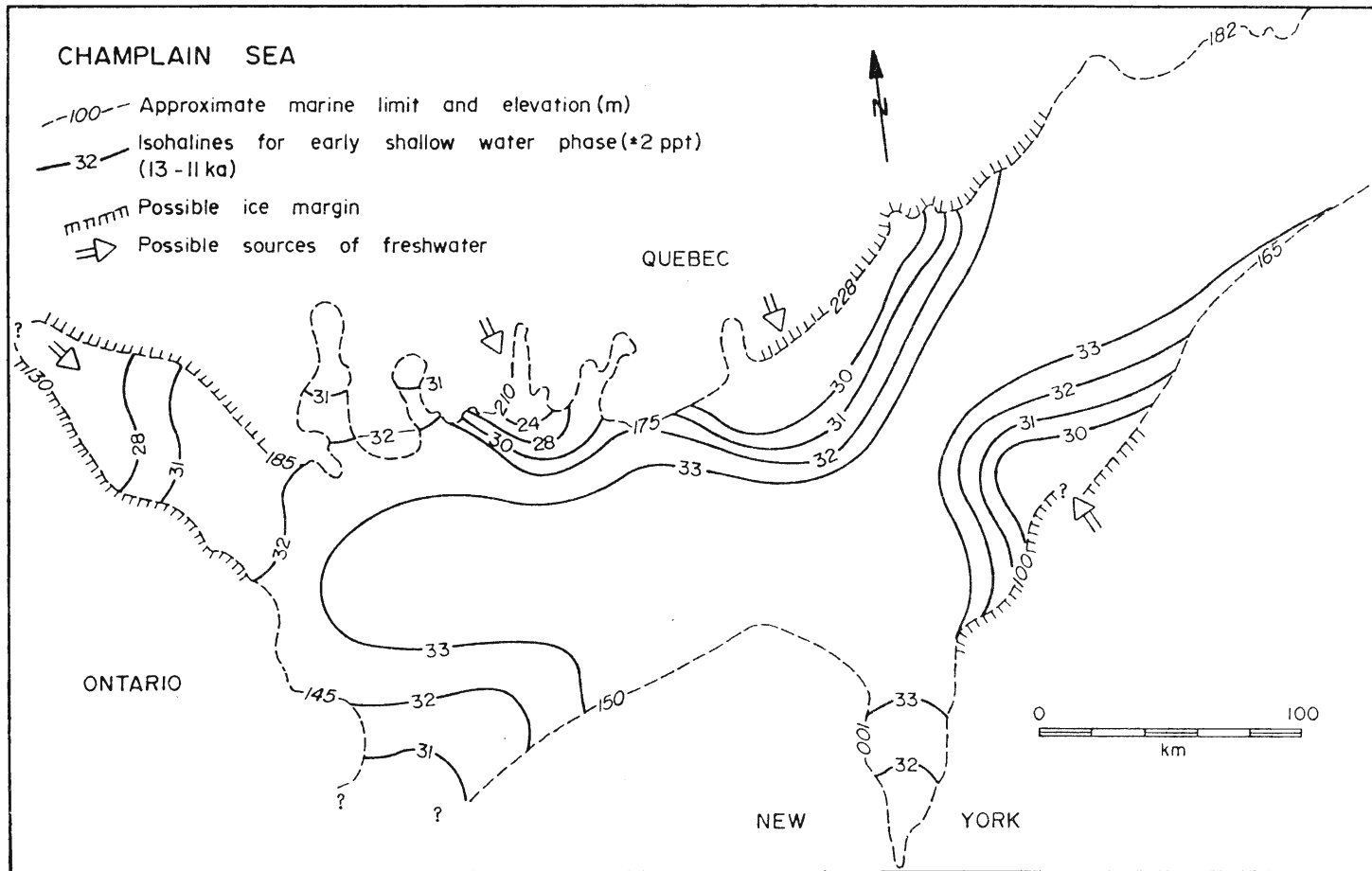
Fig. 15. Isohalines for the shallow waters of the early Champlain Sea
Geochemical data as in Fig. 14. Arrows denote possible freshwater sources.

from surficial geology maps and reports (Gadd, 1971; Sharpe,1979; P. LaSalle, pers. com.,1985).

The deeper water data for the late Champlain Sea (Fig.16) indicates a slight reduction in salinity, ranging from 31-33 ppt. The deeper water data also record the large influx of freshwater near Shawinigan, Québec, where the Trois Riviére delta was defined in the northeast part of the basin by Gadd (1971).

The shallow waters of the late Champlain Sea ranged in salinity from 28 to 31 ppt (Fig. 17). The data indicate freshwater influences from Lake Iroquois, Lake Algonquin, the Lake Champlain area, near Montréal, and the Trois Riviére delta. The southeastern Champlain Sea basin varied about 29-31 ppt, and, along with warmer summer water temperature (Elson,1969a) allowed for colonization by the boreal pelecypod *Mya arenaria*.

Overall, the deeper waters were generally more saline (31-36 ppt) than the more variable shallow waters (24-33 ppt). The geochemical data from aragonitic molluscs also indicate that the marine shallow waters of the Champlain Sea at no time fell below 24 ppt. This is in agreement with the interpretations of foraminiferal asemblages by Cronin (1976), Fillon and Hunt (1974) and Hillaire-Marcel (1980), but contradicts the hypotheses by Elson (1969a) and Hillaire-Marcel (1981) that salinities between Montreal and Ottawa varied about 15-26 ppt. Salinities of 16-22 ppt determined from foraminiferal assemblages in extreme marginal Champlain Sea areas, where no molluscs have been found (cf., Catto *et al*,1981; Cronin,1977), are possibly due to dilution by freshwaters. The transition to freshwater conditions is documented by foraminiferal assemblages (Fillon and Hunt, 1974; Cronin, 1977, 1979), freshwater sediments and macroinvertebrates of "Lampsilis Lake" (Elson and Elson, 1959; Richard,

CHAMPLAIN SEA

- ―100― Approximate marine limit and elevation (m)
- ―32― Isohalines for late deepwater phase (±2 ppt) (11-10 ka)
- ⇒ Possible sources of freshwater

QUEBEC

ONTARIO

NEW YORK
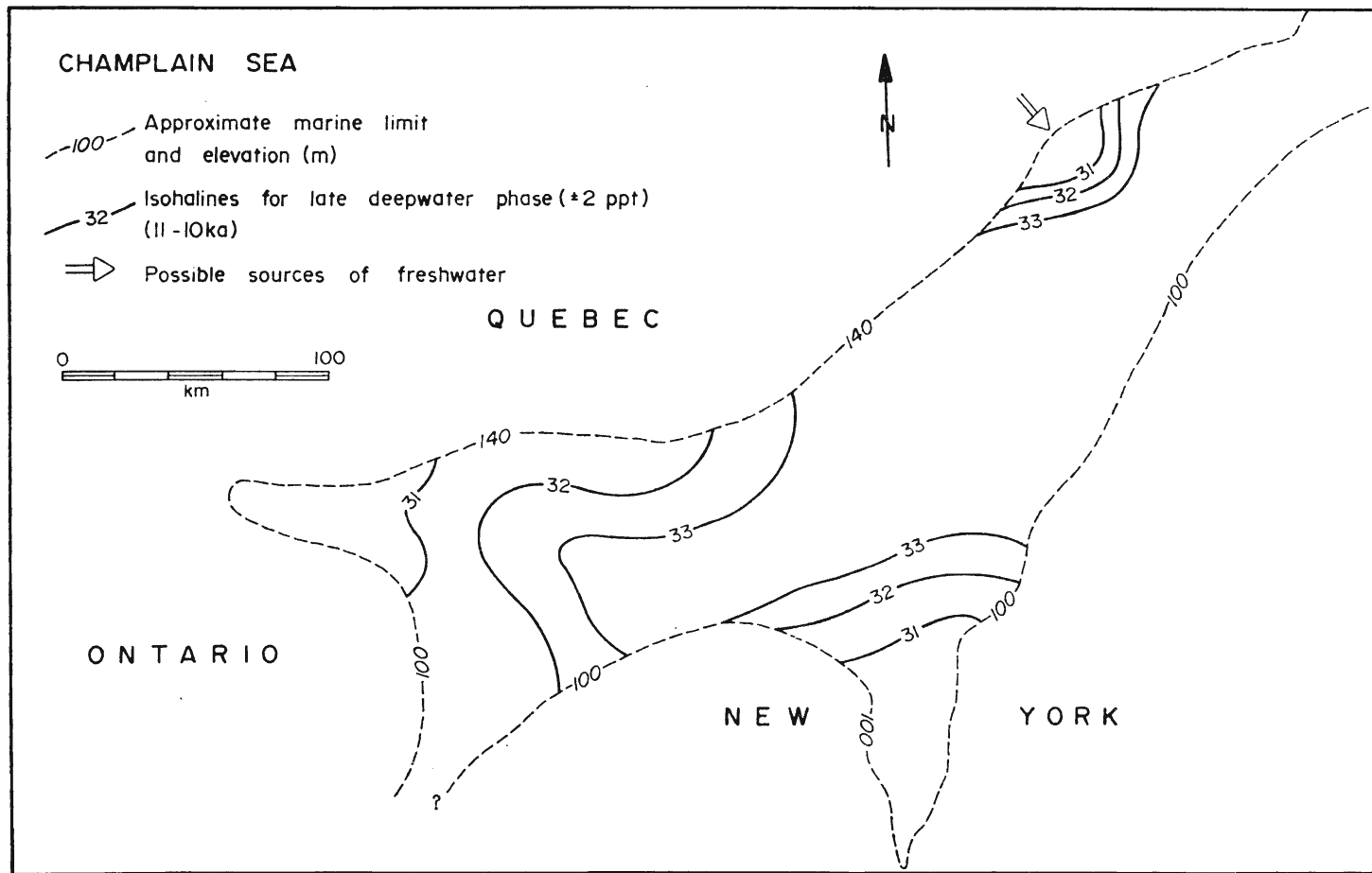
Fig. 16. Isohalines for the deeper waters of the late Champlain Sea (11-10 ka). Data source as in Fig. 14.
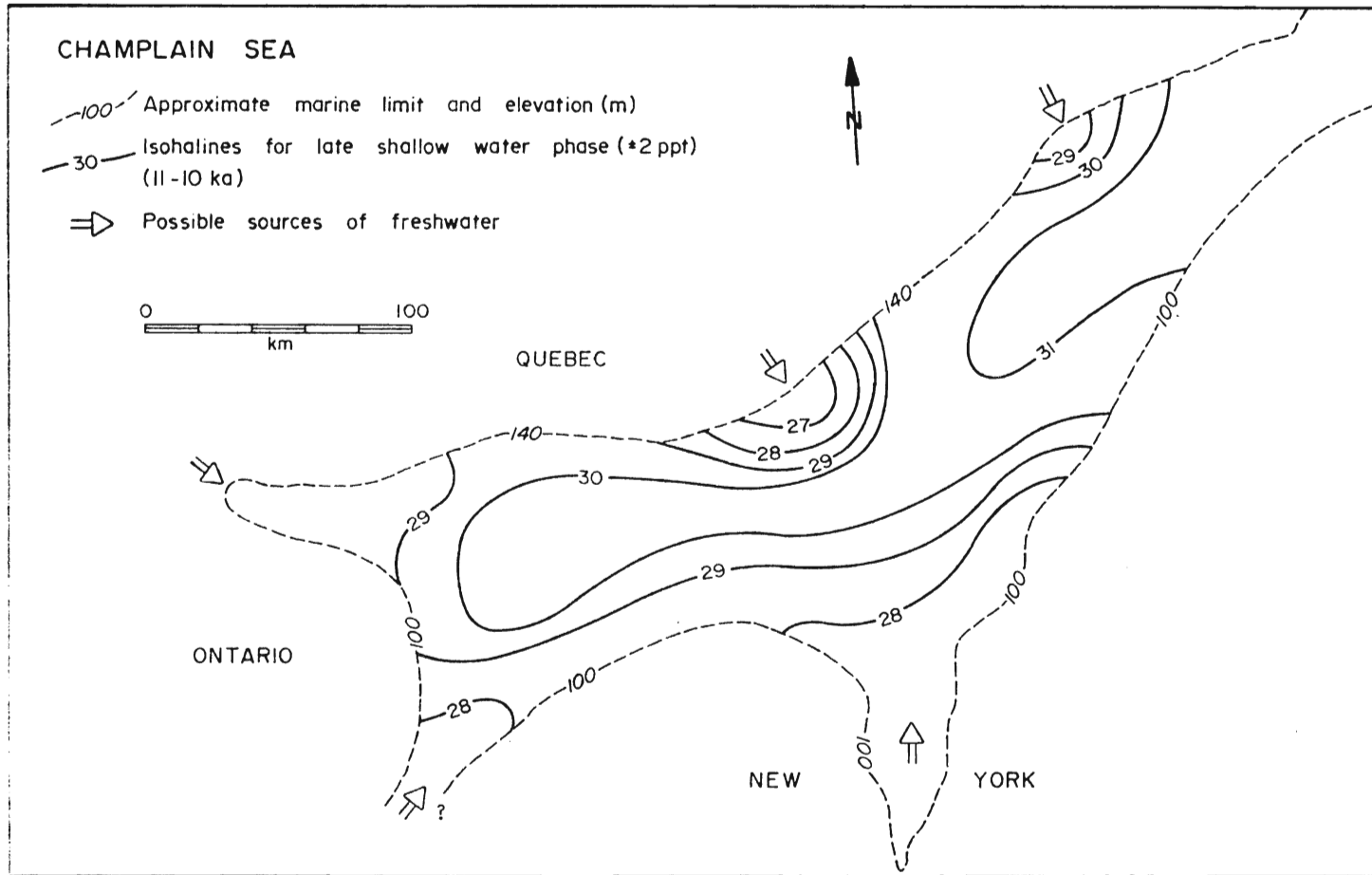
Fig. 17. Isohalines for the shallow waters of the late Champlain Sea.
Data source as in Fig. 14.

1978). Although the final transition to freshwater conditions are not documented by a truly brackish-water molluscan fauna in this study, a rapid negative shift in the oxygen isotope content of benthic foraminifers near the top of Lake Champlain cores suggests that a transition to freshwater conditions occurred rapidly after 10.8 ka in that region (Corliss *et al.*, 1982).

Paleotemperatures and $\partial^{18}O$

$\partial^{18}O$ and Water Salinities

Most molluscs precipitate their skeletal carbonate in isotopic equilibrium with the ambient waters (Epstein *et al.*,1953),whereas, some do not (Morrison and Brand, in press). For aragonitic molluscs that do precipitate shells in isotopic equilibrium, it is possible to calculate paleotemperatures using Equation 13 formulated by Grossman and Ku (1981) for aragonite. While ∂_c is measured directly from the sample, the value for ∂_w is less certain. Present day seawater has an average $\partial^{18}O$ value of 0 °/oo (SMOW) (Anderson and Arthur,1983). Moreover, during glaciation the preferential incorporation of ^{16}O into glacial ice, in addition to an increase in ocean salinity, will raise the $\partial^{18}O$ of ambient seawater to an estimated +1.6 °/oo (Broecker,1982). The determination of paleotemperatures for the Champlain Sea using these glacial maximum parameters, however, yields unrealistic temperatures as shown in Table 7, columns A and B. The temperatures derived are too high for a post-glacial sea (18.2°C to 69.7°C). Clearly, there are other factors that need to be considered such as the effect of a reduction in salinity. As discussed previously, it has been shown that the $\partial^{18}O$ composition of seawater is related to changes in salinity by means of Equation 9 (Epstein and Mayeda,1953; Craig and Gordon,1965), where salinity is in ppt and the freshwater contaminant has

a $\partial^{18}O$ composition of about -20 º/oo, the average for meteoric waters at high latitudes is shown in Fig. 18, line A (Faure,1977, Ch.18). Paleosalinities for the Champlain Sea previously determined by means of the trace element technique, independent of glacial or temperature influences and corrected $\partial^{13}C$ salinity data, are shown in Table 7. However, paleotemperatures determined while considering only the salinity effect still yield unrealistic water temperatures (14.2° to 63.6°C) as shown in column C of Table 7.

There are only two possibilities that can account for these anomalous temperatures. Either all the molluscs fractionated against the equilibrium incorporation of $\partial^{18}O$ into shell carbonate, or the freshwater contaminant, glacial meltwater, must have had a $\partial^{18}O$ isotopic composition different from average meteoric water of -22 º/oo. It is unlikely that all the molluscs fractionated against isotopic equilibrium, thus, we must assume that glacial meltwater had a different isotopic composition than present day meteoric water. From Table 7 we know that the salinity of the Champlain Sea was variable (24-36 ppt, Sr/Na method, corrected $\partial^{13}C$ salinities). Therefore the difference in salinity from normal marine conditions (cf., Ruddiman and Duplessy,1985, 36 ppt between 10 and 13 ka) at the time of the Champlain Sea must represent the glacial meltwater influence. The isotopic composition resulting from the mixture of two known solutions can easily be determined by means of a simple mixing model (Fig. 19). Figure 19 represents a hypothetical glaciomarine environment. The salt wedge effect, salinity stratification and mixing shown in Fig. 19 are typical of estuaries where freshwater input is an important physical factor (Pritchard,1968). Entrainment of higher salinity, deeper waters with the upper and less saline layer results in the
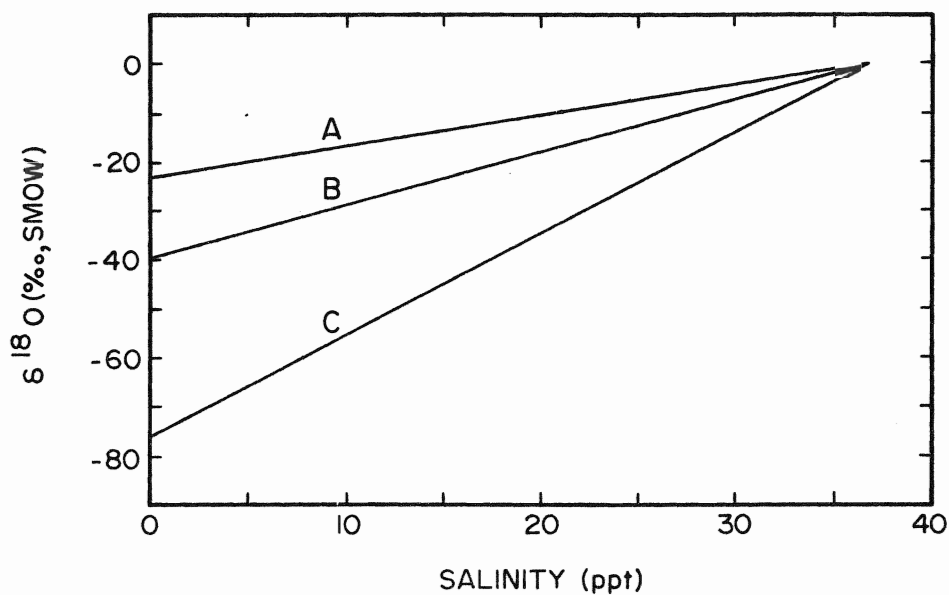
Fig. 18. Mathematical relationships for the mixing of isotopically different solutions:

A δ_W = 0.16 (Salinity) + (-21.2), when mixing present seawater with meteoric water ($\delta 18_O$ = -20 permil) as demonstrated by Craig and Gordon (1965).

B δ_W = 1.136 (Salinity) + (-40.0), mixing Quaternary seawater ($\delta 1.8_O$ = +1.6 permil) with mean glacial meltwater of ($\delta^{18}O$ = -40 permil) (Mix and Ruddiman, 1984).

C δ_W = 2.154 (Salinity) + (-77), mixing with late Quaternary seawater ($\delta^{18}O$ = +0.8 permil) with mean eastern Laurentide meltwater ($\delta^{18}O$ = -77.0 permil).

100 75 50 30 20 10 5

% Glacial Meltwater (0 ppt ; - 40 ‰)

0 25 50 70 80 90 95

% Seawater (36.4 ppt ; +1.0 ‰)

GLACIAL
ICE

0; 9.9; 18.7; 25.8; 29.3; 32.9; 34.6;
-40 -29.8 -19.5 -11.3 -7.2 -3.1 -1.1
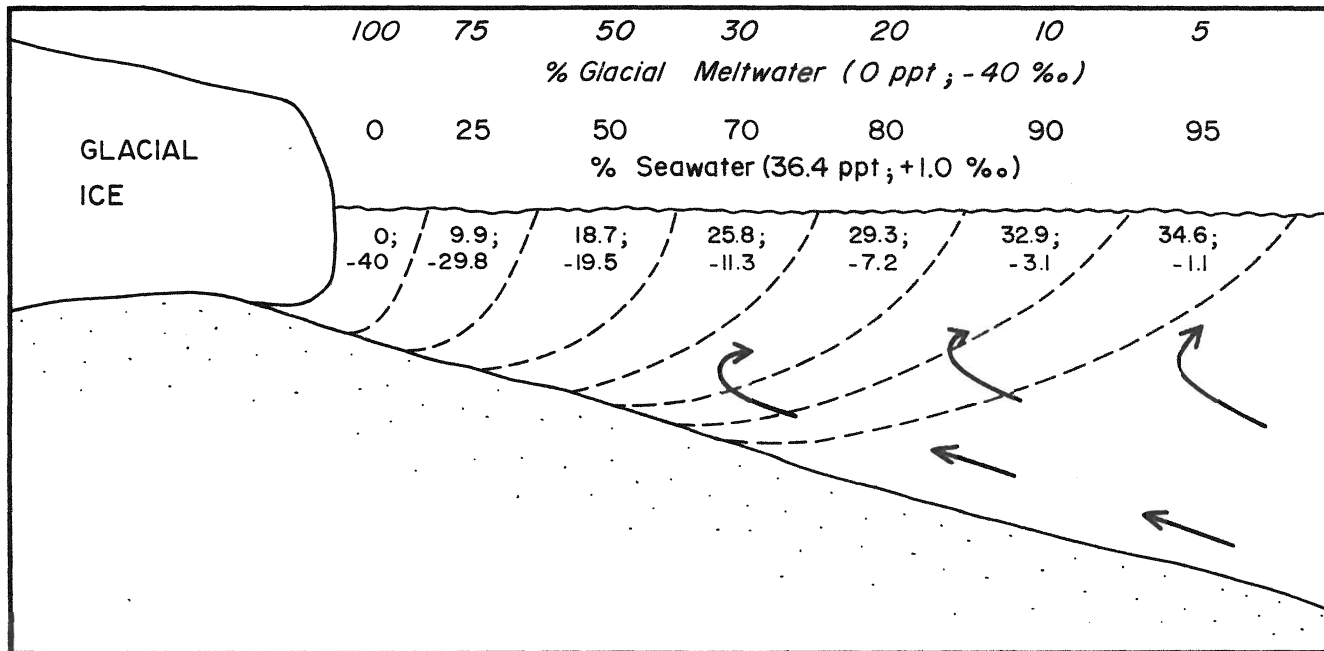
Fig. 19. Hypothetical glaciomarine model for salinity and isotopic mixing of glacial meltwater and seawater.

development of salinity gradients (Bowden,1967). In this model, seawater is assumed to have a salinity of 36.4 ppt with a $\partial^{18}O$ of +1.0 $^0/oo$, whereas glacial meltwater has a salinity of 0 ppt with a $\partial^{18}O$ of -40 $^0/oo$, thus, a 50/50 mixture of the two solutions will result in a net final solution (∂_w) with a salinity of 18.2 ppt and a $\partial^{18}O$ of -19.5 $^0/oo$. Salinity mixing effects of this kind for present seawater and meteoric water were demonstrated by Epstein and Mayeda (1953) and later modified by Craig and Gordon (1965) (line A, Fig. 18). Equation 15 defines this linear relationship between $\partial^{18}O$ of seawater with salinity. The postulated relationship is given by the equation;

$$\partial_w = 1.136 \, (S) + (\partial_{ice}) \qquad \qquad (15)$$

where S is the measured salinity, ∂_w is the isotopic composition of the final mixture, and the $\partial^{18}O$ composition of the glacial meltwater contaminant (∂_{ice}) is assumed to be -40 $^0/oo$ (line B, Fig. 18). Any variation in the isotopic composition of the contaminant, however, will cause a shift in the slope of the equation.

The Champlain Sea existed during a time of deglaciation (13 to 10 ka). Most workers agree, on the basis of field evidence and oceanic records, that between 13 and 10 ka roughly 40-50% of the Laurentide ice had ablated (Ruddiman and Duplessy,1985). Thus, if glacial seawater had a $\partial^{18}O$ composition of +1.6 $^0/oo$ and a salinity 3.5 % higher than present ocean water (Broecker,1982), average seawater during the time of the Champlain Sea had a $\partial^{18}O$ of +0.8 $^0/oo$ and a salinity of 36 ppt. We know that the shallow water of the early Champlain Sea had temperatures of 5-10°C (Cronin,1976,1977; Hillaire-Marcel,1980) and salinities of 28.7 to 33.7 ppt

(Table 7, Sr/Na salinity). Thus, one can extrapolate the hypothesis to determine the $\partial^{18}O$ composition of the glacial meltwater during this time. Substituting into Equation 13, where ∂_c is the value from the carbonate and using a mean temperature of 7.5°C for the shallow water fauna (*Macoma balthica*), we find that ∂_w must follow the relationship;

$$\partial_w = 2.154\,(S) + (\partial_{ice}) \tag{16}$$

where S is the calculated salinity, and 2.154 is the slope of the line. Solving for ∂_{ice} we find that the $\partial^{18}O$ of the glacial meltwater must have been about -77 ^{o}/oo (line C, Fig. 18). As shown in Table 7, column D, the paleotemperatures determined using an average ∂_{ice} of -77 ^{o}/oo, with a range of -75 to -80 ^{o}/oo, will yield water temperatures that are indeed in accordance with the tolerance limits of the fauna and realistic for a post-glacial sea. It is impossible to resolve the standard deviation of ±8°C inherent in the extrapolation, since the isotopic composition of the eastern Laurentide Ice Sheet probably varied throughout its extent.

Verification - St. Lawrence Estuary

The postulated isotopic mixing relationships previously discussed can be verified with information from the present St. Lawrence Estuary. Aragonitic *Hiatella arctica* collected by Hillaire-Marcel (1981) at Sept-Iles, Québec, at a depth of 50m yielded a $\partial^{18}O$ of +3.2 ^{o}/oo and a $\partial^{13}C$ of -0.3 ^{o}/oo. Moreover, water at that depth has a temperature of about 1°C. Measured salinities in the Sept-Iles region vary from 29 to 32 ppt with seasonal variations of 2 to 3 ppt (Fradette and Bourget, 1980). The average $\partial^{18}O$ of meteoric freshwater in the Sept-Iles region is about -14 ^{o}/oo

(Strain and Tan,1979). Mixing of that freshwater with present Atlantic seawater (salinity = 35.5 ppt; $\partial^{18}O = 0$ $^o/oo$) defines the equation;

$$\partial_w = 0.4 \text{ (salinity)} - 14 \tag{17}$$

where ∂_w is the isotopic composition of the final mixture. The salinity at Sept-Iles calculated from the $\partial^{13}C$ of *H. arctica* and Equation 11 is calculated to be 29.9±1 ppt, which is in excellent agreement with measured salinities (Fradette and Bourget,1980). Knowing the effect of salinity (Equation 17), and substituting into Equation 13, the temperature calculated with the $\partial^{18}O$ of +3.2 $^o/oo$ for *H. arctica* is 1.3°C, which is in excellent agreement with the measured temperature of about 1°C (Hillaire-Marcel,1981).

This example from the present St. Lawrence Estuary illustrates both the validity of the methods and the importance of knowing the $\partial^{18}O$ of the freshwater contaminant for determining realistic paleotemperatures. Conversely, if temperatures can be determined qualitatively from faunal assemblages, and salinities can be determined from aragonitic molluscs using trace element techniques, it is then also possible to approximate the $\partial^{18}O$ of the freshwater contaminant.

Laurentide ice and oceanic $\partial^{18}O$

The singular feature of these paleotemperature reconstructions is the requirement of a $\partial^{18}O_{ice}$ of about -80 to -70 $^o/oo$. The present concensus is that maximum glacial ice had a mean $\partial^{18}O_{ice}$ of about -35 $^o/oo$ (Broecker,1978). This estimate for mean glacial ice has been made on the basis of measurements and comparisons with the present day Greenland and Antarctic Ice Sheets (Shackleton,1967a) and the isotopic composition of

present day precipitation. In addition, an equilibrium ice flow model is tacitly assumed where the $\partial^{18}O$ of the total Ice Sheet is equivalent to that of snow falling near the centre (cf. Flint,1971; CLIMAP,1976). Then, despite changing ice volume over time, the $\partial^{18}O$ of the Ice Sheet is held constant at -35 $^o/oo$ and is linearly related to changes in oceanic $\partial^{18}O$ as reflected in benthonic and planktonic foraminifers (Shackleton,1967b). Recently, Mix and Ruddiman (1984) have questioned these assumptions of glacial isotopic equilibrium model. Firstly, they maintain that it is invalid to maintain a mean $\partial^{18}O_{ice}$ inferred from glacial maximum conditions because smaller ice sheets should have less isotopically negative ice than large ice sheets. Secondly, the assumption of isotopic equilibrium is questionable since the oxygen isotope record clearly shows rapid volumetric fluctuations for the Pleistocene Ice Sheets. And thirdly, there is a considerable discrepancy between ice volume inferred from oceanic benthic foraminiferal $\partial^{18}O$ records and sea levels determined from fossil reefs that require large ice volumes or temperature effects for their resolution.

Although large variations in the $\partial^{18}O$ of glacial ice have been postulated (Shackleton, 1967a; Broecker,1978; Olausson,1981), no attempts have been made to further document that possibility. Data from this study indicate that the eastern Laurentide Ice Sheet had a $\partial^{18}O$ as negative as -80 $^o/oo$. This is possible considering that continental precipitation roughly follows a Rayleigh distillation process (Fig. 20; Siegenthaler,1979; Anderson and Arthur, 1983). Precipitation events originating in either western or south-western North America will, generally, become progressively more isotopically depleted with respect to ^{18}O on progression eastwards. Thus, maritime precipitation is closer to isotopic equilibrium
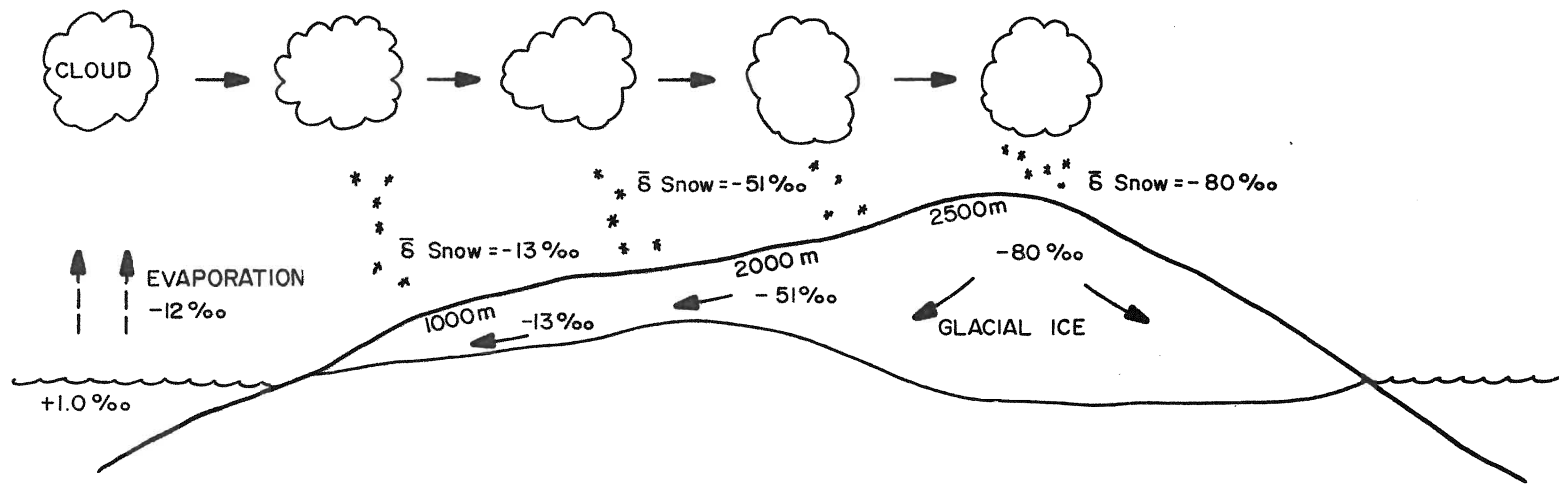
Fig. 20. Conceptual model of an isotopic disequilibrium ice sheet affected by Rayleigh cycle, altitude, and temperature. (after Mix and Ruddiman, 1984).

with seawater than continental precipitation. The overall degree of depletion depends on geographic parameters such as latitude, altitude, distance from coast, and the amount of precipitation (Yurtsever,1975; Gat,1980). Yurtsever (1975) demonstrated that the isotopic variations of precipitation can be attributed primarily to temperature changes.

Epstein *et al.* (1953) demonstrated that the $\partial^{18}O$ composition of depleted Antarctic ice of -55 ^{0}/oo is consistent with a Rayleigh distillation process for maritime air cooled to -50°C that was originally saturated with water vapor at 20°C. At present, precipitation falling over Hudson Bay has a mean annual $\partial^{18}O$ of less than -20 ^{0}/oo (Yurtsever,1975). While there is little direct evidence, Flint (1971) postulated that the origin of precipitation for the Laurentide Ice Sheet was derived primarily from tropical sources in the Atlantic and Gulf of Mexico. Therefore, when one considers the climatic conditions required to produce a large continental ice sheet, such as extreme temperatures and increased albedo, along with a Rayleigh distillation effect, it becomes entirely conceivable that the Laurentide Ice Sheet incorporated snow in isotopic disequilibrium with $\partial^{18}O$ as low as -80 ^{0}/oo. Additional support for this fact is shown in the isotopic compositions of modern freshwater molluscs from Lake Erie where the molluscs have a $\partial^{18}O$ of about -7.0 ^{0}/oo (Keith *et al.*,1964), while late Pleistocene molluscs have a $\partial^{18}O$ of about -12.0 ^{0}/oo (Fritz *et al.*,1975). Furthermore, recent ice cores from Antarctica, dated to before 15 ka have indicated glacial ice $\partial^{18}O$ compositions as negative as -63 ^{0}/oo (Lorius *et al.*, 1985). Thus, if this hypothesis holds true, then the Cordilleran Ice Sheet on the west coast of North America, derived primarily from Pacific maritime precipitation, should be isotopically heavier than the contemporaneous eastern continental Laurentide ice.

It is beyond the scope of this thesis to attempt to model the global effects of an isotopically more-negative ice sheet since that would require extensive glaciomarine isotopic data from all portions of the Laurentide Ice Sheet. However, the data indicate that the isotopic disequilibrium model proposed by Mix and Ruddiman (1984) is probably more accurate than the glacial equilibrium model with its mean $\partial^{18}O_{ice}$ of -35 ^{o}/oo.

Finally, the likelihood of a more isotopically negative Laurentide Ice Sheet than previously thought has a number of implications for the oceanic $\partial^{18}O$ record as an indicator of global glacial ice volume. Firstly, it is probable that there is a substantial lag of oceanic $\partial^{18}O$ behind true glacial ice volume. Therefore, the isotopic composition of the oceanic record is not linearly related to glacial ice volume (Mix and Ruddiman ,1984). Secondly, the enormous additional ice volume needed to reconcile the discrepancy between ice volume determined by the oceanic $\partial^{18}O$ record and that of sea levels indicated by fossil reefs (Broecker, 1976) may be resolved by a more negative $\partial^{18}O_{ice}$, which implies that, the ice volumes previously determined from the oceanic $\partial^{18}O$ record assuming a mean $\partial^{18}O_{ice}$ of -35 ^{o}/oo are probably too large. An isotopically more negative ice sheet may accomodate field evidence suggested by Occhietti (1983) that the Laurentide Ice Sheet was smaller than that proposed by Flint (1971) and CLIMAP (1976).

Paleotemperatures of the Champlain Sea

The persistent unrealistic temperatures calculated with the $\partial^{18}O$ of *M. calcarea* and *Neptunea despecta* even with corrections, (Table 7, column D, as low as -21°C) suggest that these particular molluscs probably fractionated against equilibrium incorporation of ^{18}O. The aberrant temperatures determined for *H. arctica* at localities 7 and 14 are due to

analytical error. Within a $\partial^{18}O_{ice}$ range of -80 to -75 ^{o}/oo all other molluscs fall within their temperature tolerance limits of 0° to 15°C (Hillaire-Marcel,1980). For those localities (Table 7,column D) where mean $\partial^{18}O_{ice}$ temperatures are too high (i.e.,Clayton), a slightly more negative $\partial^{18}O_{ice}$ influence can be expected, whereas, too low $\partial^{18}O_{ice}$ temperatures (i.e., Lacolle) are resolved with a slightly less negative $\partial^{18}O_{ice}$.

Considering all factors, there is a consistent temperature difference between deeper water fauna (mean = 4.5°C, std. dev. of ±8°C) and the shallow water species (mean = 12.4°C, std. dev. of ±8°C), which is due to stratification along temperature and salinity gradients in the Champlain Sea. These mean temperatures reflect time transgressive average summer growth temperatures in molluscs for the Champlain Sea waters, but the data cannot confidently document the late Champlain Sea warming trend postulated by Elson (1969a) due to variations in the isotopic composition of the eastern Laurentide Ice Sheet.

Conclusion

Marine invertebrates collected from the Late Quaternary Champlain Sea are preserved in their original mineralogical, microstructural, and chemical state. Paleosalinities determined from the Sr/Na content and corrected $\partial^{13}C$ content of aragonitic molluscs indicate that in the greater part of the basin, the Champlain Sea shallow waters had salinities ranging from 24-33 ppt, whereas, deeper waters had salinities ranging between 31-36 ppt. Salinities for the Champlain Sea were primarily related to the depth of water and proximity to the glacial meltwater/ freshwater input.

The oxygen and carbon isotopic data from aragonitic molluscs of the Champlain Sea are extremely negative due to the influence of isotopically light glacial meltwater, salinity and temperature variations, and changes in

the $\partial^{13}C$ of the TDC of the glacial oceans during glaciation. Correcting for these effects, it is determined that eastern Laurentide ice meltwater ranged from about $\partial^{18}O$ -70 to -80 ^{0}/oo, and that the shallow waters of the Champlain Sea had a time transgressive mean temperature of 12.4°C, whereas, the deeper waters had a time transgressive mean temperature of 4.5°C.

I propose that a more isotopically negative Laurentide Ice Sheet than previously assumed lends support to the glacial isotopic disquilibrium model of Mix and Ruddiman (1984), and that the $\partial^{18}O$ oceanic record ought to be re-evaluated in terms of a smaller glacial ice volume. Further research is needed on faunas from glaciomarine environments to establish a quantitative model for a disequilibrium Laurentide Ice Sheet.

Chapter 3

Geochemical Evaluation and Paleosalinities using Molluscs
of the Ft. Langley Formation and Capilano Sediments,
Southwestern British Columbia

Abstract

One hundred and fifty-five marine invertebrate macrofossils were collected from glaciomarine sediments of the Ft. Langley Fm and Capilano Sediments at four locatities in the Fraser Lowlands of southwestern British Columbia. The sediments were deposited during the marine innundation that followed the retreat of the Late Quaternary Vashon glaciation.

All mollusc samples were found to be preserved in their original chemical, mineralogical, and micro-structural state as determined by x-ray diffraction, trace element analyses, and scanning electron microscopy.

Quantitative paleosalinities, determined from the Sr/Na content of the chemically unaltered aragonitic molluscs, indicate normal marine conditions (31-36 ppt) for the marine submergence of the Fraser Lowlands that followed the Vashon glaciation. The data is in agreement with previous interpretations of invertebrate macrofaunal and foraminiferal assemblages that suggest normal marine conditions.

Introduction

The marine sediments of the Late Quaternary Ft. Langley Fm and Capilano Sediments were deposited during the marine invasion of the Fraser Lowlands, British Columbia, following the recession of the Cordilleran Ice Sheet. The sediments contain a molluscan fauna characterized by low diversity and abundance. Moreover, the Pleistocene marine invertebrates of southwestern British Columbia have been the subject of only a few studies (Wagner,1959; Smith,1970; Balazarini,1983). Geochemical or isotopic data for invertebrates from the Ft. Langley Fm and Capilano Sediments are non-existent.

One hundred and fifty-five marine macroinvertebrates were collected from four Pleistocene fossil localities in the Fraser Lowlands and Howe Sound (Fig. 21). The purpose of this chapter of the thesis is to report on the chemical, mineralogical, and microstructural integrity of the invertebrate macrofossils from the Ft. Langley Fm and Capilano Sediments, and to obtain quantitative estimates of paleosalinity using aragonitic molluscs.

Previous Work

Paleotemperatures and paleosalinities for the Late Quaternary Ft. Langley Fm and Capilano Sediments have been qualitatively inferred on the basis of molluscan and foraminiferal assemblages (Wagner,1959; Smith,1970; Balazarini,1983). Although more than 70 species of invertebrate macrofossils have been found in the Ft. Langley Fm and Capilano Sediments, more than 90% represent molluscs (Wagner,1959). Moreover, those molluscs are dominated (>95%) by two to eight species of pelecypods (Armstrong,1981) and all species can presently be found living off the coast of Alaska between 60° and 62°N latitude (Balazarini,1983).
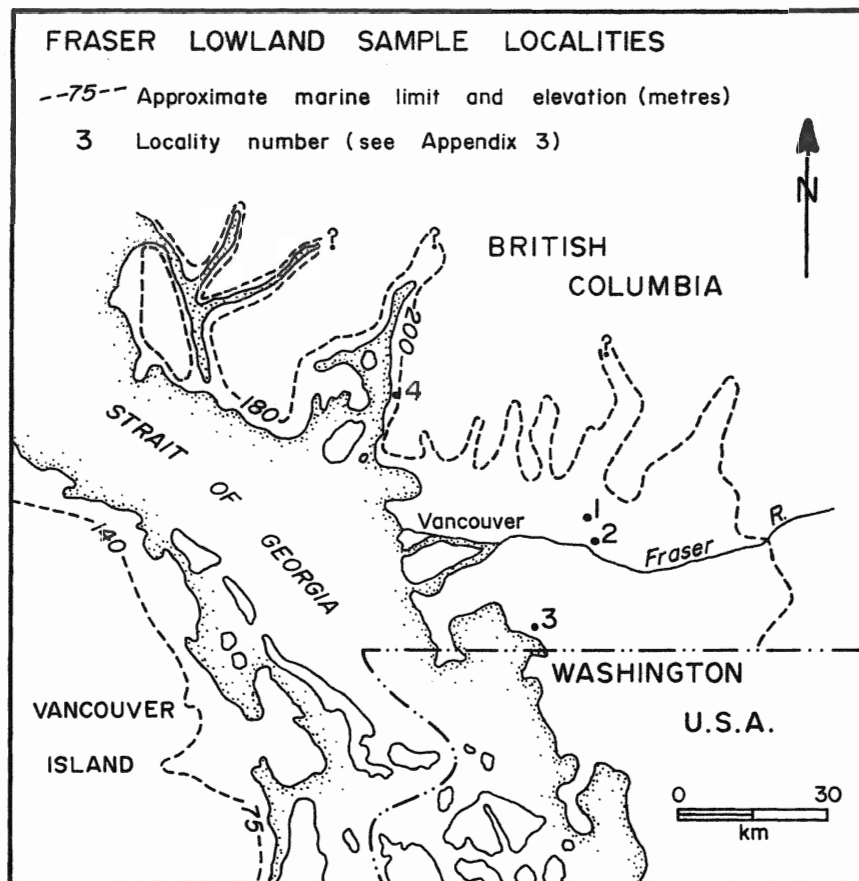
Fig. 21. Map showing sample localities from
the Ft. Langley Fm and Capilano Sediments,
southwestern British Columbia.

This led Wagner (1959) to conclude that the macrofauna assemblages of the Ft. Langley Fm and Capilano Sediments were typical of normal marine salinities at depths of 30-40m. Foraminiferal assemblages of the Ft. Langley Fm and Capilano Sediments described by Smith (1970) also indicate depths of 30-60 m, normal marine salinities and temperatures of about 0°-5°C for most of the year.

General Geology

The Fraser Lowlands of southwestern British Columbia are bounded on the west by the Strait of Georgia and Puget Sound, on the north by the Coast Mountains and on the south to southeast by the Cascade Mountains (Clague and Luternauer, 1983). The Lowlands are part of a structural trough which has subsided since the late Cretaceous and contains more than 4000m of accumulated sediments eroded from the surrounding mountains (Matthews, 1972).

The Quaternary sediments (Fig. 22) in the Fraser Lowlands are up to 300 m thick and lie unconformably above Tertiary freshwater sedimentary rocks. These Tertiary strata are composed of fine to coarse siliciclastics, and are rarely inter-layered with Tertiary basalt flows (Armstrong, 1981). All Tertiary rock types are poorly indurated and weather rapidly when exposed in outcrops. Both the Coast and Cascade Mountains are underlain by granites and associated metamorphic rocks. All glacial and non-glacial deposits are composed primarily of sediments derived from the montane regions to the north and east (Clague and Luternauer, 1983).

Fort Langley Formation and Capilano Sediments

Following the retreat of Vashon ice in the Fraser Lowlands and Strait of Georgia during the Late Quaternary, the region was isostatically depressed up to 300 m below present sea level (Matthews *et al.*, 1970). Near
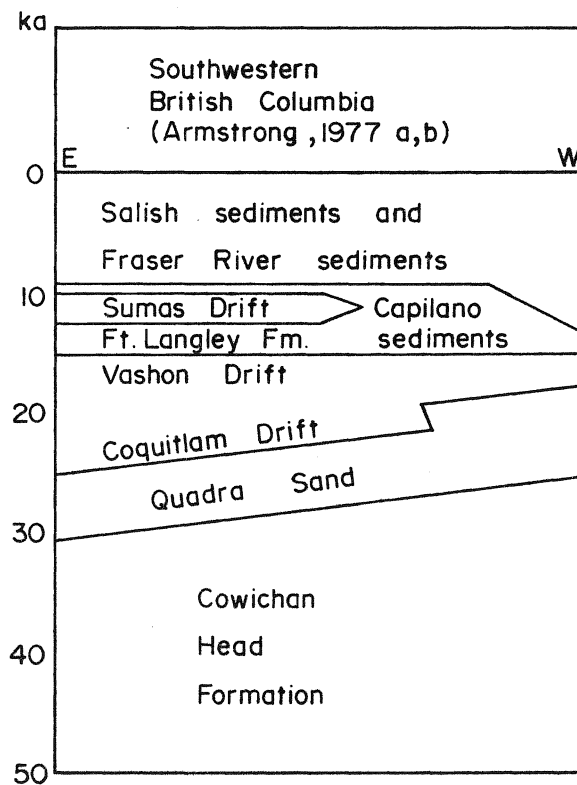
Fig. 22. Generalized stratigraphic
sequence for Wisconsin and
Holocene sediments in the Fraser
Lowlands, B.C.

the fluctuating recessional ice margin, thick successions of interbedded glaciomarine, glacial, deltaic and ice contact sediments were deposited, which are up to 200 m thick, and are known as the Fort Langley Formation (Armstrong,1981). The Ft. Langley Fm. is bounded by older Vashon drift and younger Sumas Drift (Fig. 22). The sediments were deposited during the invasion of the sea that followed the retreating Vashon ice and have been dated from 13 to 11.4 ka (Clague,1980; Armstrong,1981). The Ft. Langley deposits are typically stoney to stoneless, fine grained glaciomarine and marine sediments that may be stratified and often contain marine fossils. Deposition of the Ft. Langley Fm. sediments was ended by the later advance of Sumas ice (Armstrong,1981).

The correlative Capilano Sediments are composed of thick sequences of glaciofluvial, glaciomarine, and marine deposits, and are underlain by Vashon Drift and overlain by Salish and Fraser River deposits (Fig. 22). The Capilano sediments vary from 10 to 50 m in thickness and represent such diverse facies such as seafloor muds containing dropstones and marine fossils, raised delta sand and gravels, and intertidal and beach deposits (Armstrong,1981; Clague and Luternauer, 1983). The sequence is overlain by extensive, terraced, fluvial surficial deposits resulting from the changes in sea level due to isostatic uplift (Armstrong,1981).

The Capilano Sediments and Ft. Langley Fm are coeval, the only difference being, by definition, that the Ft. Langley Fm. ended with the advance of Sumas ice from the east, whereas the Capilano sequence ended with regression of the sea (J.E. Armstrong, pers. comm., 1985). Following deglaciation, eustatic sea level emergence was rapid and isostatic uplift was probably complete by 8 ka (Matthews *et al*, 1970).

Late Quaternary Chronology

The large number of radiocarbon dates on a variety of Quaternary samples in southwestern British Columbia has provided a relatively complete chronological framework for its Late Quaternary history (Clague, 1980, 1981). These data cover the late Quaternary history from the Olympia nonglacial to the postglacial interval (Clague, 1981). The stratigraphic relationships are shown in Figure 22.

Summaries of the Quaternary history of southwestern British Columbia can be found in Fyles (1963), Clague (1976), Armstrong and Hicock (1976), Hicock (1980), Armstrong (1981), Clague (1981), Hicock and Armstrong (1983), and Clague and Luternauer (1983).

Pre-Olympia Nonglacial

The oldest named Quaternary unit is the Westlynn Drift (Fig. 22). A poorly-studied unit, it consists of till, glaciomarine deposits, and stratified sands and gravels (Armstrong, 1975; Fulton, 1984). This unit is overlain by the nonglacial Muir Point and Highbury Sediments (Fig. 22). These sediments were deposited during the last interglacial (Hicock and Armstrong, 1983) in fluvial and locally marine environments (Fulton, 1984). These are in turn overlain by Dashwood Drift (Fyles, 1963; Hicock, 1980) and Semiahmoo Drift (Armstrong, 1975), consisting of complexes of lodgement till, glaciofluvial sediments, marine and glaciomarine sediments greater than 62 ka in age. A brief period of marine submergence followed this glaciation (Fulton, 1984).

Olympia Nonglacial Interval

The Olympia nonglacial interval refers to the time of ice free conditions preceding the last major glaciation event in southwestern British Columbia. Deposits of this age occur primarily in the Fraser

Lowlands and montane valleys (Fulton,1984) and have been dated from about 58 to 23 ka (Clague,1981).

The Cowichan Head Fm. (Fig. 22) conformably overlies the Dashwood-Semiahmoo Drift and consists of sediments deposited in fluvial, estuarine and marine environments. A lower marine member consists mainly of clayey silt and sand, whereas, an upper member represents predominantly estuarine and fluvial conditions as indicated by gravels and silt that are rich in organic and plant remains (Clague,1981; Fulton,1984).

Fraser Glaciation

Overlying the Cowichan Head Fm is a thick, white, cross-stratified and well-sorted glaciofluvial sand known as the Quadra Sand (Clague,1976, 1977). This sand represents the transition from nonglacial to glacial conditions of the Fraser glaciation, and is believed to represent proglacial distal outwash deposits (Fulton,1984). The base has been dated at 28 ka in the north, and 22 ka in the south in the Strait of Georgia (Clague,1981).

The last major ice advance in southwestern British Columbia deposited the Vashon Drift (Fyles,1963). This major ice sheet advanced into the Fraser Lowlands by 18 ka, reaching Vancouver Island by 17 ka (Clague *et al.*,1980). One lobe branched into the Puget Lowlands by 15 ka (Mullineaux *et al.*,1965) and another towards the Pacific. At its maximum, the ice surface elevation was probably near 1500 m on Vancouver Island mountains and near 1000m near Victoria (Clague,1981).

Ice retreat, followed by marine inundation due to isostatic depression, allowed for the deposition of the Ft. Langley Fm and the Capilano Sediments. A final glacial advance represented by the Sumas Drift, overlying the Ft. Langley sediments (Armstrong,1981), occurred about 13 ka, followed by

rapid retreat such that the Fraser Lowlands were ice free by 11 ka (Clague,1981).

Results and Discussion

Diagenetic Evaluation

The geochemical data of the marine invertebrates of the Ft. Langley Formation and Capilano Sediments are reported in Appendix II and summarized in Table 8.

The pelecypods *Clinocardium ciliatum*, *Nuculana pernula*, *Mytilus californianus* (inner layer), *Macoma calcarea*, and *Hiatella arctica* were determined to be preserved in their original aragonitic mineralogy by x-ray diffraction (Table 4; cf., Milliman,1974; Morrison and Brand, in press). In addition, SEM examination of shell fragments revealed the preservation of typical aragonitic microstructures (Table 5, Plate 2 and 3; cf. Carter,1980).

X-ray diffraction indicated that the pelecypod *Pecten* sp. consists of calcitic and aragonitic layers, whereas, the cirriped *Balanus* and outer portion of *M. californianus* were determined to entirely calcitic (Milliman,1974). The few fragmented samples of *M. californianus* and *Balanus* were not examined by SEM.

The aragonitic molluscs from the Ft. Langley Fm and Capilano Sediments contain between 1356 and 1667 ppm Sr, which is within the range of 800-6500 ppm for Recent aragonitic molluscs (Fig. 23, Table 8; Brand,1981). Moreover, the aragonitic molluscs contain less than 350 ppm Mg (Fig. 23), which is also in accord with chemical data for Recent molluscs (Milliman,1974). Finally, the Na content of all the marine invertebrates fall within the 2000-6500 ppm range (Fig. 24) for Recent marine molluscs (Milliman,1974, Table 29,32,33). *Mytilus californianus* (aragonitic layer) exhibits more variable Sr and Mg contents of 572 to 600 ppm and 460 to

Table 8. Means of major, minor, and trace element content of skeletal carbonate from marine fauna of the Ft. Langley Fm and Capilano Sediments, southwestern British Columbia (ranges in parentheses).

Species	Ca %	Mg ppm	Sr	Na	Mn	Al	Fe	Zn	Ni	Cu	Mineralogy
Nuculana pernula	38.7 (33-44)	120 (20-380)	1451 (440-2610)	4235 (3380-5560)	14 (7-30)	196 (50-970)	36 (9-80)	-	-	-	A
Hiatella arctica	37 (32-40)	227 (100-570)	1368 (650-2730)	5423 (4230-6620)	58 (10-220)	124 (50-380)	26 (3-50)	-	-	-	A
Mya truncata	42 (33-50)	84 (20-290)	1667 (840-2760)	4255 (3140-5730)	33 (10-160)	111 (40-580)	38 (20-60)	-	-	-	A
Mytilus californius (outer)	36	460	600	3020	49	115	50	-	-	-	LMC
Mytilus californius (inner)	39	30	870	5350	8	90	60	-	-	-	A
Macoma calcarea	38 (32-48)	123 (6-300)	1662 (780-2450)	4280 (3190-5500)	22 (8-100)	113 (40-390)	86 (9-260)	-	-	-	A
Clinocardium ciliatum	37 (32-40)	150 (100-400)	1356 (920-2020)	4370 (3170-5520)	20 (10-30)	128 (40-280)	43 (10-90)	-	-	-	A
Pecten sp.	38 (36-39)	600 (270-910)	572 (510-640)	2975 (2300-4060)	681 (530-847)	552 (350-780)	19 (4-40)	-	-	-	LMC+A
Balanus sp.	34 (30-37)	1990 (1470-2580)	2678 (2140-3750)	4624 (3050-5540)	271 (210-370)	273 (190-400)	16 (0-30)	-	-	-	LMC

A = aragonite LMC = Low-Mg calcite
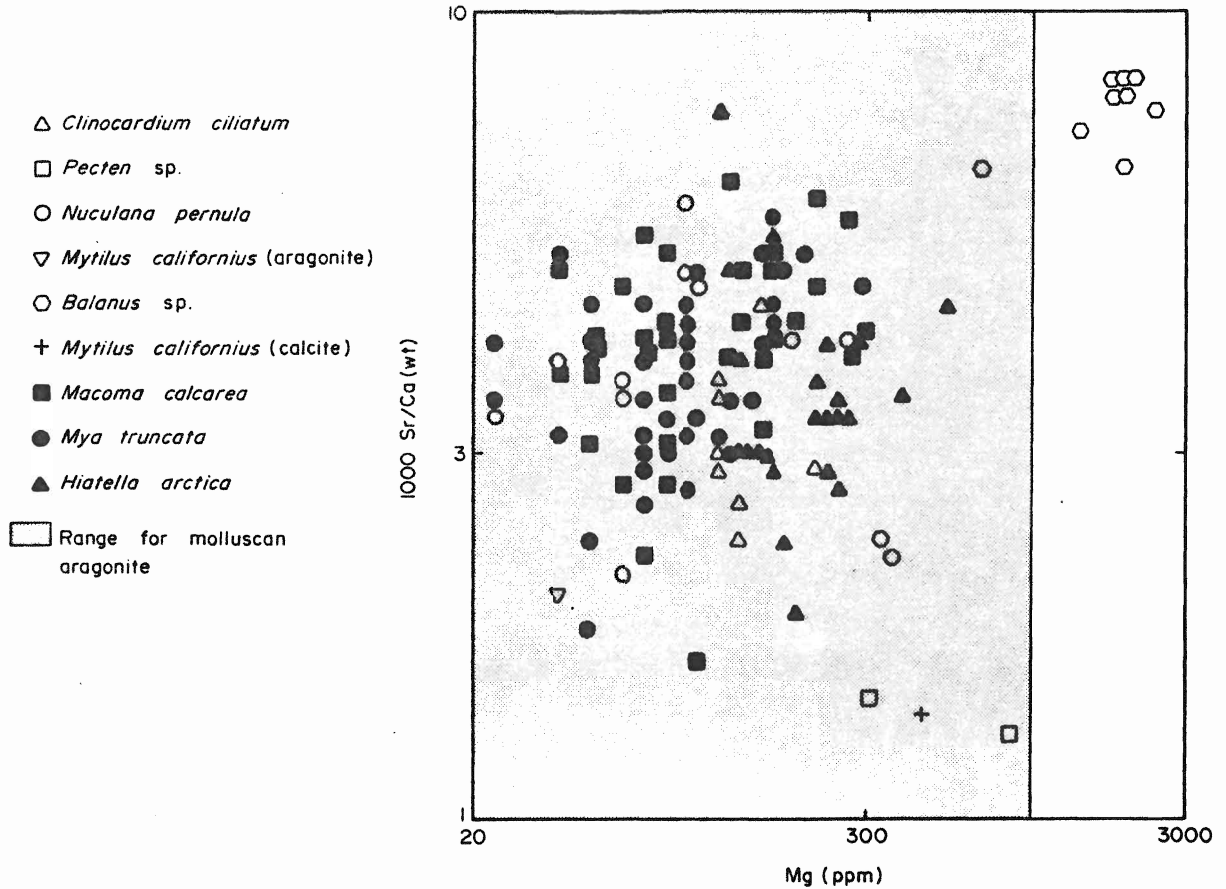
Fig. 23. Scattergram of 1000 Sr/Ca vs Mg for
marine invertebrate macrofossils from the Ft.
Langley Fm and Capilano Sediments, southwestern
British Columbia. Range for aragonite
from Morrison and Brand (in press). Ordinates
are logarithmic.
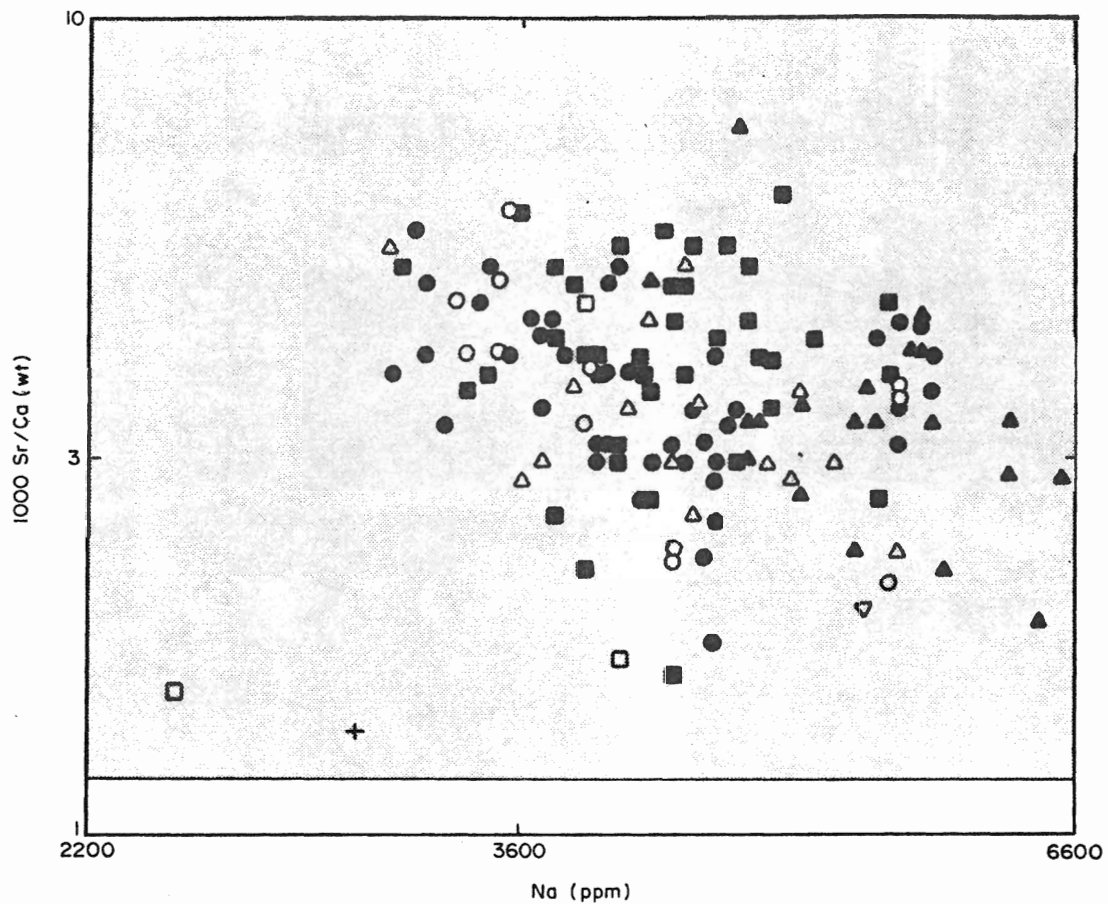
Fig. 24. Scattergram of 1000 Sr/Ca vs Na for marine invertebrate macrofossils from the Ft. Langley Fm and Capilano Sediments, B.C. Symbols and source as in Fig. 23.

600 ppm, respectively, but these are still within the range for its Recent counterparts. The calcitic cirriped, *Balanus* sp., on the other hand, shows higher Mg and Sr concentrations than aragonitic and mixed calcitic and aragonitic pelecypods (Fig. 23), but is similar to that of Recent cirripeds (cf., Milliman,1974; Morrison and Brand, in press).

Diagenetic alteration of metastable aragonite to calcite in the meteoric or deep burial environment will lead to a covariant decrease in Sr content and increase in Mn content (Brand and Veizer,1980; Baker *et al.*,1980). A scattergram of Sr and Mn for the data (Fig. 25), however, does not indicate any diagenetic trends. The Mn content for each species are similar to those of their Recent species (Milliman,1974). Thus, considering the preservation of original mineralogy, microstructures, and chemistry, it can be concluded that the marine invertebrates of the Ft. Langley Fm and Capilano Sediments have not undergone any chemical or structural alteration in their 13 ka year history, and can subsequently be used for paleoenvironmental interpretations.

Paleosalinities

Paleosalinities can be determined using the Sr/Na content of chemically unaltered aragonitic molluscs and Equation 10 (Brand,1984). A summary of mean salinities for molluscs from the Ft. Langley Fm and Capilano Sediments is shown in Table 9.

All the molluscs from the Ft. Langley Fm and Capilano Sediments can be considered to be deep-water species (Wagner,1959). The molluscs, from localities 1-3 have been radiocarbon dated and range in age from 12.9 to 12.6 ka (Clague,1980). Those at locality 4, on the other hand, have been dated at about 10.6 ka (Clague,1980). The salinity data in Table 9 indicate that the molluscs from localities 1-3 grew in normal marine conditions
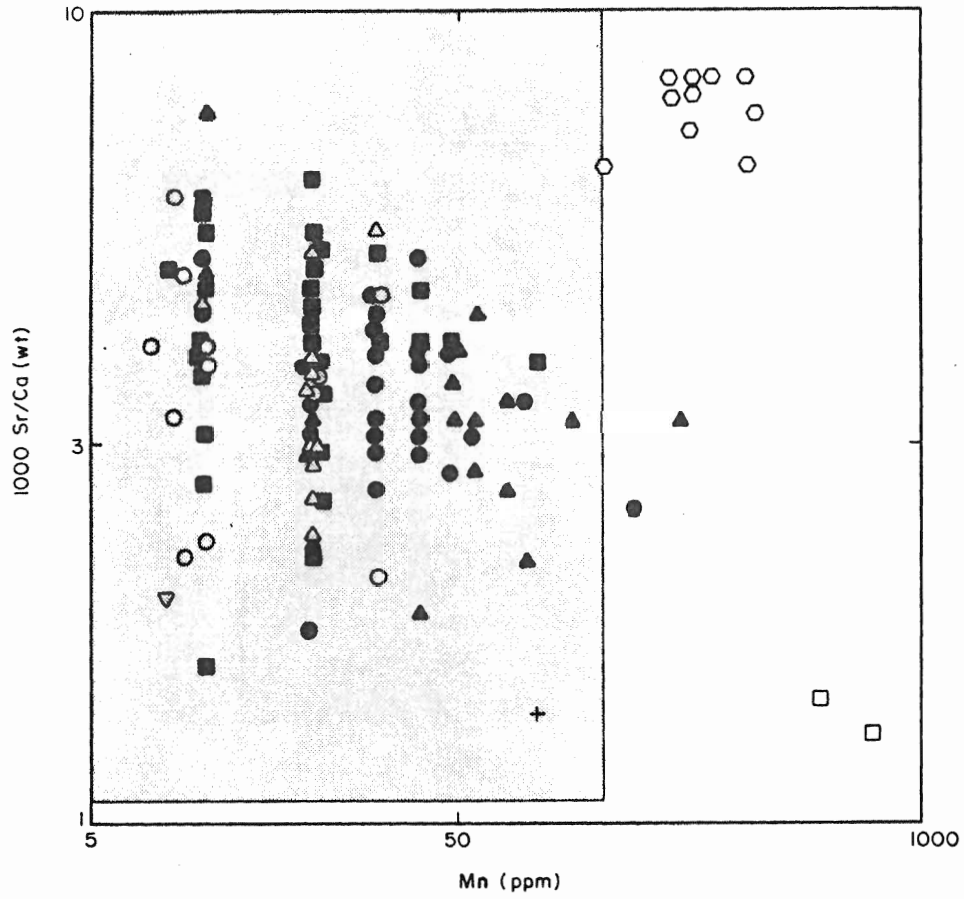
Fig. 25. Scattergram of 1000 Sr/Ca vs Mn for marine invertebrate macrofossils from the Ft. Langley Fm and Capilano Sediments, B.C. Sources as in Fig. 23.

Table 9. Paleosalinities determined using Equation 10 and aragonitic molluscs of the Ft. Langley Formation and the Capilano Sediments. Mean depths from Wagner (1984).

Localities:		1	2	3	4
Species	Depth (m)	Salinities (ppt)			
Hiatella arctica	41	34.0	36.2	–	33.6
Macoma calcarea	32	32.2	34.3	34.5	33.5
Mya truncata	27	–	34.9	35.2	31.7
Nuculana pernula	48	36.1	36.4	34.5	31.1
Clinocardium ciliatum	30	34.5	–	–	–

with salinities ranging from 32.2 to 36.4 ppt (mean = 34.8 ppt). The molluscs from locality 4 indicate a slight reduction in salinity to 31.1 to 33.6 ppt (mean = 32.5 ppt) due to the influx of freshwater and the fjord-like nature of Howe Sound.

The data indicate normal marine conditions and salinities for the seas of the Late Quaternary submergence of southwestern British Columbia. The data are also in complete agreement with the interpretation of macro-fauna assemblages (Wagner,1959) and foraminiferal assemblages (Smith,1970; Balazarini, 1983) which indicate normal marine conditions for the environments of the Ft. Langley Fm and Capilano Sediments.

Salinities at present in the Strait of Georgia range from 28.5 to 33.5 ppt with a pronounced stratification along salinity gradients. These reduced salinities are primarily due to the large influx of freshwater from the Fraser River and restricted circulation with the open sea due to the nature of the Straits of Juan de Fuca (Thomson,1981). Relative sea level during the Late Quaternary submergence, however, was up to 300 m higher than at present (Clague,1981), permitting inflow of marine water from the Pacific ocean. In addition, a slightly higher salinity of about 3.5% is expected during the last glaciation due to the removal of ocean water into glacial ice (Broecker,1982).

No quantitative $\partial^{18}O$ paleotemperature data exists for the marine waters of the Ft. Langley Fm and Capilano Sediments. Faunal assemblages (Wagner,1959; Smith,1970) suggest that water temperatures from 12.9 to 10.6 ka was about 0°C for some parts of the year (Armstrong,1981). This is in contrast with present day temperatures that range from 5° to 10°C in the Straits of Georgia (Thomson,1981). Further research using the $\partial^{18}O$ of these marine molluscs, however, is needed to establish quantitative

paleotemperatures and to provide insights into the isotopic nature of the Cordilleran Ice Sheet.

Conclusion

Geochemical, mineralogical, and microstructural examination of marine invertebrates from the Late Quaternary Ft. Langley Fm and Capilano Sediments indicate no diagentic alteration after more than 13 ka years of burial. Paleosalinities, based on the Sr/Na of deep-water aragonitic molluscs, indicate normal marine conditions of 32 to 36.4 ppt for this marine submergence. The data shows no evidence of salinity stratification as was the case for the correlative Champlain Sea in eastern Canada.

Acknowledgements

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Appendix I

Geochemical Data for Marine Invertebrate Macrofossils from Late Quaternary Sediments of the Champlain Sea Basin

Geochemical data of project CHAMPLAIN SEA

Sample	SP	LM	IR	Ca	Mg	Sr	Mn	Na	Al	Fe	Zn	Cu	Ni
1	1	1	2.8	349470	60	1760	30	2230	30	70	5	6	40
2	1	1	.8	350690	150	2050	20	2970	20	60	4	4	60
3	1	1	.7	351810	60	1460	30	3050	0	110	6	10	30
4	1	1	.3	345790	70	2130	30	2920	20	70	6	7	40
5	1	1	.9	352020	140	1760	30	3030	20	110	4	2	20
6	1	1	.6	375150	70	1920	40	3150	40	90	5	7	60
7	1	1	.6	382470	20	1510	50	3450	0	90	5	0	60
8	1	1	0.0	363300	70	1730	40	3110	0	110	4	5	60
9	1	1	.8	386630	100	1960	40	3730	0	30	5	0	70
10	1	1	.1	374620	130	1370	30	3650	0	40	5	0	70
11	1	1	1.3	399210	80	2120	20	3110	60	20	6	0	60
12	1	1	2.2	405490	480	2070	60	3420	90	60	10	0	70
13	1	1	.7	391100	80	2330	10	2940	0	20	4	0	70
14	1	2	.7	390590	80	1760	10	3370	40	40	10	0	60
15	1	2	.3	398210	100	1850	50	3640	80	20	5	0	70
16	1	2	.9	421530	20	1760	20	3140	60	0	6	0	70
17	1	2	.7	408420	90	2030	30	3980	60	80	6	0	50
18	1	2	.2	398310	30	1960	2	5060	150	0	10	0	40
19	1	2	.4	352550	30	2350	40	3230	0	0	20	20	50
20	1	2	2.6	321820	570	2060	40	2920	60	120	6	10	70
21	1	2	.7	344460	170	1720	50	2900	50	0	8	20	60
22	1	2	.3	328510	70	2220	30	3050	30	50	6	10	70

Sample	SP	LM	IR	Ca	Mg	Sr	Mn	Na	Al	Fe	Zn	Cu	Ni
23	1	2	.3	349110	20	2150	50	3130	0	20	6	10	60
24	1	2	0.0	348300	50	2620	30	3110	40	40	7	20	60
25	1	2	.2	328000	70	2480	20	3560	0	20	6	8	40
26	1	2	.8	317410	30	2710	40	3350	80	0	10	7	70
27	1	2	0.0	324780	60	1900	30	3510	40	60	5	20	50
28	1	2	.7	353240	90	2260	10	3660	50	0	20	20	40
29	1	2	.7	372390	150	2410	130	4010	150	0	20	10	60
30	1	2	1.1	388210	30	2040	120	4730	0	40	10	10	40
31	1	2	2.0	349740	50	1940	40	3680	90	40	9	20	60
32	1	3	.6	356270	90	2130	7	4500	90	140	7	6	50
33	1	3	2.2	362860	70	1970	40	5180	290	50	10	20	50
34	1	3	1.7	394750	40	1960	80	4590	120	60	10	10	60
35	1	3	1.9	322380	70	2080	90	4330	40	100	10	8	50
36	1	3	1.5	365500	250	2170	8	3650	200	50	8	9	40
37	1	3	1.6	383600	80	2330	40	3480	170	50	9	10	70
38	1	3	1.1	384650	120	2130	30	4300	90	110	8	10	60
39	1	3	.9	351090	70	1640	1	4240	0	20	4	9	50
40	1	3	1.4	365230	20	1800	10	3220	120	80	4	20	50
41	1	3	.5	365940	70	1920	1	3590	180	60	4	10	70
42	1	3	.6	355610	200	1930	50	3870	80	80	4	10	70
43	1	3	.9	369950	200	1830	50	3320	190	50	4	6	60
44	1	3	1.2	365730	230	1540	50	3280	190	0	4	20	70

Sample	SP	LM	IR	Ca	Mg	Sr	Mn	Na	Al	Fe	Zn	Cu	Ni	
45	1	3	.9	347090	40	1410	50	3140	210	20	5	7	60	
46	1	3	.8	361950	100	1820	50	3300	50	130	5	10	60	
47	1	4	2.4	326990	60	2200	40	3530	90	30	4	10	60	
48	1	4	.9	364930	50	1850	30	3600	120	40	4	10	60	
49	1	4	.5	379710	90	2990	1	4250	0	20	4	5	60	
50	1	4	.6	366430	70	2800	6	4030	0	40	4	5	70	
51	1	4	2.9	282160	70	1900	10	3340	0	20	4	4	50	
52	1	4	1.2	752640	160	4870	40	7300	0	110	10	10	120	$(x\frac{1}{2})$
53	1	4	10.4	347840	70	2990	0	3370	0	40	4	4	60	
54	1	4	28.5	484780	110	4260	1	5330	0	50	5	6	80	$(x\frac{1}{2})$
55	1	4	1.6	365960	100	3100	20	3830	0	40	5	5	50	
56	1	4	1.3	346160	80	2680	1	4120	0	60	5	5	50	
57	2	5	1.1	357980	170	2170	7	5150	80	40	5	7	60	
58	2	5	2.0	754950	380	4180	30	9700	20	110	10	20	100	$(x\frac{1}{2})$
59	2	5	2.0	368390	160	1700	60	3170	0	50	4	4	60	
60	2	5	3.7	330070	180	1660	100	3070	70	50	4	1	50	
61	2	5	9.4	327110	240	1790	30	3020	20	40	3	0	50	
62	2	5	1.5	719100	490	4090	40	7950	190	100	8	6	130	$(x\frac{1}{2})$
63	2	5	4.9	350910	150	1860	10	4350	120	40	4	1	60	
64	2	5	6.0	323790	190	1530	50	4100	100	20	3	1	50	
65	2	5	.6	359330	190	810	20	4720	110	90	3	6	0	
66	2	5	7.6	248050	130	580	0	3470	90	50	2	2	0	

Sample	SP	LM	IR	Ca	Mg	Sr	Mn	Na	Al	Fe	Zn	Cu	Ni	
67	1	6	.8	582980	160	3560	10	7490	270	130	8	8	5	$(x\frac{1}{2})$
68	1	6	7.4	342580	110	1290	0	3690	180	50	6	6	0	
69	1	6	.8	340860	40	1000	1	3620	230	100	2	6	0	
70	1	6	2.3	348920	50	1340	0	4050	210	70	3	2	0	
71	1	6	1.2	375580	40	1620	1	4040	170	70	4	7	0	
72	1	6	1.3	360690	60	1490	1	4250	60	70	5	6	0	
73	1	6	5.4	367020	60	1730	5	4000	50	30	6	4	7	
74	1	6	1.5	354460	70	1990	6	4090	60	20	7	4	5	
75	1	6	1.2	369880	120	2630	30	3860	60	70	6	5	2	
76	6	6	1.3	353930	90	2520	20	3900	60	40	6	6	8	
77	6	6	1.3	376170	110	2080	30	3790	60	100	5	10	3	
78	6	6	1.3	367950	110	1910	20	3400	60	40	4	7	2	
79	6	6	.9	373370	100	1860	30	3950	50	50	5	10	5	
80	6	6	1.5	373730	140	2290	20	4330	0	90	5	7	8	
81	6	6	1.3	365990	150	2090	20	3960	0	80	6	10	9	
82	6	6	1.9	342940	170	2370	30	4280	60	80	4	10	4	
83	6	6	1.5	379490	130	2450	20	4000	70	10	5	6	3	
84	6	6	.7	378350	110	2320	10	3720	0	20	5	3	1	
85	2	7	.3	376470	190	1530	30	3470	70	0	5	0	1	
86	2	7	.4	382200	180	1530	20	3960	70	30	5	5	1	
87	2	7	.4	384580	210	1530	10	4390	60	50	6	2	1	
88	2	7	.6	360330	160	1360	30	4360	0	30	7	0	2	

Sample	SP	LM	IR	Ca	Mg	Sr	Mn	Na	Al	Fe	Zn	Cu	Ni
89	2	7	10.0	360300	200	960	30	3050	50	20	4	4	3
90	2	7	.5	375890	220	1240	20	3620	60	40	4	0	0
91	2	7	1.5	371490	170	1060	30	3510	140	40	9	0	0
92	2	7	3.2	384510	190	1490	20	3730	100	8	4	6	4
93	2	7	.6	354440	200	1010	20	2970	0	80	2	20	7
94	2	7	1.3	359070	210	1450	20	3310	0	0	4	8	10
95	2	7	9.2	351520	180	1000	30	4780	50	20	2	4	10
96	2	7	.5	374290	180	1090	10	3250	70	20	4	10	10
97	2	7	1.9	324440	140	1070	20	4910	0	50	4	3	9
98	1	7	0.0	360370	30	1280	9	2660	0	40	3	10	7
99	1	7	1.2	381640	70	1440	1	2830	0	20	5	8	0
100	1	8	5.5	374600	70	1920	8	3720	90	50	4	7	10
101	1	8	1.9	366300	30	2180	8	3320	0	60	3	3	20
102	1	8	2.4	356340	60	2010	20	3520	0	50	4	9	3
103	1	8	5.9	359530	50	2690	7	4430	80	80	6	8	9
104	1	8	4.0	340170	90	2220	10	4420	60	60	6	10	7
105	1	8	1.6	344870	100	2120	5	4450	60	60	5	5	8
106	1	8	4.7	295660	40	1790	10	3800	50	30	4	8	4
107	1	8	3.5	375700	110	2500	5	4600	110	50	4	2	6
108	1	8	5.7	368420	50	1910	10	4080	50	60	5	6	7
109	1	8	5.8	345940	80	2010	5	4760	100	90	5	5	5
110	1	8	2.0	332110	90	1980	7	5170	0	90	7	9	10

Sample	SP	LM	IR	Ca	Mg	Sr	Mn	Na	Al	Fe	Zn	Cu	Ni
111	1	8	4.5	308690	110	2040	10	4550	50	60	4	3	6
112	1	8	1.9	355330	60	2410	30	5550	70	40	7	1	5
113	1	8	5.7	345140	150	1800	10	3410	900	50	4	0	3
114	1	9	4.2	359990	240	2140	2	4220	300	80	9	0	20
115	1	9	6.4	345410	250	2210	4	160	0	110	10	0	20
116	1	9	4.6	315080	300	1940	2	3940	140	110	7	20	3
117	1	9	4.2	366600	290	2180	2	4440	250	100	6	0	20
118	1	9	3.4	332460	150	2350	2	3090	110	60	10	3	10
119	1	9	4.1	362580	170	1820	3	4180	170	40	2	0	4
120	1	9	2.7	356140	70	1710	2	3370	120	60	9	0	6
121	1	9	3.0	347910	80	1840	4	2900	150	40	5	0	10
122	1	9	4.7	367290	300	1810	3	4220	340	0	6	0	4
123	1	9	2.1	389190	150	2080	10	3890	150	60	6	20	20
124	1	9	3.2	384200	190	2020	20	4220	330	100	4	20	3
125	1	9	9.5	388500	1150	1190	30	5980	350	100	9	2	0
126	1	9	2.7	321810	120	1560	2	2910	120	30	3	8	9
127	1	9	3.8	340760	170	1230	3	4970	0	0	5	0	10
128	2	9	1.9	340600	280	1440	20	4780	80	60	3	10	0

IR is the Insoluble Residue in percent   All Elemental Concentrations are in ppm

Geochemical data of project CHAMPLAIN SEA

Sample	SP	LM	IR	Ca	Mg	Sr	Mn	Na	Al	Fe	Zn	Cu	Ni
129	2	9	19.7	463190	160	1530	40	4140	550	50	10	5	50
130	1	10	1.8	394120	60	2170	10	3160	590	40	10	3	30
131	1	10	3.7	440070	80	2350	30	3080	1030	70	10	2	50
132	1	10	2.7	427300	100	1940	10	2760	1100	40	20	4	40
133	1	10	2.8	443260	100	2240	10	3330	940	40	20	3	30
134	1	10	2.3	400130	60	2100	10	2500	1060	40	20	4	40
135	1	10	2.0	430950	70	2520	10	2020	1200	40	20	2	40
136	1	10	2.6	432390	80	2560	10	2520	990	50	10	0	50
137	1	10	.3	347180	70	2350	8	3090	120	50	6	8	50
138	1	10	.5	282050	100	1980	8	2700	150	40	4	2	40
139	1	10	.2	350710	70	2390	20	2590	120	40	5	4	50
140	1	10	.9	358680	70	2020	20	2800	230	50	6	3	40
141	1	10	.6	299530	100	2050	10	1940	210	40	4	3	30
142	1	10	.9	331670	100	2280	20	3360	230	60	7	4	50
143	1	10	.3	360060	80	2480	20	3570	250	50	6	4	60
144	1	10	.4	335470	80	2480	20	3870	260	50	5	3	50
145	1	10	1.6	322330	70	2590	10	3100	130	40	4	3	50
146	1	11	2.2	378570	140	2280	20	3700	410	50	8	2	60
147	1	11	.5	435840	110	2300	20	3550	120	50	6	4	40
148	1	11	.7	428380	80	2240	10	3350	280	60	6	4	40
149	1	11	.7	415320	70	2530	20	2980	160	50	20	10	30
150	1	11	.4	458980	80	2340	10	3860	140	60	6	5	30

Sample	SP	LM	IR	Ca	Mg	Sr	Mn	Na	Al	Fe	Zn	Cu	Ni
151	1	11	.1	437690	150	2370	20	3680	180	70	30	5	30
152	1	11	.1	405310	100	2390	20	4060	180	70	20	3	40
153	1	11	.1	389510	130	3130	10	3980	160	50	20	10	30
154	1	11	.2	402810	160	2700	20	3970	180	70	30	5	60
155	1	11	0.0	441050	80	2300	10	4240	140	70	20	8	40
156	1	11	.5	392270	110	2280	20	4030	40	80	20	4	40
157	1	11	.1	355960	110	2240	10	3780	0	40	6	6	50
158	1	11	.2	364600	100	1880	20	3240	0	50	10	4	40
159	1	11	.2	391010	190	1740	20	3420	0	50	10	4	40
160	1	11	.2	366880	100	1820	10	3720	0	30	8	2	40
161	1	13	.1	342640	90	2140	10	3750	0	50	6	4	50
162	1	13	0.0	337460	90	2170	10	3240	0	40	7	5	60
163	1	13	.8	364090	70	2020	8	3410	0	30	4	2	40
164	1	13	.0	352620	80	1790	8	3580	0	40	5	3	40
165	1	13	.9	361070	50	1690	9	3650	0	40	5	3	50
166	1	13	.5	312920	80	1790	10	3120	0	30	5	3	40
167	1	13	1.1	359240	60	3120	10	3700	50	70	8	4	30
168	1	13	.3	340770	90	2620	7	3450	60	40	5	3	40
169	1	13	.8	390240	100	2540	7	3780	40	50	6	4	40
170	1	13	.9	355950	60	3160	8	2560	60	40	6	3	30
171	2	13	.8	330520	260	2220	20	3130	50	80	5	4	40
172	2	13	.9	379440	240	2180	20	3280	40	90	6	3	40

Sample	SP	LM	IR	Ca	Mg	Sr	Mn	Na	Al	Fe	Zn	Cu	Ni
173	2	13	.9	376840	270	2250	20	3970	50	70	6	5	30
174	2	13	1.0	385280	230	1870	20	3200	50	60	5	4	30
175	2	13	1.1	352930	260	2050	20	3960	50	70	4	4	30
176	2	13	2.6	338210	170	1860	20	4020	30	40	5	2	30
177	2	13	1.5	332360	200	1150	30	3430	60	60	6	5	50
178	2	13	1.6	346200	220	1130	30	3930	90	50	5	4	40
179	2	13	1.4	354510	200	1410	30	2920	70	70	4	6	50
180	2	13	2.1	358720	230	1410	20	2720	80	50	5	5	60
181	2	14	.7	379040	260	1860	10	3280	50	40	4	3	40
182	2	14	.7	369460	280	1790	20	2700	60	30	4	5	40
183	2	14	.7	349000	270	1390	30	3330	80	40	6	7	40
184	2	14	1.7	355880	130	1460	30	2810	60	30	5	5	50
185	2	14	.6	370480	240	1500	30	3050	50	40	5	4	50
186	2	14	2.2	347340	180	1360	30	2760	80	40	5	5	50
187	2	14	2.2	307560	140	1580	40	2800	40	30	5	6	40
188	2	14	2.6	285240	150	1930	30	2770	40	40	6	5	40
189	2	14	1.9	324180	180	1940	30	3390	50	30	7	5	40
190	2	14	2.0	291290	150	1800	30	2810	50	30	6	5	30
191	2	14	1.2	307520	140	1750	30	2890	70	40	4	2	40
192	2	14	1.5	289690	170	2010	40	2690	70	50	6	2	40
193	2	14	1.5	384880	220	2130	40	4050	70	40	5	2	40
194	2	14	1.9	377050	230	1980	20	3930	30	40	5	2	40

Sample	SP	LM	IR	Ca	Mg	Sr	Mn	Na	Al	Fe	Zn	Cu	Ni
195	7	14	2.1	368970	1690	3150	130	3360	60	180	6	3	40
196	2	15	2.6	368310	190	1840	30	3840	50	30	3	3	40
197	2	15	.9	366830	180	1540	30	3720	30	50	5	3	40
198	2	15	3.1	364870	150	1690	20	4270	30	30	5	3	40
199	2	15	4.2	354030	150	1670	30	3790	40	40	4	2	40
200	2	15	.8	362820	150	1620	30	4400	40	40	5	3	40
201	2	15	2.4	366110	190	1710	20	3940	30	40	6	5	40
202	2	15	10.6	331760	120	1600	20	3530	20	30	4	3	40
203	2	15	1.6	372280	170	2070	40	3990	40	40	6	3	40
204	2	15	2.3	375820	150	1900	20	3550	50	40	6	5	40
205	2	15	2.0	382140	140	1840	20	3260	40	50	7	4	40
206	2	15	3.4	360290	140	1730	20	3300	50	40	5	5	30
207	2	15	6.5	343870	180	1950	20	3900	40	30	3	2	30
208	2	15	10.8	329250	170	1510	30	3710	20	30	4	3	40
209	2	15	2.7	379820	100	1540	20	4550	30	40	5	4	40
210	2	15	2.8	370920	140	1600	20	3830	40	50	6	4	40
211	2	16	6.1	365480	220	1660	20	4390	30	40	5	2	40
212	2	16	3.9	359350	190	1540	20	3690	30	40	6	2	40
213	2	16	5.0	363320	190	1300	30	3870	40	50	6	2	40
214	2	16	3.9	367040	120	1170	20	4080	50	30	6	2	40
215	2	16	3.6	338420	200	1320	20	4440	40	30	5	2	40
216	2	16	3.2	348820	150	1330	10	3550	60	70	8	1	40

Sample	SP	LM	IR	Ca	Mg	Sr	Mn	Na	Al	Fe	Zn	Cu	Ni
217	2	16	3.4	343440	130	1160	30	3690	60	30	5	1	40
218	2	16	3.9	358580	150	1680	30	3740	50	40	7	2	40
219	1	16	3.0	359790	50	2230	6	3840	30	30	6	0	40
220	1	16	9.5	319910	80	2000	7	3450	40	30	5	1	40
221	1	16	3.1	368500	80	2840	7	3510	40	30	4	4	50
222	1	16	9.0	349040	60	2430	6	3570	30	20	3	3	40
223	1	16	3.2	382500	70	2750	9	3990	40	40	6	5	40
224	1	16	3.4	359860	80	2590	8	3710	30	60	6	3	40
225	1	16	4.1	368030	80	2630	8	3880	60	30	5	2	50
226	2	17	4.1	352790	270	1680	30	4470	20	40	4	5	40
227	2	17	4.6	364220	130	1530	20	5080	40	30	7	4	40
228	2	17	.7	363430	190	1540	30	3970	60	30	4	5	40
229	2	17	4.2	385460	190	2100	20	3780	30	30	6	5	40
230	2	17	8.6	317990	140	1640	20	3750	20	20	5	3	40
231	2	17	5.7	329190	190	1390	20	3180	30	20	3	2	30
232	2	17	5.7	355780	240	1340	30	2970	20	40	5	3	40
233	2	17	1.2	353790	280	1950	40	2600	0	30	4	4	40
234	2	17	4.8	371820	190	1640	40	2820	0	280	6	6	40
235	2	17	4.2	368930	300	1900	50	2650	30	40	5	4	40
236	2	17	2.6	363170	320	1690	30	3250	40	40	3	4	30
237	2	17	3.8	358970	270	1650	30	3010	30	40	5	4	30
238	2	17	3.1	353680	240	2010	30	3050	60	40	4	6	40

Sample	SP	LM	IR	Ca	Mg	Sr	Mn	Na	Al	Fe	Zn	Cu	Ni
239	2	17	4.5	364290	210	1490	40	3920	70	30	5	3	40
240	2	17	3.7	336960	200	1550	30	3470	30	40	5	5	40
241	5	18	1.0	388380	940	1760	20	1490	20	120	20	9	50
242	5	18	1.0	388330	830	1620	20	1230	60	150	10	9	60
243	5	18	.9	377310	820	1660	20	1100	50	140	20	7	50
244	5	18	1.4	404280	850	1790	20	1120	80	220	20	8	50
245	5	18	.9	395560	990	1710	20	1250	30	150	10	5	50
246	1	18	1.3	385090	70	3240	10	3080	60	30	5	6	40
247	1	18	2.4	387200	150	3100	10	3100	40	50	5	4	50
248	1	18	10.2	350080	70	2360	10	2930	20	30	4	2	40
249	1	18	8.2	359580	90	2470	10	3030	30	20	3	2	40
250	1	18	1.3	384810	60	3470	10	3140	60	30	4	2	40
251	1	18	2.6	368800	60	2360	20	2650	100	40	5	4	30
252	1	18	2.7	353700	80	2340	20	2740	50	30	4	3	40
253	1	18	.7	356070	70	2270	20	2230	30	30	4	4	40
254	1	18	2.5	373560	110	2750	20	2370	60	30	7	5	40
255	1	18	.7	342290	130	180	20	2320	50	810	4	4	10
256	2	19	3.9	404690	290	550	30	3540	60	940	4	5	30

IR is the Insoluble Residue in percent   All Elemental Concentrations are in ppm

Geochemical data of project CHAMPLAIN

Sample	SP	LM	IR	Ca	Mg	Sr	Mn	Na	Al	Fe	Zn	Cu	Ni
257	2	19	.6	352190	210	1490	30	4210	0	70	3	0	30
258	2	19	1.6	366740	180	1460	30	4450	0	50	5	0	50
259	2	19	1.2	410350	210	2080	20	4140	20	30	6	1	40
260	2	19	3.8	328940	170	1710	20	3860	20	40	5	0	50
261	2	19	2.9	371940	180	1790	20	3640	20	120	2	1	50
262	2	19	16.6	306870	140	1600	20	3210	5	20	2	0	40
263	2	19	2.1	341390	190	1920	20	4030	20	40	8	0	50
264	1	19	1.6	337610	90	2340	10	3360	0	50	2	1	50
265	1	19	.6	379000	70	2320	10	2980	50	50	5	5	50
266	1	19	.3	391020	50	2440	20	3050	40	50	4	3	60
267	1	19	4.4	390850	80	2180	10	3410	60	40	3	3	40
268	1	19	.7	385860	90	2500	20	3600	60	60	4	4	60
269	1	19	1.4	405950	70	2300	10	3910	40	50	3	3	50
270	1	19	.2	351370	60	2660	20	3350	70	50	70	3	40
271	2	20	1.7	384620	130	2960	1630	3780	50	60	6	3	40
272	2	20	1.9	490850	190	1620	60	4920	50	60	6	5	50
273	2	20	2.5	422900	220	2030	30	5000	50	100	5	4	50
274	2	20	4.7	372990	140	1660	40	4580	30	50	5	4	40
275	2	20	3.8	284120	150	1770	30	3310	30	60	5	4	30
276	2	20	2.5	293690	110	1660	30	3480	30	40	5	2	50
277	2	20	2.5	333870	170	1930	40	3630	40	50	4	3	40
278	2	20	2.8	304430	250	1650	30	3660	70	60	6	2	40

Sample	SP	LM	IR	Ca	Mg	Sr	Mn	Na	Al	Fe	Zn	Cu	Ni
279	2	20	1.2	329350	150	1760	40	3230	10	50	3	4	40
280	2	20	3.1	295450	160	1420	30	3590	60	50	3	4	40
281	2	20	1.4	293680	200	1670	40	3640	60	70	4	4	40
282	2	20	2.3	307460	190	1480	40	3610	40	70	6	2	50
283	2	20	2.3	276350	230	2070	30	3660	40	40	5	2	40
284	2	20	2.1	267810	180	1870	40	3410	50	40	4	1	50
285	8	20	1.4	337880	110	1180	110	2040	60	40	4	3	40
286	2	21	1.8	320280	190	1630	30	3920	90	50	7	5	40
287	2	21	2.2	362240	140	1420	20	4490	60	50	8	4	30
288	2	21	2.6	363070	250	1480	20	4220	60	40	7	1	40
289	2	21	1.9	358600	170	1550	30	4290	60	40	7	4	40
290	2	21	3.0	346910	200	1540	20	3980	80	40	9	1	40
291	2	21	1.3	376330	190	1340	30	4350	90	70	9	2	40
292	2	21	1.8	379510	200	1570	20	4980	80	80	9	2	40
293	2	21	1.1	336570	220	1510	30	4860	90	50	5	1	40
294	2	21	1.4	344570	360	1410	30	4870	60	40	7	2	30
295	2	21	1.9	340950	260	1390	30	4600	90	60	4	0	50
296	2	21	1.6	340360	150	1320	40	4810	90	40	0	0	50
297	2	21	1.6	332720	140	1440	30	4520	90	50	3	0	50
298	2	21	3.4	329950	120	1470	30	4420	80	30	4	0	40
299	2	21	3.0	303610	210	1140	20	4510	90	50	5	0	40
300	2	21	2.0	342580	170	1450	30	4300	100	60	4	0	40

Sample	SP	LM	IR	Ca	Mg	Sr	Mn	Na	Al	Fe	Zn	Cu	Ni
301	2	22	3.3	332240	200	1580	20	4230	90	40	6	0	40
302	2	22	10.9	262710	170	1440	20	4110	50	30	2	0	40
303	2	22	3.0	370510	160	1320	20	3960	40	40	4	0	40
304	2	22	4.2	287350	190	1550	30	4070	130	40	5	0	40
305	2	22	3.7	324870	160	1860	30	4310	50	40	5	0	40
306	2	22	2.9	386250	170	1610	20	4050	30	40	8	3	40
307	2	22	2.4	385470	130	1390	20	4410	50	50	6	3	50
308	2	22	3.8	344560	160	1620	30	4410	20	30	6	2	40
309	2	22	3.0	336410	110	1350	20	4300	40	40	6	3	40
310	2	22	3.9	335760	140	1380	30	4470	40	40	4	3	40
311	2	22	3.4	333880	180	1430	30	3880	20	40	5	2	40
312	2	22	5.0	363110	170	1600	30	4720	40	40	7	2	50
313	2	22	3.1	373760	150	1650	20	4480	40	30	6	3	40
314	2	22	4.8	395310	190	1650	20	3920	40	30	7	3	40
315	2	22	4.3	338520	150	1590	20	5260	20	40	8	3	40
316	2	23	3.3	350250	190	1230	30	4200	40	40	8	3	40
317	2	23	3.0	351150	210	1550	20	4030	10	40	10	2	40
318	2	23	3.1	298130	140	1280	30	4410	30	40	8	3	40
319	2	23	2.6	311390	180	1460	30	3980	30	40	20	3	40
320	2	23	5.7	338810	890	1200	40	3720	30	80	10	4	30
321	2	23	2.6	352120	200	1560	20	3830	0	30	9	3	30
322	2	23	2.2	336760	150	1880	30	3620	0	40	10	4	30

Sample	SP	LM	IR	Ca	Mg	Sr	Mn	Na	Al	Fe	Zn	Cu	Ni
323	2	23	2.6	363870	110	1320	20	4340	0	40	6	4	30
324	1	23	1.6	356500	90	2380	10	3410	0	40	8	3	40
325	1	23	1.5	327380	70	2110	10	3530	0	40	10	4	40
326	5	24	4.0	371570	520	1290	50	1930	60	120	5	4	30
327	5	24	4.2	361780	500	1590	40	2330	90	180	6	4	30
328	5	24	4.5	338780	720	1110	70	1440	100	260	8	4	40
329	5	24	8.1	362590	870	1190	70	1410	220	290	9	4	40
330	2	24	4.1	375060	210	1700	40	4410	20	60	4	4	40
331	2	24	3.7	373830	180	1680	30	3750	20	50	6	4	20
332	2	24	3.4	352570	190	1970	40	4020	10	40	6	3	30
333	2	24	3.5	363310	180	2070	40	3990	9	40	6	4	30
334	2	24	4.0	395910	140	1690	30	4060	10	50	4	5	30
335	2	24	6.3	332880	230	1900	40	4420	30	50	6	4	40
336	2	24	2.9	352730	210	1620	40	4170	20	80	6	3	40
337	2	24	2.7	336060	130	1470	30	3540	20	40	50	4	30
338	2	24	3.6	332430	160	1720	30	4100	9	40	5	3	30
339	2	24	4.0	260290	100	1940	50	4690	40	70	8	2	30
340	4	24	5.9	313640	100	2630	20	4150	10	40	6	4	40
341	4	24	3.9	286590	100	2320	10	3550	4	50	5	3	40
342	4	24	3.8	328810	70	2310	30	3710	20	40	7	4	40
343	4	24	6.6	279250	60	2490	40	3740	10	40	6	3	30
344	4	24	3.9	310130	120	2190	10	3590	30	80	5	3	40

Sample	SP	LM	IR	Ca	Mg	Sr	Mn	Na	Al	Fe	Zn	Cu	Ni
345	4	24	4.6	307410	90	2490	20	3550	30	50	5	3	30
346	4	24	5.8	328410	70	2390	20	3560	20	40	7	3	40
347	4	24	9.2	280120	100	2460	20	3620	4	50	7	2	40
348	4	24	5.4	296280	110	2430	10	3510	30	40	7	4	30
349	4	24	5.7	366860	130	2880	20	2670	40	50	5	5	40
350	3	24	6.9	339770	130	3020	20	3160	60	70	6	5	20
351	3	24	3.1	351680	120	2140	20	3290	10	40	5	3	30
352	3	24	3.1	401560	210	2660	30	3790	40	40	7	6	30
353	3	24	2.7	406070	160	2160	30	3600	50	40	6	6	40
354	3	24	2.8	407770	170	2790	30	3800	40	40	7	4	20
355	1	24	1.3	334790	110	2990	20	2810	40	70	5	4	40
356	1	24	.4	375730	110	3240	20	3020	50	80	7	1	30
357	1	24	1.3	370920	120	2830	20	2770	80	80	6	3	30
358	1	24	1.0	373810	140	2980	10	2760	50	70	6	3	30
359	7	24	2.2	287600	2170	2890	200	3330	120	130	10	5	40
360	7	24	6.3	267100	1670	3010	240	3740	60	70	10	10	30
361	1	25	6.8	319210	100	2740	20	3290	50	50	7	6	30
362	1	25	7.7	433650	440	3140	30	4030	90	60	8	10	40
363	1	25	6.0	297230	120	2790	20	2920	50	30	9	7	30
364	1	25	2.8	262580	500	2680	10	3390	80	40	8	8	30
365	1	25	2.7	334090	370	2420	20	3330	70	60	6	7	30
366	1	25	9.1	249840	300	2310	20	3220	40	30	4	3	30

Sample	SP	LM	IR	Ca	Mg	Sr	Mn	Na	Al	Fe	Zn	Cu	Ni
367	1	25	11.1	247340	60	2350	10	2960	40	30	4	4	20
368	1	25	4.9	285550	280	2770	20	3630	60	40	8	7	30
369	1	25	2.7	195900	180	1740	10	1340	0	30	3	3	20
370	1	25	2.4	374590	110	3180	10	3030	9	70	8	6	40
371	2	25	2.2	365910	370	2320	30	4080	6	30	6	5	30
372	2	25	1.9	345450	160	1840	30	4110	10	40	5	8	30
373	2	25	2.6	324630	200	3050	30	3560	0	70	6	8	40
374	2	25	2.0	365040	190	1710	40	3500	0	40	6	4	40
375	2	25	1.9	339970	150	2030	20	3890	0	40	6	5	40
376	2	25	10.0	328770	230	2100	20	3230	0	20	4	4	30
377	2	25	3.1	353400	230	2530	30	3710	0	30	5	6	40
378	2	25	2.7	321320	250	1840	20	3690	0	90	6	5	40
379	2	25	2.1	257320	190	2240	30	4240	80	60	6	4	30
380	2	25	2.5	258930	170	1890	20	4300	30	40	5	5	30
381	6	25	2.3	256340	100	3060	30	3680	50	50	4	5	40
382	6	25	3.0	272220	130	3920	30	3580	50	50	7	6	30
383	6	25	3.7	238880	140	3490	20	3970	40	40	10	4	30
384	6	25	4.2	242690	140	3410	30	3770	70	100	7	7	30

IR is the Insoluble Residue in percent   All Elemental Concentrations are in ppm

Geochemical data of project CHAMPLAIN SEA

Sample	SP	LM	IR	Ca	Mg	Sr	Mn	Na	Al	Fe	Zn	Cu	Ni

Sample	SP	LM	IR	Ca	Mg	Sr	Mn	Na	Al	Fe	Zn	Cu	Ni
385	6	25	1.8	349530	120	2960	30	3020	170	50	6	9	50
386	6	25	1.5	342440	150	3240	50	3650	150	70	6	8	50
387	6	25	1.1	347890	180	3790	30	3020	160	70	6	6	50
388	6	25	1.2	313820	120	2980	30	3490	160	60	3	4	40
389	7	25	1.5	344140	1670	4210	230	4450	180	300	4	3	30
390	2	26	1.5	335630	170	2390	20	5180	180	50	4	5	40
391	2	26	1.5	314140	180	2320	30	3750	170	50	4	4	30
392	2	26	1.6	343280	190	2320	30	3620	170	40	3	5	50
393	2	26	1.4	347230	200	2000	40	4910	40	50	2	5	60
394	2	26	2.1	349480	240	1840	40	4900	40	50	2	4	60
395	2	26	10.1	269240	180	1370	30	4560	20	30	1	3	40
396	2	26	1.7	287530	220	1710	30	4270	40	60	1	6	50
397	2	26	1.9	307300	220	1640	30	4840	50	50	2	6	60
398	2	26	2.9	289500	200	1920	30	4530	50	60	1	5	60
399	2	26	.8	302980	190	1660	30	3940	40	50	2	4	50
400	1	26	.5	285120	80	2060	30	3760	80	80	4	8	70
401	3	26	1.6	301590	120	1660	30	4760	50	50	2	6	40
402	3	26	2.8	292530	150	1680	20	3430	40	50	2	7	40
403	3	26	1.9	364350	80	1950	20	4540	30	50	5	3	40
404	3	26	1.4	307160	110	2110	20	3890	30	60	4	5	50
405	3	26	1.8	347750	120	1870	30	4210	30	50	2	6	50
406	3	26	2.4	311910	160	2320	20	4020	30	50	4	5	40

Sample	SP	LM	IR	Ca	Mg	Sr	Mn	Na	Al	Fe	Zn	Cu	Ni
407	3	26	.9	305970	150	2290	30	4480	30	60	2	4	40
408	3	26	2.2	290730	90	1780	20	4440	40	50	3	3	40
409	3	26	1.5	322580	160	2520	20	4380	40	40	4	6	50
410	3	26	1.8	354850	150	2520	30	4190	30	60	1	4	50
411	9	26	2.6	328630	730	1680	90	2820	60	100	2	3	50
412	9	26	.4	356870	710	1540	70	2640	50	70	4	4	50
413	9	26	6.1	298520	150	1820	20	3930	80	110	7	6	40
414	2	27	1.4	343330	170	1660	30	4430	30	60	6	10	50
415	2	27	1.5	285730	170	1680	40	4910	30	50	5	10	40
416	2	27	1.6	335380	130	1620	20	4720	30	40	5	8	50
417	2	27	6.2	271390	170	1750	20	4740	30	30	3	8	50
418	2	27	7.9	319440	130	1310	30	4810	20	30	4	5	30
419	2	27	.8	296420	200	1500	30	4280	50	50	5	10	50
420	2	27	1.4	304210	150	1650	30	4700	30	40	5	8	50
421	2	27	1.1	285950	140	1220	40	4950	40	40	3	8	50
422	2	27	2.0	342630	220	1400	30	3900	30	50	2	10	50
423	2	27	11.4	331790	170	1890	30	4510	10	30	3	7	60
424	1	27	9.5	288590	60	2630	9	3640	2	30	1	5	50
425	1	27	1.2	290670	90	2560	10	4210	20	50	3	10	70
426	1	27	5.8	263630	70	2730	10	3430	10	40	1	5	40
427	1	27	5.4	278220	90	2700	10	3910	2	40	3	5	60
428	1	27	1.1	271870	90	3090	10	3750	30	50	2	7	60

Sample	SP	LM	IR	Ca	Mg	Sr	Mn	Na	Al	Fe	Zn	Cu	Ni
429	1	27	2.1	279830	70	2970	10	3500	0	60	4	5	50
430	1	27	1.9	262640	80	2620	10	3430	3	50	2	7	60
431	1	27	9.3	241530	60	2510	10	3140	20	40	3	4	50
432	1	27	7.8	263970	70	3020	10	3220	10	30	2	5	50
433	1	27	11.8	240910	70	2130	10	3940	20	30	1	4	50
434	4	27	2.0	276850	50	2070	20	4210	30	50	3	6	50
435	4	27	10.4	291350	40	2040	20	3630	20	30	3	5	40
436	4	27	2.3	282240	60	2120	20	3720	40	60	2	3	50
437	4	27	1.9	272550	70	2440	20	3380	40	60	2	5	50
438	4	27	1.7	323390	60	2170	20	3340	30	50	4	5	50
439	4	27	1.4	304410	90	2410	10	3270	40	50	4	4	50
440	4	27	1.2	271230	130	2450	20	3380	40	40	4	5	50
441	4	27	1.2	264940	90	2150	20	3900	30	40	2	8	40
442	4	27	1.9	281430	60	2320	20	3680	40	60	4	6	30
443	4	27	1.3	323690	150	3630	20	3200	30	60	4	9	40
444	2	28	1.2	328680	180	1800	30	4440	30	100	3	7	60
445	2	28	1.4	330230	190	2450	30	3810	20	80	4	6	50
446	2	28	1.9	318640	230	2040	20	4810	20	60	4	6	50
447	2	28	1.4	321380	190	2460	30	4740	10	90	4	6	60
448	2	28	1.6	309640	220	2030	20	4800	9	70	4	6	60
449	2	28	2.0	309490	170	1630	40	4340	120	40	5	3	70
450	2	28	3.4	301760	190	2000	20	4390	150	50	5	2	70

Sample	SP	LM	IR	Ca	Mg	Sr	Mn	Na	Al	Fe	Zn	Cu	Ni
451	2	28	1.2	307490	240	2210	20	4190	210	60	4	2	70
452	2	28	1.2	300950	190	1840	20	4400	200	70	4	1	70
453	2	28	1.1	333890	210	1800	20	4470	230	60	4	2	80
454	10	28	.7	378770	690	1000	30	1940	450	190	60	1	60
455	10	28	7.4	319060	620	930	20	2140	210	30	8	2	60
456	10	28	1.3	346440	810	1110	40	1860	230	40	20	0	50
457	10	28	3.8	386650	770	1070	70	2150	40	40	4	1	70
458	10	28	1.0	344340	770	1090	30	2260	70	150	20	0	60
459	10	28	.4	380100	730	1060	30	2210	70	130	30	2	70
460	3	28	1.1	345790	180	1850	10	3760	60	70	4	1	70
461	3	28	1.2	369530	140	1330	10	4050	80	80	4	0	70
462	7	28	1.2	367760	1850	3100	270	3490	80	290	4	2	70
463	7	28	2.6	339360	2930	2890	350	3230	90	210	8	0	60
464	6	28	.9	357740	110	2580	20	3720	100	80	4	1	60
465	6	28	1.0	336980	80	2290	20	2840	110	70	3	0	50
466	6	28	1.1	339430	80	2130	10	3230	110	70	4	1	70
467	6	28	.6	295810	120	2870	20	3580	30	70	4	0	70
468	6	28	3.3	293640	110	2780	20	4150	40	70	5	1	70
469	6	28	1.2	310370	70	2230	10	3100	50	70	4	1	70
470	6	28	1.1	318910	80	2020	20	4150	60	60	5	2	70
471	6	28	1.3	285260	80	2060	20	3680	50	100	4	0	70
472	6	28	1.0	319660	110	2320	20	3860	50	70	4	0	60

Sample	SP	LM	IR	Ca	Mg	Sr	Mn	Na	Al	Fe	Zn	Cu	Ni	
473	6	28	1.2	326980	100	2500	10	3420	80	60	6	1	70	
474	5	28	1.9	334770	490	910	140	1650	60	220	6	1	60	LMC
475	5	28	1.5	333470	100	2440	20	4270	70	60	3	2	60	A
476	5	28	1.1	327820	490	1040	130	1400	80	240	6	4	70	LMC
477	5	28	.4	320620	50	2530	20	4020	4	70	4	2	80	A
478	5	28	1.6	368000	370	1440	140	1660	30	210	4	3	80	LMC
479	5	28	.7	344280	50	4090	10	3830	30	70	3	3	70	A
480	5	28	1.1	358670	450	1260	190	1230	50	360	4	2	70	LMC
481	5	28	1.7	346480	60	3520	20	3090	50	70	3	3	80	A
482	5	28	1.7	337590	540	1190	130	1320	50	270	4	3	70	LMC
483	5	28	1.6	359720	90	2680	20	3830	40	60	3	3	60	A
484	5	28	1.3	335250	480	1160	120	1280	40	280	3	3	70	LMC
485	5	28	1.0	340530	60	2660	20	3980	50	80	4	3	80	A
486	5	28	1.9	308820	450	1210	200	1160	60	380	4	3	60	LMC
487	5	28	1.0	295440	80	3130	20	4120	10	60	5	3	60	A
488	5	28	.9	311720	500	1030	130	1580	20	170	5	4	60	LMC
489	5	28	1.0	327740	60	2410	20	4460	0	70	5	4	70	A
490	5	28	2.4	319440	470	960	50	1570	30	220	5	4	70	LMC
491	5	28	.8	286100	80	2030	10	4180	0	50	5	4	60	A
492	5	28	1.3	303040	430	960	120	1790	20	190	5	3	60	LMC
493	5	28	1.0	292110	50	1600	30	5100	7	60	5	4	50	A
494	1	29	.9	301220	70	2000	20	3650	0	60	8	4	60	

Sample	SP	LM	IR	Ca	Mg	Sr	Mn	Na	Al	Fe	Zn	Cu	Ni
495	1	29	.9	322250	100	2100	10	4000	0	50	5	3	70
496	1	29	2.1	281330	120	2160	10	4250	20	60	5	4	70
497	1	29	.9	304470	70	2880	10	2850	30	80	7	5	80
498	1	29	.9	286890	70	2330	9	3310	30	50	5	4	80
499	1	29	1.1	342890	80	2570	10	2590	30	60	4	4	70
500	1	29	8.1	289090	90	2270	8	2240	30	50	3	3	50
501	1	29	1.3	362740	70	2910	10	2840	30	50	7	6	80
502	1	29	1.2	301920	60	2450	10	2810	30	70	60	4	60
503	1	29	1.5	350210	80	2640	10	2510	20	50	6	4	60
504	2	29	1.2	319130	170	1870	20	3350	0	50	6	4	60
505	2	29	1.0	318300	180	1770	20	3030	20	60	6	4	60
506	2	29	1.7	298580	220	2080	20	2940	20	50	5	4	60
507	2	29	1.3	324920	120	1650	20	5650	30	50	50	4	50
508	2	29	1.2	299910	160	1450	20	4210	40	40	4	4	50
509	2	29	1.4	312200	180	1500	20	4900	20	50	5	4	40
510	2	29	1.3	346810	210	1760	20	5130	20	50	4	4	50
511	2	29	1.4	296090	140	1530	20	5000	30	50	6	3	50
512	2	29	1.2	296190	110	1610	20	5660	30	50	5	4	50

IR is the Insoluble Residue in percent   All Elemental Concentrations are in ppm

Key for SP:
see APPENDIX III

Key for LM:
see APPENDIX IV

Appendix II

Geochemical Data for Marine Invertebrate Macrofossils from Ft. Langley Fm and Capilano Sediments, British Columbia

Geochemical data of project FRASER LOWLANDS

Sample	SP	LM	IR	Ca	Mg	Sr	Mn	Na	Fe	Al

Sample	SP	LM	IR	Ca	Mg	Sr	Mn	Na	Fe	Al
514	6	30	1.6	426000	180	1880	20	4540	160	40
515	6	30	1.5	429940	300	1800	10	4140	200	70
516	6	30	1.5	412300	210	2430	10	3630	220	60
517	6	30	2.4	424870	210	2100	20	3920	260	70
518	6	30	2.3	424690	280	2430	10	4240	230	50
519	6	30	2.0	391310	160	2200	20	4080	240	50
520	6	30	2.5	418390	200	2260	10	4400	250	50
521	6	30	2.4	399930	160	2090	20	3770	260	50
522	6	30	2.6	422840	150	1950	20	3790	20	60
523	6	30	2.0	373710	150	1880	20	4320	40	50
524	6	30	1.7	381500	110	1530	20	4340	40	50
525	6	30	2.3	380210	280	1520	20	4140	30	140
526	6	30	2.6	383870	160	2060	20	3190	30	100
527	6	30	2.7	391440	200	1590	20	3500	40	50
528	6	30	2.7	381660	120	1720	20	3790	60	50
529	2	30	1.5	384350	570	1810	60	5690	50	150
530	6	30	2.3	432770	300	2070	40	5480	80	50
531	11	30	3.9	375300	140	1200	20	4310	90	100
532	11	30	5.8	400650	400	1490	20	4430	50	280
533	11	30	1.9	402650	140	1880	10	4180	50	90
534	11	30	2.6	390190	100	1290	20	4790	30	60
535	11	30	2.6	365000	130	1200	20	3730	50	60

Sample	SP	LM	IR	Ca	Mg	Sr	Mn	Na	Fe	Al
536	11	30	4.3	386890	220	1220	20	4930	40	230
537	11	30	2.2	330780	190	1760	20	4340	40	120
538	11	30	2.4	348630	120	1430	20	3850	40	130
539	11	30	3.3	331970	100	1030	20	3640	60	120
540	11	30	2.5	341080	100	1270	20	4120	60	40
541	11	30	2.9	365610	120	1200	20	5170	60	70
542	11	30	3.1	387180	120	1020	20	5520	30	120
543	11	30	2.5	324990	120	920	20	4410	10	120
544	11	30	2.5	370090	100	1410	20	4970	10	170
545	11	30	2.3	371670	150	2020	30	3170	20	210
546	12	30	1.8	372630	380	920	9	4300	20	60
547	12	30	2.5	396540	340	1050	10	4330	20	70
548	13	30	3.8	377920	910	510	847	2300	20	780
549	13	30	3.0	382050	890	620	797	2480	10	670
550	2	31	2.5	339880	150	1040	60	6270	8	70
551	2	31	2.9	381500	230	1170	60	6620	10	60
552	2	31	3.7	385210	260	1380	50	6250	30	120
553	2	31	2.9	354170	230	1470	50	5710	40	100
554	2	31	2.8	364530	140	1210	20	4660	30	80
555	2	31	4.2	382940	180	850	40	6440	20	110
556	2	31	2.4	385820	200	980	80	5840	20	120
557	2	31	3.5	373740	250	1090	70	4980	20	100

Sample	SP	LM	IR	Ca	Mg	Sr	Mn	Na	Fe	Al
558	2	31	3.0	327000	220	1280	50	5360	10	380
559	2	31	2.5	334250	220	1170	50	5770	10	110
560	2	31	3.0	369770	230	1330	60	4690	3	110
561	2	31	2.5	353970	240	1290	70	4970	10	140
562	2	31	3.4	395560	240	1390	110	5420	40	60
563	2	31	3.3	359750	270	1260	220	4720	20	330
564	2	31	2.3	348390	300	1470	50	5640	20	90
565	7	31	2.3	352480	2040	2950	340	4650	30	240
566	7	31	2.6	371230	1910	2930	210	4880	20	190
567	7	31	4.2	303090	1470	2140	230	3630	0	200
568	7	31	3.5	350760	2060	2760	230	4350	30	400
569	7	31	2.9	336990	1860	2800	210	5090	6	230
570	7	31	2.4	336050	1820	2730	270	5530	6	220
571	7	31	2.9	342010	1940	2280	340	4590	30	260
572	7	31	2.4	116360	860	880	80	1340	0	80
573	7	31	2.1	339750	2230	2830	240	5540	20	400
574	7	31	2.6	364370	2580	2690	370	4930	4	320
575	6	31	2.1	360000	160	1630	20	4320	10	90
576	6	31	1.8	355980	150	1650	20	4670	10	90
577	6	31	1.6	363610	160	1540	30	4740	9	100
578	6	31	11.0	369450	60	1600	20	3940	80	80
579	6	31	2.8	364730	70	1960	30	4670	80	120

Sample	SP	LM	IR	Ca	Mg	Sr	Mn	Na	Fe	Al
580	6	31	2.1	391490	70	1430	100	4780	80	110
581	6	31	1.4	379520	70	1610	50	4820	70	70
582	6	31	3.7	395930	70	1300	20	4640	90	90
583	6	31	5.6	350410	60	1450	90	5500	100	60
584	6	31	4.2	372460	50	1090	10	5420	70	90
585	3	31	5.4	380760	80	1510	30	5730	80	70
586	3	31	4.3	381060	90	1350	40	4600	60	60
587	3	31	5.4	371740	60	1150	50	4520	20	100
588	3	31	4.9	374550	130	1420	40	4410	40	70
589	3	31	6.7	371260	60	1060	160	4510	30	90
590	3	31	4.8	378080	100	1310	60	4480	30	70
591	3	31	4.3	368760	80	1550	40	4530	30	60
592	3	31	5.6	375450	110	1420	80	4630	30	110
593	3	31	4.3	378310	80	1280	30	4310	20	80
594	3	31	2.5	377180	70	1250	40	4530	20	100
595	13	31	2.3	393040	270	520	550	3060	4	350
596	13	31	2.6	361160	330	640	530	4060	40	410
597	12	31	2.4	354300	50	840	30	5460	30	120
598	12	31	2.1	348990	50	1310	20	5540	20	90
599	12	31	2.3	358540	50	1370	20	5560	40	130
600	3	32	2.8	334100	60	1550	30	5540	40	150
601	3	32	1.6	410320	60	1530	20	5540	40	260

Sample	SP	LM	IR	Ca	Mg	Sr	Mn	Na	Fe	Al
602	3	32	2.1	341080	30	1140	20	5530	30	150
603	3	32	2.8	343630	40	1450	10	5720	40	80
604	3	32	3.8	344930	80	1610	20	5660	30	80
605	3	32	2.5	352210	80	1580	30	5420	30	200
606	3	32	2.5	408850	80	1670	20	4090	40	50
607	3	32	3.5	405040	80	1220	30	4170	20	220
608	3	32	3.5	399090	40	1050	20	4460	30	140
610	3	32	4.1	404480	40	840	20	4540	30	60
611	3	32	1.8	408070	60	1330	30	4350	20	100
612	6	32	1.7	402040	90	780	10	4300	50	120
614	6	32	2.7	391090	30	1550	10	3410	60	130
615	6	32	4.2	406240	60	1010	20	3900	30	170
616	6	32	1.7	341990	40	1400	10	3950	80	390
617	6	32	2.4	340180	140	1360	10	3940	50	160
618	6	32	2.0	320010	50	1580	10	4430	50	170
619	6	32	.8	344570	6	990	20	3770	40	180
620	6	32	1.3	324140	40	1250	10	4180	40	80
621	6	32	2.4	355280	140	1230	10	4070	60	120
622	3	32	2.4	335780	90	1670	20	4030	40	50
623	12	32	1.2	332730	30	1330	10	3970	50	970

Sample	SF	LM	IR	Ca	Mg	Sr	Mn	Na	Fe	Al	
624	12	32	1.8	338030	40	440	20	4910	80	120	
625	12	32	2.3	335520	20	1190	8	3910	40	290	
626	12	32	2.5	403110	40	1210	10	3850	40	160	
628	5	32	.2	362700	460	600	90	3020	40	140	(LMC)
629	5	32	1.6	387440	30	870	8	5350	60	90	(A)
630	2	33	2.5	398190	110	1990	10	4230	40	150	
631	2	33	3.3	388520	170	1020	20	5290	50	70	
632	2	33	2.9	364030	100	2730	10	4620	50	50	
633	2	33	1.5	395460	220	1430	20	5300	30	70	
634	6	33	16.6	384150	120	1900	20	4370	50	270	
635	6	33	2.8	376320	70	1110	10	4200	60	190	
636	6	33	3.3	346990	30	1780	8	3850	70	50	
637	6	33	2.1	339960	40	1130	20	4080	50	80	
638	6	33	2.0	356650	40	1520	10	4790	90	50	
639	6	33	2.1	331200	70	1440	20	5010	80	250	
640	6	33	1.7	384350	110	2390	20	4840	70	210	
641	6	33	3.4	348900	60	1900	20	4580	90	340	
642	6	33	4.5	480610	70	2020	40	3910	10	120	
643	3	33	3.4	429420	140	2310	40	4070	40	60	
644	3	33	3.9	479310	80	1630	30	3940	60	60	
645	3	33	2.9	466970	110	1490	40	3950	30	70	

Sample	SP	LM	IR	Ca	Mg	Sr	Mn	Na	Fe	Al
646	3	33	4.9	451810	60	1540	40	4020	40	50
647	3	33	3.2	480280	60	1910	40	4000	50	40
648	3	33	4.3	470820	70	1520	40	4190	40	50
649	3	33	3.6	467490	140	1950	50	3840	40	100
650	3	33	3.4	490960	60	2290	10	3670	40	60
651	3	33	3.2	485650	150	2200	20	3700	40	40
652	3	33	4.8	472350	150	2070	20	3720	40	50
653	3	33	5.2	473130	40	2020	30	3250	40	580
654	3	33	4.5	474230	20	1970	20	3590	30	100
655	3	33	3.9	478070	20	1740	20	3740	60	90
656	3	33	5.8	490170	170	2440	20	3280	40	50
657	3	33	4.0	478430	160	2760	20	3210	50	60
658	3	33	5.3	503160	70	1750	30	3360	40	170
659	3	33	4.5	492770	40	2030	40	3140	60	350
660	3	33	4.8	435620	290	2120	30	3470	30	110
661	3	33	3.8	445310	40	2060	10	3790	20	120
662	3	33	5.3	423860	30	2270	10	3520	40	120
663	12	33	4.9	437040	80	2610	8	3580	9	200
664	12	33	4.1	432750	80	2230	9	3540	50	240
665	12	33	3.2	447020	180	1860	7	3420	40	50
666	12	33	4.4	447580	90	2150	30	3380	40	110
667	12	33	3.4	423430	260	1810	10	3540	30	140

Sample SP LM IR   Ca   Mg   Sr   Mn   Na   Fe   Al

IR is the Insoluble Residue in percent   All Elemental Concentrations are in ppm

Key for SP:
see Appendix III

Key for LM:
see Appendix IV

Appendix III

Key to species identification

No.	Species
1.	*Macoma balthica* (Linné)
2.	*Hiatella arctica* (Linné)
3.	*Mya truncata* Linné
4.	*Mya arenaria* Linné
5.	*Mytilus edulis* Linné
6.	*Macoma calcarea* (Gmelin)
7.	*Balanus crenatus* (Bruguiere)
8.	unidentified fragments, discarded sample
9.	*Neptunea despecta tornata* (Gould)
10.	*Hemithiris psittacea* (Gmelin)
11.	*Clinocardium ciliatum* (Fabricius)
12.	*Nuculana pernula* (Müller)
13.	*Pecten* sp.

Appendix IV

Key to Localities

Locality number   Description

A. Champlain Sea

NOTE: Elevations are interpreted from 1:50,000 topographic maps with a contour interval of 25 feet. Locality 12 does not exist.

1.   Sand and gravel pit 4.5 km SW of Prescott, ON. Elev: 90 m , *Macoma balthica* in 1-2 m of beach deposits. Map: 31B/2.

2.   Sand and gravel pit 3 km NNE of Oxford Mills, ON. Elev: 98 m , *Macoma balthica* in sandy beach deposit. Map: 31B/13

3.   Abandoned pit on W side of road S of Nolans Corners, 6 km NNW of of Kilmarnock, ON. Elev: 122 m, *Macoma balthica* in sand and gravel deposit. Map: 31B/13.

4.   Gravel pit in Loughlin Ridge 6 km NE of Kemptville, ON. Elev: 100 m , *Macoma balthica* in sandy beach deposit. Map: 31G/4.

5.   Gravel pit 8 km NE of Richmond, ON. Elev:106 m , *Hiatella arctica* in marine clay. Map: 31G/4.

6.   Excavation for Hunt Club Bridge, Uplands, Ottawa, ON. Elev: 95 m, *Macoma balthica* and *Macoma calcarea* in situ in sandy deposit. Map: 31G/5.

7.   Gravel pit in ridge E of Galetta, ON. Elev: 107 m, *Hiatella arctica* and *Macoma balthica* in top of reworked glacial deposit. Map: 31F/8.

8.   Ridge along S side of Hwy. 17, 15 km east of Arnprior, ON. Elev: 130 m *Macoma balthica* in beach ridge. Map: 31F/8.

9.   Sand and gravel pit in beach deposit, 5 km NNE of Clayton, ON. Elev:168 m , *Macoma balthica* and *Hiatella arctica.* Map: 31F/1.

10.   Sand and Gravel pit 2 km N of Goshen, ON. Elev: 143 m, *Macoma balthica* in situ at top of reworked glacial deposit. Map:31F/7.

11.   Sand and gravel pit on south side of The Pinnacle, 2 km NW of Renfrew, ON. Elev: 130 m, *Macoma balthica* in situ in beach sand overlying marine silt. Map: 31F/7.

13.   Sand and gravel pit on E side of Hwy. 105, 2 km S of Wakefield, PQ., Elev: 160 m, *Hiatella arctica* and *Portlandia arctica* in marine clay overlain by *Macoma balthica* in stratified sand and gravel. Map: 31G/12.

14.   Gravel pit 1 km N of Bearbrook, ON. Elev: 75 m, *Hiatella arctica*, *Balanus crenatus* in marine clay and sand. Map: 31G/6.

15.   Road cut 6 km E of Dunvegan, ON. Elev: 100 m, *Hiatella arctica* in 1 m of gravel overlain by sand. Map: 31G/7.

16.   Drainage ditch near Warina, ON. Elev: 100 m, *Hiatella arctica* and *Macoma balthica* in sandy gravel at base of ditch. Map: 31G/2 & 31B/15.

17.   Sand and gravel pit 1 km NE of Maple Ridge, ON. Elev: - , *Hiatella arctica* in 1 m of gravel overlain by stratified sand. Map: 31G/3.

18.   Gravel pit 1 km E of Martintown, ON. Elev: 80 m, Abundant *Mytilus edulis* and *Macoma balthica* in coarse sand and gravel deposit. Map: 31G/2 & 31B/15.

19.   Abandoned gravel pit 7 km due E of Alexandria, ON. Elev: 85 m, *Hiatella arctica* and *Macoma balthica* in 30cm of coarse sand and gravel. Map: 31G/7.

20.   Waste disposal pit, Riviere-Beaudette, PQ. Elev: 55 m, *Hiatella arctica* at base of coarse gravel and sand deposit. Map: 31G/1.

21.   Gravel pit in morainic ridge SW of Lee's Corners, PQ. Elev:75 m, *Hiatella arctica* in situ in 25 cm of coarse sand and gravel. Map: 31G/7.

22.   Abandoned gravel pit on south side of Rigaud Mt., PQ. Elev: 130 m, *Hiatella arctica* in coarse sand and gravel near marine limit. Map: 31G/8.

23.   Sand pit 2 km NNW of St.-Joseph-du-Lac, PQ. Elev: 104 m, *Macoma balthica* and *Hiatella arctica* in beach ridge. Map: 31G/9.

24.   Gravel pit in St. Philomone Ridge near St. Martine, PQ. Elev: 54 m, *Hiatella arctica, Mya arenaria, Mya truncata, Macoma balthica, Mytilus edulis, Balanus* in reworked morainic ridge. Map: 31H.

25.   Sand and gravel pit 3km N of Lacolle, PQ. Elev: 54 m, *Hiatella arctica* and *Macoma calcarea* in stony clay overlain by *Macoma balthica* and *Mytilus edulis* in sand and gravel. Map: 31H.

26.   Excavation in beach ridge S of St. Gertrude, PQ. Elev: 85 m, *Mya truncata, Hiatella arctica, Neptunea despecta tornata* in clay and silty sand overlain by *Macoma balthica* in sand. Map: 31I.

27.   Gravel pit in side of St. Narcisse morraine, E of Charet, PQ. Elev: 136 m, *Hiatella arctica* in coarse sand overlain by *Macoma balthica* and *Mya arenaria* in situ in well sorted, stratified sand. Map: 31I.

28.   Sand and gravel pit near St. Nicolas, PQ. Elev: 69 m, *Hiatella arctica, Macoma calcarea* and *Mya truncata* in marine clay overlain by *Mytilus edulis, Hemithiris psittacea, Balanus crenatus,* and *Neptunea despecta tornata* in 4 m of crossbedded sand. Map: 21L & 21K.

Additional carbon isotope data was used from the following studies:

Localites 29-55: Data from Rodrigues and Richard (1985).

Localites 56-61,68: Data from Hillaire-Marcel (1977).

Localities 62,63: Data from Lowdon and Blake (1979).

Locality 69: Data from Lowdon and Blake (1981).

Localiy 66: Data from Lowdon and Blake (1973).

Localities 64,65: Data from Lowden and Blake (1979).

Locality 72: Data from Blake (1983).

29. Clayton, ON., Elev: 168 m, *Macoma balthica*.

30. White Lake, ON. Elev: 170 m, *Macoma balthica*.

31. Val-des-Bois, PQ. Elev: 180 m, *Macoma balthica*.

32. Merrickville, ON. Elev: 119 m, *Macoma balthica*.

33. Farrelton, PQ. Elev: 180 m, *Macoma balthica*

34. Douglas, ON. Elev: 120 m, *Macoma balthica*.

35. Saint-Sixte, PQ. Elev: 145 m, *Macoma balthica*.

36. Mayo, PQ. Elev: 182 m, *Macoma balthica*.

37. Val-Paquin, PQ. Elev: 196 m, *Macoma balthica*

38. Shawville, PQ. Elev: 170 m, *Macoma balthica*

39. Westmeath, ON. Elev: 158 m, *Macoma balthica*

40. Navan, ON. Elev: 95 m, *Macoma balthica*

41. Buckingham, PQ. Elev: 180 m, *Hiatella arctica*

42. Rigaud, PQ. Elev: 160 m, *Hiatella arctica*

43. Montebello, PQ. Elev: 167 m, *Hiatella arctica*

44. Kars, ON. Elev: 98 m, *Hiatella arctica*

45. Riviere-du-Liviere, PQ. Elev: 146 m, *Hiatella arctica*

46. Saint-Lazare-de-Vaudreuil, PQ. Elev: 84 m, *Hiatella arctica*

47. Sainte-Justine-de-Newton, PQ. Elev: 74 m, *Hiatella arctica*

48. Cazaville, PQ. Elev: 71 m, *Hiatella arctica*

49. Beaver Crossing, PQ. Elev: 67 m, *Hiatella arctica*

50. Bearbrook, ON. Elev: 69 m, *Hiatella arctica*

51. Deschênes, PQ. Elev: 94 m, *Hiatella arctica*

52. Saint-Lazare-de-Vaudreuil, PQ. Elev: 82 m, *Macoma calcarea*

53. Glenroy, ON. Elev: 80 m, *Mya arenaria*

54. Sainte-Justine-de-Newton, PQ. Elev: 76 m, *Mya arenaria*

55. Sainte-Justine-de-Newton, PQ. Elev: 75 m, *Mya truncata*

56. Lachute, PQ. Elev: 120 m, *Hiatella arctica, Macoma balthica*

57.   Oka, PQ. Elev: 100 m, *Hiatella arctica, Macoma balthica*

58.   Shawinigan, PQ. Elev: 129 m, *Macoma balthica, H. arctica, M. arenaria*

59.   St. Dominique, PQ. Elev: -, *Macoma balthica, Mya arenaria*

60.   Rougemont, PQ. Elev: - , *Macoma balthica, Hiatella arctica*

61.   St. Remi, PQ. Elev: -, *Hiatella arctica*

62.   Plattsburg, N.Y. Elev: 96 m, *Macoma balthica*

63.   Peru, N.Y. Elev: 101 m, *Macoma balthica*

64.   Mont St. Hilaire, PQ. Elev: 43 m, *Macoma balthica*

65.   St. Césaire, PQ. Elev: 48 m, *Hiatella arctica*

66.   Charlesbourg, PQ. Elev: 110 m, *Portlandia arctica.*

67.   Sparrowhawk Point, N.Y. Elev: 83 m, *Macoma balthica*

68.   St-Louis-de-Terrebonne, PQ. Elev: -, *Hiatella arctica, M. balthica.*

69.   Montreal, PQ. Elev: 52 m, *Macoma balthica*

70.   Riviere-Beaudette, PQ. Elev: 56 m, *Mya arenaria*

71.   St-Stanislas-de-Koska, PQ. Elev: 42 m, *Portlandia arctica.*

72.   Granby, PQ. Elev: 85 m, *Hiatella arctica*

B. Fraser Lowland Localities

NOTE: Localities 1 - 4 of Fig. 21 correspond to localities 30 - 33 in Appendix II.

1.   Sand and gravel pit near Websters Corners, 1.4 km E of 256th street and 1.5 km N of Dewdney Trunk road. Elev: 125-150 m, silt, sand and gravel of a proglacial delta. Map: 49°14'00" N,   122°29' 35" W. Ref: Armstrong (1977,p.11).

2.   Carr Sand and Gravel pit on S side of Grant Hill, N of the Fraser River, Elev: 65-70 m, Marine fossils in stony silty glaciomarine clay. Map:

49°10'35" N, 122°31'45" W, Ref: Armstrong (1977,p11).

3.   Ditch on E side of King George Hwy., 2.6 km N of the U.S. border. Elev: 35-40 m, Abundant marine fauna in 10m of stony, sandy mud of Capilano Sediments, Map: 49°01.5' N, 122°46.0' W, Ref: Clague and Luternauer (1983, p 73).

4.   Furry Creek gravel pit (abandoned) on Hwy. 99, approximately 18 km N of Vancouver, S of Furry Creek, Elev:160 m. Ref: J.J Clague, personal communication, 1985.

Appendix V

Carbon and Oxygen Isotopic Data

for Marine Invertebrate Macrofossils from the

Champlain Sea Basin

Locality	Species	$\partial^{18}O$ $^0/_{00}$	$\partial^{13}C$ $^0/_{00}$	Dupl.
1. Prescott,ON	*M. balthica*	-5.32	-1.98	
2. Oxford Mills,ON	*M. balthica*	-5.68	-1.82	
3. Kilmarnock,ON	*M. balthica*	-7.14	-0.82	
4. Kemptville,ON	*M. balthica*	-5.44	-1.34	-1.65
5. Richmond,ON	*H. arctica*	discarded due to error		
	M. balthica	-6.78	-1.07	-0.89
6. Ottawa,ON	*M. calcarea*	-0.37	-1.06	
	M. balthica	-6.88	-1.05	-1.15
7. Galetta,ON	*M. balthica*	-8.30	-1.21	
	H. arctica	-4.97	+0.40	
8. Hwy. 17,ON	*M. balthica*	-9.19	-1.38	-1.28
9. Clayton,ON	*M. balthica*	-9.62	-0.57	
10. Goshen, ON	*M. balthica*	-9.64	-1.89	
11. Renfrew	*M. balthica*	-10.02	-2.68	-2.56
13. Wakefield,PQ	*M. balthica*	-6.68	-1.80	
	H. arctica	-3.65	+0.73	+0.65
14. Bearbrook,ON	*H. arctica*	+0.31	+1.38	
	Balanus	+3.13	+0.29	

15. Dunvegan,ON	*H. arctica*	-0.60	+1.52	
16. Warina,ON	*H. arctica*	-2.63	+0.98	
	M. balthica	-3.78	-1.47	-1.59
17. Chesterville,ON	*H. arctica*	-3.05	+0.59	
18. Martintown,ON	*M. balthica*	-10.61	-0.85	
19. Alexandria,ON	*H. arctica*	-3.45	+1.09	+0.91
	M. balthica	-11.66	-1.89	
21. Lee's Corners,PQ	*H. arctica*	-1.94	+1.05	
22. Rigaud,PQ	*H. arctica*	-1.42	+1.22	
23. St. Joseph-	*H. arctica*	-1.39	+1.23	
du-Lac, PQ	*M. calcarea*	-10.24	-1.81	
24. St. Martine,PQ	*M. arenaria*	-10.87	-1.47	
	M. truncata	-11.42	-1.73	
	B. crenatus	+1.94	-0.54	
	M. balthica	-10.09	-2.66	
25. Lacolle,PQ	*M. balthica*	-10.30	-1.62	
	H. arctica	-2.02	+0.72	
	Balanus	+3.68	+0.88	
	M. calcarea	-1.28	-1.10	
26. St. Gertrude,PQ	*H. arctica*	-1.16	+0.19	
	M. truncata	+0.65	+1.01	
	Neptunea despecta	+1.36	-0.57	-0.27
27. Charet,PQ	*H. arctica*	-2.22	+0.27	
	M. balthica	-10.52	-2.24	
	M. arenaria	-11.31	-0.92	
28. St. Nicolas,PQ	*H. arctica*	-3.40	+0.64	
	M. truncata	-1.18	+0.53	

St. Nicolas, PQ	*M. calcarea*	-0.77	-1.44	~1.58
	M. edulis (arag)	-3.66	+0.31	
	M. edulis (calc)	-4.64	-2.18	
LaFlamme, PQ	*H. arctica*	-8.57	-0.26	
Gulf	*M. balthica*	-8.58	-2.67	

Appendix VI

Results of statistical t-test of population means for chemical elements using aragonitic molluscs. Variables = Ca, Mg, Sr, Na, Fe, Mn, Ni, Cu, Zn, Al at the 95% confidence level.

Species	No. of Samples	Significantly different elemental concentrations
Champlain Sea Molluscs		
Macoma balthica	195	Ca, Mg, Sr, Na, Mn, Cu, Al, Zn
Hiatella arctica	200	
M. balthica	195	Na
Mya truncata	17	
M. balthica	195	Ca
Mya arenaria	20	
M. balthica	195	Ca, Sr
Macoma calcarea	27	
H. arctica	200	Mg, Sr
Mya truncata	17	
H. arctica	200	Ca, Mg, Sr, Na, Mn, Al
M. arenaria	20	
H. arctica	200	Ca, Mg, Sr, Na, Al, Mn
M. calcarea	27	
M. truncata	17	Ca, Mg, Sr, Na, Al
M. arenaria	20	
M. truncata	17	Mg, Sr, Na, Al, Zn
M. calcarea	27	
M. arenaria	20	Ca, Mg, Fe, Al
M. calcarea	27	

Appendix VII
Varimax rotated factor loadings of skeletal major, minor, and trace element content from late Quaternary marine invertebrates.

Note: factors with loading of less than ±0.3 were not included.

A. Champlain Sea

Macoma balthica (N=197)

Factor:	1	2	3	4	5	Communality
Element						
Log IR	-0.471	-	-	0.369	-	0.47
Log Al	-	0.458	-	0.434	-	0.44
Log Ca	-	0.779	-	-	-	0.22
Log Mg	-	-	-	0.460	-	0.38
Log Sr	-	-	0.609	-	-	0.38
Log Mn	0.577	-	-	-	-	0.39
Log Na	-	-	-	-	-	0.14
Log Fe	-	-	-	-	-	0.07
Log Zn	-	0.554	-	-	-	0.39
Log Cu	-	-	-	-	0.675	0.47
Log Ni	0.771	-	0.529	-	-	0.92
Eigenvalue	1.7	1.2	0.7	0.6	0.4	
Pct. of Var.	36.7	27.0	15.2	13.2	7.8	
Factor	?	?	?	lab leach	?	

Macoma calcarea (N=27)

Factor:	1	2	3	4	Communality
Element					
Log IR	0.733	-	-	-	0.63
Log Al	-	-	0.627	-	0.47
Log Ca	-0.741	-	-	-0.412	0.76
Log Mg	-	0.640	-	-	0.57
Log Sr	0.777	-	0.443	-	0.88
Log Mn	-	0.906	-	0.349	0.98
Log Na	-	-	-0.711	-	0.56
Log Fe	-	-	-	0.587	0.34
Log Zn	0.634	-	-	-	0.55
Log Cu	-	0.827	-	-	0.84
Log Ni	-	-0.359	0.519	0.618	0.87
Eigenvalue	3.1	2.6	1.1	0.7	
Pct. of Var.	41.3	34.4	15.0	9.3	
Factor	?	?	salinity	?	

Hiatella arctica (N=200)

Factor:	1	2	3	4	5	Communality
Element						
Log IR	–	–	0.664	–	–	0.14
Log Al	–	–	–	0.574	0.336	0.09
Log Ca	–	–	–	–	–	0.09
Log Mg	–	0.762	–	–	–	0.14
Log Sr	0.479	–	–	–	–	0.27
Log Mn	0.314	–	–	–	–	0.12
Log Na	–	–	–	–	–	0.07
Log Fe	–	–	–	–	–	0.15
Log Zn	–	0.554	–	–	–	0.06
Log Cu	–	–	–	0.375	–	0.09
Log Ni	0.960	–	–	–	–	0.37
Eigenvalue	1.4	0.9	0.6	0.5	0.3	
Pct. of Var.	37.7	24.5	15.8	12.7	9.4	
Factor	?	?	?	?	?	

Mya truncata (N=17)

Factor:	1	2	3	4	Communality
Element					
Log IR	–	0.912	–	–	0.92
Log Al	–0.414	–	–	–	0.23
Log Ca	–	–	0.634	–	0.50
Log Mg	–	–	–	0.967	0.99
Log Sr	0.482	0.431	–	–	0.53
Log Mn	0.939	–	–	–	0.90
Log Na	–	–0.710	–	–	0.60
Log Fe	–0.731	–	–0.363	–	0.66
Log Zn	–	0.391	0.791	–	0.79
Log Cu	0.806	–	–	–	0.77
Log Ni	–0.502	–0.689	–	–	0.78
Eigenvalue	3.8	2.1	1.1	0.7	
Pct. of Var.	49.0	27.0	14.7	9.2	
Factor	lab leach	salinity	?	biogenic frac.	

Mya arenaria (N=20)

Factor:	1	2	3	Communality
Element				
Log IR	–0.842	–	–	0.78
Log Al	0.675	–	–	0.47
Log Ca	–	0.629	–	0.42
Log Mg	–	0.673	–0.459	0.67
Log Sr	–	0.841	–	0.71
Log Mn	–	–	0.625	0.39
Log Na	–	–0.651	–	0.48
Log Fe	–	–	–0.539	0.36
Log Zn	–0.778	0.436	–	0.80
Log Cu	0.777	–	–	0.72
Log Ni	0.427	–	–	0.27
Eigenvalue	2.7	2.4	0.9	
Pct. of Var.	45.2	39.0	15.8	
Factor	lab leach	salinity	?	

Balanus crenatus (calcite, N=16)

Factor:	1	2	3	Communality
Element				
Log IR	−0.905	−	−	0.86
Log Al	−	0.723	−	0.65
Log Ca	0.956	−	−	0.92
Log Mg	−	−	0.819	0.78
Log Sr	−	0.890	−	0.97
Log Mn	−	−	0.765	0.60
Log Na	−	0.939	−	0.95
Log Fe	−	−	−	0.99
Log Zn	−0.833	−	−	0.89
Log Cu	−0.717	−	−0.573	0.86
Log Ni	0.560	−0.530	0.491	0.84
Eigenvalue	4.6	3.4	1.3	
Pct. of Var.	49.7	36.6	14.1	
Factor	lab leach	salinity	?	

Hemithiris psittacea (calcite, too few samples N=5)

Mytilus edulis (mixed mineralogy, discarded)

B. Ft. Langley Fm. and Capilano Sediments

Hiatella arctica (N=20)

Factor:	1	2	3	Communality
Element				
Log IR	−	−0.587	−	0.38
Log Ca	−	−	0.866	0.74
Log Mg	0.987	−	−	0.98
Log Sr	−	0.679	−	0.50
Log Mn	0.721	−0.481	−	0.81
Log Na	−0.406	0.685	0.423	0.81
Log Al	0.323	−	−0.350	0.22
Log Fe	−	0.363	0.559	0.45
Eigenvalue	2.9	1.2	0.8	
Pct. of Var.	58.5	25.0	16.5	
Factor	?	?	?	

Mya truncata (N=43)

Factor:	1	2	3	Communality
Element				
Log IR	–	-0.559	–	0.32
Log Ca	0.888	–	–	0.79
Log Mg	–	–	0.898	0.86
Log Sr	0.735	–	–	0.65
Log Mn	–	–	–	0.12
Log Na	-0.789	–	–	0.64
Log Al	–	0.604	–	0.42
Log Fe	–	0.776	–	0.69
Eigenvalue	2.2	1.4	0.9	
Pct. of Var.	50.0	31.2	18.8	
Factor	salinity	lab leach	biogenic frac.	

Macoma calcarea (N=43)

Factor:	1	2	3	Communality
Element				
Log IR	–	–	0.496	0.28
Log Ca	0.626	–	–	0.50
Log Mg	0.818	–	–	0.67
Log Sr	0.585	–	–	0.41
Log Mn	–	–	0.432	0.22
Log Na	-0.870	0.353	0.343	0.99
Log Al	-0.536	–	–	0.32
Log Fe	–	0.817	–	0.70
Eigenvalue	2.5	0.9	0.6	
Pct. of Var.	61.9	22.4	15.7	
Factor	salinity	?	?	

Clinocardium ciliatum (N=15)

Factor:	1	2	3	4	Communality
Element					
Log IR	0.799	-0.490	–	–	0.96
Log Al	0.783	–	–	-0.388	0.79
Log Ca	0.398	–	0.651	–	0.58
Log Mg	0.840	–	–	–	0.77
Log Sr	–	0.897	–	–	0.86
Log Mn	–	–	-0.627	–	0.46
Log Na	–	-0.522	0.468	–	0.52
Log Fe	–	–	–	0.864	0.76
Eigenvalue	2.2	1.4	1.2	0.8	
Pct. of Var.	39.0	24.4	21.8	14.7	
Factor	lab leach	salinity	?	?	

Nuculana pernula (N=14)

Factor:	1	2	3	Communality
Element				
Log IR	0.962	–	–	0.92
Log Ca	0.850	0.423	–	0.95
Log Mg	–	0.871	–	0.85
Log Sr	0.779	–	–0.318	0.70
Log Mn	–	–	0.793	0.64
Log Na	–0.619	–	0.632	0.78
Log Al	–	–0.844	–	0.80
Log Fe	–	–0.361	–	0.19
Eigenvalue	3.4	1.5	0.8	
Pct. of Var.	59.2	26.4	14.4	
Factor	salinity	?	?	