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Glacigenic Clays of the Ottawa Valley

by

Dana L. Naldrett

A thesis
presented to the University of Ottawa
in partial fulfillment of the
thesis requirement for the degree of
Ph.D.
in
Geology

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"Whatever it is, it's very, very little."

FRONTISPIECE

ABSTRACT

Laminated and massive fine-grained facies were examined at the Foster pit, 10 km south of Ottawa and in cores from several localities in the Ottawa and Gatineau River Valleys.

The lower, laminated clay (previously termed the Rideau Varves), is interpreted as episodic rather than annual rhythmites (varves). Two types are recognized: continuous types (I) and (II), and discontinuous. Continuous type (I) occurs rarely, and consists of an unbroken fining upwards sequence representing a single flow event. Deposition is most likely by hypopycnal turbidity current. The more common continuous type (II) represents the same depositional mechanism, but with superimposed minor flow events represented by coarser laminae within the finer layers. The couplets show no thinning trend upsection, and individual couplets fine upwards with a gradual decrease in the silt/clay ratio. No trace fossils were found in any couplets. XRD and total carbonate analyses indicate that all carbonate is detrital, and underwent solution in undersaturated water.

The lower 2/3 of the rhythmites shows abundant features indicating slump, shear by grounding icebergs and other ice-contact features, and lenses of ice-rafted debris. The ubiquitous ice-contact features show the importance of (floating) ice in the early period of rhythmite deposition. This zone is barren, but the upper 1/3 contains a sparse <u>Candona</u> sp. fauna consistent with a deep (proglacial) lake.

Correlation with the Belleville phase of Lake Iroquois, and the Ft. Ann phase of Lake Vermont indicates the presence of an extensive lake with a shoreline at an elevation of approximately 216 m asl. This agrees with water depths of up to 180 m based on presence of Candona sp. and other freshwater ostracodes found in surface samples and cores.

The deep nature of this lake suggests that it probably existed as a single, large water body, but the uneven bedrock and ice topography of the lake bottom may have restricted water and sediment movement, creating smaller depocentres or basins. The episodic sedimentation and possibly different depocentres within the lake resulted in poor correlation of rhythmite layers.

In the Ottawa Valley and upper Rideau Valley, the local lake episode is called Lake Rideau, after the type locality on the Rideau River (Foster pit). Maximum extent of the lake has not yet been determined: the limits shown are based on detailed observations of the local area.

Removal of the ice dam blocking the lower St. Lawrence River allowed trapped fresh water to escape and marine water to enter. Drainage was apparently rapid, and the lake short-lived. As water level lowered, the Frontenac Arch separated Lake Ontario from the Champlain Sea. At this point, the elevation of the Champlain Sea was roughly 160 m asl.

At the top of the rhythmites, a rippled silt bed containing plant fragments and a varied insect fauna separates laminated and massive sediments. The exact age of the fossils is uncertain, but it is thought they may postdate deposition. The upper surface of the rippled silt may represent a disconformity between late glaciolacustrine sedimentation and early glaciomarine sedimentation, or simply a disturbance created by the sudden inflow of marine water and the replacement of fresh water by marine water.

Sediments overlying the rippled silt bed consist of vaguely laminated silty clay becoming massive upsection. This change reflects the increasing influence of marine water on sedimentation, as underflow and interflows changed to homopycnal flow. To achieve such flow, minimum salinity required would be 3-4 ppt.

Continued sediment input produced rare rhythmite-like couplets when sediment load was high enough to produce underflows. With increasing ice-distal position, and the high density of brackish Champlain Sea water, underflows rapidly stopped and the silty clay facies became massive.

Harsh conditions brought on by mixing marine and fresh water bodies are reflected in the barren massive clay facies. The upper portion indicates an amelioration of conditions, and the Islandiella-Cassidulina-Elphidium/Protelphidium assemblage indicates water depths of 30-100 m and salinity of 22-33 ppt for the earliest Transitional phase of the Champlain Sea.

DEDICATION

"To those who have not studied this subject (glacial deposits) this will appear the more remarkable, when it is added that there is abundant proof that the formation is one of the most recent of all, its date being immediately before the creation of the existing species, so that the unsettled state of the problem places the geologist in the unpleasant predicament, that while he can boldly and truly answer for events that occurred myriads of ages before the advent of his race, yet when questioned concerning that which comes almost within the period of human history, he must confess his inability to give but a conjectural reply."

E. Billings (1856)
The Boulder Drift Formation
The Canadian Naturalist and Geologist
Volume 1, Number V, page 322

ACKNOWLEDGEMENTS

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Several individuals have provided valuable assistance. Core material and logs were made available by N.R. Gadd, Geoloical Survey of Canada; plant and insect macrofossil identification was done by J.V. Mathews, Jr., Geological Survey of Canada. Assistance with SEM work was given by P. Lecompte, Parks Canada and H. Melville, Brock University. J. Terasmae provided radiocartbon dates from the Brock University Radiocarbon Laboratory.

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trials and tribulations of student life.

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Finally, I would like to express my deepest appreciation for the constant support given to me by my parents, and by Lynne, who made it all possible, and worthwhile.

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Chapter I

INTRODUCTION

1.1 PURPOSE, SCOPE AND METHODS OF STUDY

1.1.1 Purpose

The purpose of this study is to investigate the late glacial and early marine sediments in the Ottawa Valley, and to develop a depositional model for the fine-grained rhythmite and massive silt and clay facies. A second objective is to develop a paleoenvironmental reconstruction for the glacial-marine transition in the Ottawa Basin.

The Ottawa Basin is defined as that portion of the Champlain Sea and the preceding fresh water body which occupied the Ottawa Valley to just west of Pembroke, as shown in Figure 1. The term basin is used here as defined by McCormick and Thiruvathukal (1976), and delineates an area having a unique depositional environment which separates it from the remainder of the water body.

1.1.2 Scope

The University of Ottawa has been engaged in geologic studies of Champlain Sea sediments of the Ottawa-St. Lawrence Lowlands since 1970. Studies have focussed on the coarse-grained subaqueous outwash facies of the ridges in the Ottawa area, and on the littoral deposits of the receding Champlain Sea, as shown in Figure 2.

Little attention has been paid to the early deposits of the Champlain Sea, characterized by silt and clay

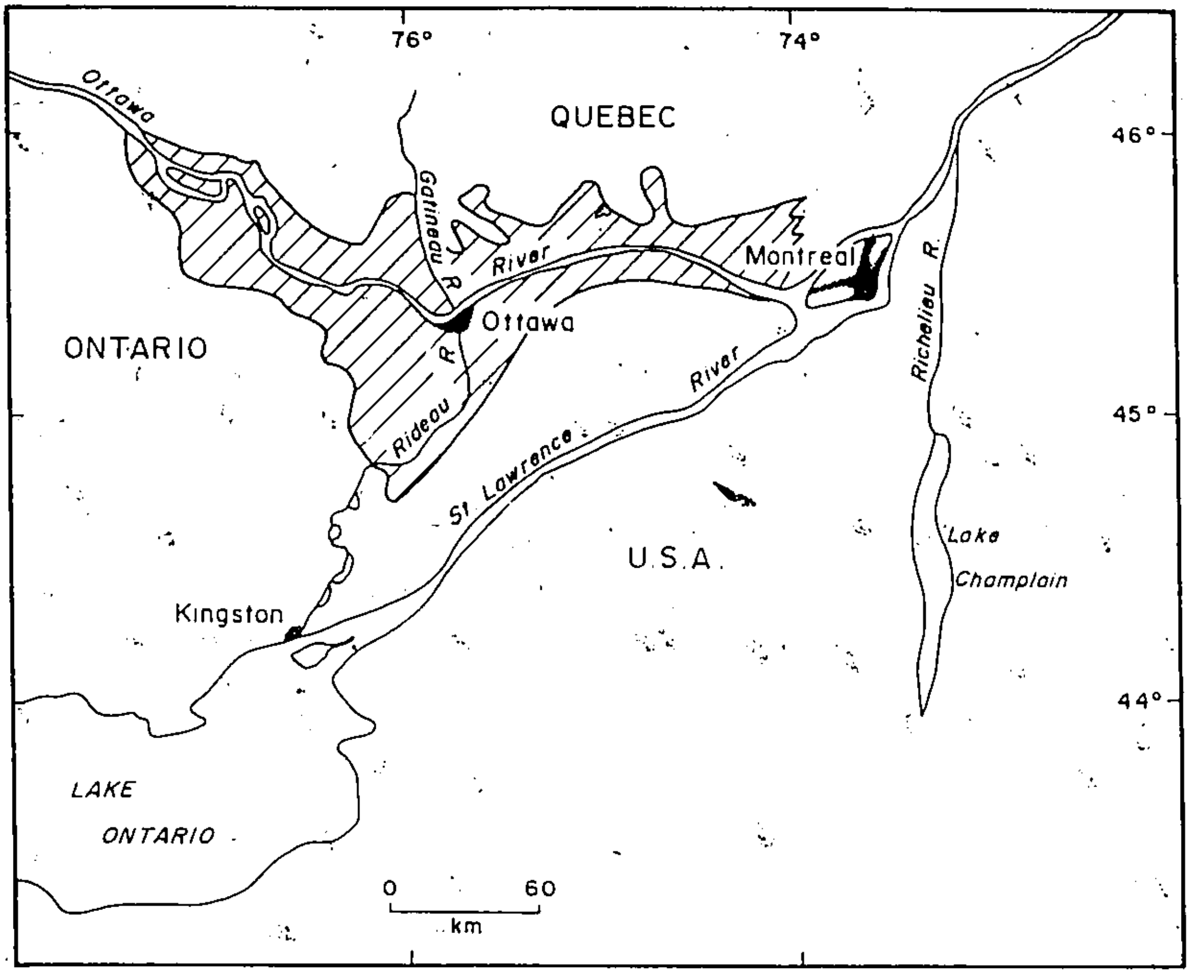


Figure 1: Ottawa Basin Study Area

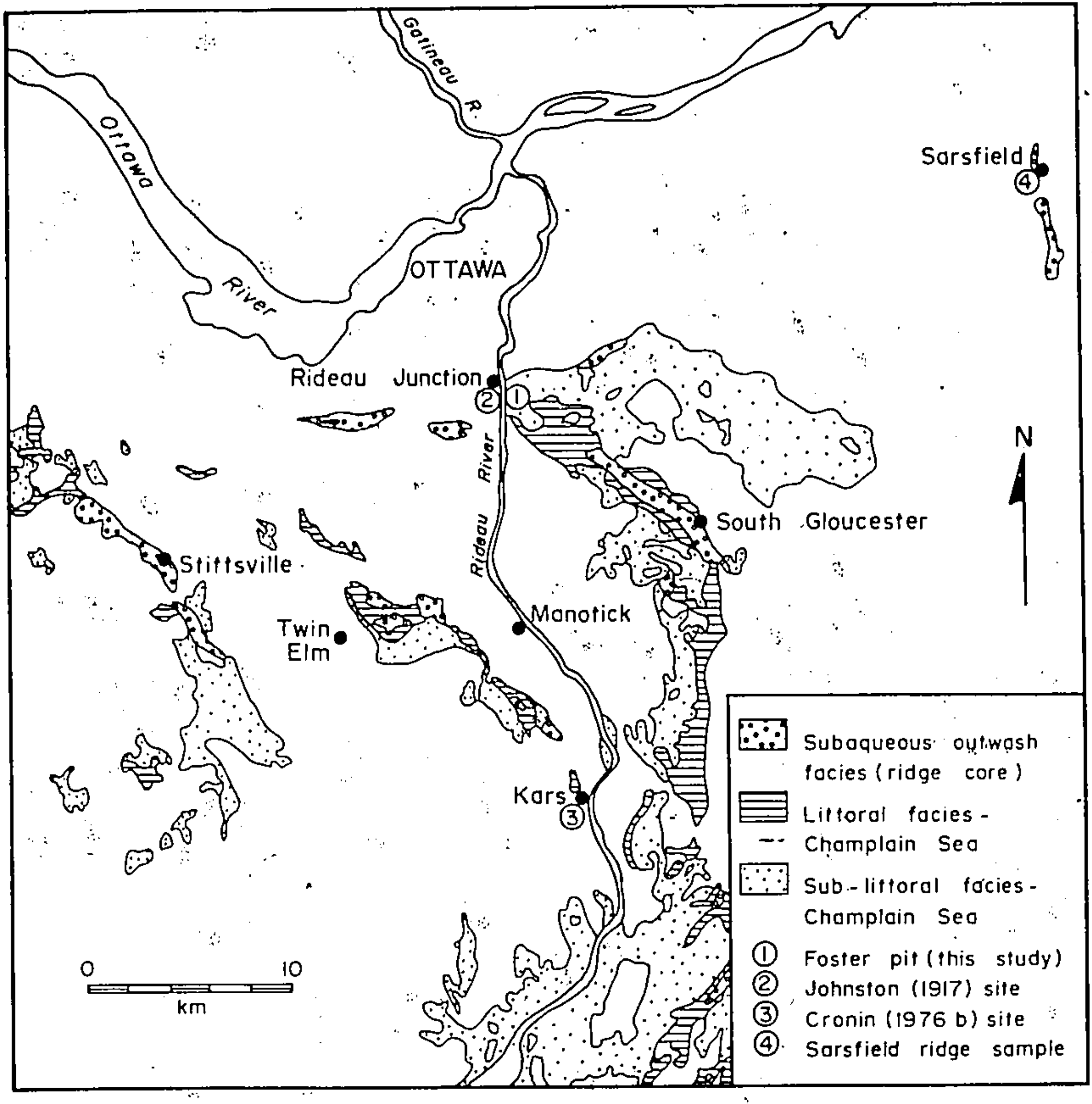


Figure 2: Subaqueous Outwash Facies and Littoral Deposits (After Richard et al., 1977)

rhythmites and till flow facies. This is partly because these facies are largely unexposed, or are unsuitable for aggregate use. Recent construction activity and a drilling program by the Geological Survey of Canada Terrain Sciences Division have facilitated surface and subsurface examination of these facies.

The study was limited to the local area by both financial and time constraints. However, thorough analysis of relevant previous studies and examination of cores and core data from the Ottawa Valley allowed expansion of the study into the larger Ottawa Basin area. Fieldwork was restricted to the best exposures in the Ottawa area, as explained in the following section. Some paleoceanographic aspects of this investigation could benefit from a more regional study, particularly those related to water mass circulation. The majority of the sedimentological work, however, is unaffected by the scope of the study, or has benefitted from the close scrutiny afforded by the proximity of the study sites.

1.1.3 Methods of Study

In the first field season, 35 sand and gravel pits in the Ottawa area were examined, and per cent exposure and lithofacies noted. The following field season, one of these localities was studied in detail, and two others were used for background information. Detailed study was limited to one pit because others lacked exposure of the required lithofacies.

Field methods included the measurement, sampling, description, and photography of sections and stratigraphic columns, and the collection of paleocurrent and other directional data wherever possible.

Laboratory methods were used to investigate sediment grain size, macro- and micro-fossils, and palynology. Each method is described in the text, and in the appendices in more detail.

Because of the limited exposure of the rhythmite facies, cores and core data supplied by the Geological Survey of Canada Terrain Sciences Division were used. This material greatly expanded the data base and geographic area of study. In addition, it allowed comparison of surface and subsurface data from the Ottawa Valley, where surface control could be used to check findings from core analysis.

1.2 HISTORY OF CHAMPLAIN SEA INVESTIGATIONS

G.W. Dawson was the first to study Champlain Sea deposits. Logan (1863) summarized Dawson's work to that time: 83 species had been recognized, and Dawson (1893) noted 200 species. The assistance of G.S. Brady and H.W. Crosskey for the ostracode fauna and W.K. Parker, T.R. Jones and G.M. Dawson for the foraminifera greatly aided Dawson's efforts. Dawson's work is important because he was the first to use oceanogrphic explanations for apparently unusual occurrences and to suggest that temporal environmental changes might have occured in the Champlain Sea. Dawson divided the Champlain Sea sediments into three groups:

Boulder Clay (till), Saxicava sand (shallow water deposits), and Leda clay (deep water deposits).

The early (?) marine clays were given the name Leda clay after the common fossil Portlandia arctica Gray, formerly Yoldia arctica Sars, and previously Leda glacialis (Elson, 1969a; Wagner, 1970, 1984). The term Leda clay is now restricted to a late (?) thixotropic marine clay found in the Ottawa-St. Lawrence Lowlands which has unique geotechnical properties, often resulting in failure and landslide (Bentley and Smalley, 1978; Gadd, 1975; Gillott, 1970, 1971). The term now seems to be used mainly by engineers, and is rarely used by geologists in either a chronostratigraphic or paleontologic context.

Sands locally overlying the marine clay and once believed to represent a separate later episode were called Saxicava sand after the common fossil Saxicava rugosa Lamark, now called Hiatella arctica Linne.

While others were involved in mapping the extent and nature of the Champlain Sea deposits, Billings (1856) noted the separation of deposits into "Drift" and "Lawrencian Formation". He noted the similarity between Champlain Sea fossils and the modern fauna of the Gulf of St. Lawrence, and postulated that land east of Kingston was submerged beneath the sea. The area described closely resembles the area now known to have been covered by the Champlain Sea.

Antevs (1925) postulated a deep marine phase represented by clay, a shallow phase represented by sand and gravel, and a younger marine transgression represented by a second clay body. Antevs (1939) later distinguished these as deposits of two marine transgressions separated by a fluvial interval. The older marine episode was the Champlain Sea which followed immediately upon the retreat of the last local glaciation. The younger episode he called the Ottawa Sea, with upper limits ranging from 122 m (400 ft.) at Pembroke to 73 m (240 ft.) at Ottawa. According to Antevs' hypothesis, both clays are found below 73 m, and only the older clay is found above 73 m. Mackay (1949) disproved this when he found more than one body of clay above 122 m. Gadd (1961) also opposed Antev's interpretation, favouring that of Johnston (1916, 1917), who regarded the younger clay as lacustrine in origin, hence Lake Ottawa. The Lake Ottawa phase of the Champlain Sea may correspond to the <u>Lampsilis</u> Lake freshwater phase proposed by Elson (1969a, b), as discussed in more detail in section 1.6, Champlain Sea Phases.

1.3 <u>EXTENT OF THE CHAMPLAIN SEA</u>

Elson (1969a) estimated ~~the~~ maximum extent of the Champlain Sea to be approximately 54,000 km^2, as shown in Figure 3. Early workers thought the Champlain Sea extended into the Lake Ontario basin, across the Frontenac Axis. Gilbert (in Walcott, 1897) postulated that an Oswego shoreline was contiguous with marine shorelines in the Champlain Valley and thus the Champlain Sea reached the Ontario basin. Fairchild (1907) and Mather (1917) called this extension the "Gilbert Gulf".

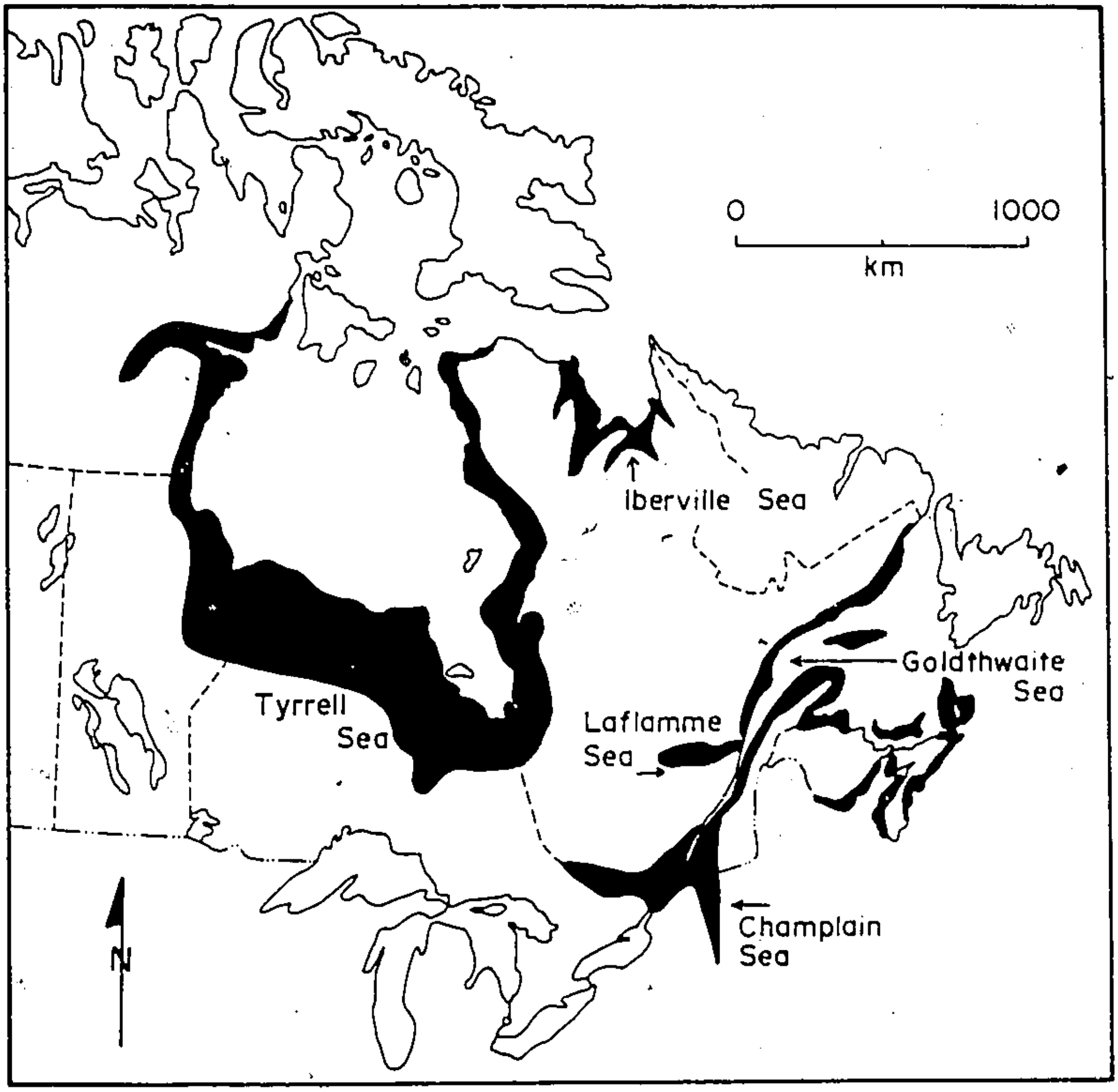


Figure 3: Postglacial Seas in Eastern Canada
(After Elson, 1969a)

This concept rapidly lost support, but there remain some authors who believe in the marine invasion of the Lake Ontario basin. Goldthwait (1933) provided evidence that the marine limit was much lower in elevation than that required to inundate the region west of Brockville, Ontario. Also, the character of the laminated clay west of Brockville suggests a freshwater origin, while massive clays several km east of Brockville contain marine fossils.

Although Hough (1958) referred to the "St. Lawrence Marine Embayment" in the Lake Ontario basin and to the "St. Lawrence Sea" (1963), by the end of the mid 1960's there was no field evidence to support the extention of the Champlain Sea into the Lake Ontario basin.

This is still an area of great interest, as shown by the present investigations of the Geological Survey of Canada (Anderson, pers. comm., 1984). Some believe that a low level phase of the Champlain Sea may have invaded the Ontario basin. It is unclear, however, how a low level phase could have extended past the Frontenac Axis. The only evidence found is apparently at the lowest levels of the lake floor where access is most difficult. This possibility has been investigated by Karrow (1984) and Clark and Karrow (1984). Investigations at the east end of the lake by subsurface profiling (Sly and Pryor, 1984) may also aid in determining whether the Champlain Sea reached the Lake Ontario basin. Some still adhere to the marine invasion views, but most are agreed that the Frontenac Axis was the western limit of the sea.

The observed maximum extent of the Champlain Sea in the Ottawa Valley is west of Chalk River at Rapides-des-Joachimes (Catto et al., 1981). The sea reached up the Gatineau Valley as far as Martindale (Romanelli, 1975), and up other tributary valleys. The incursion is dated at around 12,200 BP, and was short lived: by 11,500 BP the "Gatineau Gulf" had narrowed considerably. The maximum extent along the north shore of the Ottawa River is uncertain because of the rapid changes in elevation experienced during deposition. Terraces are not well developed and in the absence of shell material it is difficult to distinguish between glaciofluvial outwash, glaciomarine and glaciolacustrine sediments. Tracing of terrace elevations and calculation of paleodischarges based on estimated volumes of meltwater have been attempted by French and Hanley (1975) and Catto et al. (1981). In the Gatineau Hills, the maximum recorded elevation of marine deposits appears to be at Kingsmere, elevation 210 m (690 ft.).

Evidence of maximum marine limits to the south is not clear, although Prichonnet (1977) reports nearly 200 relict shorelines with a maximum height of 222 m (728 ft.) above sea level. Kirkland and Coates (1977) give a good summary of work in the St. Lawrence Valley in the United States, and earlier American work is discussed by Muller (1965).

In the area between the St. Lawrence Valley and the Ottawa Valley, much of the evidence is fragmentary and difficult to correlate. Isolated fossil evidence and strand lines have been used to construct the limits shown in Figure 4. Marine mammals, particularly seals and whales, have been useful in documenting the extent of the Champlain Sea in this area (Harington, 1977).

1.4 CORRELATION

Three prominent inundations related to deglaciation events have been studied in eastern Ontario. These are:

1. The Champlain Sea- marine submergence of the Ottawa-St. Lawrence Lowlands;
2. Glacial Lake Iroquois in the Lake Ontario basin;
3. Glacial Lake Algonquin in the Lake Huron-Georgian Bay basin.

These events are considered prominent (Terasmae, 1980) because of their (at least partial) co-existence during Late Wisconsin time.

Lake Algonquin presumably drained via the Kirkfield-Fenlon Falls outlet into Lake Iroquois. In turn, Lake Iroquois drained into the Champlain Sea when ice retreated north of the upper St. Lawrence Valley. Lake Algonquin also drained into the Champlain Sea when ice retreated north of the Ottawa and Mattawa River Valleys between Pembroke and North Bay. These three events can help correlate late-glacial events between the Ottawa-St. Lawrence Lowlands, the Lake Ontario Basin, and the upper Great Lakes (Terasmae, 1980).

The early and pre-Champlain Sea events of the Ottawa Valley, then, are extremely important in understanding the

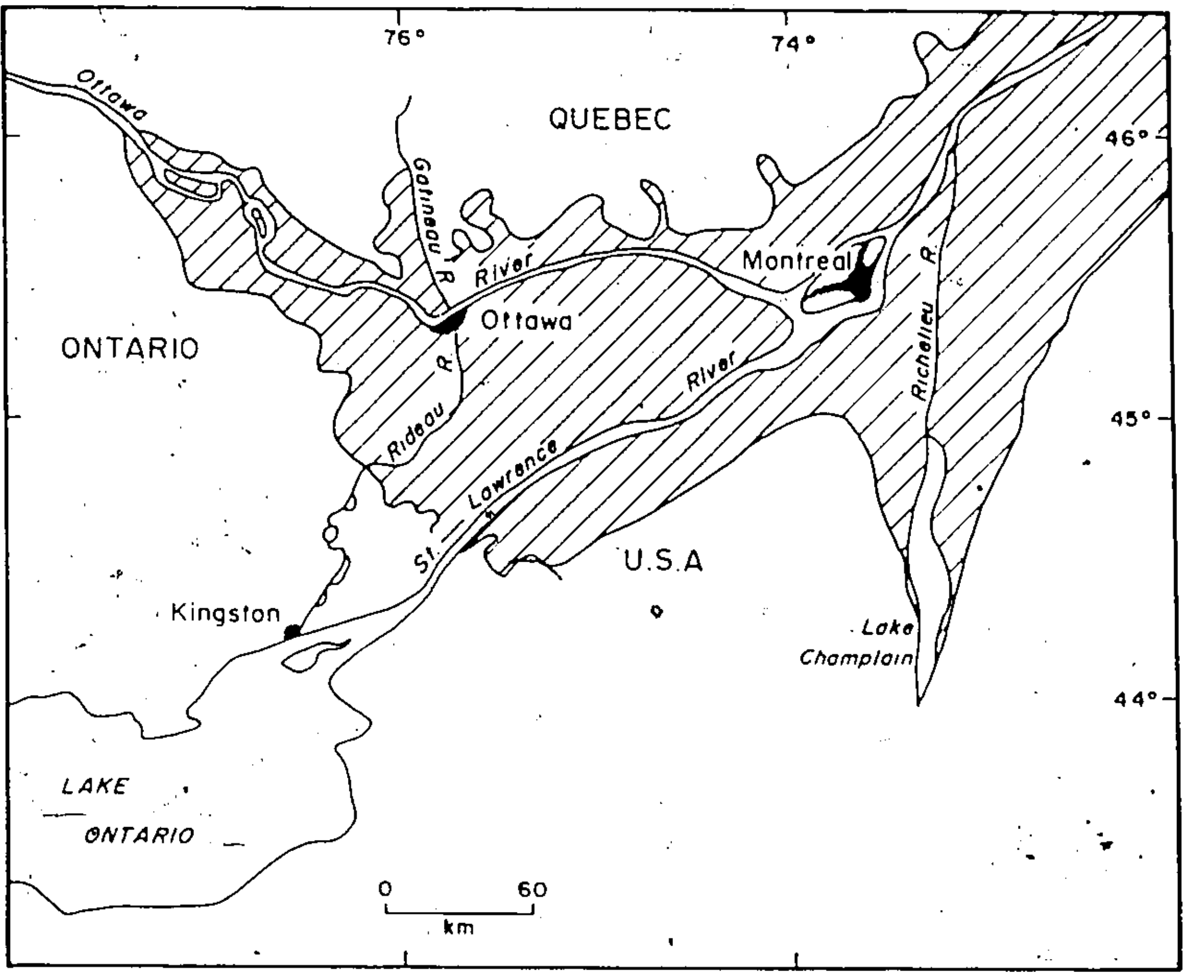


Figure 4: Limits of the Western Champlain Sea (after Anderson et al., 1985)

connection of these late-glacial events in southern Ontario, and in providing useful evidence for their correlation. Age and correlation of these events has been the subject of a great deal of debate, for example: Karrow et al. (1975), Richard (1975, 1978) and Sharpe (1979). Several reviews of the deglaciation chronology of south(eastern) Ontario have been published, for example: Prest (1970), Terasmae et al. (1972), Dreimanis (1977a, b) and Dreimanis and Karrow (1972).

Although evidence of several glacial and interglacial stages and substages has been found in the St. Lawrence Valley and the Great Lakes areas (Dreimanis and Karrow, 1972) little or no evidence has been found in the Ottawa Valley area. Evidence of glacial activity in the Ottawa area seems to be restricted to that left by the last (Wisconsinan) glaciation and the post-glacial Champlain Sea.

1.4.1 The Champlain Sea and Lake Iroquois

Great care must be taken in correlation of Lake Iroquois and Champlain Sea events. For example, MacDonald (1968) and Kirkland and Coates (1977) suggested that the waters of Lake Iroquois and the Champlain Sea were confluent. Clark and Karrow (1984) have demonstrated the improbability of such a relationship because the uplifted Iroquois strandline has an altitude of more than 240 m northwest of Kingston, Ontario, whereas the marine limit is not far from the present Lake Ontario level at 75 m. Kirkland and Coates (1977) joined isobases of Lake Iroquois to isobases of the Champlain Sea, bending them northward around the Adirondacks. They explained the bend as due to thin ice, but Clark and Karrow (1984) consider this inappropriate since the two water bodies were miscorrelated and forced to fit into a single warped surface.

Rather than a post-Iroquois phase, Clark and Karrow (1984) proposed correlation of marine strandlines in the St. Lawrence Lowland with the Trenton phase strandline in the Lake Ontario basin. In their view, the Champlain Sea might have initially entered the Lake Ontario basin, but in pre-Iroquois time. Coalescence of the water bodies is supported by high concentrations of acidic amino acids sampled from Lake Ontario bottom sediments (Shroeder and Bada, 1978), suggesting a marine origin. To date, however, no direct fossil evidence has been found for marine incursion into the Lake Ontario basin.

Anderson et al. (1985) proposed a high level proglacial lake that extended northward out of the Lake Ontario basin to the Ottawa Valley, starting during the Trenton phase of glacial Lake Iroquois. Since the Trenton phase is very close in time and elevation to the Belleville phase, and thus difficult to identify, it seems prudent to assign the lake to the already documented Belleville-Ft. Ann phase. This would create a single, large glacial lake in the Ottawa Valley, the Champlain Valley, and the St. Lawrence Lowland, as shown in Figure 5.

It is proposed here that the portion of this pre-Champlain Sea fresh water body occupying the Ottawa basin

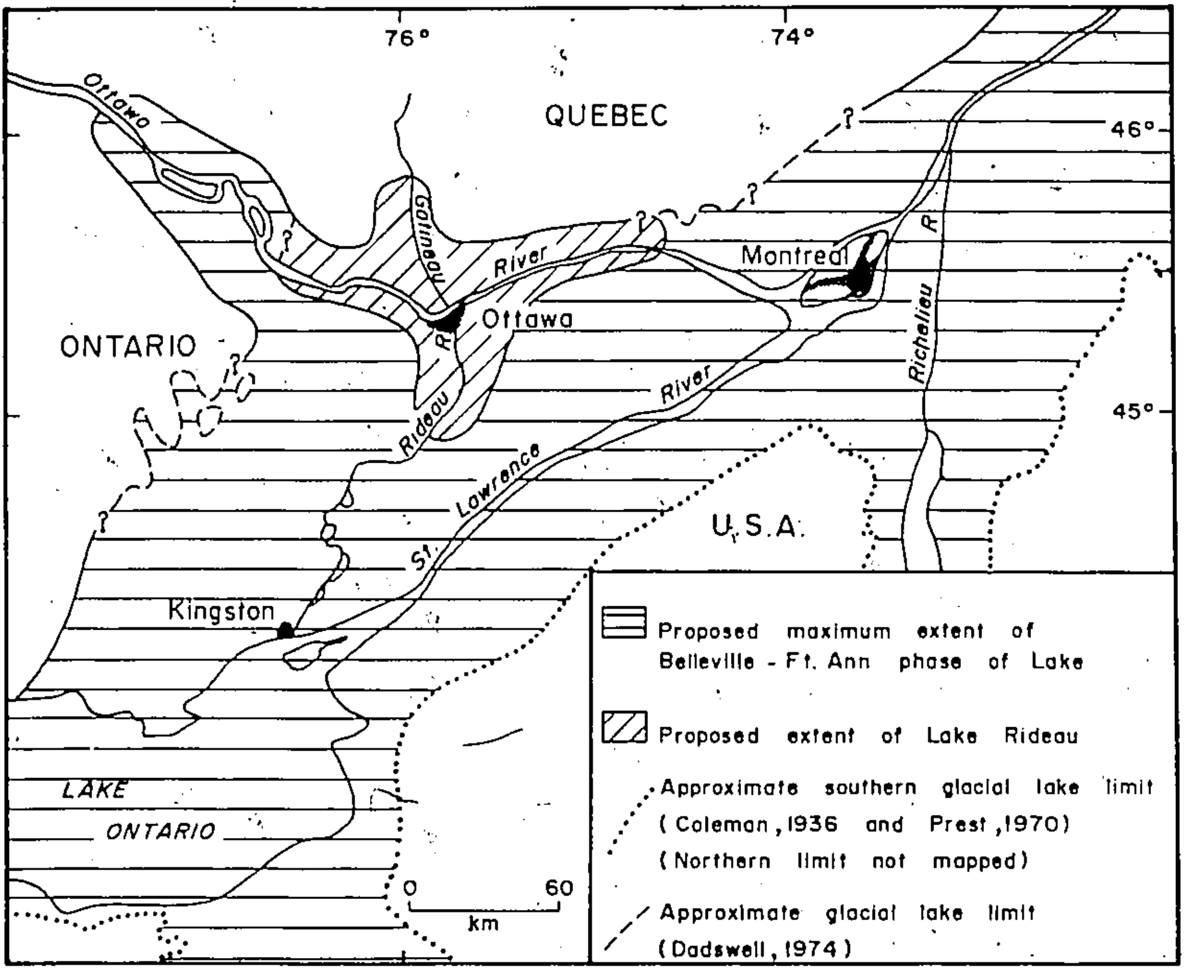


Figure 5: Extent and Distribution of Proglacial Lakes, Including Lake Rideau

area be called Lake Rideau. This name is taken from the type section on the bank of the Rideau River where the Foster pit is located. Banerjee (1973) described the laminated clay from this site as the Rideau Varves. Lake Rideau in the Ottawa basin correlates with the Belleville phase of Lake Iroquois in the Lake Ontario basin, and with the Ft. Ann phase of Lake Vermont in the Lake Champlain basin. The exact extent of the lake is not clear, as will be discussed in subsequent chapters.

The early, Transitional phase of the Champlain Sea was interpreted by Cronin (1977a) as indicating low and fluctuating salinities. This may be partly due to the influence of the fresh water from the Lake Ontario basin. Separation of the water bodies into the Lake Ontario basin and the Champlain basin probably occurred as a result of isostatic uplift. Confinement of the Champlain Sea to the Ottawa-St. Lawrence Lowlands then resulted in the more normal marine Hiatella arctica Phase (Cronin, 1977a).

1.4.2 The Champlain Sea and Lake Algonquin

Fresh water also apparently entered the Champlain Sea from Lake Algonquin. The connection between these water bodies has been established on the basis of geomorphological evidence such as terraces, outwash plains and a delta, and studies of the surficial deposits of the North Bay area (Chapman, 1975; Harrison, 1972) and the Chalk River area (Gadd, 1963; Catto et al., 1981, 1982). The principal link in this correlation is the drainage of Lake Algonquin through several outlets in the North Bay area into the westward extention of the Champlain Sea in the Petawawa-Chalk River area. There a large volume of sand was introduced, forming the Petawawa Sand Plain.

Terasmae and Hughes (1960) postulated that Lake Algonquin water drained through the North Bay outlet between 11,000 and 10,000 BP. Catto et al. (1982) estimated the outlet opened at 10,500 to 10,400 BP. Barnett and Clarke (1980) discovered freshwater shells at an elevation of 122 m (400 ft.) in a small delta southeast of Cobden, Ontario. The presence of these shells supports the proposed Georgian Bay-Lake Nipissing-Petawawa drainage route for water from Lake Algonquin to enter the Champlain Sea.

The mixing of fresh Lake Algonquin water and marine Champlain Sea water would result in salinity stratification and so, during the later stages of the Champlain Sea, both fresh water and marine water may have coexisted, but at different depths. The overlap between dates for freshwater and marine species demonstrates the care required in distinguishing between biostratigraphic and chronostratigraphic divisions of deposits in the Ottawa Valley area.

Alternatively, the relatively low salinity (and therefore low density) of seawater and the open nature of the basin may have allowed wind-driven overturn of the water mass. Thus, the co-existence of freshwater and marine species might simply reflect a tolerance for varying salinity, as is found in many intertidal species in modern environments.

1.5 PROBLEMS WITH RADIOCARBON DATING

A chronological discrepancy has arisen between radiocarbon dates from marine shells from the Ottawa Valley (Champlain Sea) and those obtained from freshwater materials in the basins of Lake Iroquois and Lake Algonquin. Radiocarbon dates have been cited to support the view that the Champlain Sea reached the Ottawa area as early as 12,000 BP (Richard, 1975), but the reliability of these dates has been questioned (Karrow, 1981; Hillaire-Marcel, 1981b) since almost all were obtained from marine mollusc shells. Dates on any material are subject to many sources of error (Olsson, 1970), but it seems that wood is the most reliable material for dating (Karrow and Anderson, 1975). In fact, Hillaire-Marcel (1977) suggested that dates from other sources be referred to as "shell dates" and so on.

1.5.1 The Old Carbon Effect

One point of controversy seems to be whether a constant radiocarbon error should be present in space and time. Hillaire-Marcel (1977) and Karrow and Anderson (1975) suggested old carbon from bedrock and glacial meltwater as possible sources of contamination. However, how much of this old carbon is able to enter the biosphere is unknown. The influence of these factors could easily vary in a restricted marine basin such as the western part of the Champlain Sea, where the oldest dates appear to be those from localities furthest from the ocean (Gadd, 1981). Since at least some of the carbonate involved could have originated from the

Paleozoic bedrock, the apparent ages of the samples would be greater than the true ages. This phenomenon has been termed the "old carbon" effect (Karrow and Anderson, 1975; Olsson, 1970) or the "old water" effect (Terasmae, 1980). Although some dates may be correctable for sources of error, the old water effect presents a special problem. As shown by Hillaire-Marcel and Vincent (1979), there is no evidence that the effect is constant in all marine basins or has remained unchanged through time in any one basin. Therefore, no reliable means of correcting radiocarbon ages to true ages is available for marine shell dates. Hillaire-Marcel (1981a) noted that some workers have identified the old carbon effect and attempted to correct it using dendrochronology methods, but these have obvious temporal limitations, and may not be applied to all dates. Terasmae (1980) proposed that this possible variance in error may explain some of the problems associated with the Champlain Sea chronology. There is also the possibility of old carbon contamination from groundwater interaction with the fossils.

1.5.2 The Mangerud Effect

Dating of marine mollusc shells presents another important problem because the Champlain Sea chronology is based almost exclusively on such dates. According to recent debate, these dates could be too old by several hundred years (Mangerud and Gulliksen, 1975; Hillaire-Marcel, 1977) or very close to accurate (Stuvier and Borns, 1975). Mangerud (1972) showed that modern marine shells from Norway averaged 450 years old because of the marine reservoir effect, and suggested that they could have apparent ages of as much as 2,500 years where other factors are involved. Mangerud and Gulliksen (1975) found errors of between 350 and 750 years for modern shells: 440 years for Norway, 510 years for Spitsbergen, and 750 years for Ellesmere Island, Canadian Arctic.

This problem arises from lack of isotopic equilibrium, usually in high latitudes where ice cover prevents surface circulation. Depending on circulation patterns, each body of water produces shells today yielding apparent ages which could be used as possible correction factors for dates. Shells from deep water probably yield ages which are too old because of old carbon in the water in which they live (Cronin, 1977b). Hillaire-Marcel (1977) demonstrated that deep Champlain Sea waters were deficient in ^{14}C in contrast to the surface waters which were in isotopic equilibrium with the atmosphere. Lowden and Blake (1975) also showed that deep water fossils from the the same locality gave anomalously old ages. Most fossils, however, lived in shallow, well-agitated environments which should have had normal interchange with atmospheric CO_2. The effect of seasonal ice cover on isotopic equilibrium seems to be unknown and largely ignored.

The apparent error may also change with the method of calculation of the date. For example, Blake (1975, 1979) noted that the Geological Survey of Canada dates are calculated so that the maximum possible error is 350 years.

1.5.3 Champlain Sea Dates

Most dates on Champlain Sea shells in southeastern Ontario and western Quebec range from 10,500-11,800 BP (Terasmae, 1980). However, two older dates have been obtained from shells in the Gatineau River Valley and from near Clayton, Ontario. The Gatineau dates are 11,900±160 BP (GSC 1772) and 12,200±160 BP (GSC 1646). Acceptance of these two dates would imply that ice retreated northward from Covey Hill (roughly 64 km south of Montreal) at nearly 13,000 BP. The problem with this is that the ice dam at Covey Hill (see Prest, 1970) presumably confined glacial Lake Iroquois, and if this dam disappeared shortly after 13,000 BP, allowing the Champlain Sea to extend westward into the Ottawa-St. Lawrence Lowlands, serious problems in deglaciation history would be created. For example, Gadd (1980a) proposed coeval marine and lacustrine events in the Ottawa Valley and the Lake Ontario basin, respectively. Gadd proposed an ice barrier at the east end of the present Lake Ontario separating the Champlain Sea from Lake Iroquois and post-Iroquois lakes (the calving-bay concept of Thomas, 1977). Karrow (1981) noted the physical difficulties in maintaining an ice dam. According to ice mechanics theory (Clark and Karrow, 1984), a dam of this size is possible, but would rapidly deteriorate, followed by calving. Thus, it seems unlikely that such a dam could have separated the Champlain Sea and Lake Iroquois.

Only three sites with wood and shell material have been reported. Near Burlington, Vermont, Wagner (1972) reported a date of 10,950±350 BP on wood (W 2309) and 11,420±350 BP on shells (W 2311), a difference of 470 years. Lowdon and Blake (1979) reported two dates from Mont St Hillaire, Quebec: wood at 10,500±90 BP (GSC 2200) and shells at 10,800±100 BP (GSC 2195), a difference of 300 years. They also reported a pair of dates from Saint-Cessaire, Quebec: wood at 10,500±90 BP (GSC 2861) and shells at 10,300±90 BP (GSC 2586).

Mott (1968) obtained similar dates from marine shells and algae from the Ottawa area and concluded that the validity of the shell dates was thereby established. However, both live in the same environment, and should reflect similar conditions. Expressed in a different way, the samples could be equally contaminated.

Bone is also not considered to be a very reliable material (Karrow, 1981), although acceptable ages have been obtained (Barker, 1970; Terasmae, 1981). Collagen, in contrast to bone, has provided very good dates since it is composed of organic rather than inorganic carbon compounds. Organic carbon apparently is more resistant to isotopic contamination, according to studies of material of known age (Berger, 1970; Overman and Clark, 1960). Bones of marine mammals have been dated from a few Champlain Sea localities with inconclusive results. Richard (1978) reported that Macoma balthica shells at the same altitude as the bone (believed to be the marine limit) near Clayton, Ontario yielded a date of 12,700±100 BP (GSC 2151). A sample dated earlier from the same locality provided an age of 12,800±100 BP (GSC 1859). Richard (1978) noted that the inner shell material from the second run was more reliable for this site. A date of 11,500±90 BP (GSC 2269) was obtained from the forefin of a bowhead whale (Harington, 1977) collected at 168 m at White Lake (35 km northwest of Clayton). Richard had anticipated that the mollusc and bone dates would be similar (presumably since they originated at the same elevation), and the reason for the 1,200 year discrepancy is unknown.

This result is significant, since the 11,500 BP age obtained from the bone at White Lake provides a minimum for deglaciation of the Clayton area and for arrival of marine waters into the western limits of the Champlain Sea. This date is notably the oldest for postglacial marine submergence in the Champlain Sea basin. However, as Catto et al. (1981) noted, the reliability of these dates has been questioned.

The above discussion serves to highlight some of the problems associated with radiocarbon dating and correlation. There are explanations for many variations of dates but all discussion points to variability of shell dates and the need to look at any date with critical analysis in light of all relevant information. Clearly, more data are needed from sites where shells and wood occur together.

1.6 CHAMPLAIN SEA PHASES IN THE OTTAWA VALLEY

Elson and Elson (1959) proposed the Hiatella and Mya phases of the Champlain Sea episode and the subsequent Lampsilis Lake phase for the freshwater period based on observations from the Montreal, Quebec area. Cronin (1977b) subsequently proposed an earlier Transitional phase at the beginning of the Champlain Sea, based on observations from the Champlain Valley in New York and Quebec. Initial studies did not provide detailed bathymetric estimates for each phase, but subsequent paleoecologic studies (eg Hillaire-Marcel, 1981) of the dominant species allow depth estimates to be made (see Figure 8).

Elson (1969a, b) reported the earlier, deep water *Hiatella* phase lasted from about 11,800 BP to between 10,800 and 10,600 BP (post St. Narcisse advance). In the Ottawa Valley area, the *Hiatella arctica* assemblage ranges from 11,600 to 9,910 BP (Rodrigues and Richard, 1983). The *Macoma balthica*, *Mytilis edulis*, *Portlandia arctica* and *Mya arenaria* associations were also present in different parts of the sea at the times shown in Figure 6.

The presence of more than one fossil assemblage during a given interval is related to the lateral and depth variations in the physical and chemical properties of the bottom water, substrate, and nutrient supply. Thus, *Hiatella arctica*-dominant assemblages are not necessarily characteristic of a particular time interval, but reflect local, often transient environmental conditions. This has been shown by Hillaire-Marcel (1981a) and Rodrigues and Richard (1983).

The later, shallow water *Mya* phase of Elson and Elson (1959) lasted from 10,870±100 BP (GRO 2031, Elson, 1969b) to 9,950±185 BP (Gif 2107, Hillaire-Marcel, 1974), the

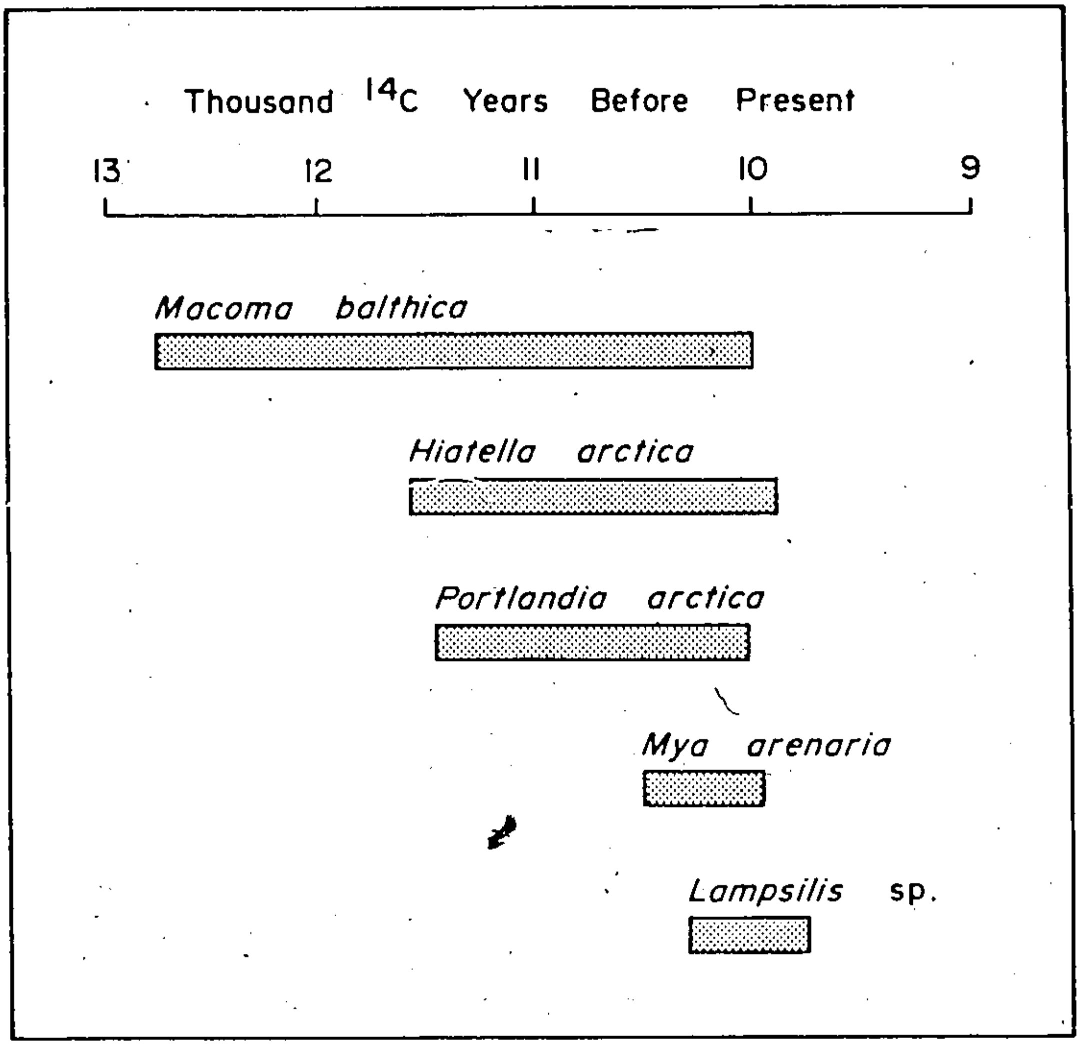


Figure 6: Duration of Fossil Assemblages in the Western Champlain Sea (after Rodrigues and Richard, 1983)

beginning of the Nipigon advance. In the Ottawa Valley, no reported radiocarbon dates are available for Mya arenaria: Rodrigues and Richard (1983) report the species was not observed in the western portion of the Champlain Sea, even during the Mya phase. The presence of cold, surface water from 10,800 BP to 10,500 BP may have prevented its westward migration.

After the Champlain Sea had fallen to a level of approximately 50 m above present sea level, the Ottawa Valley Lowland had emerged, but water remaining in the St. Lawrence Lowland between Cornwall and Deschaillons became fresh, forming Lampsilis Lake (Elson and Elson, 1959; Elson, 1962, 1964, 1968, 1969a, b; Prest, 1970). Elson (1969a, b) postulated that the Lampsilis phase succeeded the Mya phase in southwestern Quebec about 10,000 BP. Two radiocarbon dates support this view: 9,750±150 BP (GSC 2414) and 9,730±130 BP (GSC 1796, Lasalle et al., 1977) for shells from the Saint-Stanislas-de-Kosta and Quebec city areas, respectively.

Lampsilis shells from the Ottawa Valley, however, have yielded older dates: 10,300±90 BP (GSC 3235) and 10,200±90 BP (GSC 1968) from Vankleek Hill and Bourget sites, respectively. As shown by Rodrigues and Richard (1983), the difference between the dates for freshwater shells from the Ottawa Valley and southwestern Quebec and the overlap between the dates for freshwater and marine species are of particular interest. The above discussion shows the appearance of freshwater species in the Ottawa Valley was diachronous: the freshwater species appear to have arrived somewhat later in the Ottawa Valley than in southwestern Quebec.

1.7 THE BASIN CONCEPT

The concept of basins and basin analysis has been used in sedimentology and tectonics for some time. On a global scale, oceanographers routinely refer to world ocean basins, and on a smaller scale, limnologists refer to basins such as those in the Great Lakes area (Davidson-Arnott et al., 1982; Sly and Pryor, 1984; Lewis and Sly, 1971; Thomas et al., 1972). This terminology is now being used in the study of post-glacial marine water bodies such as the Champlain Sea, and large proglacial lakes.

Elson (1969a) introduced the basin concept, and proposed four basins for the Champlain Sea:

1. Champlain Valley
2. Lake St. Peter
3. Lake St. Francis
4. Ottawa Valley

Recent studies have shown that these basins are of different size and have very different characteristics. The original basins were loosely defined, and require redefinition. The Lake St. Peter and Lake St. Francis basins are small, and may represent short-lived events. It may be more prudent to suggest basins of similar size such as those of the Ottawa and Champlain Valleys, and to consider instead the upper and lower St. Lawrence Valleys as basins. As shown in the following discussion, there is strong isotopic and faunal evidence to support this view.

Division of the Champlain Sea into these basins follows the basin definition of McCormick and Thirvathukal (1976), ie: a roughly equidimensional depression with a narrow, shallow outlet to the open ocean (or water source). It also follows the example set by Sly and Pryor (1984) in which structural control (sills in the Lake Ontario basin) is used to separate smaller basins within a larger, unified basin. In the Champlain Sea basin, structural control is provided by the Ottawa Valley, the Champlain Valley, the St. Lawrence Valley, and the Frontenac Axis.

The first indirect evidence for these basins was given by Goldring (1922), whose study of sizes of Recent and Pleistocene molluscs showed the Champlain Sea fauna to be "stunted". Specimens from Montreal and Ottawa were studied, although most of the work concentrated on the Champlain Valley of New York and Vermont. Goldring noted a decrease in the number of species and a dwarfing of the fauna towards the west, which she attributed to decreased salinity away from the open ocean. She considered specimens from Montreal to be indicative of nearly marine conditions.

Wagner's (1970) results show less variation between Ottawa and Montreal fauna, but agree in part with Goldring's work. Wagner concluded that the small size of indicator species suggests brackish water conditions throughout the entire Champlain Sea, with the least salinity farthest from the ocean.

Later workers have disputed this claim and it has now become apparent that some of these differences may be attributed to regional variations from basin to basin. These are in turn a result of different physical, chemical and hydrologic conditions existing in each basin at a given time. Hillaire-Marcel (1980) demonstrated this in his study of the paleoecology of the marine post-glacial seas of Quebec, elaborating on the growth habits of the bivalves and explaining apparent contradictions using basinal parameters.

Thus, a new approach to the study of the Champlain Sea and other large ice-marginal water bodies is the use of paleoceanographic techniques. The methods of physical oceanography have been used for some time (eg Anicouchine and Sternberg, 1973) but the application of these techniques and concepts to paleoceanography appears to be much newer and promising (eg Hay, 1974; Schopf, 1980).

Determination of paleotemperature, paleosalinity and chemical composition of water may help in reconstructing water mass characteristics such as density, which affects circulation. When derived temperature and salinity conditions are combined with paleogeographic reconstruction of the basin margins, circulation patterns may be deduced, and used in the interpretation of paleoecology and sedimentary environments. The role of other factors such as wind is much more difficult to assess.

Several investigators have successfully used isotopic techniques to deduce paleotemperatures, salinity and circulation patterns (Corliss et al., 1982; Hillaire-Marcel, 1977, 1980). Many studies have reported paleotemperatures determined on the basis of oxygen isotope composition of fossils (eg Urey et al., 1951; Lowenstam and Epstein, 1954; Emiliani, 1955). Actually, the first suggested use for the oxygen isotope composition of fossils was to distinguish between freshwater and marine organisms (Urey, 1947). Epstein and Mayeda (1953) first showed that the oxygen isotope composition of sea water varies directly with salinity but little use of this relation has been made in determining paleosalinites. Possibly part of the problem may lie in the separation of temperature and salinity effects on isotopes.

Temperature is a complicating factor because it independantly affects the the isotopic composition of the shell. However, if one can assume (or prove) that temperature was constant for the period in question, then the isotopic composition of the shell will reflect only the composition of the water. The difficulty with this method is in finding a truly independant method of determining temperature stability.

Before paleosalinities can be determined, the isotopic composition of the fresh and marine waters mixed to produce the intermediate brackish water must be determined. These may be obtained by analyzing shells of freshwater and marine organisms which lived at the same time in the area in question. Again, the problem arises with maintaining constant or comparable temperatures between these two reference groups. Hillaire-Marcel (1981a) estimated the salinities of the melting Laurentide ice sheet, the sea water in the St. Lawrence Gulf, and the intermediate Champlain Sea water, as shown in Figure 7.

Using isotopic evidence, Corliss et al. (1982) showed that there was a major pulse of fresh water into the Champlain Sea, most likely from melting Laurentide ice, around 10,800 BP. Hillaire-Marcel's profiles for the late (ca 10,300 BP) Champlain Sea, based on carbon and oxygen isotope measurements, show strong temperature and salinity changes with depth. In the upper 50 m, salinity increases from less than 10 ppt to 30 ppt, and temperatures decrease from 10 °C to 0 °C (Figure 8).

In the Ottawa basin, Rodrigues and Richard (1983) have used paleoceanographic techniques to explain the diachronous appearance of freshwater shells in the Ottawa Valley and southwestern Quebec, and the overlap of marine and freshwater shell dates. Macrofossil assemblages characterized by both freshwater and marine shells support the concept of salinity stratification.

1.8 RHYTHMITE BACKGROUND AND DISTRIBUTION

Logan (1863) first referred to the Champlain Sea sands and clays of the Ottawa district. Others followed, describing the clays in general terms: DeGeer (1892); Dawson (1893); Wilson (1898); Ells (1898, 1901); Ami (1900); Keele and Johnston (1913). Dawson (1893) noted upper (= non-marine?) and lower (=marine) clays in the St. Lawrence Lowlands with similar characteristics to the clays of the

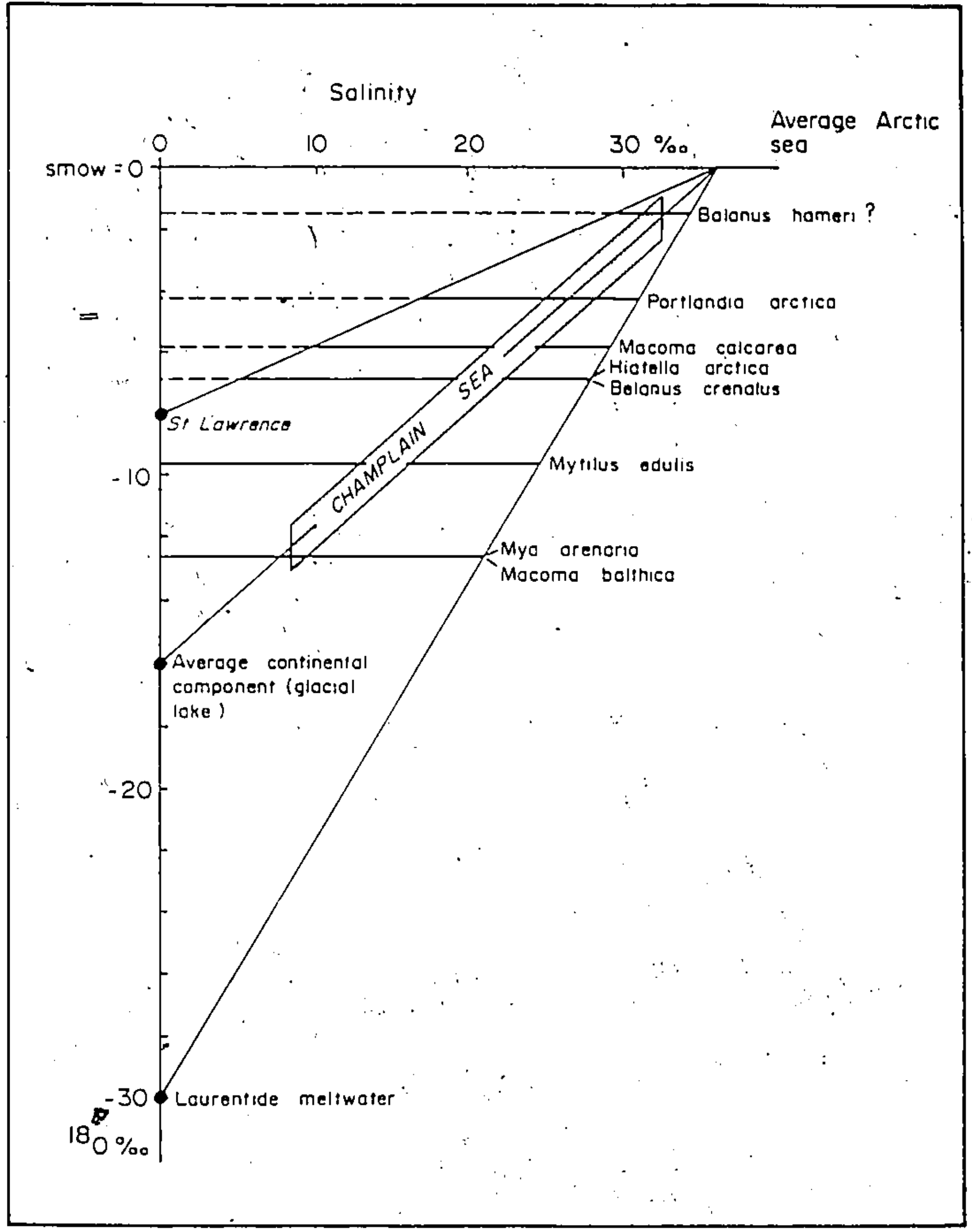


Figure 7: Estimated Champlain Sea Paleosalinity based on Oxygen Isotopes (After Hillaire-Marcel, 1981a)

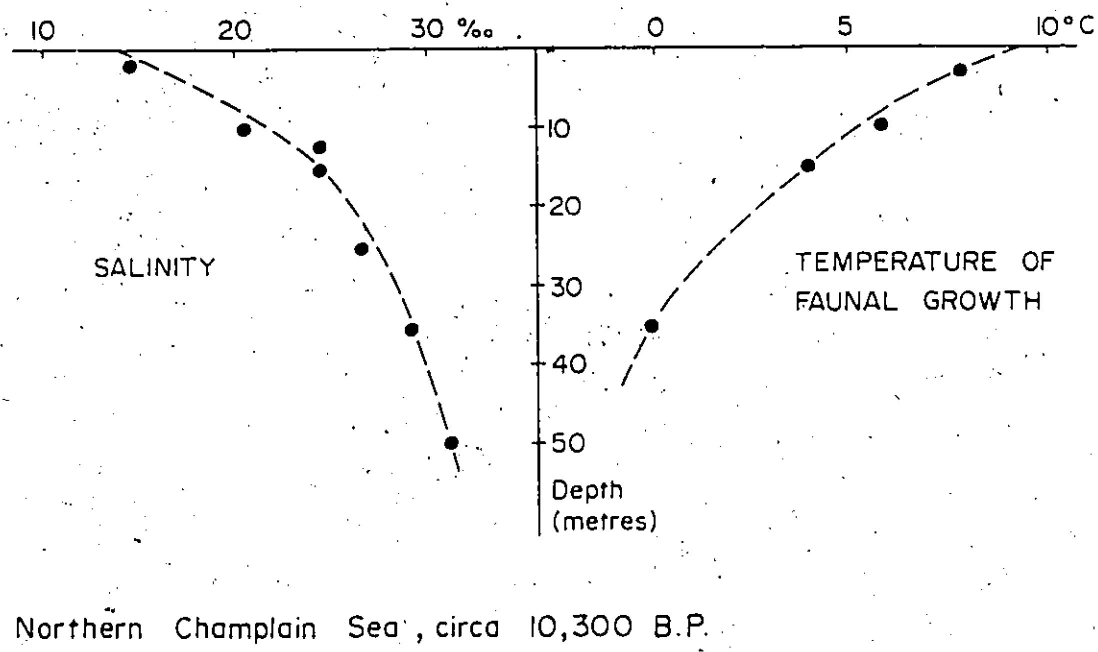


Figure 8: Paleotemperature and Paleosalinity with Depth in the Champlain Sea (After Hillaire-Marcel, 1981a)

Ottawa Valley.

Johnston (1916, 1917) studied the clays in detail. He noted their occurrence and distribution, accurately describing and dividing them into upper and lower clays. He noted the well laminated nature of the lower clays, the presence of dropstones, convolute bedding attributed to ice-induced shearing, and the transition to apparently massive upper clay. Several fossils were also noted: Balanus sp., Cylichna alba Brown, Hiatella arctica, Macoma balthica, Mytilus edulis, and Portlandia arctica. In the upper clay, Johnston noted rip-up clasts and redeposited clasts of the lower clays, which he attributed to the action of ice. This is an active mixing process of modern arctic fjords (Gilbert, 1983). Johnston (1917) documented several exposures of laminated and massive clay in the Ottawa area, the best stratigraphic section being located at Rideau Junction, near the Foster pit study site on the Rideau River (Figure 2).

Gadd (1958, 1959) greatly expanded the observed area of occurrence of the laminated clay when he noted it in boreholes in the Chalk River area. Boreholes reached bedrock beneath a maximum clay thickness of 10 m (31.9 ft.). Structurally, these clays are thixotropic (Catto, 1978), and are similar to brackish water sediments exposed throughout the lower St. Lawrence and Ottawa Valleys, and referred to as the Leda clays (Crawford, 1963; Crawford and Eden, 1965).

Catto et al. (1981) reported that stratification in the clay becomes more pronounced upon desiccation. This appears to differ from earlier drilling studies which did not observe stratified sediments (Gadd, 1958, 1959; Gartner-Lee, 1977). Dark grey beds with modal stratal thickness of 1 cm were observed, regularly separated by light grey bands 1-2.5 cm thick. According to Catto (1978), there was no difference in grain size distribution between light and dark bands, but a difference in composition was found, with organic matter and oxidized material enriched in darker bands and clay minerals depleted in lighter bands. Similar observations regarding organic matter were made by Johnston (1916, 1917) on the upper clays. Catto (1978) speculated that the stratification is not due to turbidity currents, because they produce different grain size distributions (Banerjee, 1973).

Stratification may be the result of periodic organic input due to seasonal overturn of the watermass, as is common in fjords (Gilbert, 1983). Seasonal overturn could occur as a result of outwash- or calving-produced influx of fresh water. Overturn would occur in late summer after the influx of fresh water created a hyperpycnal density contrast, resulting in alternation of thin, dark, organic-rich winter layers and lighter, organic-poor spring layers (Catto, 1978; Catto et al., 1981).

Density stratification in the water body is also a possible mechanism to account for the similarity in grain size and the difference in mineralogy between light and dark layers. This may be a more reasonable explanation than seasonal overturn, since it is difficult to envision high organic production during winter months when biotic activity is at a minimum or greatly reduced. It is more likely that the relatively high organic content of the winter layer is due to low clastic input during the winter months when runoff and erosion are low.

Gadd (1961, 1962) postulated that the late-glacial Rideau Valley was blocked by the Bowesville Moraine (now termed the South Gloucester Ridge) and that at a stage just prior to marine submergence, the valley contained a glacial lake. He noted sections exposing 3 m (10 ft.) of "glacial lake varved sediments" overlying "glacial till" along the banks of the Rideau River between Uplands and Long Island (Manotick). He also noted that in at least one section near the northern tip of Long Island, varves grade upward into massive marine clays that contain typical fossils of the Champlain Sea deep water sediments. No evidence was given by Gadd (1961) for deep water deposition of these sediments, and it seems highly speculative that any fossils present represent deep water conditions. Although several of the fossils found have relatively wide bathymetric zonation, none are known to occupy deep water selectively.

Gadd (1962) noted an apparently rapid and direct gradation between the two types of sediments (the varved silts and the overlying marine clay) rather than an erosional break between the glacial lake and marine events as postulated by MacClintock (1958) for the area to the south. It now appears that there is some evidence for a break in sedimentation, although not erosional, as shown in the following sections.

Romanelli (1970) conducted a study of the deposits in the Foster and Grandmaitre pits and greatly expanded the knowledge of the sedimentology and stratigraphy of the clays. He identified the foraminifera *Elphidium bartletti* Cushman, *Protelphidium orbiculare* (Brady), *Cassidulina islandica* and *Pseudopolymorphina hovanglie* (Cushman) in the upper clay. Present study shows that the stratigraphic position of these fossils given by Romanelli (1970) is somewhat in error, but their presence is paleoenvironmentally significant.

Banerjee (1973) named the lower clays the "Rideau River varves", and described structures indicative of slumping at a delta front and turbidite-type deposition. The varves, however, appear to defy numerical analysis as attempted by Banerjee (1973) and Agterberg and Banerjee (1969), suggesting that they are episodic rhythmites rather than true (seasonal) varves.

Chapter II

GLACIOMARINE AND GLACIOLACUSTRINE ENVIRONMENTS

2.1 INTRODUCTION

Since the lowermost clay unit in the Ottawa Valley appears to be glaciolacustrine, and the overlying clay unit appears to be glaciomarine in origin, a thorough understanding of glaciolacustrine and glaciomarine environments is required in order to distinguish the two.

The following section summarizes those aspects of glaciomarine and glaciolacustrine sedimentation which are most important in dealing with the early Champlain Sea deposits and the preceeding (assumed) glacial lake sediments. Of particular importance are water density, sediment load and temperature effects as these control water mass characteristics and ultimately, depositional style.

2.2 THE EFFECTS OF SALINITY

Salinity has a profound effect on circulation, depositional style, faunal growth and faunal preservation potential. Paleosalinity, therefore, must be considered when analysing early and pre-Champlain Sea sediments.

Under normal conditions, the suspended sediment and freshwater discharge entering a marine basin is separated from the bedload and overflows the sea water of greater density (Gilbert, 1983). The concentration of suspended sediment (assuming dry sediment density 2.70 g/cc) necessary to overcome the density difference between fresh and marine water is shown in Table 1. Sediment loads required, however, are rarely attained in normal ice-marginal conditions. Thus, salinity has a significant effect on the mode of sediment transport within a basin. For example, density-current underflows formed directly from inflowing meltwater are recognized as playing a key role in the formation of coarse-grained portions of glaciolacustrine varves and rhythmites. Such density-current processes are thought to be supressed in the marine environment because the density of the marine water normally exceeds that of the inflowing sediment-laden meltwater (Table 1).

TABLE 1

Concentration of Suspended Sediment Required to Give Density Equal to Sea Water (From Gilbert, 1983)

Salinity (ppt)	Density at 3 °C (g/cc)	Sediment Concentration (g/l)
10	1.0080	12.7
15	1.0120	19.1
20	1.0160	25.4
25	1.0200	31.8
30	1.0240	38.1
33	1.0262	41.6

A second important aspect of salinity is the effect on depositional style. In a glaciolacustrine environment, grain sizes remain hydrodynamically separate. Wind and density-currents are able to sort texturally distinct components which ultimately are preserved as separate deposits. In contrast, flocculation in the marine environment results in simultaneous sedimentation of a variety of grain aggregates as well as separate grains of coarser texture (Syvitski and Murray, 1981). Thus, even a small amount of mixing between fresh and marine waters is important, as salinity values of 3-4 parts per thousand (ppt) are effective in flocculating fine particles (Hoskin and Burrell, 1972; Kranck, 1973). This fact has often been used to explain the absence of varved sediments in glaciomarine environments.

The third, and possibly most important aspect of fine sediment deposition, is the time factor in sedimentation. This effects the type of organism able to survive, and ultimately the preservation potential of the fossils (Dodd and Stanton, 1981). Since flocculation increases the effective fall diameter of aggregated particles, settling time is greatly reduced, and the chances of preserving faunal remains becomes greater. For example, according to Stoke's Law, a particle of 1 um diameter will reach the bottom of a 100 m deep basin at 0 °C in 13 years; a 4 um particle in 146 days, and a 14 um particle in 12 days (Gilbert, 1983).

Salinity thus becomes important in the preservation potential of the Champlain Sea fauna. Where salinities are close to normal marine, sedimentation rates may be higher, and burial rapid. If salinity tends to be very low (brackish) to fresh, there is a potential for more mixing of water, sediment, and fauna, reducing the paleoecological potential of the fauna.

The type of organism preserved will also be affected. High sediment load will place a strain on filter feeders, and high sedimentation rates will place a strain on the burrowers, since they must maintain a constant depth. Juvenile mortality may also be strongly influenced, depending on the periodic or seasonal nature of the sediment input. This is an important factor when considering the effect biota have on sediments. Smith and Syvitski (1982) have shown that biological aggregation of fines at the sediment-water interface may be an important process in the glaciolacustrine environment (where aggregates do not usually form), and fjord studies (Gilbert, 1982, 1983) have shown that bioturbation plays an important role in eliminating any primary bedding which might develop in glaciomarine sediments.

These processes, which inhibit rhythmite formation or preservation in a marine basin, would be expected to exert their greatest influence in areas distal to meltwater input which are favoured for varve deposition in glacial lakes (Ashley, 1975). Thus, glaciomarine rhythmites or varves should be associated with sediments deposited in proximal areas such as deltaic or meltwater fan environments (Domack, 1984). If this is so, then glaciomarine rhythmites may not exhibit the same textural and bedding relationship characteristics as glaciolacustrine rhythmites.

2.3 THE GLACIOMARINE ENVIRONMENT

One of the most difficult problems is the development of criteria for identification of glaciomarine sediments and their distinction from other associated sediments. Anderson (1983) noted criteria such as: particle shape and surface texture, clast fabric, mineralogic and chemical composition, stratification type, thickness and lateral extent, stratigraphic and facies relationships and bounding surfaces, dropstones and striated pavements. Unfortunately, most investigations of supposed glaciomarine deposits relied on only a few criteria, which varied with different investigators. In fact, much controversy still exists as to whether such lithified deposits, particularly diamictites, are actually glacial in origin (Boulton and Deynoux, 1971; Crowell, 1957; Eyles et al., 1983; Harland et al., 1966; Schermerhorn, 1974).

Misconceptions also exist regarding glaciomarine sedimentation. These misconceptions are generally the result of poor understanding of the modern environment, which makes interpretation of the ancient record much more difficult. Another problem is the difficulty of study in modern glaciomarine environments. Modern glaciomarine environments occur in a variety of settings from the Antarctic to coastal areas of the Gulf of Alaska (Domack, 1982). The influence of climate on these environments is profound. Sedimentation rates in the coastal embayments of the Gulf of Alaska exceed 1 m per year on average and range up to 3.75 m per year (Molnia, 1979), which can be compared with the world average rate for continental shelf sedimentation of 4.5 mm per year (Domack, 1982). In the Antarctic, rates of terrigenous sedimentation are in the order of 0.03 mm per year (Orheim and Elveroi, 1981). The facies patterns within glaciomarine environments are now being elucidated, and are proving to be distinctive (Anderson et al., 1980; Boulton and Deynoux, 1971; Domack, 1982; Drewry and Cooper, 1981; Molnia, 1983; Molnia and Bingham, 1980; Orheim and Elveroi, 1981; Powell, 1981; Wright and Anderson, 1982).

In Canada, there has been a significant amount of mid-latitude post-glacial glaciomarine deposition. Post-glacial inundation was extensive and resulted from (slow) isostatic depression of the crust, concurrent with eustatic rise in sea level. In southeastern Canada, over 225,000 km^2 were submerged, as shown in Figure 3. Thus, the Tyrrell, Iberville, Goldthwaite, Laflamme, and Champlain Seas formed in the Hudson/James Bay, Ungava Bay, Gulf of St. Lawrence, Saguenay, and Ottawa-St. Lawrence Valley Lowland areas, respectively. Dionne (1972) and Elson (1969a) give good summaries of these post-glacial seas.

2.3.1 Glaciomarine Rhythmites

Rhythmites or varves are not common in glaciomarine deposits (Domack, 1984; Edwards, 1978). This feature has been used to distinguish between glaciolacustrine and glaciomarine environments in the absence of more conclusive evidence (eg Lindsey, 1971). Carey and Ahmed (1961) suggested that glaciomarine rhythmites should exist, and recent investigations of fjord (Gilbert, 1982, 1983; Powell, 1981) and other (Domack, 1982, 1984) glaciomarine environments have shown rhythmically bedded terrigenous deposits. Domack (1984), Mackeiwicz et al. (1984) and Stevens (1985) have shown that the cyclic character of sediment colour, grain size, carbonate and organic matter content may be explained by rhythmic variation in tidal influence, sediment supply and transport mechanisms.

One of the greatest problems in the creation of glaciomarine rhythmites is the difficulty of generating underflow currents. The problem arises as to whether glacial discharges can, in addition to rising buoyantly to produce interflows or overflows, be sufficiently dense and turbulent to develop underflows that can maintain their integrity for any distance away from the effluent source. Underflows are not widely encountered since they require high sediment concentration in normal marine waters (> 40 g/l as shown in Table 1). Powell (1980) investigated the physical relationships required to produce such flows, and concluded that grain flows and turbidity currents are possible underflow mechanisms. The most likely origin of turbidity currents is rapid deposition of bedload causing oversteepening and slumping. Another possibility is that channelized meltwater with high bedload concentration entering the sea may experience a hydraulic jump (Powell, 1980).

These mechanisms are proposed for relatively continuous or steady currents. However, sporadic currents may also be generated by a number of processes. Sediment gravity flows in the marine environment are more easily achieved by slumping due to slope instability than by continuous turbidity currents from meltwater sources. Many mechanisms have been found to induce slumping such as: slope oversteepening, biogenic gas production, wave and storm action in shallow water and earthquakes (Morgenstern, 1967). Calving in ice-marginal areas is also a possibility.

Mackeiwicz et al. (1984) noted three processes whereby laminated glaciomarine "rhythmites" may form.

1. Particle settling from turbid meltwater plumes (overflows) or within the water column (interflows) produces sets of basal silt laminae grading upward to mud. These couplets are termed cyclopels.

2. Short distance (< 0.5 km) transport by traction currents from a density current that is continuously fed as subglacial meltwater discharge (underflow). This produces beds or thick laminae of coarse-grained sediment.

3. Surge type turbidity currents originating from sediment sliding (slumping) are capable of producing beds ranging in thickness and particle size.

2.4 THE GLACIOLACUSTRINE ENVIRONMENT

2.4.1 Introduction

Lake basins are relatively efficient sediment sinks and so ice-marginal lake basins become the final resting place for much glacigenic sediment. Like glaciomarine waterbodies, glacier-fed lakes range in size from a few square metres (kettles) to hundreds of thousands of km^2, such as the former Lake Agassiz (Teller and Clayton, 1983) and the Laurentian Great Lakes (Prest, 1970). Life spans vary considerably from a few days (for small ice-marginal lakes) to thousands of years (for larger bodies). Glaciolacustrine deposits similarly range widely in thickness from a few cm (small, temporarily ponded lakes) to tens of metres.

The amount and type of sediment deposited is strongly influenced by the proximity of the lake to the glacier. In this respect, post-glacial seas such as the Champlain Sea and glaciolacustrine bodies such as Lake Agassiz or Lake Iroquois represent similar, if not analogous ice-contact water bodies.

At the glacier margin, debris may be released directly by calving off the ice front, or, if the glacier edge is floating, by dropping from the subglacial surface. This process explains the "rainout" facies (Eyles and Eyles, 1983), which is a variation on ice-rafting.

The resulting deposits characteristically contain both diamictons and waterlain traction sediments, reflecting the shifting glacier margin and the intermittent release of till and other glacial sediments. A variety of terms have been given to these deposits: waterlain till, waterlaid till, lacustrotill, aquatill, subaqueous till, and subaquatic flow till (May, 1977; Evenson et al., 1977; Dreimanis, 1979).

More commonly studied are the distal sediments. These cover a larger area than the proximal sediments, and consist of all material not immediately deposited upon entering the lake. The pattern in which inflowing water and sediment interacts with the lake water affects subsequent transport and deposition of all but the coarsest bedload, so dispersal and transport mechanisms are of prime importance.

The exact pattern of inflow mixing and velocity decrease is governed by such factors as: inflow discharge and velocity, concentration of suspended matter, Coriolis effect and channel shape. Most important of all is the density difference between inflowing water and that of the lake, and the vertical density distribution of the lake water.

Thermally-induced density stratification is a common mechanism for separating water masses, and plays an important role in the distribution of fine sediment (Ashley et al., 1985). At atmospheric pressure, water attains a maximum density of 1.000 g/cc at 3.98°C (here considered to be 4°C). In ice-marginal conditions, where temperatures are low, the effect of temperature changes on water density is much smaller than at higher temperatures. For example, the density difference caused by a change from 19°C to 20°C is twenty times greater than that caused by a change from 4°C to 5°C (Figure 9).

At the low temperatures of ice-marginal environments, this thermal effect is responsible for a process called <u>cabbeling</u> (Foster, 1972) in which two water bodies of different temperatures mix and create a third, denser body due to temperature mixing: eg mixing equal quantities of 2°C and 6°C water to form a third mass at 4°C with maximum density. This thermal effect, when combined with marginal sediment concentrations, may be a very important factor in generating density current underflows. How common this effect may be is unknown, but it appears that in ice marginal areas it is relatively common.

Upon entering the lake, turbulent eddies along the margin of inflowing water cause an immediate mixing and dilution, resulting in either a two- or three-dimensional expansion of the flow and a decrease in the flow velocity towards the lake. The diluted, expanded inflow is called the plume.

The plume may spread over the basin as an overflow if the density is less than that of the lake water, or as an underflow if it is more dense (Figure 10A). These inflow

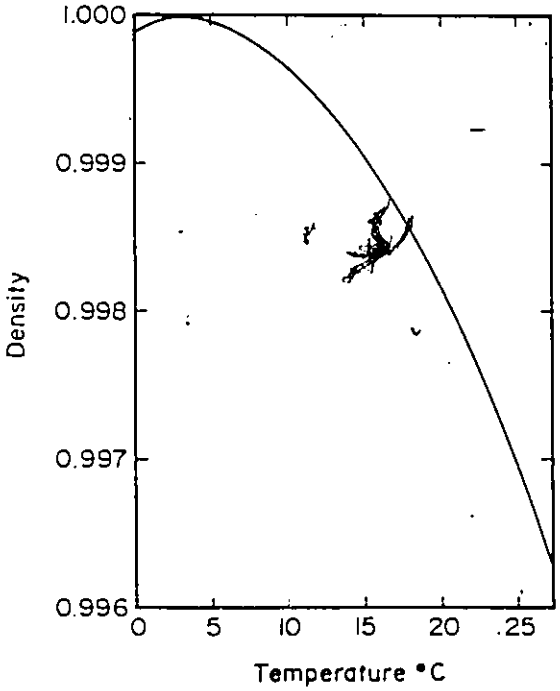
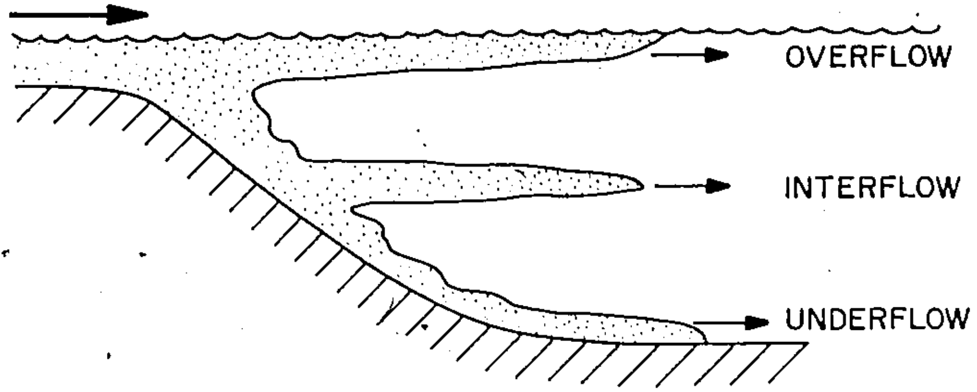


Figure 9: Temperature Versus Density for Pure Water (after Ashley et al., 1985)

A. Stratified inflow



B. Homopycnal inflow

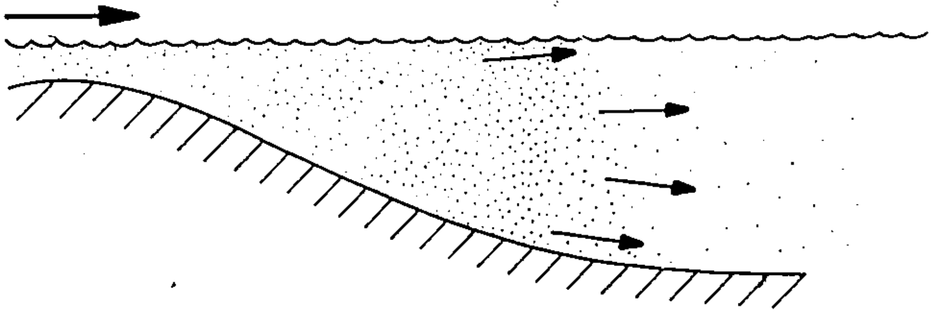


Figure 10: Principal Inflow Patterns and Mixing Types
(after Ashley et al., 1985)

types were termed hypopycnal and hyperpycnal respectively, by Bates (1953). The greater the density difference between inflow and lake water, the more energy required to mix them (Harleman, 1961; Kato and Phillips, 1969), reducing mixing of the water bodies. This tends to reduce the inflow expansion and restrict it to a discrete density current throughout the lake. This factor is particularly apparent when glaciolacustrine and glaciomarine environments are compared, since it is often impossible for incoming water to overcome the density of the marine water body (see section 2.2). Rarely, when sediment concentrations are high enough, underlows may occur in marine environments such as the Gulf of Alaska (Powell, 1981). Consequently, density underflows are much more common in glaciolacustrine environments, where lower sediment concentrations are required.

Overflow and underflow plumes may occur in initially unstratified or stratified lakes, although the presence of the plume itself makes the lake stratified at this point. For initially stratified lakes, inflowing water may be intermediate in density between cold, bottom water and warm, surface water. Interflows then occur, as shown in Figure 10A.

In weakly stratified or unstratified lakes where inflowing density is equal to that of the lake, homopycnal flow (Bates, 1953) will result (Figure 10B). Mixing is three-dimensional and the plume is rapidly dispersed. Homopycnal inflows appear to be relatively uncommon, and are probably confined to shallow, freely circulating lakes with inflow of relatively constant density. In marine bodies where water density is higher, homopycnal flow is more common.

The seasonal and weather-dependant nature of glacial discharge, temperature, and sediment concentration along with the seasonal evolution of the lake's thermal stratification result in complex mixing patterns throughout the year.. These temporal variations in sediment influx and dispersal mechanisms produce characteristic alternations of sedimentation which are essentially cyclic in nature. Rhythmic deposition is characteristic of glaciolacustrine environments, and thus any model of lake sedimentation must include mechanisms for sediment dispersal which allow for some sediment variability, and yet ensure rhythmicity.

2.4.2 Varve or Rhythmite ?

Overall rhythmicity is mainly a function of the seasonally controlled alternation between short-term glacial melt season and the rest of the year. Within this alternation, other types of rhythmic sedimentation may occur. For example, during the summer season: pulses in a single flow (minutes), slump-generated surge currents (minutes), diurnal discharge variations (hours), or normal weather changes (days) may each produce small-scale rhythmic bedding (Ashley et al., 1985). Even in the winter season, occasional slumps may produce rhythmic units such as the "winter varves" described by Shaw and Archer (1978).

Thus, there are several possible causes of rhythmic sedimentation, each representing a different time scale or mechanism of deposition. The term varve, however, is normally restricted to a sedimentation unit deposited during a one year period by any mechanism. Similar couplets that are not seasonal, or for which there appears to be poor chronological control, should be termed rhythmites. The use of this term is prudent in all cases where sedimentology or stratigraphy makes division into clear winter/summer layers impractical, and the temporal setting is either in doubt or undefined.

The term varve is defined (Gary et al., 1972) as "A sedimentary bed or lamina or sequence of laminae deposited in a body of still water within a year's time, specifically a thin pair of graded glaciolacustrine layers seasonally deposited (usually by meltwater streams) in a glacial lake or other water body of still water in front of a glacier. A glacial varve normally includes a 'summer' layer consisting of relatively coarse-grained, light-coloured sediment (usually sand or silt) produced by rapid melting in the warm months, which grades upward into a thinner, 'winter' layer, consisting of very fine-grained (clayey), often organic, dark sediment slowly deposited from suspension in quiet water while the streams were ice-bound".

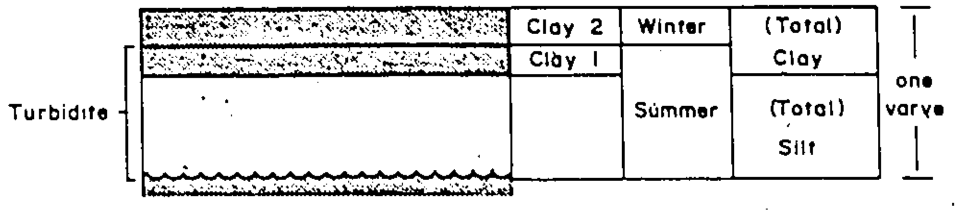
Banerjee (1973) proposed that varve is a conceptual model that includes all material deposited in one year. Varves are commonly couplets that may be divided into a summer part (silt) and a winter part (clay), however they are often more complex. There are problems, then, with this simplistic approach to fine-grained laminated sediments. For example, if the summer layer is considered to be made by a turbidity current, then there is a difference between the total clay thickness and the true thickness of the winter part (Banerjee, 1973), as shown in Figure 11A. Similarly, the silt layer may constitute only a portion of the true summer thickness. Where multiple flow events occur as in summer turbidites 1-3 in Figure 11B and summer turbidites 1-2 in Figure 11C, silt and clay are interlaminated and do not represent simple summer/winter deposits. These more complex (varve) types are more appropriately termed episodic rhythmites.

When a sequence of lacustrine sediments shows regular and repeated alternations of silt or sand with clay layers, it has usually been assumed that the couplet is a varve representing a year's deposition. Only two methods can be regarded as direct and conclusive evidence for proving the annual nature of these deposits:

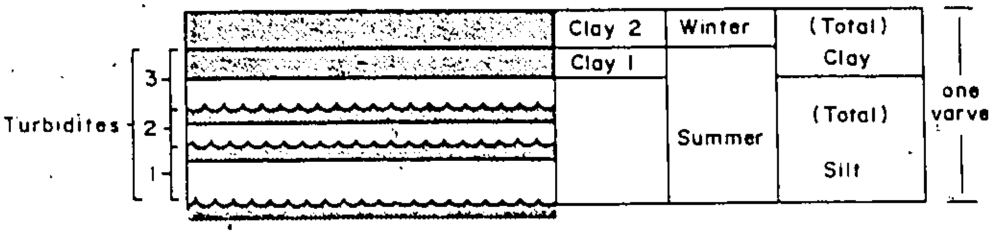
1. Pollen and spores present in the "summer" layer but rare or absent in the "winter" layer (Terasmae, 1965); and
2. A general correspondance between ages obtained by radiocarbon dating and those obtained by counting varves (Antevs, 1957).

Under somewhat unusual circumstances, the difference between winter and summer temperatures may lead to different carbonate concentrations in the couplet. Dell (1973) demonstrated that low winter temperatures may dissolve

(a) Single graded unit in summer silt.
Clay I = clay deposited during summer by the turbidity current.



(b) Multiple graded unit in the summer silt layer



(c) Cross-laminated and parallel-laminated summer silt layer

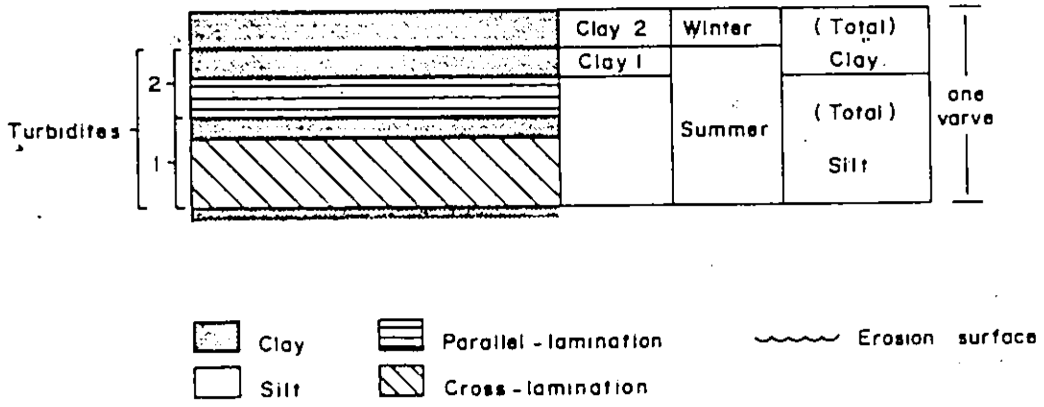


Figure 11: True Thicknesses of Winter and Summer Portions of Varves (After Banerjee, 1973)

enough detrital carbonate to produce carbonate-poor winter layers, and carbonate-rich summer layers. In ice-marginal positions, it is unlikely that there would be sufficient temperature difference to affect carbonate solution. More likely, it would reflect differences in the rate of deposition, and hence, solution. Lastly, this mechanism obviously only applies where there is sufficient carbonate input from the eroded bedrock.

2.4.2.1 Annual Versus Episodic Rhythmites

A constant problem in analyzing glaciolacustrine sediments is which factors control rhythmicity. Two processes may be responsible: randomly occurring slump-generated surge currents, and regularly alternating (seasonal) processes. Both involve sedimentation from turbid density-driven underflows, however the seasonally controlled rhythmites (varves) may involve overflow-interflows and quasi-continuous flows as well as surge currents.

Rhythmites formed exclusively from overflow-interflow currents are relatively easy to recognize, as shown in the following section. They are thin, regularly bedded, and contain no current structures, so they pose few problems of confusion with surge deposits. The difficult problem is distinguishing varves (annual rhythmites) formed predominantly by quasi-continuous underflows from episodic surge current deposits, since they have similar characteristics. Both are composed of couplets consisting of a coarser layer overlain by a finer layer. A sharp contact normally separates the two layers. Both may be thinly bedded (a few mm to a few cm) at distal sites, and appear graded. When examined in detail, however, there are important differences. For example, slump-generated surge currents can occur at any time, and so may vary from lake to lake and from site to site in a given lake.

In contrast, the rhythmicity of varves is due to variations in the sediment dispersal mechanisms which may have more universal application. Thus, one fundamental difference between surge deposits and varves is the time represented by each couplet. The temporal aspects of rhythmic sedimentation are of prime importance in any study of glaciolacustrine deposits, whether as a geochronological tool or for paleoenvironmental reconstruction (Edwards, 1978; Eyles and Miall, 1984).

The cause and duration of the two types of underflow event are quite different. Surge currents are episodic, unsteady flow events (Ashley et al., 1985) often triggered by slumps or other mass flow events in unstable deltaic or lake margin sediments. These create waning flow deposits similar to the "Bouma Model" turbidite (Bouma, 1962).

Banerjee (1973) noted the similarity of varves to turbidites, and made direct comparison between varves and the Bouma model. The common association of structures in varves is similar to or identical with that found in turbidites, ie: simple and multiple graded bedding, cross-, parallel- and contorted laminae, load structures, and the overall rhythmic alternation of silt and clay. Even though the turbidity current origin of the summer layer in varves has generally been accepted since its proposal by Kuenen (1951), few have made the direct comparison with turbidites.

In vertical sequence, true varves differ from the Bouma model in two respects. First, complete a-e sequences are very rare (as they are in turbidites), and second, d-e sequences are most common in varves, whereas c-e sequences are most frequent in distal turbidites according to Bouma (1962). Banerjee (1973) postulated that the lack of cross-lamination (c-interval) in varves may be due to the predominance of silt-sized grains. Rees (1966) noted in an experimental study that while ripples in silt are stable at certain stress conditions, if the suspended load concentration is high enough, plane beds predominate. Thus, under conditions of high suspended load, rippled silt beds in varves may be suppressed in favour of plane beds. The apparent rhythmicity is is due to repetitions of randomly occurring processes. In contrast, underflowing meltwater creates more steady flows which may persist for several days. Underflows may persist through the winter, but more commonly stop. Slump-generated surge currents can, in contrast, occur at any time.

Comparison of the two rhythmite types indicates diagnostic differences. Varves (annual rhythmites) are produced by seasonal variation in deposition extending over a year, and breaks in sedimentation may occur. The silt/clay contact is often sharp, and occasionally silt laminae occur in clay layers, or clay in silt (Sturm, 1979), as shown in Figure 11B and C.

Biogenic structures may be found in the coarse summer layer and at the base of the winter layer. Reports of trace fossils in varved glacial lake sediments are surprisingly common, and occur in units as old as Carboniferous. The assemblages generally consist of arthropod trackways, but gastropod, fish and nematode trails have also been noted (Ekdale et al., 1984). These organisms feed on plant detritus and algae. In glacial lake environments, food supply is minimal (Gibbard and Dreimanis, 1978) due to low temperatures and high turbidity, thus limiting both suspension and deposit feeding organisms. All trace fossil evidence has apparently been noted in true varve deposits (steady or continuous currents) rather than surge-type (unsteady or spasmodic) deposits.This probably is because the harsh conditions of surge currents prevent the survival of lebensspuren-producing organisms. Preservation usually occurs as a result of slight variations of sediment composition and rates of deposition between winter and summer layers. Banerjee (1973) noted burrows in sandy and silty varves from northern Ontario, but none were noted in the Ottawa area.

In varves, silt occurs as multilaminated, micrograded beds. As a unit, the silt may not necessarily be graded, but the overlying clay is frequently graded (Ashley, 1975). At a given site, the silt thickness may vary with the effectiveness of the dispersal mechanism, whereas the clay thickness is relatively constant and is a function of the settling time and basin depth (Ashley et al., 1985).

Episodic rhythmites (surge deposits) represent rapid, but continuous deposition. They therefore have a gradational contact between silt and clay. No lebensspuren occur since they either do not have time to form or conditions are too harsh to support the fauna. It is possible that some organisms might produce lebensspuren between flow events, but none have been reported to date. Since continuous deposition is involved, silt layers within the clay or clay within the silt are unlikely. At a given site, the thickness of silt and clay are in proportion since they have been transported by the same current. Thick clay accompanies thick silt layers, and so on.

Figure 12 compares generalized deposits of typical annual rhythmites (varves) with episodic (surge) rhythmites. Note that varves may contain small surge deposits as well as overflow-interflow deposits.

Ashley et al. (1985) summarize the criteria used to distinguish annual rhythmites (varves) from episodic (surge) rhythmites:

Annual Rhythmites:

1. occur as couplets; silt may have normal, inverse grading, or no trend in grain size; clay layer fines upward
2. breaks may occur within the rhythmite, possibly due to small scale surges or overflow-interflow events; breaks commonly occur between silt and clay
3. lebensspuren occur predominantly in the summer layer

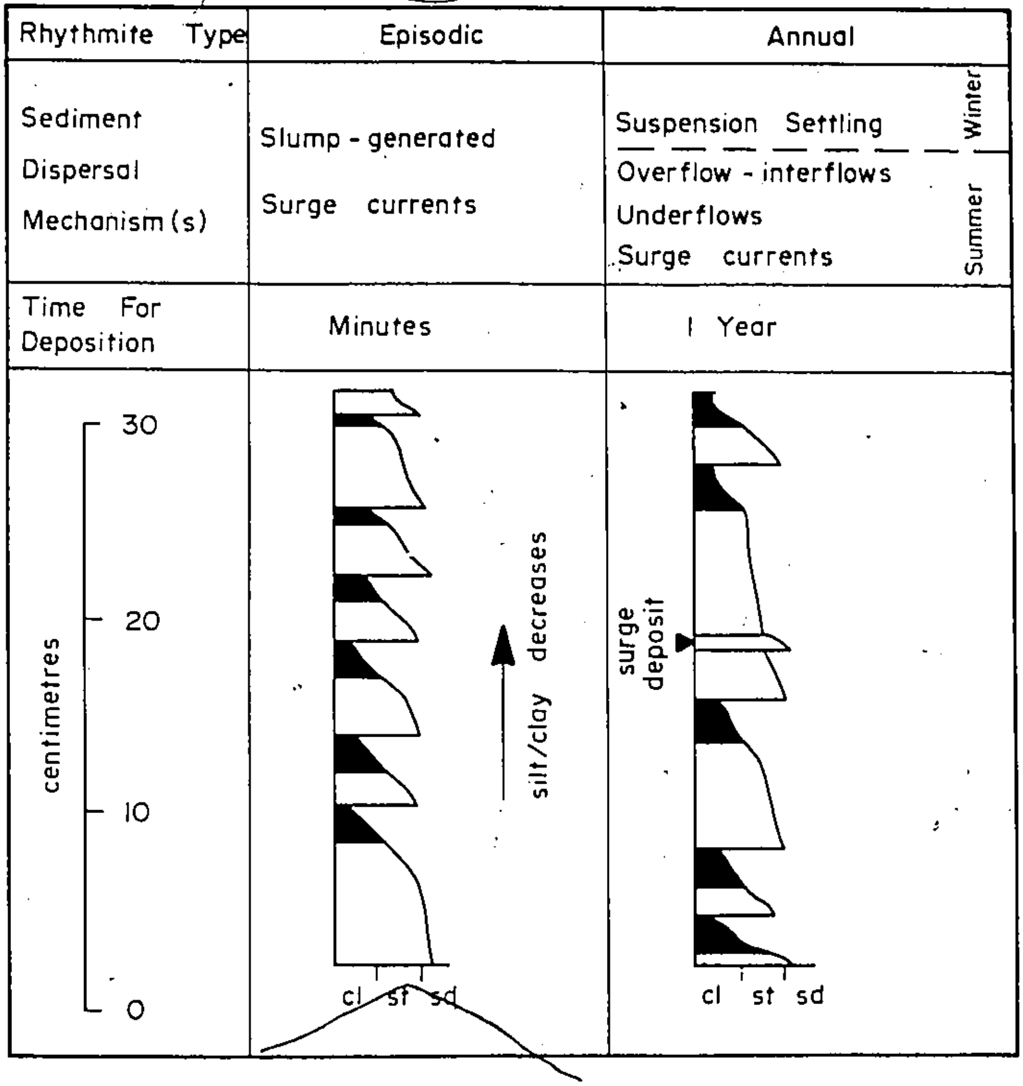


Figure 12: Comparison of Annual and Episodic Rhythmites (After Ashley et al., 1985)

and at the base of the winter layer

4. silt layer variable thickness; clay layer consistent thickness throughout the basin

Episodic Rhythmites:

1. fining upwards; gradual decrease in silt/clay ratio
2. no breaks in deposition
3. no lebensspuren
4. silt and clay layer thickness is proportional.

2.4.2 Rhythmite Classification and Description

Distal lake-bottom sediments hundreds of metres to kilometres from the point of entry into the lake tend to be thin (less than 1 cm) rhythmites consisting of a few multiple laminations. Coarser laminae are deposited from summer underflows, whereas overflows and interflows deposit laterally equivalent silts and clays along the lake margin and over topographic highs. A thin fining-upward clay layer representing sedimentation during the rest of the year evenly covers the summer layers. The contact between the two layers is usually sharp.

Sauramo (1923) recognized this characteristic and suggested rhythmites showing a clear separation of silt and clay layers be termed diatactic. Rhythmites showing a gradual increase in clay from the bottom to the top are termed symmict. The diatactic rhythmite results from an alternation of dispersal mechanisms. The silt is transported by bottom-hugging underflows whose pathways are controlled by topography. Total silt thickness may thus vary with topography throughout the basin. The finer layer then blankets the silt, accumulating during the remainder of the year from overflow-interflow currents. Thus, the diatactic rhythmite is analogous to the annual rhythmite or varve, while the symmict rhythmite is analogous to the episodic (surge) rhythmite described above.

Rhythmites may also be divided into groups based on grain size, thickness and sorting within laminations. Ashley (1975) classified rhythmites according to the relative thickness of the silt and clay fractions. This has the advantage that it is immediately useful in the field, but it does not give adequate detail for interpretation of depositional mechanisms. One of the most characteristic properties of rhythmites is the degree of sorting and grading of the coarse-grained layer. This leads to two other classification systems. Banerjee (1973) classified rhythmites according to facies changes in the coarse layer, based on weight per cent sand and lamination thickness. Sandy (10-20%), silty (1-5%) and diamictic (0-1%) rhythmites were described. Lajtai (1967) proposed a similar classification without the proximal to distal facies consideration. Sorting and grading defined rhythmites as graded, complex, or diamictic. Note that of the two types of diamictic varves described above, only that proposed by Lajtai (1967) follows the present convention for grain size distribution and sorting as it is applied to the term diamicton, namely that diamicton represents a nonsorted sediment composed of sand-sized or larger particles dispersed through a fine-grained matrix.

2.4.4 Overflow-Interflow Rhythmites

Sediment deposited on the lake floor above the thermocline tends to be homogeneous silt and clay (Ashley et al., 1985). This lack of stratification may be the result of bioturbation, wave disturbance, or mixing by wind-driven currents. Sediments below the thermocline are generally rhythmically bedded silt and clay, with successive couplets separated by sharp contacts.

These couplets commonly reflect seasonal alternation between sediment transported directly to the site by overflow-interflow currents and finer-grained sediments (usually clay) which was distributed throughout the basin and gradually settled out during the following winter. These couplets are the classic varve couplets, representing "summer" and "winter" deposition, respectively.

Sediment dispersal mechanisms are reflected in the sedimentary structures. Each rhythmite is a fining upward unit consisting of a sand/silt layer overlain by a silt/clay layer. The contact between the two may be gradational, but more often is sharp. Multiple laminations in the silt layer are common in the proximal deposits, reflecting short-term fluctuations in sediment input and dispersal.

When compared to other sediment-carrying mechanisms such as underflows, overflow-interflows are relatively low in sediment concentration (5-30 g/l) (Smith, 1978; Smith et al., 1982), so that annual rhythmites are relatively thin.

Proximal annual rhythmites may be up to 1 cm thick, while distal rhythmites may be 1 to 5 mm thick (Ashley et al., 1985).

Overflow-interflow rhythmites have been summarized (Ashley et al., 1985) as follows:

1. thin (1 cm thick), regular, fine-grained (silty clay) couplets with no current structures;
2. couplets have sharp basal contacts and generally sharp contacts between couplet layers;
3. spatial variation includes thinning and fining both downlake and from right to left in the northern hemisphere (Coriolis effect);
4. found at all elevations in the lake basin, but may have stratification destroyed biogenically in shallow water (above the thermocline).

2.4.5 Underflow Rhythmites

Turbid underflows are of two distinct types: 1) quasi-continuous currents originating from glacial outwash and 2) slump-generated surge currents triggered mainly by mass movement in unstable deltaic or lake margin sediments. Banerjee (1973) termed these "steady" and "spasmodic" turbidity currents. Their distinction is based on both origin and the time-velocity characteristics (ie the continuity and steadiness) of the flow. Of the two types of current, quasi-continuous underflows carry the bulk of sediment in lakes dominated by underflows. At some times (ie sporadically), surge currents may dominate deposition.

Chapter III

SEDIMENTOLOGY AND STRATIGRAPHY

3.1 SURFACE EVIDENCE-FOSTER SAND PIT

3.1.1 Section Description

Laminated and massive fine-grained sediments were examined in exposures at the Foster sand pit, located on the east bank of the Rideau River near Uplands Airport, approximately 10 km south of Ottawa (Figure 13). Two sections were examined in detail: FO1, located in a drainage ditch running into the the Rideau River (Figure 13, 1) and oriented perpendicular to paleoflow; FO2, located in a cut embankment of the Rideau River at the base of the Hunt Club Bridge (Figure 13, 2) and oriented parallel to paleoflow. Paleoflow direction was determined by the orientation of overlying rippled and cross-bedded sand. Other sections within the pit (Figure 13, 3 and 4) were examined to enable construction of composite stratigraphic sections and to sample material for radiocarbon dating (Figure 13, 4).

Although measured sections occurred within 100-200 m of each other, the covered interval between exposures either had not or could not be excavated. Thus, the (lateral) facies relationships between sediments in adjacent sections are speculative unless otherwise noted.

In all sections observed, rhythmites overlie either a tabular cross-bedded to rippled medium-grained sand (Figure 14a) or a poorly sorted diamicton (Figure 14b). These sediments are grouped into facies (1) for further

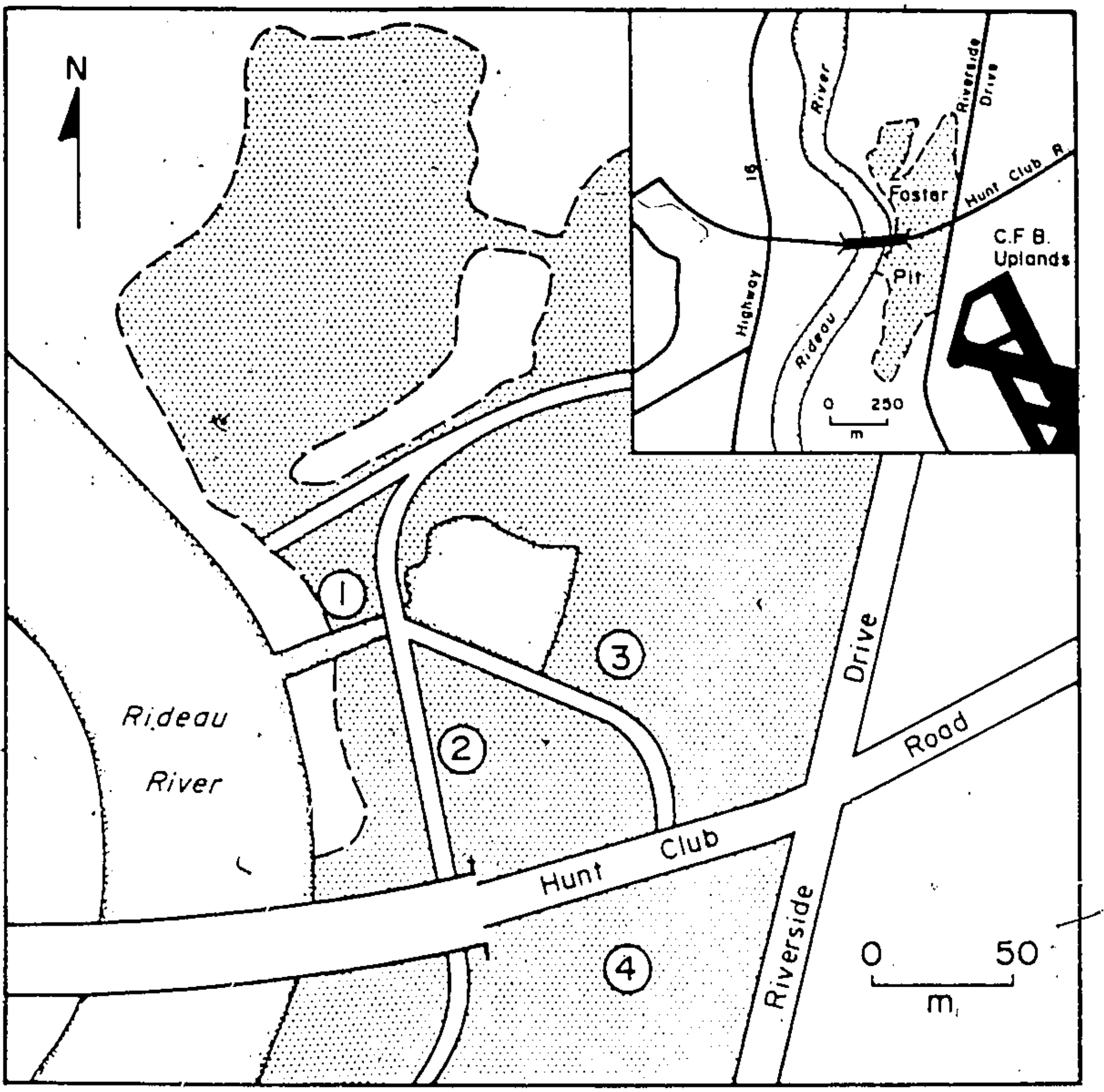


Figure 13: Location of measured sections in Foster Pit 1-FO1; 2-FO2; 3-FO3; 4-FO4.

a: Tabular cross-bedded sand at section FO2 showing foreset, toeset and attenuating bottomset beds. Note the regressive ripples on bottom and toesets (right). Shovel 60 cm.

b: Diamicton overling sand (recessive dark area at base) and underlying rhythmites at section FO1.

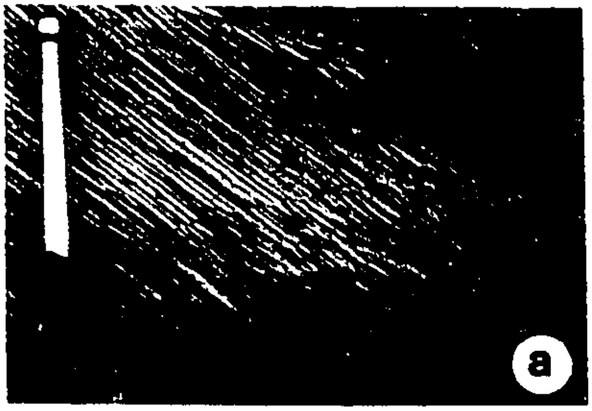
c: Grit covered clast from diamicton above. Carbonate-cemented grit removed at lower right to reveal clast inside. Scale in cm.

d: Flat, vertical face of section FO2 showing fault-bounded block of loaded, sheared ripples.

e: Convolute interbedding of fine silt and silty sand overlying tabular sand cross-beds at section FO2.

f: Close-up of section shown in e showing soft sediment deformation and fluid escape trails. Area shown roughly 30 x 40 cm.

Figure 14: Plate I


a


b

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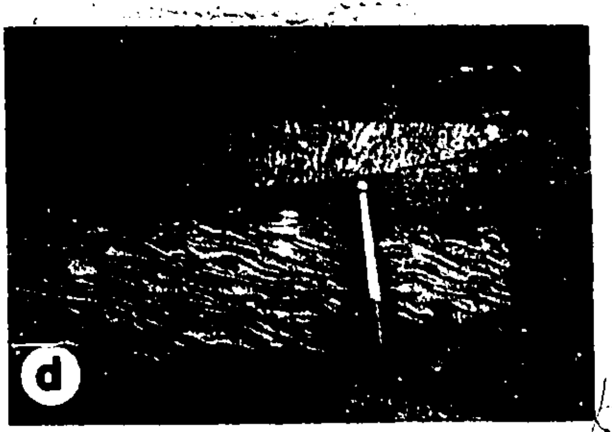

d


e


f

discussion. In section F01, the sand is overlain by diamicton and in section F02, the diamicton is absent.

A possible till flow origin is indicated for the diamicton at section F01 on the basis of stratigraphic position, fabric, poor sorting, and lack of sedimentary structures. Till flow facies may be associated with the interchannel sand facies of the Ottawa area ridges (Rust, 1982). Other coarse-grained facies such as the proximal gravel are clast-supported with large imbricate clasts. In contrast, the diamicton is matrix-supported and poorly sorted with no preferred orientation of large clasts. Clasts are subrounded to rounded and range in size up to 20 cm in longest dimension. Many are covered with subangular to subrounded carbonate-cemented grit from the diamicton matrix. Figure 14c shows one such clast with covering partly removed. Drilling has revealed similar diamicton at the base of the South Gloucester Ridge, immediately to the south in the direction of paleoflow (French and Rust, 1981; Graham and Jackson, 1982). This facies does not commonly appear in the Geological Survey of Canada cores, possibly because they were taken until refusal, where diamicton may have been mistakenly interpreted as bedrock or till. Only surface investigation or deep drilling through bedrock can determine without doubt whether refusal was because of bedrock, till or diamicton of other origin.

In section F02, the sand facies consists of a 1.5 m thick tabular set of cross-bedded sand overlain by convoluted interbedding of fine silt or clay and silty sand. The section is oriented roughly parallel to the local paleocurrent direction which follows the direction of the South Gloucester Ridge.

The tabular set consists of well defined and preserved foreset, toeset and attenuating bottomset laminae distinctively displayed by heavy mineral concentration (Figure 14a). Foreset laminae are disrupted by small-scale faults (Figure 14a) with displacements of less than one cm. In places the foresets can be traced through toesets and then into bottomsets. These are similar to structures in the Brampton esker reported by Saunderson and Jopling (1980).

The continuity between foreset, toeset and bottomset bedding indicates that they were formed contemporaneously. The rate of sedimentation of the suspended load was sufficient to form a fine sandy and silty drape over the dune front, in places merging into regressive ripples in the bottomset. Regressive ripples (Jopling, 1961) have been described by Boersma (1967), Boersma et al. (1968) and Aario (1972a, b). The regressive ripples probably formed when suspended load settled throught the zone of flow separation to the lee side of the dune front, where backflow was competent to move the settling particles in an upstream direction to form climbing ripples.

In the upper rippled facies, transitional ripples (Jopling and Walker, 1968) have low angle erosional scours merging into a fault-bounded block of loaded and sheared ripples (Figure 14d). The deformation of the laminations is difficult to explain, and the structure's origin problematic: several origins are possible. If collapse were to take place at a foreset or slipface of a dune, the usual result would be avalanching of particles down the oversteepened face. If the sand was in a frozen or partially frozen state, then it may have broken off as a large (1.5 m long and 20 cm thick), intact piece. Thus, the block may have originated in a partially frozen state. If the material were transported frozen, it is possible that collapse may have resulted from the decrease in volume as the ice melted. Deformed laminations (Figure 14d) then result in response to gravity during thaw and subsequent collapse. Rotational collapse of the block is also possible, and does not require that the sediment be frozen for deformation to occur. Another possibility is that the block may have been dislodged by the shearing action of a grounding iceberg.

Overlying the sand facies and transitional to the rhythmites is convoluted interbedding of fine silt or clay and silty sand. There are at least two complete cycles in which ripple amplitude decreases upward and laminations change from type C ripple drift cross-lamination (Jopling and Walker, 1968) at the base to nearly planar lamination at the top. These beds appear to have been deposited as regressive ripples of a bottomset as in the unit below, but have been disrupted (Figure 14e) by loading and slumping, resulting in fluid escape structures. These form as a result of rapid deposition of silty sand over clay. The trapped water is forced to travel upwards through the coarser, overlying sand to escape. Figure 14f shows two such water escape structures, with the column on the right indicating local flow of escaping water the left, opposite to the paleoflow direction.

Slump structures also occur (Figure 14f) where parts of the clay bed have been detached when slumping silty sand cut into the clay, separating part of the underlying bed. Because of the high cohesion of the clay, the detached sediment formed small spheres rather than disaggregating.

Banerjee (1973) described similar fluid escape structures and attributed them to slumping at a delta front. Echo-sounding and seismic reflection studies of active glaciolacustrine deltas have shown almost ubiquitous gravity deformation features (Ashley et al., 1985) similar to those described above. The features most commonly found are: pull-apart zones, small slump terraces, hummocky mounds and pressure ridges (Figure 15). The slump structures shown in Figures 14e and 14f most likely represent portions of the compressional zone, where strata are folded and thrust over the lake floor by slumps moving downslope.

In section F01, directly overlying the diamict is a lens of convolute laminated silt and clay which pinches out. Thickness varies up to 20 cm, and in places the convolute lamination forms crude pseudonodules, typically due to vertical loading and water escape. In contrast to the obvious slump features of section F02, these features seem to occur in a variety of orientations rather than the more unidirectional deformation expected as a result of slumping. This disrupted bedding (Figure 16a) may be the result of

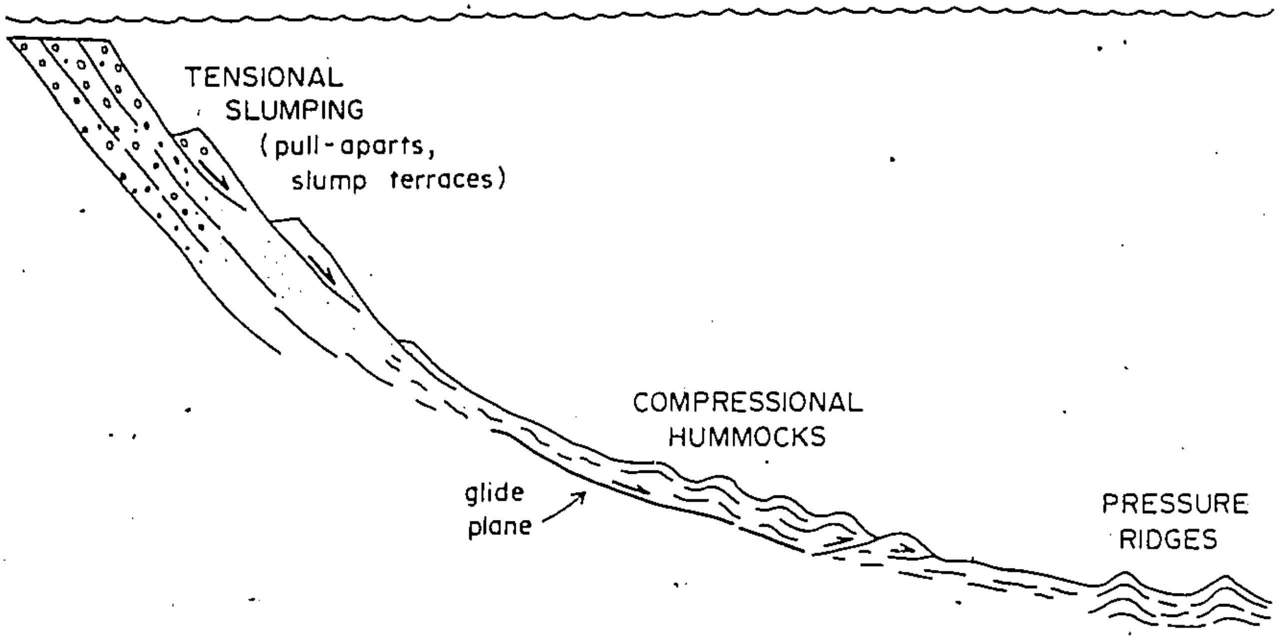


Figure 15: Gravity Deformation Structures of Glacio-lacustrine Deltas (After Ashley et al., 1985)

grounded ice shearing the underlying sediments and producing deformation in several directions.

Conformably overlying the disrupted bedding is a thin (10 cm) drape of laminated sand and silt, which represents the first true rhythmite deposit. The drape consists of medium to faintly laminated medium sand with the middle 5 cm composed of laminated silt and clay. The top laminations appear to form current riples. They grade upwards into medium to coarse sand with pseudonodules and convolute laminations of silt and clay. Pseudonodules (Figure 16b) occur in medium sand, and are composed primarily of clay to fine silt with minor amounts of medium silt. The structures appear to be completely isolated, and are usually less than 10 cm in maximum dimension.

In section F01, the contact between lower laminated silt and clay and upper massive clay is sharp. A rippled silt bed (Figure 16c) between the two units marks the position of a disconformity separating the laminated and massive clay bodies. Several fossil insects and plants were found in this unit, including flies, wasps and ants, sow bugs, weevils, beetles, millipeds and the maxillae of a fish (Naldrett and Rust, 1984). Subsequent examination revealed this material to be younger than its stratigraphic position would indicate. Floral and faunal evidence (GSC Plant Macrofossil Report No. 84-25, Appendix E; GSC Fossil Arthropod Report No. 24, Appendix F) suggests that the material must be significantly younger than the surrounding sediments, although the exact temporal relationship has yet to be a: Deformed rhythmite laminae at base of section F01, attributed to shearing by grounded iceberg. Most deformation appears as recumbent folds, but some (right) is like pseudonodules. Knife 20 cm.

b: Silt pseudonodules in medium sand bed overlying rhythmites shown in a. Area shown is roughly 10 x 15 cm.

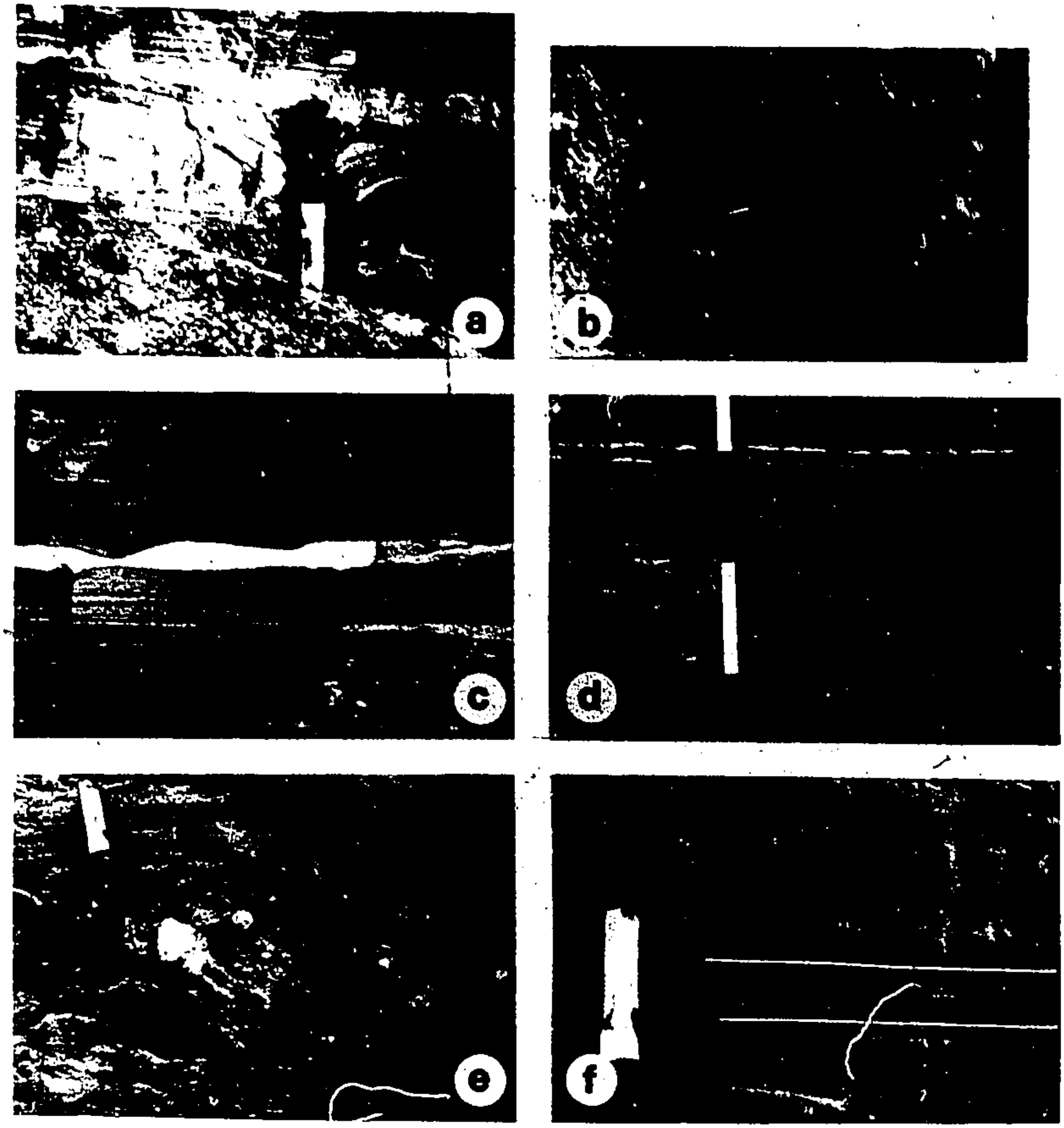
c: Rippled silt bed at disconformity separating marine massive clay (top) from lacustrine laminated clay (base) at section F01. Silt bed approximately 5 cm thick.

d: Rhythmites in section F01. Scale in 0.5 m intervals.

e: Lens of ice-rafted debris in central portion of rhythmites in section F01. Knife 20 cm.

f: Close-up of discontinuous and continuous type (II) rhythmites in section F01 shown in Figure 16d. Knife 20 cm.

Figure 16: Plate II


a
b
c
d
e
f

determined. The possibility of modern contamination during sampling seems unlikely in this case, since the unit in question is both underlain and overlain by silty clay, and is relatively thin (3-4 cm) on the exposed face giving minimal chance of contamination. The presence of young fauna and flora, however, does not seem to have another explanation.

3.1.2 Rhythmites

Rhythmites, previously described as varves by Banerjee (1973) and Gadd (1961, 1962), are restricted to a 1 m thick section overlying the cross-bedded sand and diamicton facies (Figure 16d). The rhythmites may be divided into three broad depositional packages. The basal 15 cm consists of couplets up to 4-5 cm thick of alternating massive clay and laminated silt and clay with convolute laminations. The central 40 cm has similar lamination and grain size, with common isolated clasts and lenses of diamict (Figure 16e). The upper 45 cm consists of laminated to bedded silt and clay forming less clearly defined couplets than below. To simplify discussion in the following chapters, these rhythmites are grouped into facies (2).

A composite section of the Quaternary age sediments at the Foster pit locality is shown in Figure 17. Rhythmites are shown in detailed sections in Figure 18 and Figure 19. Unlike conventional sedimentary logs, those shown in Figures 17-19 indicate modal rather than mean grain size. This avoids the difficulty of misrepresenting grain size and not indicating the degree of sorting. For example, sandy clay can be distinguished from clayey sand, both of which would normally be shown with mean grain size of silt. Using the present system, the modal grain size of either sand or clay is indicated by the horizontal scale, and the modifying grain size indicated by the stipple pattern.

Since rhythmite layers alternate many times in a one cm interval, couplets shown in the stratigraphic columns are diagrammatic representations and do not represent the actual number of silt and clay laminations in a given interval.

In order to better understand rhythmite deposition and to place them within a temporal framework, several independant lines of investigation were followed. To distinguish between annual rhythmites (varves) and episodic (surge) rhythmites, grain size distribution, carbonate type and content, and trace fossil presence or absence were noted. The palynology of the rhythmites was also examined, as described in section 3.1.2.

Five couplet pairs were separated in well developed rhythmite beds at sample point F070 (Figure 19). Dark and light laminations were separated with a single-edge razor blade, and layers examined to determine grain size distribution, carbonate content, and calcite/ dolomite ratios. Variations of these parameters are summarized in Figure 20.

Because of the small sediment volume recovered on separation, conventional grain size methods were not possible, and Coulter counter analysis was used. With care, this method gives continuous grain size distribution

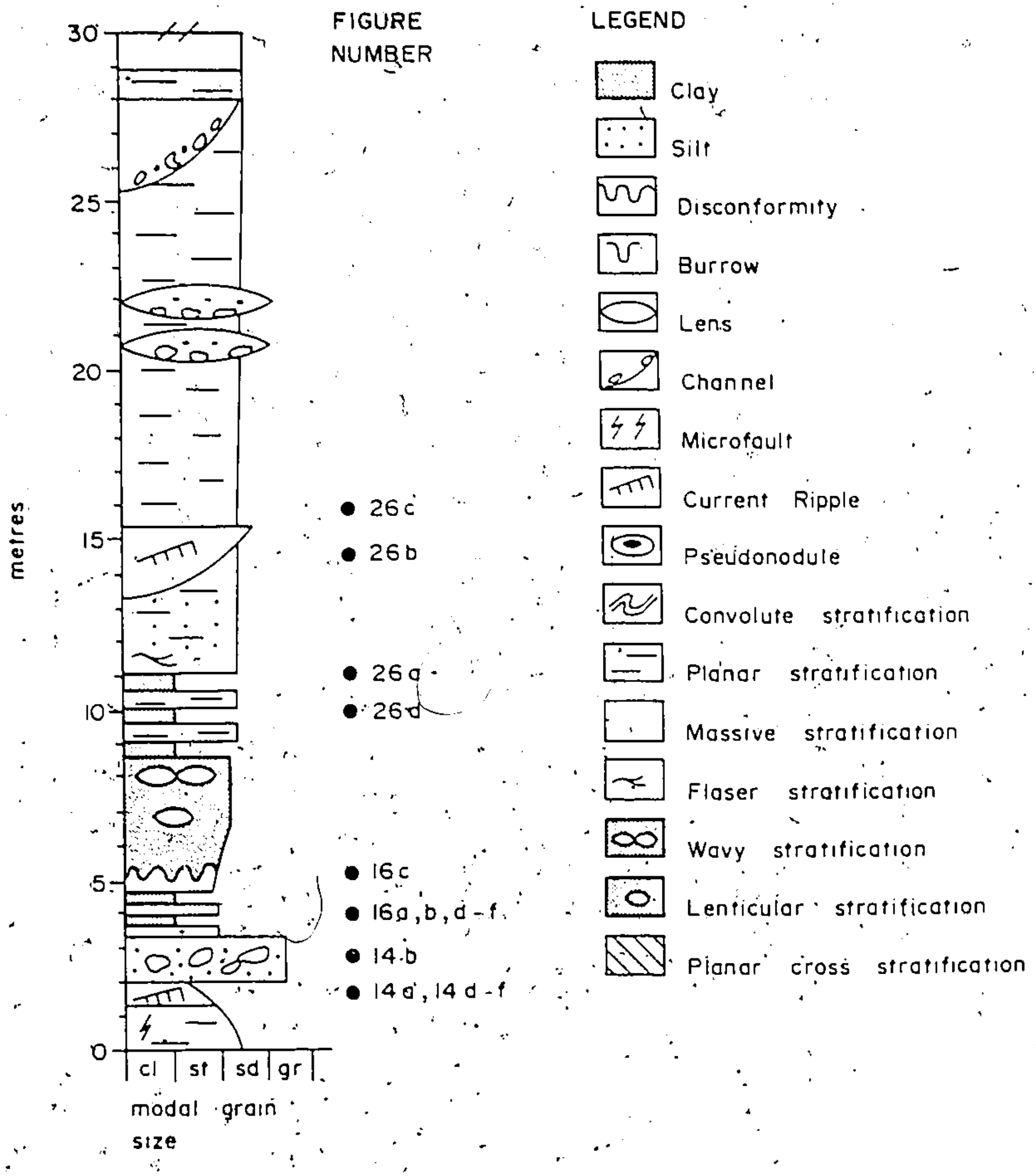


Figure 17: Composite Stratigraphic Column, Foster Pit. Datum (0 m) pit floor.

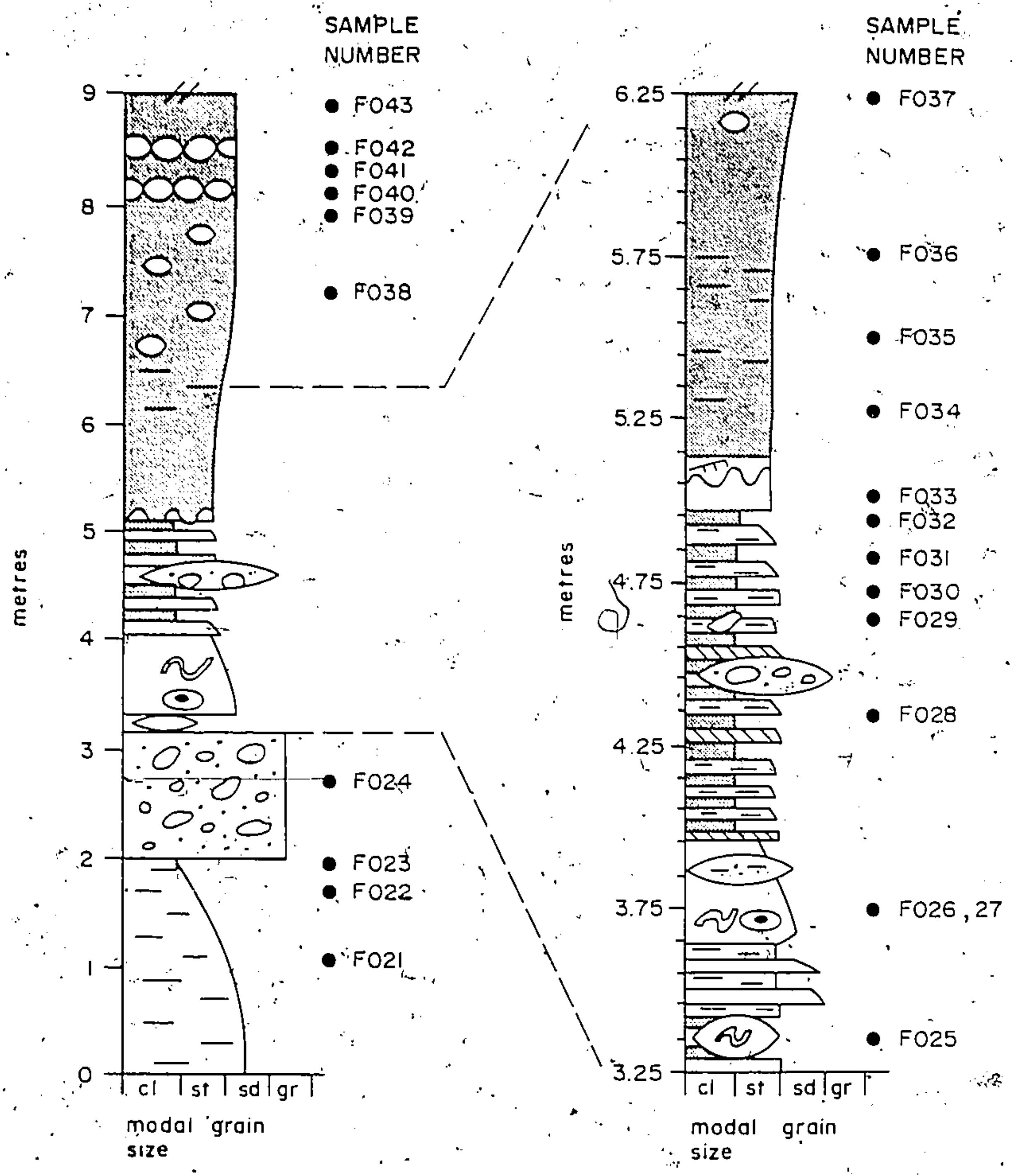


Figure 18: Detailed Stratigraphic Column F01, Foster Pit. Datum (0 m) pit floor; key as in Figure 17.

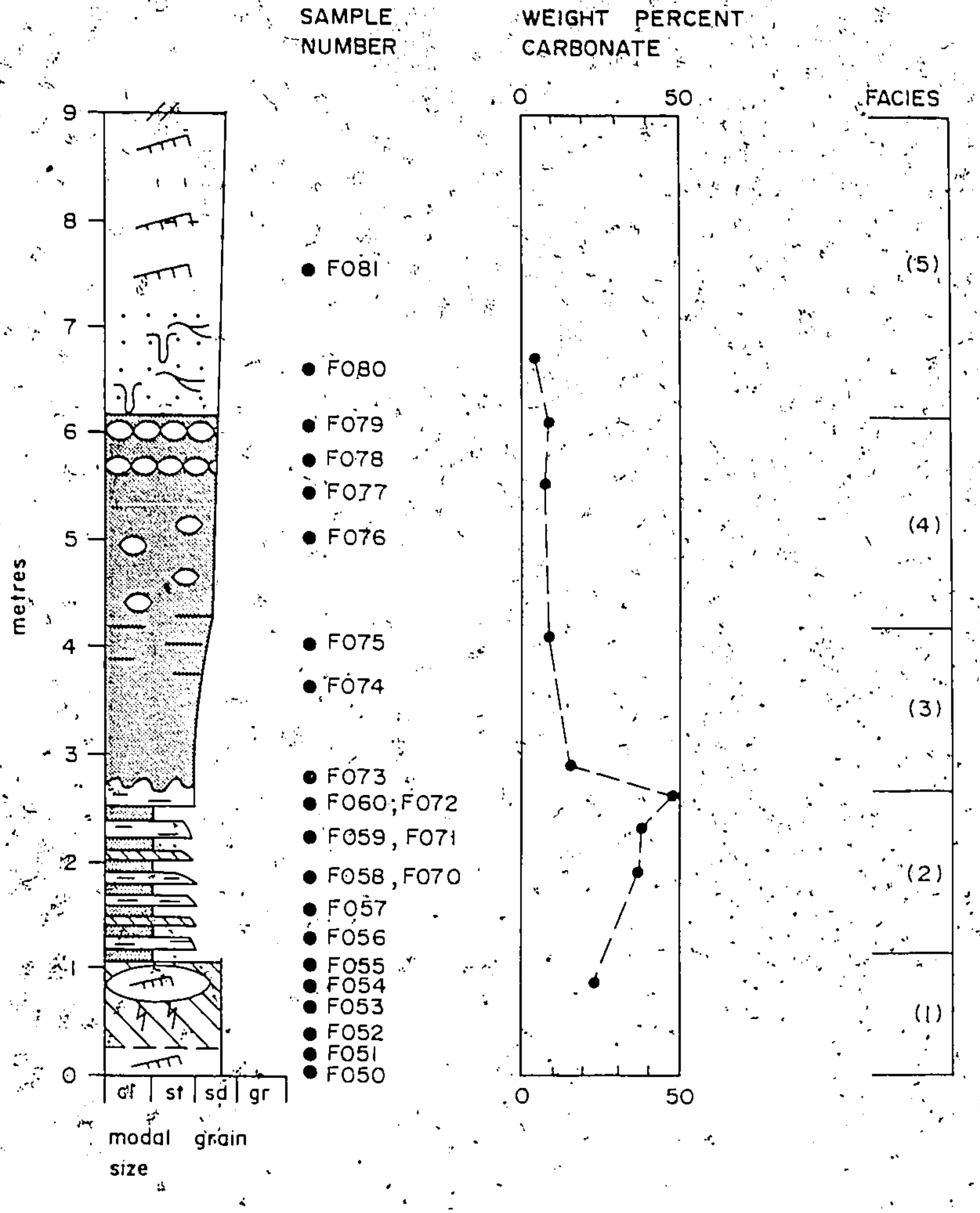


Figure 19: Detailed Stratigraphic Column, F02, Foster Pit. Datum (0 m) pit floor; key as in Figure 17.

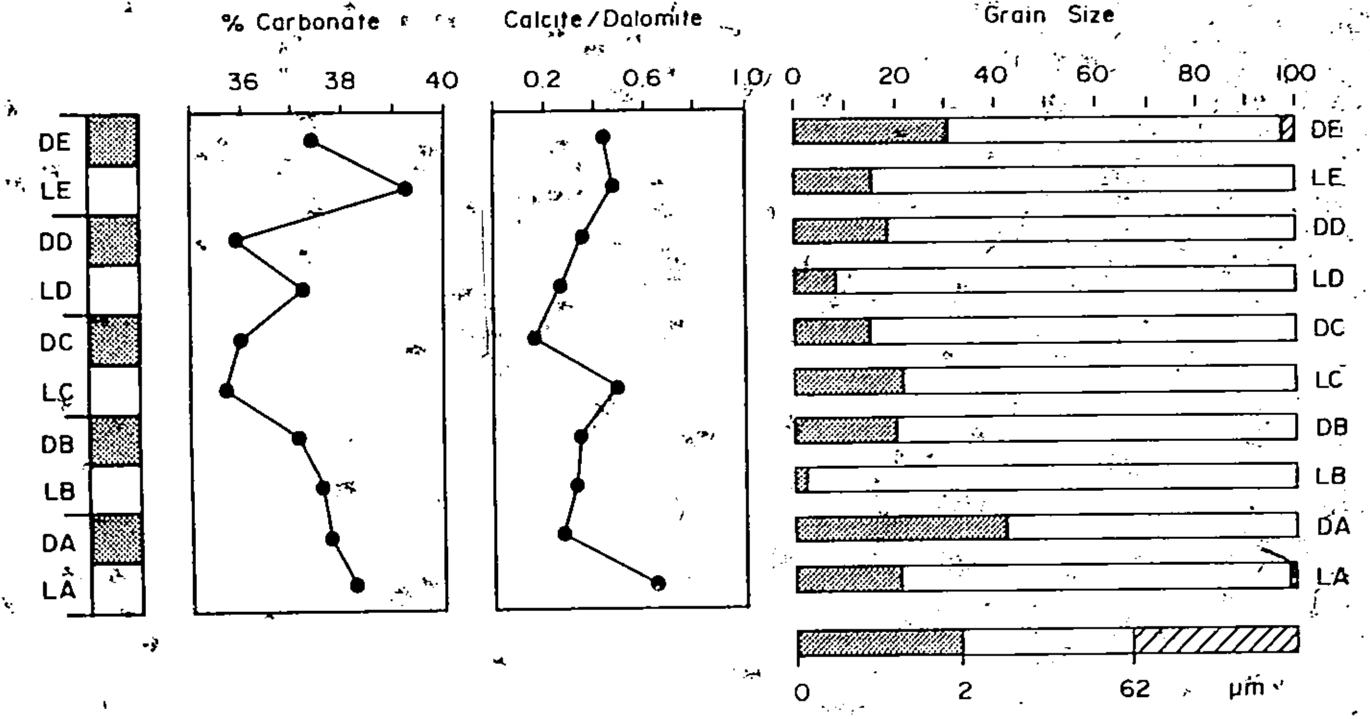


Figure 20: Variation of Carbonate Content, Calcite/Dolomite Ratio and Grain Size in Rhythmites

measurements in the range from + 2 phi to + 10 phi. In most samples, this analysis leaves an open ended grain size distribution curve. Therefore, in cases where cumulative weight per cent fell short of 90%, the curve has been extrapolated as described by Banerjee (1973). Grain size parameters were determined graphically according to Folk (1980).

The sampled silt intervals have cross and parallel laminae and simple grading. Most sampled layers are structurally homogeneous, but the fine-grained units tend to be multiple graded and many consist of several sedimentation units.

Rhythmite type should have an effect on the grain size distribution, since sediment dispersal mechanisms differ between annual and episodic rhythmites. Annual rhythmites should show a difference in grain size distribution and possibly sorting between summer layers deposited by traction currents and winter layers deposited from suspension. Similarly, with episodic rhythmites, the transport mechanism is usually by turbidity current underflows which decrease in competence and result in a fining upwards trend.

The second of these distributions appears in the five dark (D) and light (L) couplets from sample F070 (Figure 21c). Grain size parameters (Table 2) do not seem to vary significantly between dark and light groups: there is a difference of 0.21 phi between dark and light mean grain size with a standard deviation of 0.17 phi (dark) and 0.15 phi (light) indicating very little variation in grain size within the dark and light groups. This grain size distribution seems to indicate that the rhythmites tested were deposited by a steady, gradually decreasing current, typical of episodic (surge) currents.

Figure 21 compares the grain size distributions of the Ottawa Valley rhythmites with those of varves from various localities as reported by Banerjee (1973). The most obvious difference is the poor separation of the dark and light layers in the episodic rhythmites. The envelope in Figure 21c represents the grain size distribution of ten dark and light layers, and indicates the close range of grain sizes within and between the two groups. This occurs because of the episodic nature of deposition- many small flow events are superimposed on the primary, waning event interlaminating coarse and fine sedimentation units in the episodic rhythmite (see Figure 23 for examples) where a homogeneous unit is present in the annual rhythmite (varve). The thin nature of the Ottawa area rhythmites precluded exact separation of these units, resulting in poor grain size separation. Dark and light layers were thus plotted together. In comparison, annual rhythmites (varves) shown in Figure 21a and b show clear separation of grain size between winter and summer layers in all except the silty varves. This most likely occurs because Banerjee (1973) was able to sample layers with thicknesses of several cm, each consisting of a single sedimentation unit. Winter and summer layers consequently represent single, continuous events rather than a series of events as seen in the episodic rhythmites.

Carbonate type and distribution was studied from the

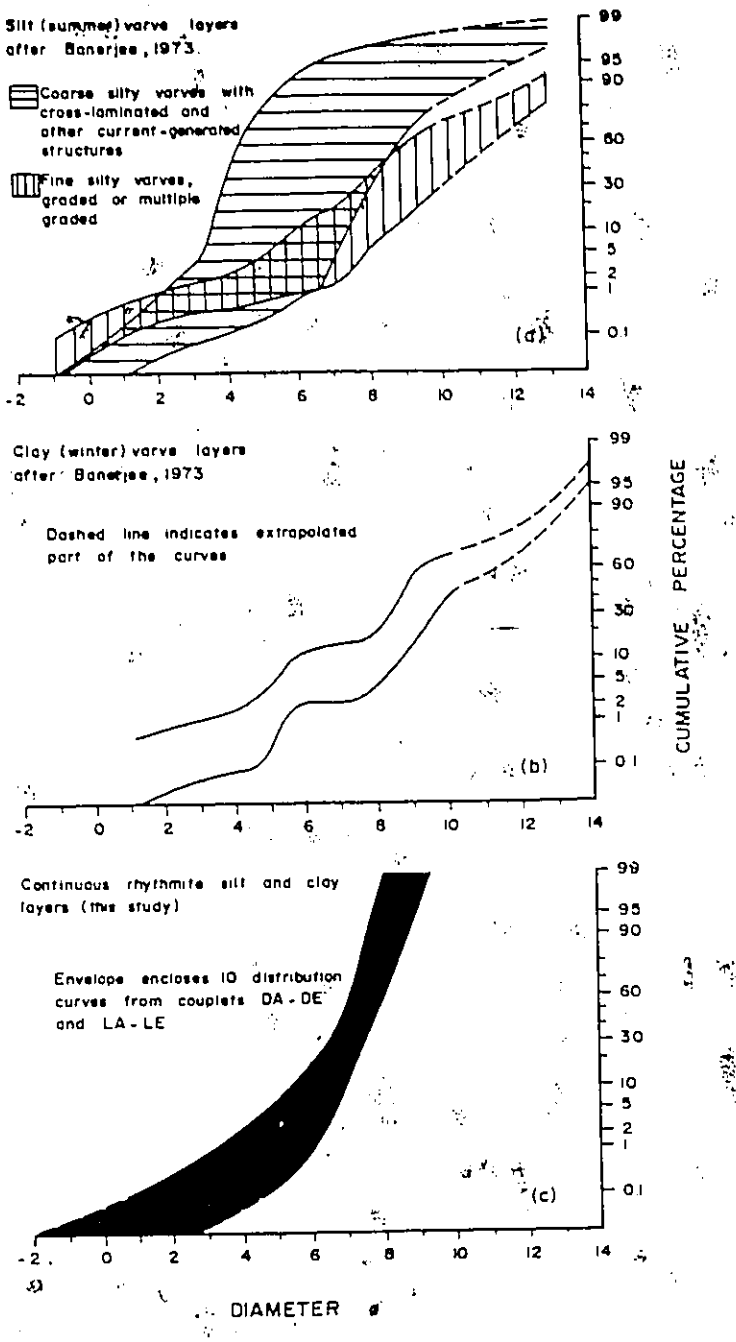


Figure 21: Rhythmite Grain Size Distribution

TABLE 2

Comparison of Grain Size Parameters for Dark and Light Rhythmite Layers

Couplet Layer	Mz	1	Sk	Kg
DA	7.77	0.83	-0.17	1.05
DB	7.55	0.68	0.00	1.15
DC	7.27	0.78	+0.01	1.09
DD	7.40	0.68	-0.32	1.04
DE	7.40	1.06	-0.28	1.02
LA	7.32	0.88	-0.12	2.07
LB	7.03	0.52	-0.05	1.09
LC	7.27	0.92	+0.06	0.96
LD	7.30	0.52	+0.08	1.23
LE	7.43	0.52	+0.01	1.02

TABLE 3

Weight Per Cent Carbonates in Section F02

Sample Number	Weight Per Cent
F080	3.52
F079	7.07
F077	6.54
F075	9.90
F073	14.92
F072	48.30
F071	38.44
F070	37.14
F054	21.76

bedding scale to the rhythmite layer scale. Bulk carbonate content was measured through the entire F02 section. Samples were taken as shown in Figure 19. Measurement of weight per cent carbonate was made possible by treating all samples with warm dilute HCl prior to x-ray diffraction studies

TABLE 4

Total Carbonate, Calcite and Dolomite Content of Rhythmites

Sample Number	Weight % Carbonate	Calcite (cps)	Dolomite (cps)	cct/dol
DA	37.80	6	22	0.27
DB	37.11	24	71	0.34
DC	36.02	6	37	0.16
DD	35.93	25	67	0.37
DE	37.46	17	40	0.43
mean	36.86	16	47	0.31
std. dev.	0.38	4.2	9.4	0.05
LA	38.22	34	53	0.64
LB	37.64	19	58	0.33
LC	35.70	51	107	0.48
LD	37.20	17	62	0.27
LE	39.27	56	127	0.44
mean	37.61	35	81	0.43
std. dev.	0.57	2.4	14.9	0.06

(described in Chapter 4). The presence of calcite and dolomite was tested by scanning for the (104) peaks of each mineral. No peaks were found, and all carbonate was assumed destroyed. Difference in weight before and after acid digestion was measured, giving weight per cent carbonate. Results are shown in Table 3 and in Figure 20.

The trend of decreasing carbonate content going upsection (Table 3 and Figure 19) parallels the increase in grain size in this direction. Since carbonates are relatively soft, they are easily reduced in size by glacial abrasion and concentrated in fine-grained facies (rhythmites).

Variation of carbonate content and type was studied within rhythmite couplets A to D. Total carbonate content was determined by the warm HCl method described above. Carbonate contents of couplet halves (Table 4 and Figure 20) generally agree with the bulk carbonate content values shown in Table 3, and show a slightly lower carbonate content in the winter layers, but not significantly so.

Assuming ice-marginal waters are undersaturated with respect to carbonate (Keller and Reesman, 1963), and that all carbonate is detrital, variations in carbonate content within rhythmite couplets may be the result of variations in the rate of solution and hence, the rate of deposition. Dell (1973) proposed such a mechanism for glacial varves in Lake Superior, and showed that the undersaturated water caused dissolving of ostracode carapaces. In such an ice-marginal setting, it is unlikely that seasonal temperature variations would be sufficient to cause carbonate contents to change due to temperature-induced solution.

In order to determine the relative amounts of carbonate species in dark and light layers, these were analyzed by XRD and the abundance of calcite and dolomite noted. This was done by recording the number of counts per second (cps) shown on the diffractogram for each mineral. This is directly proportional to the mass of each mineral present (Miles, pers. comm., 1985). An example diffractogram is shown in Figure 22. As with all other diffractograms, the dominant carbonate mineral is dolomite rather than calcite. This most likely shows the effect of solution on the minerals, since calcite is more soluble.

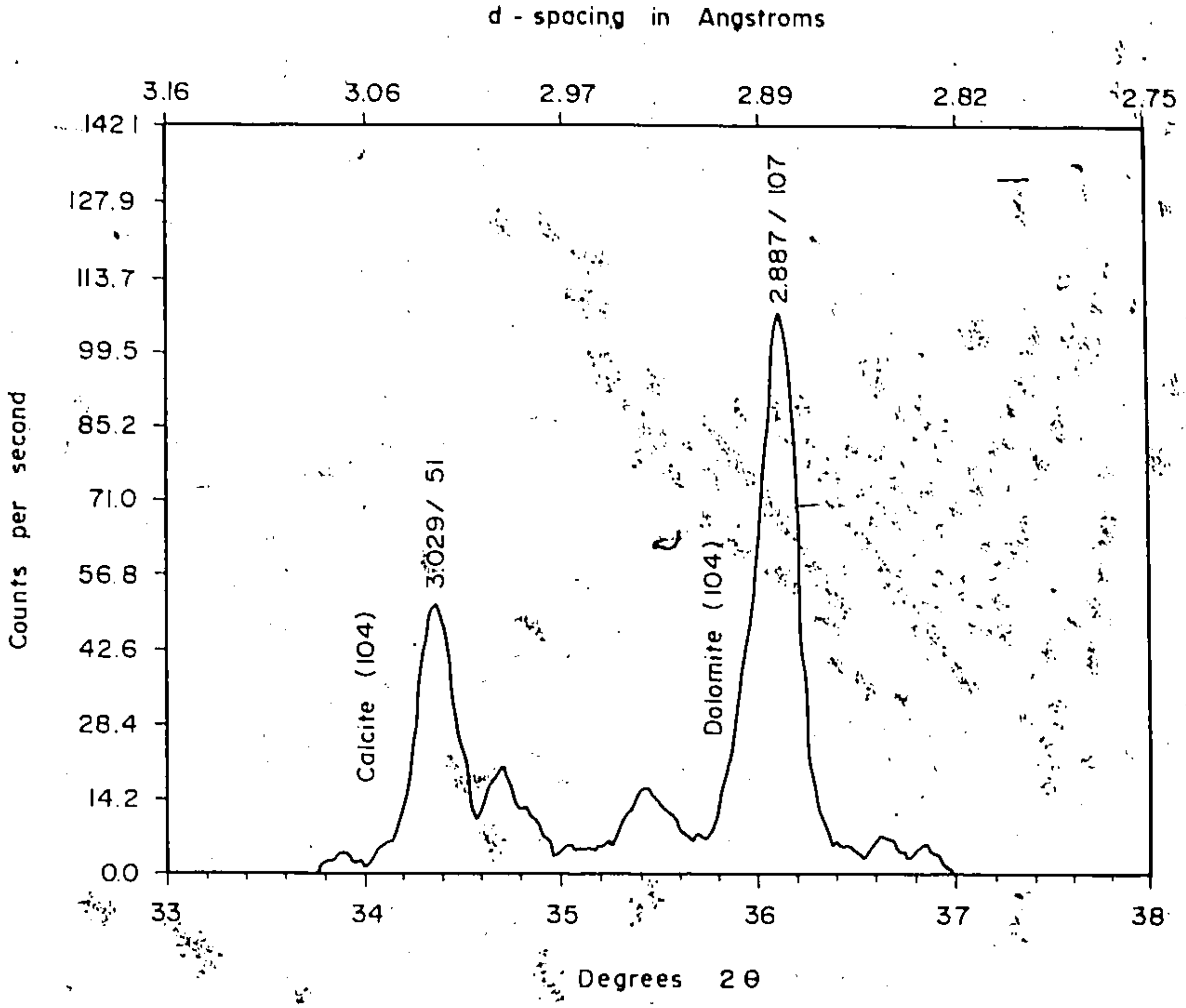


Figure 22: Example XRD Chart showing Calcite (104) and Dolomite (104) Peaks for Sample LC

X-ray diffractograms show well defined peaks of both calcite and dolomite, indicating well ordered crystal structure (Figure 22). This structure is typical of slow growing crystals, and indicates few imperfections. Such well ordered crystals are unlikely to have been precipitated in a proglacial environment, thus ruling out local origin of the carbonates. Microscopic examination of rhythmites did not show any evidence of carbonate cementation of detrital grains. It is thus assumed that all carbonate material present is detrital, and originated from regional bedrock. Variation in carbonate content must then be a result of variations in carbonate content of the regional bedrock, and of secondary alteration by solution. The Paleozoic bedrock of the Ottawa area is predominantly limestone (Wilson, 1946) with approximately one third dolostone by volume. Thus calcite would be expected as the predominant carbonate mineral, unless locally derived bedrock from the lower, dolostone-rich portion of the sequence was the source. Thus, the dolomite either comes from a very local bedrock source, or is due to solution of the more dominant calcite. Locally derived rock flour does not seem likely, given the mineralogical composition (see Chapter 4) and fine size of the grains.

Several nodules or concretions up to 5 cm in diameter were recovered from samples F028, F029, and F031, taken from the lower portion of the rhythmites at section F01. The concretions are not apparent in outcrop, and were recovered during processing of microfossil samples. The concretions appear to be composed of the same sediment as the surrounding materials, and show only very weak reaction to cold dilute HCl. Several concretions have been found in the Ottawa area (see Gadd, 1980b; Hillaire-Marcel et al., 1979; Champagne et al., 1979); some contain fossil material post-dating the Champlain Sea. This has generated controversy regarding the age and origin of the concretions. Determination of the exact mode of origin of the concretions found at the base of the rhythmites is beyond the scope of this study, but it appears that material was cemented after deposition by carbonate-rich groundwater created by leaching the surrounding clay. Since the clay is relatively impermeable, and the concretions are only found in the lower portion of the rhythmites, groundwater may have entered the clay zone from beneath, traveling through the highly permeable underlying diamicton or sand.

Approximately 200 couplet samples from sample points F025, F026, F027, F028, F029, F030, F031, F032, F058, F059, F060, F070, F071, and F072 (Figures 18 and 19) were split between light and dark laminations to search for trace fossil evidence and to determine internal structure, if any, of the light coloured layers. No trace fossil evidence was found in any of the samples examined. In 45 samples, straight, discontinuous grooves up to 3 mm wide were observed at the base of the coarser portion of the couplet (Figure 23). The small size and straight form of the grooves precludes biogenic origin. The grooves are interpreted to be caused by traction load. In a few cases, the grooves were not preserved, but sole marks in the overlying clay were. It is thought that compaction by the overlying clay may have expelled water from the silt, causing minor readjustment of the silt grains and obliterating the grooves. Thus, the cohesive nature of the finer grained material preserved the sole marking, even after the groove had been destroyed.

Two types of grading and internal structures were observed in the rhythmites, as shown in Figure 23. These are divided into continuous series (I) and (II), and discontinuous series rhythmites.

Continuous series (I) occur rarely, and consist of an unbroken fining upwards from (coarse) silt to clay. The sediments are well sorted from the base to the top and represent a single flow event consisting of a steady flow underflow current of decreasing velocity. Such a rhythmite is shown in Figure 23, and is analogous to the symmict rhythmite proposed by Sauramo (1923).

Continuous series (II) rhythmites are the most commonly observed. These are shown schematically in Figure 23, and in Figure 16f. They show a fining upwards trend, with finer couplet layers interrupted by thin (2-3 mm) laminae of (un)graded coarser material. A sharp contact occurs between coarse and fine laminae, but transition from coarse to fine layers is gradational. These rhythmites represent multiple flow events: single, major flow events have minor events superimposed to give the silt stringers found in the finer layer of the couplet. As in the first case, the proposed

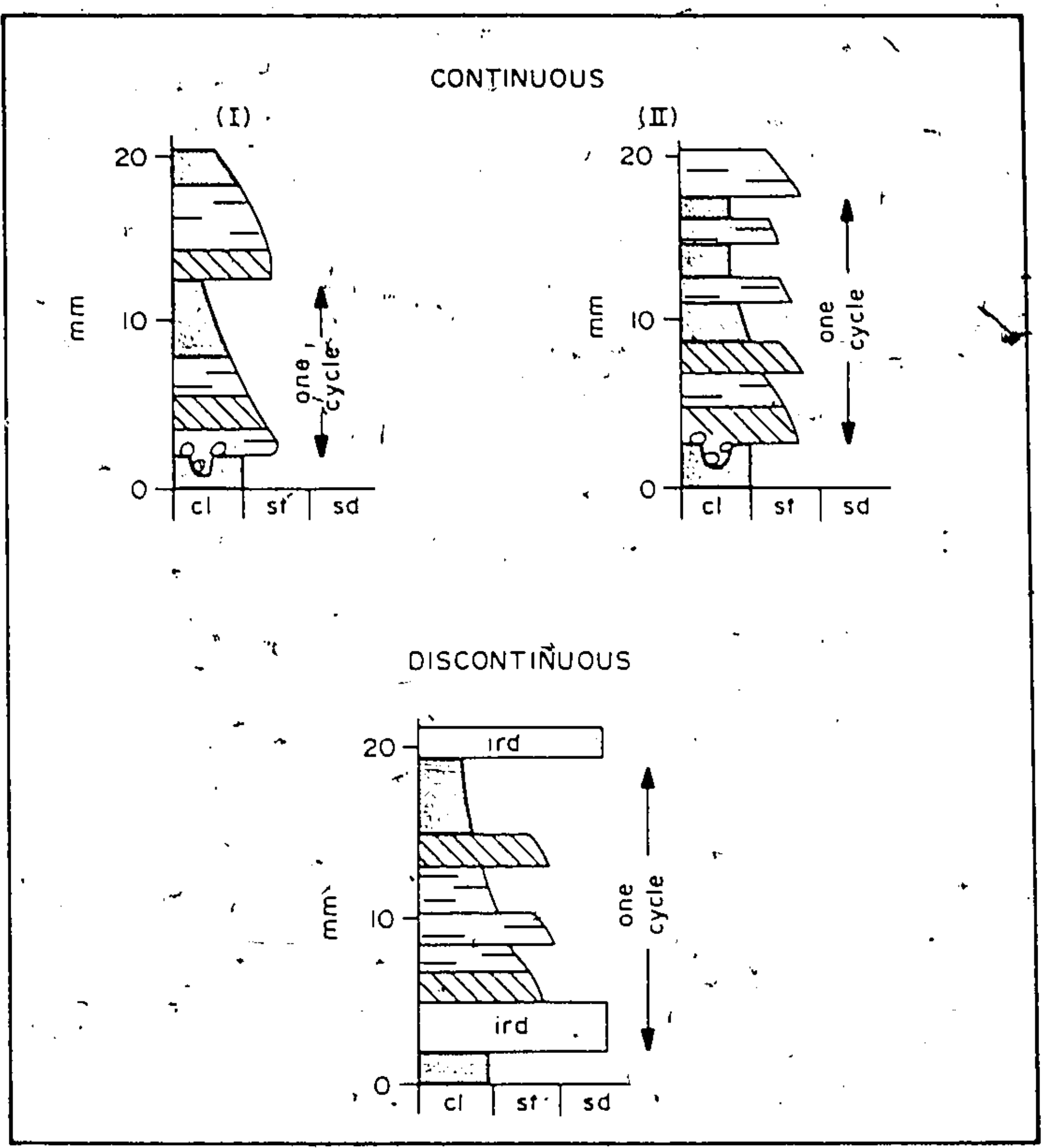


Figure 23. Continuous and Discontinuous Rhythmite Series

flow mechanism is by underflow, but it is possible that with decreased sediment concentration the underflows changed to interflows or overflows. The distinctive break between tractive underflow deposits and overflow/interflow deposits seen in the true varve sequence is not found in these continuous series rhythmites, hence there is no sharp contact between coarse and fine layers.

The second rhythmite type, the discontinuous series, is a modification of the previous continuous series. They are shown in Figure 23. A sharp break occurs between the coarse and fine layers. The coarser layer is coarser than in other couplets- medium sand to coarse silt rather than the fine silt found in other couplets. The coarse layer contains single clasts up to 5 mm in diameter which are assumed to be ice-rafted debris (ird). The coarse material is massive and ungraded. Above the disconformity separating coarse and fine layers, the rhythmite is identical to the continuous series (II).

The presence of the coarser layer in this case likely indicates a (summer ?) melting event at the beginning of the depositional cycle. Settling of ird through the water column leads to the unsorted nature of the lower layer since no current sorting mechanism is available. At the end of this event, the beginning of underflow traction currents produces the abrupt disconformity observed at the top of the ird.

Couplet thickness and thickness trend was noted in sections F01 and F02. Because of the interlaminated nature of the rhythmnite "couplets" it was often difficult and somewhat arbitrary to determine couplet boundaries. For example, assumed couplet boundaries are shown in Figure 16f, but they are not clearly defined and consequently couplet thickness could change. Average couplet thickness is 2.4 cm, with high variation in thickness reflected by a standard deviation of 0.4 cm. This variation probably does not reflect a true variation in couplet thickness, but rather an inability to adequately identify couplet pairs. In surface exposures, sedimentary structures may sometimes be used to distinguish couplet halves.

No trend in couplet thickness was observed going upsection. In a true varve sequence, thickness commonly diminishes upsection as sediment supply wanes if the ice front is retreating, but this was not seen. Couplet character changes upsection, showing a consistent increase in the massive nature of the sediment. The apparently short duration of rhythmite deposition, represented by one metre of sediment, may be the reason for the lack of any trend in rhythmite thickness. If deposition had continued for a longer period of time, it is possible that evidence of diminished sediment supply would be shown by decreasing couplet thickness, reflecting the change from proximal to distal ice-marginal position.

Organic content of the rhythmites could not be adequately determined because of the consistently low organic values, as shown in Table 5. Other investigators have attributed rhythmite layer variations to seasonal differences in organic matter production, but the low organic contents (generally less than 5% and many less than 1%) and the poor resolution of the loss on ignition method (Appendix B) do not allow recognition of changes within rhythmite couplets.

Minor facies changes occurring over a very short stratigraphic and lateral interval make correlation and analysis of sedimentation patterns difficult. This is well documented in sections F01 and F02 (shown in Figures 18 and 19), where minor facies changes occur within 100 m, and result in differing patterns of silt and clay deposition. The following characteristics appear to be common in all sections and core examined:

1. rhythmites always overlie either sand or diamicton, with sharp lower contact;
2. the basal 20-30 cm contain convolute or disrupted lamination: in places this is consistently asymmetric, and is attributed to slumping;
3. lenses of diamict are restricted to the central portion of the section; and
4. lamination becomes less common in the upper part of the deposit: close inspection, however, reveals that lamination is still present in the apparently massive upper clay.

3.1.3 Palynology

In order to obtain more environmental information and possibly add a temporal framework to the rhythmites, palynological analysis was done on the rhythmites from F01.

Terasmae (1958) has shown this method of analysis to be useful in Quaternary stratigraphy and environmental reconstruction. Methods are described in Appendix A. Samples were taken every 10 cm, or closer, as stratigraphy dictated. Sample locations are shown in Figure 24.

Early palynological work in the Ottawa area by Potzger and Courtemarche (1956a, b) included studies of peat bogs from the Gatineau area to the north, and the Ottawa Valley to the east, but were incomplete and lacked radiocarbon control. Several sites were studied by Mott and Camfield (1969) and Camfield (1969), but these were at low elevations and postdate the Champlain Sea episode. Mott and Farley-Gill (1981) studied sites in the Gatineau Park which covered the last 11,000 radiocarbon years. Thus, vegetation changes during the Champlain Sea episode were documented.

Table 5 lists the pollen found in samples FO1 to FO20, and their relative organic matter contents. Organic matter content was determined using the method in Appendix B. Very few pollen grains were found: not enough to place an interpretation on the results. Problems of sample processing, pollen abundance, and preservation in Champlain Sea sediments are common, as described by Ouimet (1983). Considering the nearest vegetated area would have been some distance away, and the relatively long fetch of the sea in the prevailing wind direction, it is not surprising that pollen is scarce. Poor preservation may be the result of marine deposition.

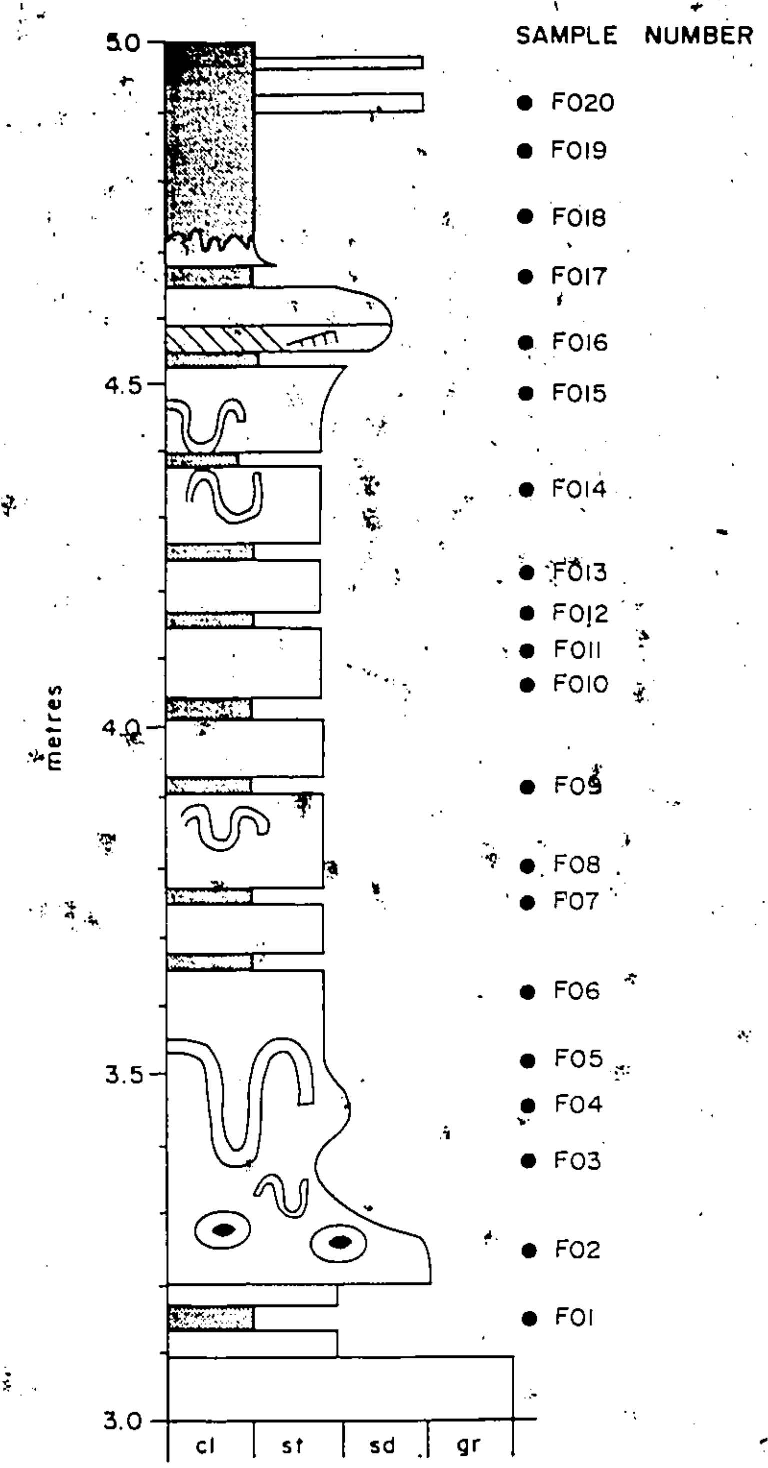


Figure 24: Location of Palynological Samples at F01. Height above pit floor datum (0 m); key as in Figure 17.

TABLE 5

Palynology and Organic Matter Content of Rhythmites in Section FO1

Sample Number	Pollen	Organic Matter
FO1	none	none
FO2	none	rare
FO3	none	none
FO4	none	none
FO5	none	minor
FO6	none	minor
FO7	none	none
FO8	Picea (spruce): 1	minor
FO9	Picea (spruce): 1	minor
FO10	Pinus (pine): 1	minor
FO11	none	none
FO12	Betula (birch): 1	rare
FO13	none	rare
FO14	none	none
FO15	none	minor
FO16	none	none
FO17	Shepherdia (soapberry): 1 Picea (spruce): 1	none
FO18	none	none
FO19	none	none
FO20	Pinus (pine): 2	yes

Organic Matter Content:

rare	less than 1%
minor	less than 5%
yes	more than 5%

3.1.3 Nearshore or Tidal Facies

Overlying the rhythmites is a well documented coarsening upward sequence (Gadd, 1977) of silt and sand. The section described here represents the fine-grained facies (facies 4) where muds predominate. The uppermost sandy facies (facies 5) are not described.

Approximately 1.5 m above the contact with masive silty clay (shown in Figure 17c), a number of juvenile Portlandia arctica occur. Of 37 individuals collected, all were less than 5 mm long, with the majority between 2-3 mm long, as shown in Figure 25. The small size and close range in size indicates a high juvenile mortality rate: spat-kill must have occurred at an early stage, eliminating an entire generation of individuals. No adult remains were found. Hillaire-Marcel (1980) noted that Portlandia arctica is typical of early glaciomarine environments, however the environment here must have been too harsh even for this hardy species. 1-2 m upsection Balanus are abundant, but not found in life position.

The sedimentary structures in this interval are the result of the transition from fine-grained to coarse-grained facies. A continuous series of lenticular, wavy and flaser bedding formed with upward decreasing mud content and increasing sand content (Figures 18 and 19).

One example of this mixed bedding type is shown in Figure 26a which shows clustered, load-casted ripples. The lower group are in the initial stage of deformation, while the upper group are clustered and load-casted ripples. The structures are cylindrical masses of sand or coarse silt, which occur in bedding planes, and have a radial internal structure of laminated sand wedges and fingers. They form when a number of ripples are loaded into weak mud at the same site: each new ripple presses the preceeding one farther down and forward until a radial structure is created. Once locally weakened, the mud tends to remain at

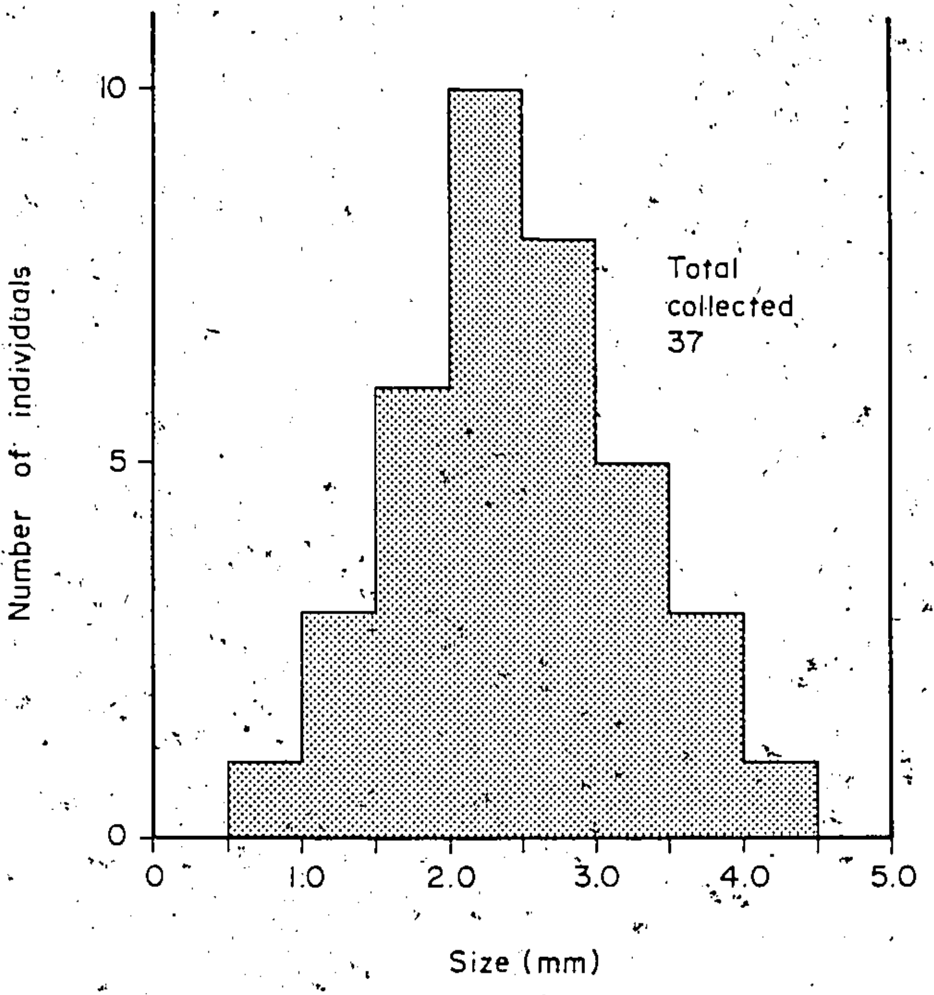


Figure 25: Portlandia arctica Size Distribution

reduced strength, permitting further deformation. Allen (1982) described the deformation as syndepositional. If a suitable supply were in suspension, the sand could penetrate the entire depth of the mud bed.

Gutter casts are found in close proximity to the deformed ripples (Figure 26b). They occur immediately below one of several channels or large angular unconformities (position shown in Figure 17). A corrasional origin (Allen, 1982) for these features has generally been accepted. The best evidence for this is the striated bottom and sides and the presence of possible tools such as subangular pebbles as infillings. Usually gutter casts are found in muddy substrates where they have been scoured by coarser materials.

The morphology of the gutter casts was investigated by excavating into the section. In cross section, the casts are up to 15 cm wide and 10 cm deep, with sinuous longitudinal profile. This profile has been attributed to helical flow (Allen, 1982).

In the wavy to flaser bedded mud and sand, articulated Mytilus edulis, Macoma balthica and Balanus crenatus were found in growth positions. Mytilus is found in groups or colonies, with larger individuals located at the centre and smaller individuals on the periphery, and growing on the larger shells. Macoma was also associated with the smaller Mytilus. A few Balanus encrusted the larger Mytilus. Radiocarbon dates were obtained fom these shells, and are discussed in section 3.1.3.

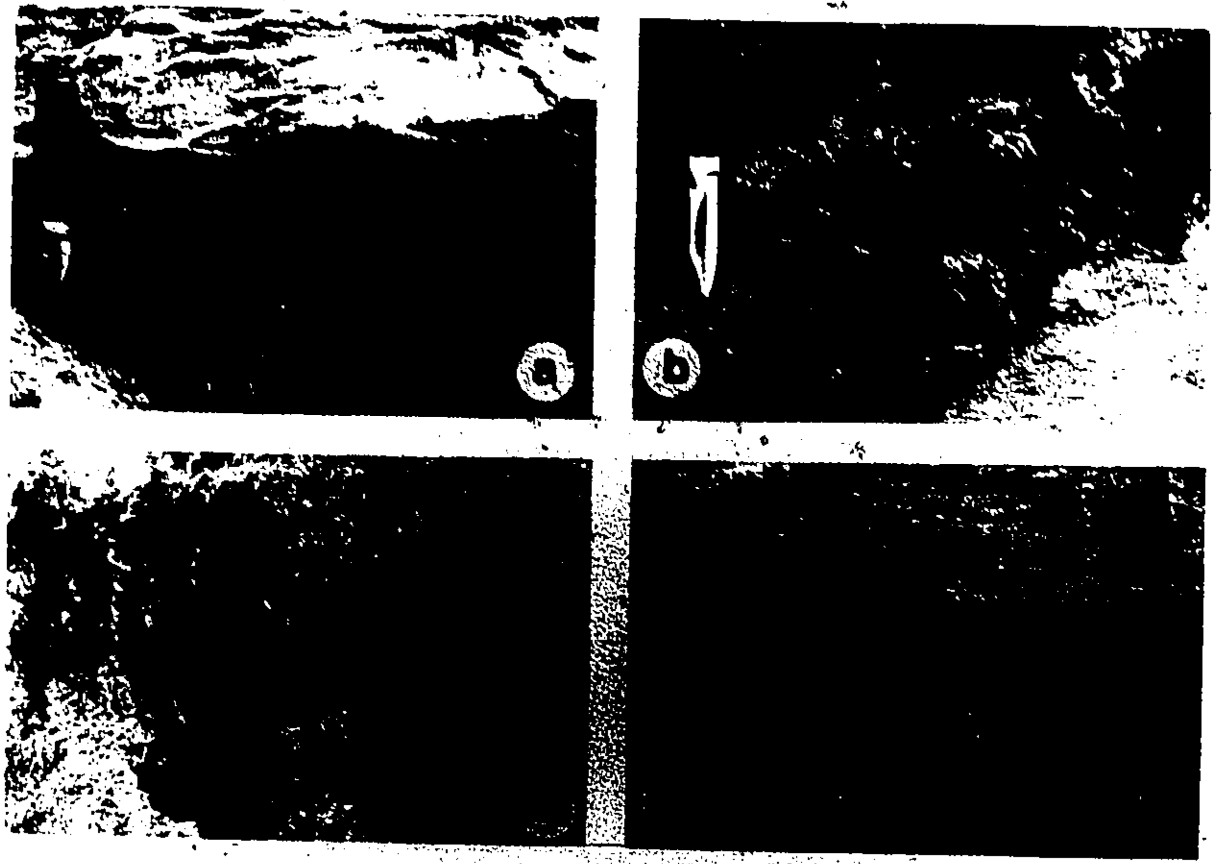
a: Clustered, load-casted ripples in silt and sand beds at section FO3. Lower ripples are undeformed: deformation increases upwards. Knife 20 cm.

b: Mud-filled gutter casts in sand bed at section FO3.

c: Probable polychaete burrows at section FO4.

d: Burrow-like iron stain in rippled silty sand bed at section FO2. Note break in stain halfway from top, and lateral diffusion of iron into adjacent sediment.

Figure 26: Plate III


a
b

This faunal series illustrates a common transition found in arctic and subarctic tidal and intertidal environments. In low energy environments where mud or muddy sand predominates, Macoma balthica occurs. With increasing energy, sands become cleaner, and Hiatella arctica dominates in either infaunal or epifaunal form. In the highest energy environments, Mytilus edulis and barnacles dominate. Modern studies of arctic tidal flat environments (Gilbert et al., 1982) have shown similar communities. Hillaire-Marcel (1981a) has also noted parallel depth zonation in Champlain Sea fossils, as indicated by isotopic studies (Figure 27).

As well as body fossils, trace fossil burrows (Figure 26c) are present. Burrow density is high, but intervening sediments have primary bedding preserved. The size and shape of the structures is consistent with a burrow origin. Sediment within the structures is 1-2 phi sizes finer than the surrounding sediment. Spiral and intersecting morphologies indicate a biotic rather than physical origin. The density and size of the structures suggests that they may be polychaete rather than bivalve burrows.

Polychaetes have rarely been reported in the Champlain Sea. This is probably because they are soft-bodied and only their chitinous jaws are preserved after death. Two of the three reported genera of the Champlain Sea have been found in the Ottawa area (Wagner, 1984).

Polychaetes have been reported in similar environments in modern studies (Gilbert et al., 1982), and are a source of food for the harp seal, the remains of which have been

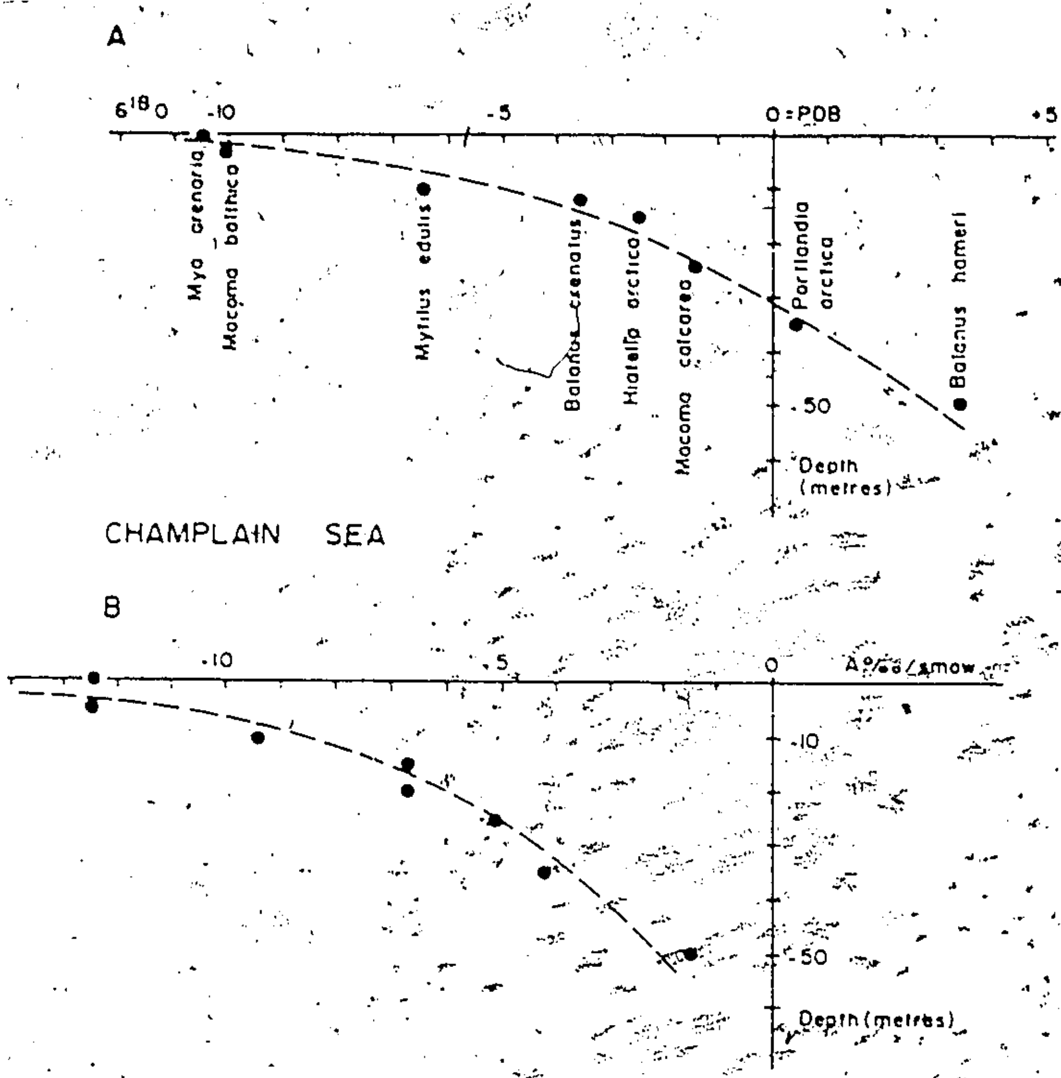


Figure 27: Fossil Depths Based on Oxygen Isotope Data (After Hillaire-Marcel, 1981)

found in the overlying sediments at this locality (Harington, 1977).

Excavation into the section revealed that burrow structures penetrate the sediment, thus ruling out the possibility of a superficial phenomenon. A 10 by 10 cm grid pattern was established on several cut faces to estimate burrow density. Square grids were placed on the top and two adjacent sides of a one metre cube of sediment in three locations, and the burrows counted. Results were compared, and similar numbers were found in each case, so orientation apparently has no effect on density. Burrow density was calculated to be approximately 30,000 burrows per metre^3 of sediment. Assuming the simplest geometry of a cylindrical burrow of diameter 1 cm and length 8 cm, each burrow has a volume of 6.3 cm^3 and the minimum volume of burrowed sediment in one metre^3 is 189,000 cm^3, or roughly 20% of sediment volume.

Much of the rippled fine sand and silt has periodically spaced iron-stained beds of medium sand. Spacing varies from 20-50 cm with individual bed thickness ranging from 5-10 cm. This phenomenon has been noted in marine and non-marine sediment, and usually involves periodic precipitation of manganese and/or iron with the release of hydrogen sulphide.

Johnston (1917) first noted these strata, which he called reddish bands. They occur most abundantly at the base of the upper fine-grained silty clays and in places extend through a vertical interval of 2-3 m, but are not extensively developed. Johnston noted the material to be extremely fine and largely weathered, in contrast to the material of the present study which is coarser (sand).

Gadd (1971) noted similar deposits, calling them the black-mottled facies. Freshly exposed surfaces of the massive upper silty clay body contain black patches in places and streaks of an oily or greasy material that appears to be due to concentration of finely divided organic matter. Hollow black tubes of organic matter, probably root fragments, are common and in several places there are shell molds after Portlandia sp.. These molds are lined with a thin, black film which Gadd interpreted as the remains of the periostracum. Shells apparently have been destroyed, leaving behind the surface covering.

The clays have a pungent sulphurous odour when freshly exposed, and release sulphur dioxide and/or hydrogen sulphide when cold dilute HCl is applied. Apparently, the compounds producing these reactions are not stable, since they disappear upon exposure.

Gadd also noted that in some places rusty coloured bands on the surface mark the position of black bands in freshly cut clay. When exposed to surface conditions, the black bands changed to a rusty colour. Gadd assumed these clays were deposited in a deep basin under anaerobic conditions, where a drowned glacial topography hampered normal circulation. Deep water deposition may be possible as in the fjord postulation of Catto et al. (1981), but sections in the Ottawa area do not indicate a drowned glacial topography and sedimentary structures indcate intertidal deposition. The rusty bands may therefore have been deposited in shallower water than Gadd envisioned, and may be due to diagenetic change within the sediment.

When fine organic matter is dispersed through the substrate, a series of decomposition reactions begins, based on the bacterial decomposition of the organic matter. A biochemical succession forms, which leads to a vertical zonation based on electron acceptor use in the various chemical constituents (McCall and Teveoz, 1982). From the sediment-water interface downwards, layers rich in oxygen, nitrate, manganese, iron, sulphate and carbon dioxide form. With changing redox conditions (for example with changing water level), periodic precipitation occurs.

Donovan and Lajoie (1979) reported this phenomenon in Champlain Sea sediments, noting that the presence of diagenetic iron sulphide in the glacigenic clays effects their geotechnical properties.

In this particular case, bands of iron oxide have been precipitated. In other cases, the reaction geometry is somewhat different, forming rings around organic particles. For example, the black-mottled facies of Gadd (1971) may be the result of precipitation around fecal pellets or other point sources of organic matter capable of decomposition. Examples of such reaction geometries are shown in Figure 28.

High concentrations of available iron have also caused the formation of a burrow-like structure, shown in Figure 26d. However, several factors indicate that the structure is not a burrow. The structure is too large- the only burrowing

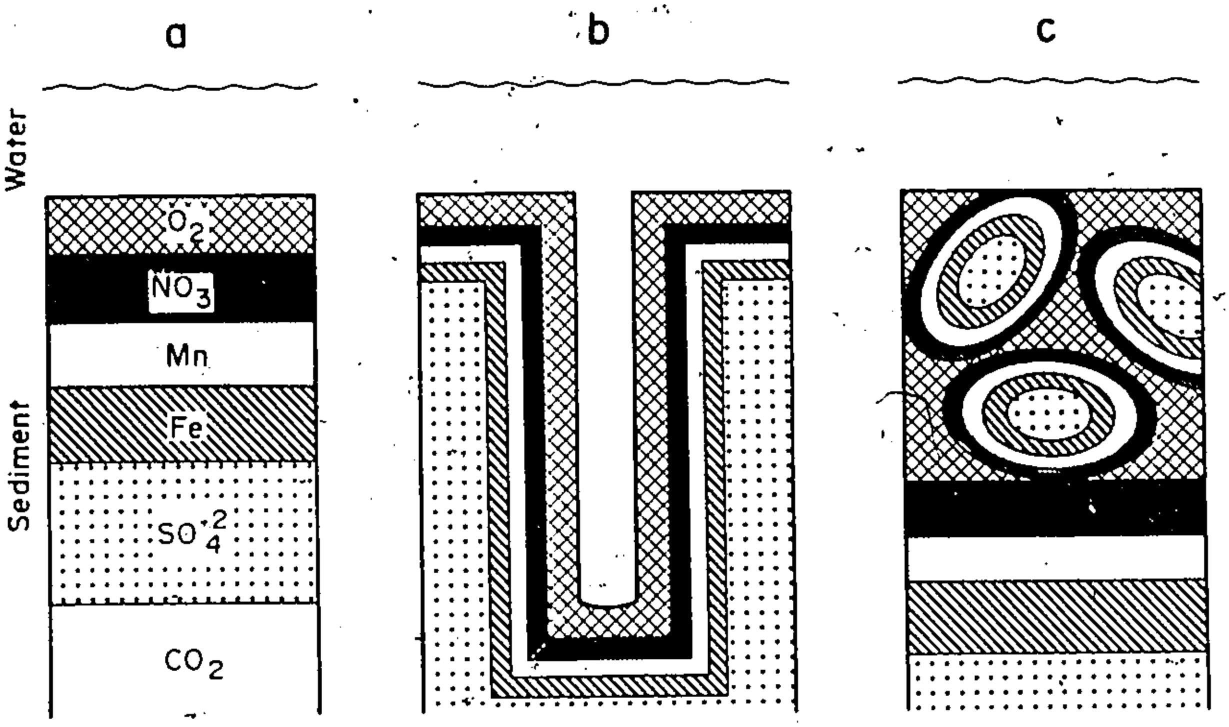


Figure 28: Geochemical Reaction Geometries
(After McCall and Teveoz, 1982)

organisms known to exist in the surrounding sediment are bivalves and possibly polychaetes, both of which are smaller than the structure. At least two laminae penetrate the structure, including a prominent sand lens shown in the upper half of the illustration. Tracing individual laminae through the structure, some bend downwards as would occur following fluid escape and subsequent sediment collapse.

Although the exact mechanism is not known, it appears that the structure formed by precipitation of free iron which was mobilized by the flow of groundwater through the iron-rich beds described above. Groundwater travels freely through the overlying sand beds to this level, where the underlying fine-grained sediments act as a barrier to further downward movement of water. In a cut section, this results in the discharge of high volumes of water through the sediment where the structure was found. Upon exposure to surface conditions, the iron is immediately oxidized and forms the crust seen on the sand grains.

3.1.4 Radiocarbon Dates

No datable material has been recovered from either the rhythmites or the underlying material. Several dates have been obtained on shells collected above the rhythmites. These are summarized in Figure 29. Preston et al. (1955) reported a date of 10,850±300 BP (Y 216) on shells of *Macoma* with some *Balanus* and *Saxicava* (*Hiatella*) found at an elevation of 98.5 m (325 ft.) in a pit at the northwest corner of Uplands airport. Olson and Broeker (1961) reported

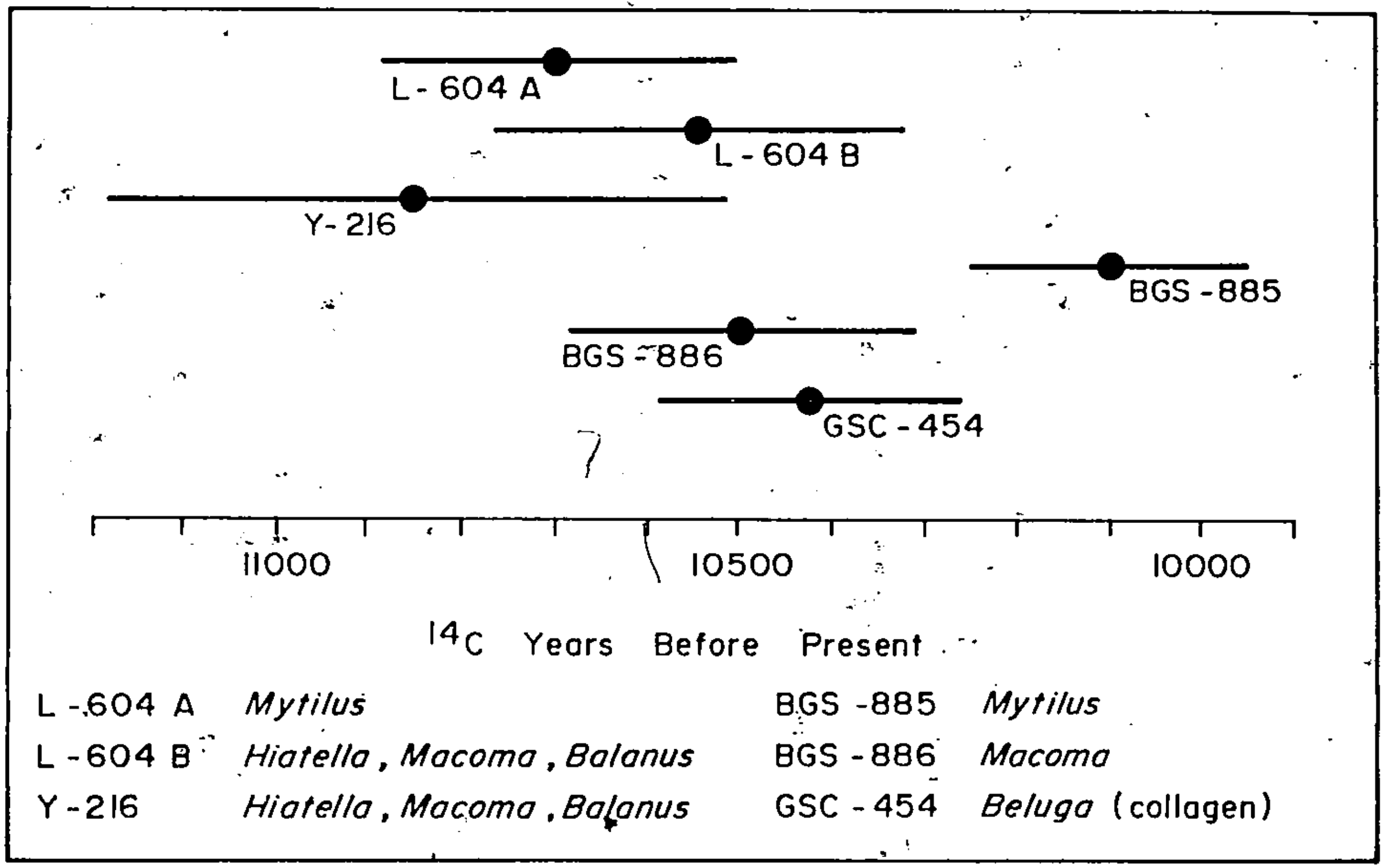


Figure 29: Radiocarbon Dates from Shell and Bone at the Foster Pit

two dates from marine shells collected at an elevation of 91 m (100 ft.) at the Foster pit. Mytilus from 12 m (40 ft.) below the ground surface yielded a date of 10,700± BP (L 604A) and a collection of Hiatella, Macoma and Balanus from 11 m (35 ft.) below the ground surface yielded a date of 10,550+200 BP.

Since all previous radiocarbon dates except L 604A were from a mixture of species, it was decided to sample single species to see whether a more precise date could be obtained. Each bivalve has a different rate of carbon uptake, so there may be slight variations of dates between species.

A 2.5 m section was measured and sampled for shells, as shown in Figure 30. A lens of light pinkish brown medium to coarse sand contained in situ articulated Mytilus edulis, Macoma balthica, and Balanus crenatus. Two radiocarbon dates were obtained from the Brock University Radiocarbon Lab: Mytilus gave a date of 10,100+130 BP (BGS 885) and Macoma gave a date of 10,500±180 BP (BGS 886). Since these shells were observed in life position, and separated by species, it was hoped that their ages might give more precise information as to the age of the materials overlying the rhythmites. As indicated in Figure 29 however, the error involved in the age determinations makes interpretation of ages by species impossible.

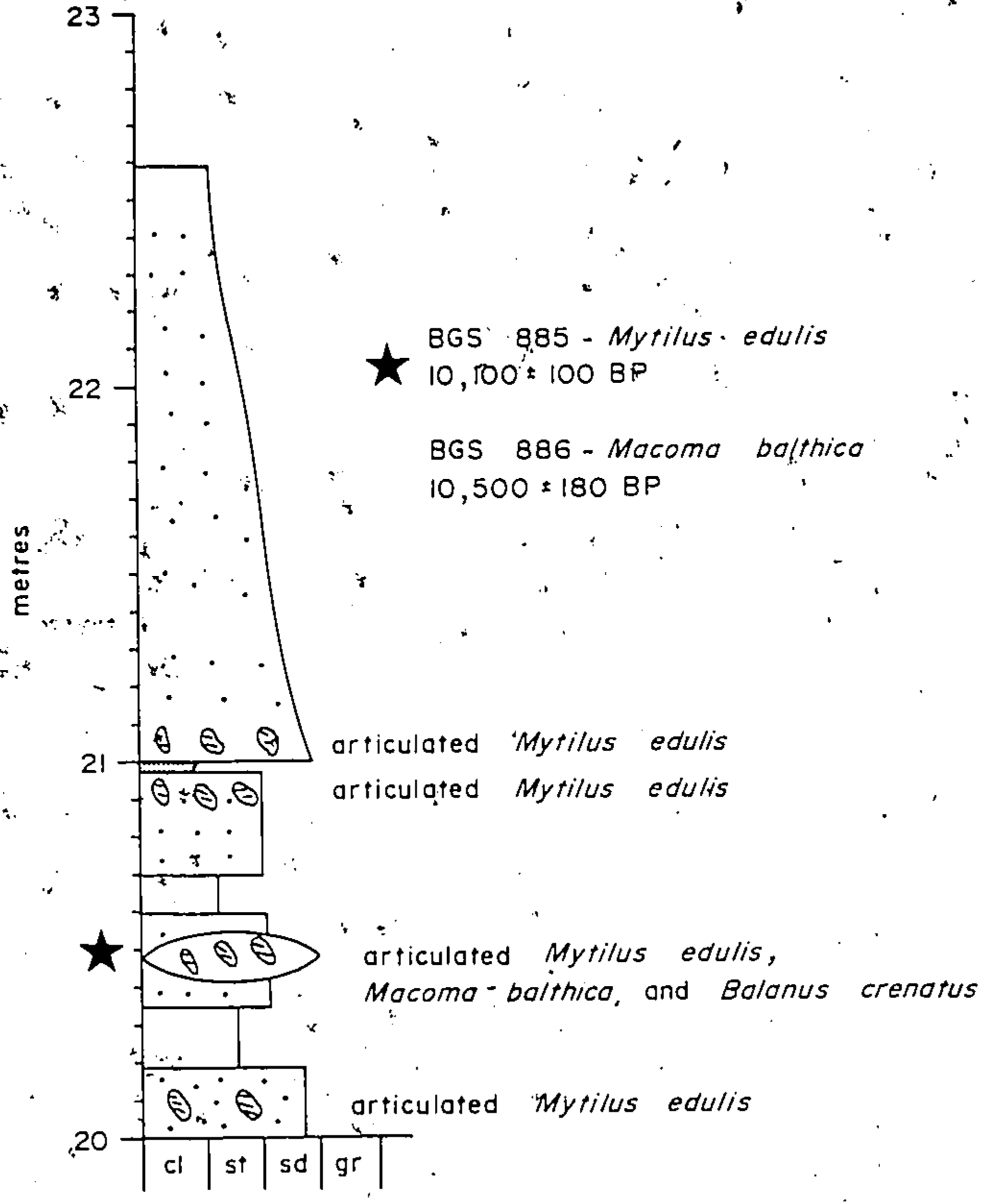


Figure 30: Stratigraphic Column F04 Showing Location of Shells for Radiocarbon Dates. Elevations as in Figure 17.

3.1.4 Vertebrate Remains

Over the past 30 years, remains of the Beluga (White) whale and the Ringed seal been found in the Foster pit. Sternberg (1951) collected most of a skeleton including a well preserved cranium lacking the lower mandibles, 20 vertebrae, several ribs, a scapula, humerus, radius, and various bone fragments of a White whale Delphinapterus leucas (NMC 8883). It is probable that the complete skeleton was present originally, but removal of the surrounding sand caused the loss of some bones. A few days later, the broken mandible of a younger individual was recovered (NMC 8884). The partial skeleton of a White whale was collected for N.R. Gadd in 1956. Parts of the cranium, limbs and ribs were recovered. Bones were found at a depth of 6.1 m (20 ft.) below the ground surface, and approximately 6 m (15-20 ft.) above the location of the bivalve shells for dates L 604A and L 604B. A date of 10,420+ BP (GSC 454) was obtained on bone collagen (Figure 29).

The remains of a ringed seal have also been found (Harington, 1977). The right calcareum (NMC 13749) was collected in 1975 from the sand surface of the Foster Pit approximately 9 m (30 ft.) below the ground surface.

3.2 SUBSURFACE EVIDENCE-GSC BOREHOLES

During the 1974, 1975 and 1976 field seasons, the Geological Survey of Canada made 27 stratigraphic borings through the late Quaternary deposits of the Ottawa Valley (Figure 31). Over 200 shelby tube cores were taken at close

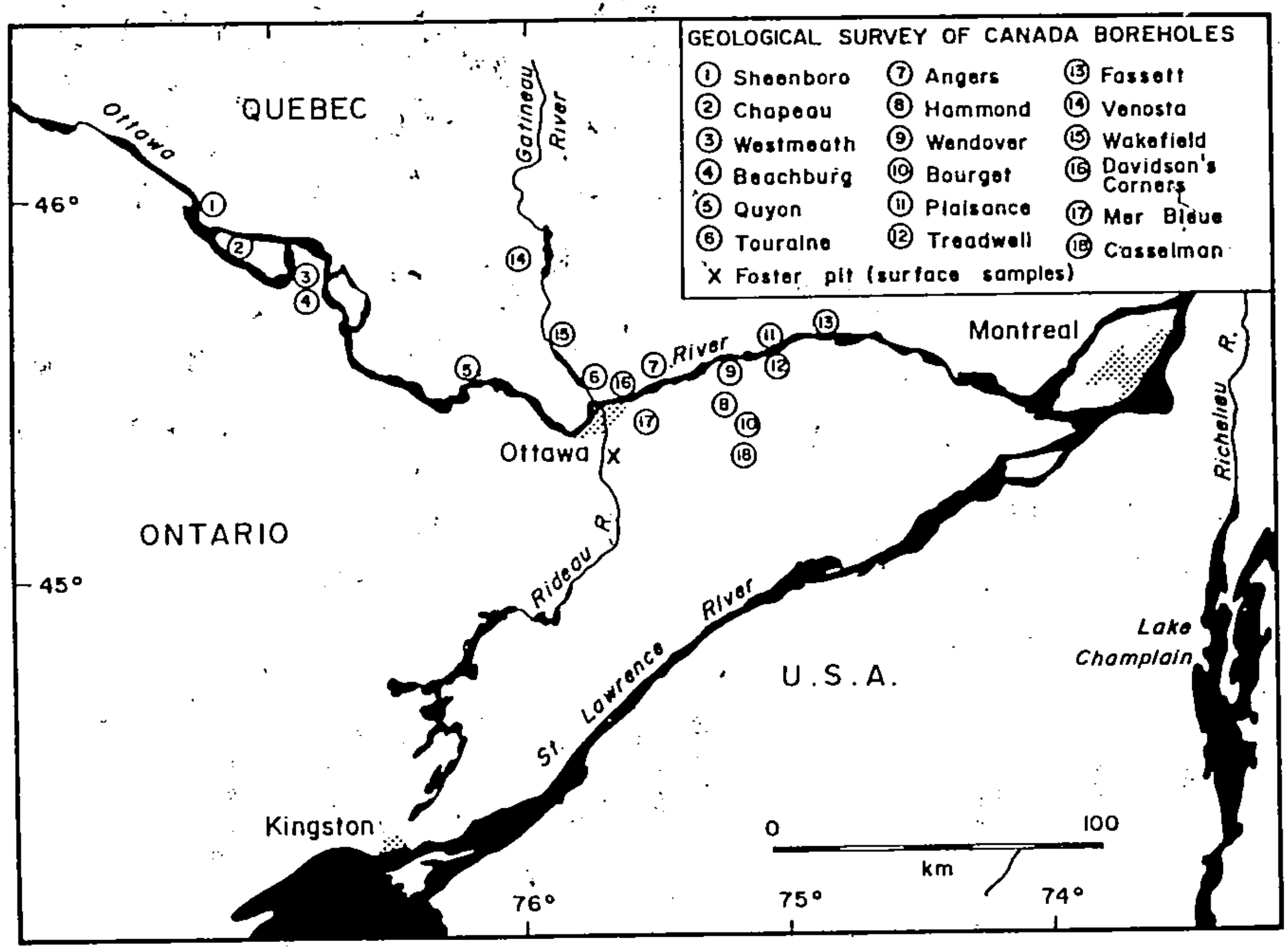


Figure 31: Location of GSC Borehole Transects in Ottawa and Gatineau Valleys

intervals through the entire suite of silt and clay sediments.

The first information revealed is that the laminated sediments are much more widespread than previosly thought, and the concept of a narrow glacial lake (Gadd, 1962) must be discarded, or modified. Gadd (1986) proposed that the rhythmites were deposited in an early glaciomarine phase of the Champlain Sea, however sedimentary evidence from surface exposures and boreholes does not support this claim and points to the original concept of a glacial lake.

Fransham et al. (1976) and Gadd (1977) identified at least four principal facies in upward sequence in the late Quaternary deposits:

1. Varved clay with characteristic colour banding and graded bedding commonly overlying till, grades upwards to faintly stratified to massive dark blue-grey clay and silty clay;
2. Silty clay, commonly mottled throughout by unstable black sulphurous material which disappears upon exposure. The mottling shows an irregular pattern similar to burrows or bioturbation structures. Commonly fossiliferous (pelecypods, foraminifera, ostracodes), this facies grades upwards to
3. Regularly banded, coarse grey silty clay and fine red clay with bands of sulphurous black material in discrete layers. Relative thickness of grey-red couplets (coarse-fine) increasing upwards, as does grain size.

4. Clay to sand, with sand dominant in upper strata. Distinguished mainly on the basis of structures.

Gadd (1977) suggested that the basin received fine sediment under four principal conditions:

1. Freshwater glacial lake;
2. Deep water, quiescent marine basin or pro-delta environment of maximum salinity;
3. Bottom-set facies of a prograding delta, and
4. Upper delta facies of the prograding delta.

Gadd (1986) modified his original proposal of a glacial lake to an ice-proximal glaciomarine water body. This interpretation is confused, and Gadd did not clearly distinguish between glaciomarine and glaciolacustrine conditions. He noted "the gradational relationship (between diamicton and overlying rhythmites) indicate a continuity of sedimentation, presumably in one basin, and a rapid and gradational transition from glaciolacustrine or glaciomarine to marine conditions... In such an interpretation, a glacial lake, as such, may never have existed, instead there may have been a (estuarine?) part of a larger marine basin that had relatively short term glaciolacustrine and glaciomarine conditions imposed on it during the persistence of glacier ice in nearby highlands... Rather than a separate freshwater lake, the barren to sparsely fossiliferous varves may represent essentially glacial conditions near the ice margin in the marine basin" (page 17).

One major problem in analyzing individual rhythmites of the Ottawa Basin is that they do not correlate well, if at all between cores. There appears to be no basin-wide depositional event or marker which could be used to tie depositional history together: close examination reveals that while the depositional pattern is similar in all subsurface rhythmite sequences, each couplet displays its own particular sedimentation rhythm. Agterberg and Banerjee (1969) and Banerjee (1973) attempted to develop a stochastic model for rhythmite deposition, but it is extremely complex, and the Ottawa Valley core does not appear to fit the model.

The preceding discussion assumes that the rhythmites are true varves: in fact, evidence seen in surface exposures strongly suggests that the rhythmites are episodic. If this were the case, then correlation between cores would be difficult or impossible. The stochastic model of Agterberg and Banerjee (1969) applies only to annual rhythmites, and would not be valid for episodic events.

Examination of the core logs from the Geological Survey of Canada (Gadd, 1986) indicates wide variation in the use of terms such as "varve", "rhythmite", "interlaminated" and "varve-like". Clearly, no interpretation of the sediments can be made unless an objective basis can be used to indicate the relationship between rhythmically alternating silt and clay units. Until such unbiased measurements can be made, no correlation of rhythmites between cores will be possible. The use of a single investigator should aid in keeping description consistent, but objective criteria are still necessary to be able to relate depositional packages from different areas to each other.

Rhythmite thicknesses indicated in Figures 32 and 33 vary over the Ottawa basin, and the exact thickness is in doubt because of the variations in description mentioned above. It is not clear whether indicated thicknesses are true thicknesses or other sediment types have been included with the rhythmites. A case in point is the contact between the rhythmites and the overlying massive clay observed in surface exposure and in cores. This contact is not sharp or easily defined except in cases where there is a disconformity clearly indicated as in section F01 (Figure 16c). Since the division between the two units is based on bedding style which is variable near the contact, division is somewhat arbitrary. As a result, the exact thickness of the rhythmites cannot be determined from the core logs.

In addition, bottom topography of proglacial lakes is uneven, and sediment thicknesses often vary greatly within a lake. This has been observed by echo-sounding of Lake Ontario (Anderson, pers. comm., 1984) and other glacial lake basins. As a result, it is expected that rhythmite thickness might vary within the Ottawa Valley.

Serious consideration, however, should also be given to the possibility that more than one basin may be involved, and consequently sediment thicknesses would vary from place to place within the larger water body.

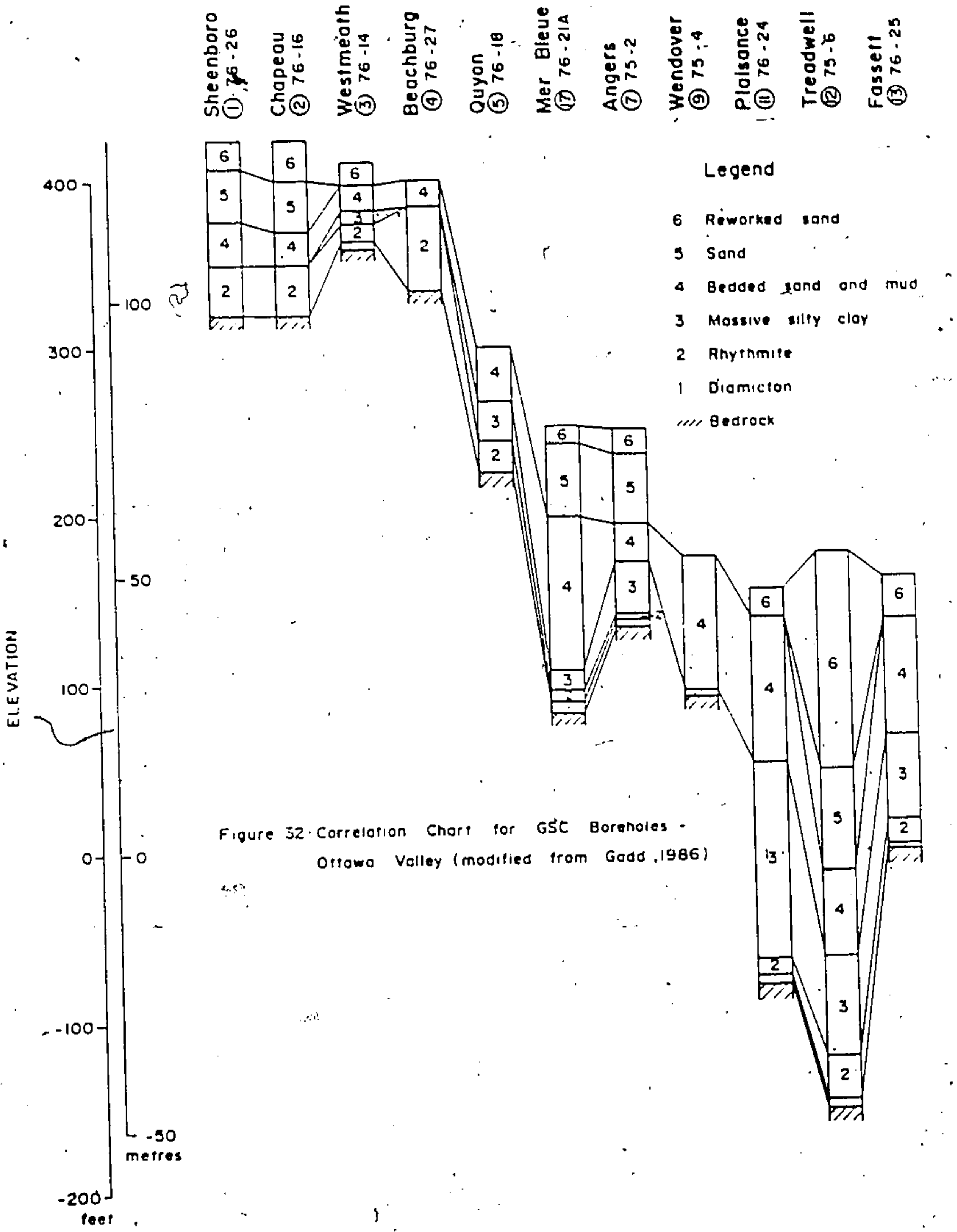


Figure 32 · Correlation Chart for GSC Boreholes - Ottawa Valley (modified from Gadd, 1986)

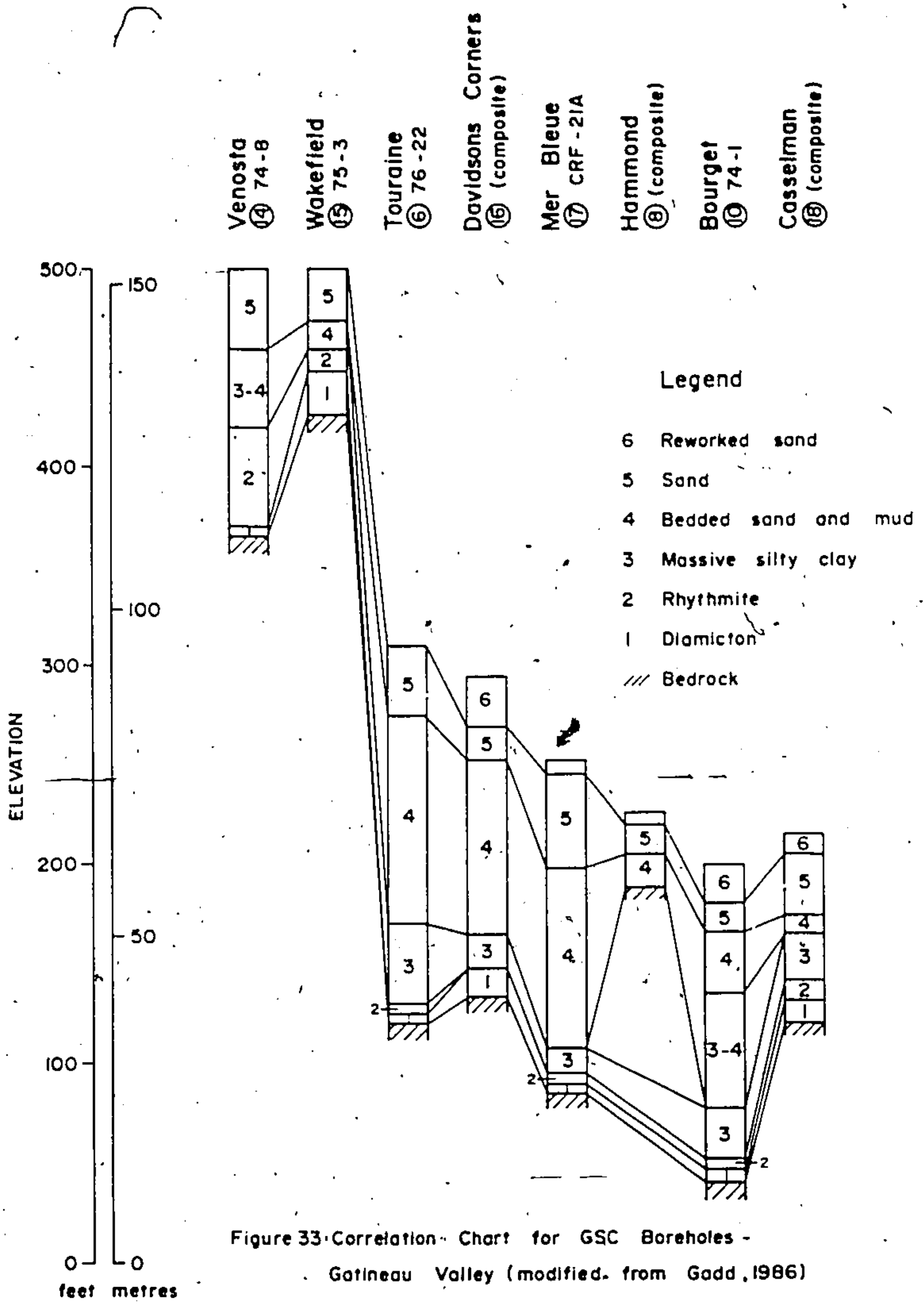


Figure 33·Correlation Chart for GSC Boreholes - Gatineau Valley (modified from Gadd, 1986)

3.3 DISCUSSION

Correlation of sediments and analysis of depositional mechanisms may be greatly complicated if more than one basin is involved. The pre-Champlain Sea lake was deeper than the subsequent sea, and therefore very likely occurred as a single water body. It seems possible, however, that several smaller basins or depocentres could have been created during the final decay of the ice sheet in the shield areas of the Rideau Lakes and the Gatineau Hills to the north. The irregular bedrock topography and poor drainage would result in local ponding of water either by bedrock hollows, or in ice-dammed areas. Similar depositional environments have been documented in Scandinavia (Terasmae, pers. comm., 1985), particularly in Sweden where similar bedrock topography occurs.

The small size of the basins and possible ice damming would result in short lives for the lake segments, producing the thin sediment package observed in the rhythmites. The approximately 1 m rhythmite section implies an extremely short life: Rust (pers. comm., 1986) estimated possible time of less than 20 years, and Gadd (1986) proposed a period of 30-50 "varve years". Although the rhythmite couplets cannot be proven annual, these estimates seem to be at least the correct order of magnitude for the duration of the proglacial lake.

Maximum sedimentation rate for rhythmite deposition may be calculated assuming minimum deposition time of 20 years and maximum sediment thickness of 1.0 m, giving a sedimentation rate of 5.0 cm/year. Gadd (1986) estimated a sedimentation rate of 3.5-5.0 cm/year for the overlying Champlain Sea clay (here termed facies (4) or massive silty clay), based on thicknesses observed in the Ottawa Valley boreholes and radiocarbon dates giving marine maximum and freshwater minimum ages for the Champlain Sea. These estimates fall into the middle of the range for glaciomarine sedimentation discussed in section 2.3.

If a series of isolated depocentres or basins were created, it would be very difficult to analyze and correlate the sediment between basins. In the case of distinguishing between annual and episodic rhythmites, the distinction between suspension and traction deposition and relative unit thicknesses of winter and summer layers may not be clearcut. For example, in true varves, the thickness of winter layers should be consistent since all material is deposited from suspension. This assumes, however, that the sediment is suspended in a single basin. If several smaller basins are involved, the unit thickness may not be consistent since sediment input to each basin could vary. This means that if several small basins are involved, the possibility of correlating rhythmite units is greatly diminished, and the distinction between annual (varves) and episodic rhythmites will not be clear if based on sedimentological criteria alone.

Chapter IV

MICROPALEONTOLOGY

4.1 INTRODUCTION

4.1.1 Previous Work

Dawson (1857) appears to have been the first to identify Champlain Sea foraminifera. He figured (without identification) seven foraminifera from the Montreal area, now identifiable at the genus level as Elphidium sp., Quinqueloculina sp., Oolina sp., Guttulina sp., and Triloculina sp.. Logan (1863) reported further work, and Dawson (1871) noted the foraminifera were most abundant in sandy clay, especially where molluscs are numerous, and identified Polystomella crispa (Linne) (probably Elphidium excavatum Terquem) as the most frequent species. Brady and Crosskey (1871) appear to be the first to report Champlain Sea ostracodes.

Wagner (1970) stressed molluscs in her study of Champlain Sea fauna, and illustrated only 25 species of foraminifera and ostracodes, listing most ~~as~~ indeterminate.

The paleoecological implications of the Champlain Sea benthonic foraminifera have been discussed in detail by Corliss et al. (1982), Cronin (1976a, b, 1977a, b, 1979a, b, 1981) and Fillon and Hunt (1974). All of these studies have concentrated attention on the later, more well established biofacies rather than the early, transitional Champlain Sea microfauna.

With the exception of studies by Guilbault (1980) and

Rodrigues and Richard (1986), no ecostratigraphic studies of microfauna have been made. These two studies concentrated on the younger, littoral sediments and have generally ignored the older, early Champlain Sea sediments. Pre-Champlain Sea sediments either were not included in previous studies, or were not recognized by investigators. The present study therefore represents the first ecostratigraphic study of the early and pre-Champlain Sea sediments in the Ottawa Valley.

Fillon and Hunt (1974) analyzed three piston cores from the Lake Champlain basin and proposed a biostratigraphic zonation based on dominance. The zones (in order of decreasing age) are: V: *Islandiella teretis*; W: *Islandiella islandica* and *Islandiella teretis*; X: *Protelphidium orbiculare* and *Elphidium bartletti*; Y: *Elphidium clavatum* and *Protelphidium orbiculare*; and Z: *Elphidium clavatum*. These species are all common in the Canadian arctic region and the eastern continental shelf in water less than 100 m deep (Cooper, 1964; Hooper, 1968; Loeblich and Tappan, 1953; Phleger, 1952; Vilks, 1968). *Elphidium clavatum* is dominant in very shallow, low salinity environments. Guilbault (1980) noted that because of its abundance and association with *Islandiella helenae* (=*Islandiella teretis*), it is possible the species Fillon and Hunt (1974) reported as *Islandiella islandica* is in fact *Cassidulina reniforme*. Fillon and Hunt suggested salinities of 30-33 ppt for zones V and W; 22-28 ppt for zones X and Y; and 18-24 ppt for zone Z.

Cronin (1976a, b, 1977a, b, 1979a, b, 1981) has made the most comprehensive study of the Champlain Sea microfauna to date. He studied foraminifera and ostracode fauna from sediment in the Lake Champlain, southern Quebec and eastern Ontario areas. All samples came from surface localities, and their stratigraphic location was often not considered. Good systematic and paleoecological description of the foraminifera (1977b, 1979a) and the ostracodes (1981) are given with roughly 79 benthonic foraminifera species and 40 ostracode species listed as shown in Table 6 and Table 7. Guilbault (1980) also gives a good systematic listing of the foraminifera.

Cronin (1976b) described a fauna from near Kars, Ontario, at the extreme southern end of the Twin Elm Ridge. The most significant point is the large number of species (Table 8) found at this site. Seldom are more than 10 species found at any one Champlain Sea locality (Wagner, 1970; Cronin, 1976b), but the Kars locality yielded 41. This indicates high species diversity, even for recent arctic faunas, where average species number per locality is 27 (Loeblich and Tappan, 1953). A ^{14}C date of 10,900±100 BP (GSC 2312) was obtained on shells of Hiatella arctica found at the same site. The fauna documents a normal marine, arctic-subarctic environment with bottom water temperatures at or below 0°C for most of the year, and rarely exceeding 10°C to 12°C during the warmer months; salinities ranged from 30-35 ppt.

Cronin (1979a, b) summarized previous work, giving a synthesis of geographic variations of species diversity and

TABLE 6

Champlain Sea Foraminifera (after Cronin, 1977a)

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

Triloculina trihedra Loeblich and Tappan
Pyrgo williamsoni (Silvestri)
Silicosigmoilina groenlandica (Cushman)
Pateoris hauerinoides (Rhumbler)
Virgulina schreibersiana Czjzek
Virgulina loeblichi Feyling-Hansen
Buccella frigida (Cushman)
Patellina corrugata Williamson
Cibicides lobatulus (Walker and Jacob)
Astacolus hyalacrulus Loeblich and Tappan
Nonion labradoricum Dawson
Trifarina fluens (Todd)
Astrononion *gallowayi* Loeblich and Tappan
Bolivina subaenariensis Cushman
Bolivina sp.
Bulimina cf. *B. marginata* d'Orbigny

faunal changes over a period of time. These factors reflect the evolution of the Champlain Sea basin(s) and the response of the fauna to water mass characteristics. A nearshore, shallow (less than 30 m) water fauna was dominated by *Elphidium* sp. and *Protelphidium orbiculare* and a second assemblage dominated by *Cassidulina crassa*, *Islandiella helenae* and *Elphidium excavatum* forma *clavata* represents offshore, deeper (30-100 m) water.

Ostracodes were studied (Cronin, 1977a) and three stages of Champlain Sea development were inferred. In the Transitional phase (12,500 to 11,600 BP) a mixed association of freshwater and euryhaline ostracodes and molluscs were found, suggesting a periodic input of glacial meltwater into the marine water. Water temperatures were considered to be below 5-10 °C. The *Hiatella arctica* phase proposed by Elson (1969a) followed (11,600-11,000 BP), and was marked by the abundance of *Hiatella arctica* and a polyhaline subarctic-arctic ostracode and foraminifera fauna, with the absence of

TABLE 7

Champlain Sea Ostracoda (after Cronin, 1977a)

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

freshwater ostracodes. Based on faunal evidence, salinities of 18-35 ppt and temperatures of less than or equal to 12 °C during the warmer months were inferred. The *Mya arenaria* phase followed (11,000 to 10,600 BP). This phase was characterized by the presence of *Mya arenaria* as the dominant bivalve, the appearance of the gastropod *Hydrobia totteni*, the absence of *Hiatella arctica* and *Portlandia arctica*, and an ostracode assemblage different from the previous two

TABLE 8

Foraminifera at Kars, Ontario (after Cronin, 1976b)

Elphidium incertum (Williamson)
Elphidium excavatum forma *clavatum* Cushman
Elphidium frigidum Cushman
Elphidium subarcticum Cushman
Elphidium bartletti Cushman
Protelphidium orbiculare (Brady)
Islandiella teretis (Tappan)
Islandiella islandica Norvang
Islandiella norcrossi (Cushman)
Cassidulina crassa d'Orbigny
Eosyrinx curta (Cushman and Ozawa)
Glandulina laevigata d'Orbigny
Pseudopolymorphina novangliae (Cushman)
Guttulina glacialis (Cushman and Ozawa)
Guttulina cf. *G. lactea* (Walker and Jacob)
Guttulina sp.
Dentalina ittai Loeblich and Tappan
Dentalina melvillensis Loeblich and Tappan
Fissurina marginata (Montagu)
Fissurina cucurbitasima Loeblich and Tappan
Fissurina ventricosa (Weisner)
Fissurina serrata (Schlumberger)
Fissurina sp.
Oolina melo d'Orbigny
Oolina caudigera (Weisner)
Oolina scalareforme-sulcata (Weisner)
Oolina lineata (Williamson)
Oolina hexagona (Williamson)
Lagena apiopleura Loeblich and Tappan
Lagena semilineata Wright
Virgulina loeblichi Feyling-Hanssen
Virgulina sp.
Buccella frigida (Cushman)
Cibicides lobatulus Walker and Jacob
Astrononion gallowayi Loeblich and Tappan
Laryngosigma hyalascidia Loeblich and Tappan
Laryngosigma williamsoni (Terquem)
Triloculina trihedra Loeblich and Tappan
Quinqueloculina seminulum (Linne)
Bolivina cf. *B. pseudoplicata* (Heron-Allen and Earland)
Bolivina sp.

phases. The data suggested a warming during the interval, with water temperature as high as 20° C during the summer months and estimated paleosalinites of 3-18 ppt. Foraminifera found in this interval are characteristic of estuarine and bay-mouth environments, with modern salinities of 8-18 ppt.

In comparison, studies of proglacial lake microfauna are relatively rare. This may be because of the sparsity of the fauna in the nutrient-poor water. Since the water is fresh, foraminifera are absent, and studies are generally restricted to ostracodes. Delorme (1969) noted the importance of ostracodes as Quaternary paleoecology indicators, showing well documented ostracode evolution in post-glacial lakes in Canada (Delorme, 1970a, b, c, d, 1971). Diatoms are also useful environmental indicators, but diatom paleoecology is beyond the scope of the present study.

4.1.2 Reproducibility

The reproducibility of much micropaleontology work is at best, poor. The problem arises for three reasons. Faunal distribution (Dodd and Stanton, 1981) may be patchy, and is difficult to establish in the field. It is thus often difficult to determine whether a sample is representative of a particular facies (or population). Much of the previous work has been conducted as inventory (systematic paleontology), without regard to stratigraphic position. Thus, the paleoecological information derived is of limited value. Lastly, much of the faunal material is dependant on processing techniques for adequate recovery. If methods are not clearly stated, it may not be apparent that a given faunal component is missing.

In order to test the reproducibility of surface samples, a random sample (F038) was chosen for duplication. Four samples were taken on a 0.5 m grid pattern around the original sample. Subsequent picking failed to exactly duplicate faunal results. Most common species were duplicated, however similar rare species were not found in three samples, and one sample was barren (Table 9).

This illustrates the importance in assessing the faunal distribution within a given sedimentary facies or stratigraphic unit. Microfossil distribution may be one of the following types:

1. regular
2. patterned
3. patchy
4. random

Regular distribution occurs rarely, where the fauna has the same spatial distribution and density over a relatively large area.

Patterned distribution occurs where the fauna has the same density within a small area, which is repeated at regular and predictable intervals. This distribution is not as rare as the regular type, but nevertheless is fairly uncommon. Factors such as water circulation patterns, nutrient supply, predation and competition often cause local shifts in population.

Patchy distribution occurs most frequently, and displays an apparently disorganized distribution based on the factors mentioned above. Although the fauna may be spatially disrupted, the species abundance and diversity

TABLE 9

Comparison of Duplicate Surface Samples F038

Genera/Species	a	b	c	d	e
Islandiella helenae	53	65	--	50	45
Cassidulina crassa	31	44	--	28	22
Elphidium/Protelphidium	21	32	--	19	20
Quinqueloculina sp.	6	8	--	5	4
Cibicides lobatulus	3	1	--	1	1
Dentalina pauperata	1	--	--	--	[illegible]
Glandulina laevigata	1	--	--	--	1
Oolina williamsoni	2	1	--	--	1
indeterminate ostracode	1	3	--	--	1
Total number in 200 g	117	154	---	103	95

still maintain the parameters defining the biocoenosis.

Random distribution occurs when several factors interact to produce a completely random and often complex distribution. This may occur as a result of post-mortem changes in the fauna, or through other natural processes such as mixing of water masses (eg by cabbeling) which contain distinct and otherwise separate fauna.

Analysis of the samples discussed above suggests that faunal distribution is patchy. Faunal distribution between duplicate samples suggests a single environment of deposition (shown by identical dominant species in all samples containing microfossils) with no faunal mixing. Distribution therefore is not random. Lateral variation, however, appears within this environment. This rules out regular faunal distribution. Minor environmental differences and local population variations are reflected in the variation of the subordinate and rare species. The distribution observed does not appear to repeat itself at a regular and predictable interval, and density varies over a short distance (0.5 m). Distribution is therefore considered patchy, and the dominant species representative of a single environment of deposition with minor local variations. There is no evidence of faunal mixing, post-mortem changes or other modifying factors.

While the presence of a particular species or association represents at least part of the population existing in that environment, it is possible that certain species may have been missed by chance, or the sample may be barren. Where faunal distribution changes over such a short interval (0.5-1.0 m), caution must be exercised in the interpretation of subsurface evidence since it may not represent the entire fauna. Wherever possible, corroboration from surface exposures is best, since direct control over sedimentary facies may be used and biofacies better interpreted.

4.1.3 Methodology

Microfossils were extracted from surface samples and cores. Due to the limited amount of material available from the cores, and the necessity of saving some material for other analyses, the most efficient method possible was required for sample processing. This method is described in Appendix D.

Many previous studies have failed to provide adequate microfossil information. Noting only the presence of a given taxon does not give as much information as might often be derived from sample material. For example, shell surface texture may indicate the effects of solution, or evidence of transport. A simple improvement to most studies would be the indication of sample size (ie weight of dry sediment) and the number of individuals recovered. Species abundance may then be calculated and compared. In the case of species which disarticulate upon death (ie ostracodes) only right or left valves should be counted to identify the presence of a single individual.

Careful attention to such details will provide more information to determine whether a population has been transported or not, whether there have been significant post mortem changes, and the relative abundance of each taxon.

In the present study, constant sample size of 200 grams was used in surface and subsurface samples to allow comparison of species abundance. In counting ostacodes, only left valves were used to indicate the presence of an individual. Unless otherwise stated, all individuals are assumed to be in situ and unaltered.

The problem of contamination between samples was considered. This arises when tests are trapped and then dislodged from sieves during subsequent processing. One method of identifying contaminant material is to soak sieves in a solution of methyl blue, thus dying any remaining material. Testing with this method indicates contamination is not a serious problem. The number of contaminant tests picked up is not statistically significant since the number is so small (< 1%).

To test sample recovery technique, a sample from the flank of the Sarsfield ridge (Figure 2) known to be rich in microfossils was processed and the results compared with previous studies of similar deposits.

Macrofossils recovered include sponge (*Tethya logani* Dawson) spicules; bryozoan fragments; juvenile Balanus sp. plates; juvenile gastropods, possibly *Natica* sp., but more globose in shape and protoconches of an unidentified gastropod. The presence of bryozoans and gastropods is rare and appears restricted to the Ottawa Valley area (Wagner, 1984). Sponges are also relatively rare in the Champlain Sea deposits, but have been recovered fom the Ottawa and Montreal areas (Wagner, 1984).

Microfossil abundance and diversity (Table 10) is high, as is typical for littoral sediments of the *Hiatella* phase of the Champlain Sea. In contrast to other assemblages, however, the Sarsfield ridge assemblage is strongly dominated by ostracodes rather than by foraminifera. In normal assemblages, the foraminifera outnumber the ostracodes in number and species by roughly ten to one.

The number of each species shown in Table 10 most likely represents the extreme upper limit of microfaunal abundance. The diversity of the Sarsfield sample is not as high as the sample from Kars described by Cronin (1976b) and shown in Table 8, but is close to the average of 27 for modern arctic assemblages (Loeblich and Tappan, 1953), and higher than the less than 10 species normally found in Champlain Sea samples (Wagner, 1970; Cronin, 1976b).

Thus, both foraminifera and ostracodes were found in number and species which correspond well with previous studies. It was therefore concluded that sample processing technique is acceptable.

4.2 BASINAL VARIATION AND DIVERSITY

As shown in section 1.3, there must be both intra- and inter-basinal variations in the environment which can be reflected by the fauna. One measure of these variations is species diversity. It is well established that high latitudes have fewer species than equatorial latitudes (Dodd and Stanton, 1981). Arctic assemblages of foraminifera and ostracodes are usually characterized by circumpolar distribution of relatively small fauna, while lower latitude fauna show endemism and provincialism (Cronin, 1979a).

Unfortunately, quantitative studies of high latitude ostracode species diversity are lacking. The most recent qualitative study is by Neale and Howe (1975), who found that certain species reach their greatest abundance in arctic waters, but generally few can tolerate the harsh arctic conditions. Hazel (1970) recognized subarctic and arctic faunal provinces from limited high latitude collections that were previously unidentified.

Although ecological studies of brackish water ostracodes are relatively common (Elofson, 1941; Puri et al., 1964; Wagner, 1957), quantitative analyses of diversity are rare. However, the abundant data provided by these studies lead to the following conclusions. Typical brackish

TABLE 10

Champlain Sea Foraminifera and Ostracoda from Sarsfield

Species	Number
Elphidium excavatum	2,000
Protelphidium orbiculare	2,160
Cassidulina crassa	260
Oolina melo	25
Oolina hexagona	65
Oolina squamosa-sulcata	15
Oolina williamsoni	15
Pseudopolymorphina novanglie	180
Triloculina trihedra	80
Quinqueloculina cf. *Q. seminulum*	300
Cytheropteron inflatum	340
Cytheropteron paralatissimum	100
Cytheropteron nodosum	240
Schlerochilus contortus	80
Heterocypideis sorbyana	1,925
Eucytheridea bradii	2,400
Number of Specimens	10,185

water ostracode assemblages are of low diversity, containing high numbers of one or two species and few others. Many species are well enough known to be used as reliable paleoenvironmental indicators of brackish water (Cronin, 1979b). In fact, some entire genera are nearly always found in low salinities (Sandberg, 1964).

Foraminifera have received much more attention. Gibson and Buzas (1973) used quantitative measures and found increasing species diversity with depth from the western Atlantic and Gulf of Mexico; arctic diversities showed no such pattern. Shallow (0-100 m) water arctic assemblages were more diverse than southern assemblages. Cronin (1979a) believed that data used by Gibson and Buzas (from Phleger,

1952) may not be representative, since Lagoe (1976) found decreasing diversity with depth. Lagoe considered only the 1,000-4,000 m. depth interval, but the inverse relation between depth and diversity was also shown by Loeblich and Tappan (1953) who noted average shallow water species numbering 27, versus an average of 16 and a maximum of 24 for Lagoe's deep water assemblages. Thus arctic foraminifra are apparently more diverse than some temperate assemblages, but not nearly as diverse as those of the tropics. In the arctic, the highest diversity values are from the shallowest depths.

Brackish environments such as the Champlain Sea are characterized by the small number of species and large number of individuals (Remane and Schlieper, 1971). Inhabitants are usually R-strategists (a term designating reproductive strategy of species tolerant of fluctuating, often unpredictable environments) (MacArthur and Wilson, 1967). Salinity fluctuations may result partly from periodic (usually seasonal) freshwater influx. The number of brackish water species can be quite small compared with that of marine and freshwater environments.

The early study of Champlain Sea macrofauna by Goldring (1922) was the first detailed work on species diversity. Goldring attributed low molluscan diversity in the southern and western regions to decreased salinities, which excluded the stenohaline taxa. She compared the paleoenvironmental conditions with that of the modern Baltic Sea. Remane and Schlieper (1971) presented a most comprehensive study of the brackish water biology of the Baltic area. They showed that both benthic foraminifera and ostracode species decrease in number from the North Sea towards the Baltic Sea, where salinities are reduced.

Quantitative foraminiferal diversity values for estuaries, and other brackish water environments are discussed by Murray (1973) using the Fisher Diversity Index. Modern hyposaline environments favour low diversity fauna, dominated by tolerant arenaceous species and contain a smaller number of calcareous species. This contrasts sharply with the faunal distribution of the Champlain Sea. Cronin (1976a) noted that Champlain Sea foraminifera are almost exclusively benthonic, calcareous species, with very few reports of arenaceous forms. Fillon and Hunt (1974) considered this a function of preservation. Studies of modern arctic fauna (Anderson, 1963; Belanger and Streeter, 1980; Bergen and O'Neil, 1979; Cooper, 1964; Cushman, 1933; Lagoe, 1977, 1979a, b; Loeblich and Tappan, 1953; Vilks, 1976) show a small but nevertheless present population of arenaceous foraminifera, possibly adding weight to the view that they may not have been preserved in the Ottawa area. Direct comparison, however, is not possible since temperature and salinity values do not always correspond.

4.3 SURFACE EVIDENCE

Two sections (F01 and F02) at the Foster pit having rigorous stratigraphic control were sampled for foraminifera and ostracoda. Tables 11a and b summarize the fauna found.

Sample locations are shown in Figures 18 and 19.

Representative examples of most foraminifera and ostracoda recovered from surface and subsurface samples are illustrated in Figures 34 and 35. Not all species could be recorded, because of the delicate or thin-walled nature of the shells, particularly with the ostracodes.

A major constituent of the fauna are members of the common and confusing genus Elphidium. The most commonly recognized species are: E. excavatum forma clavata (E. clavatum), E. incertum, E. bartletti, E. subarcticum and Protelphidium orbiculare.

Identification to the species level can be difficult or impossible due to gradation in test morphology (Loeblich and Tappan, 1953). Cooper (1964) found continuous intergradation among Elphidium species in samples from the Chuckchi Sea. Similar problems exist with Champlain Sea fauna. Taxonomic characters such as the presence of sutural pores, the number of chambers in the final whorl, the size and shape of the test, and the development and number of retral processes are variable in each species, making positive identification difficult. Some specimens clearly show characteristics of a given species, but identification is often tentative and hence they are placed in the Elphidium-Protelphidium group.

Previous investigations have not emphasized the taxonomic problems associated with Elphidium. Cronin (1976a) suggested a better understanding of Elphidium requires more

TABLE 11a

Foraminifera and Ostracoda from Surface Samples

	Facies 1				Facies 2							Facies 3						Facies 4					
Species/Sample Number	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36	37	38	39	40	41	42	43
Elphidium incertum																		3			10		7
Elphidium excavatum													3					14			25		27
Elphidium bartletti																					5		
Elphidium subarcticum																					5		3
Protelphidium orbiculare																		4			40		45
Islandiella islandica																							
Islandiella helenae																		53			35		
Cassidulina crassa																		31			24		
Pseudopolymorphina novangliae																					6		
Guttulina sp.																					2		
Dentalina pauperata																		1					
Oolina melo																							
Oolina hexagona																							
Oolina williamsoni																		2					
Oolina squamosa-sulcata																							
Quinqueloculina seminulum																		6					
Triloculina trihedra																							
Cibicides lobatulus																		3			5		
Eucytheridea bradii																					4		2
Eucytheridea macrolaminata																					6		4
Cytheropteron inflatum																					1		
Cytheropteron latissimum																					1		
Cytheropteron pseudomontrosiense																					1		
Heterocyprideis sorbyana																					4		3
Sclerochilus contortus																					2		
Candona cf. *C. subtriangulata*											3												
Roundstonia globulifera																					2		
Finmarchinella logani																					1		
Palmenella limicola																							
Total Number of Specimens	0	0	0	0	0	0	0	0	0	0	3	0	3	0	0	0	0	117	0	0	179	0	91

TABLE 11b

Foraminifera and Ostracoda from Surface Samples (cont'd)

	Facies 1						Facies 2								Facies 3			Facies 4				5	
Species/Sample Number	50	51	52	53	54	55	56	57	58	59	60	70	71	72	73	74	75	76	77	78	79	80	81
Elphidium incertum																		11		8			5
Elphidium excavatum																		42		43			27
Elphidium bartletti																							3
Elphidium subarcticum																							
Protelphidium orbiculare																		60		55			30
Islandiella islandica																		5					
Islandiella helenae																		40		38			6
Cassidulina crassa																							
Pseudopolymorphina novangliae																		2		3			
Guttulina sp.																							
Dentalina pauperata																							
Oolina melo																							
Oolina hexagona																							
Oolina williamsoni																							
Oolina squamosa-sulcata																							
Quinqueloculina seminulum																							
Triloculina trihedra																							
Cibicides lobatulus																		8		5			4
Eucytheridea bradii																		3		2			
Eucytheridea macrolaminata																							
Cytheropteron inflatum																		2		2			
Cytheropteron latissimum																							
Cytheropteron pseudomontrosiense																							
Cytheropteron paralatissimum																		1					
Heterocyprideis sorbyana																		2		3			
Sclerochilus contortus																							
Candona cf. *C. subtriangulata*													5										
Roundstonia globulifera																							
Finmarchinella logani																							
Palmenella limicola																		2					
Number of Specimens	0	0	0	0	0	0	0	0	0	0	0	0	5	0	0	0	0	178	0	159	0	0	75

a: Sclerochilus contortus (Norman)
LV x 100, Sarsfield

b: Finmarchinella logani (Brady and Crosskey)
RV x 100, F041

c: Palmenella limicola (Norman)
LV x 120, F076

d: Cytheropteron latissimum (Norman)
RV x 120, F041

e: Eucytheridea bradii (Norman)
RV x 120, F041

f: Cytheropteron paralatissimum Swain
LV x 200, Sarsfield

g: Roundstonia globulifera (Brady)
LV x 200, F041

h: Cytheropteron pseudomontrosiense Whatley and Masson
RV x 200, F041

i: Eucytheridea macrolaminata (Elofson)
LV x 100, F041

j: Heterocyprideis sorbyana (Jones)
RV x 100, F076

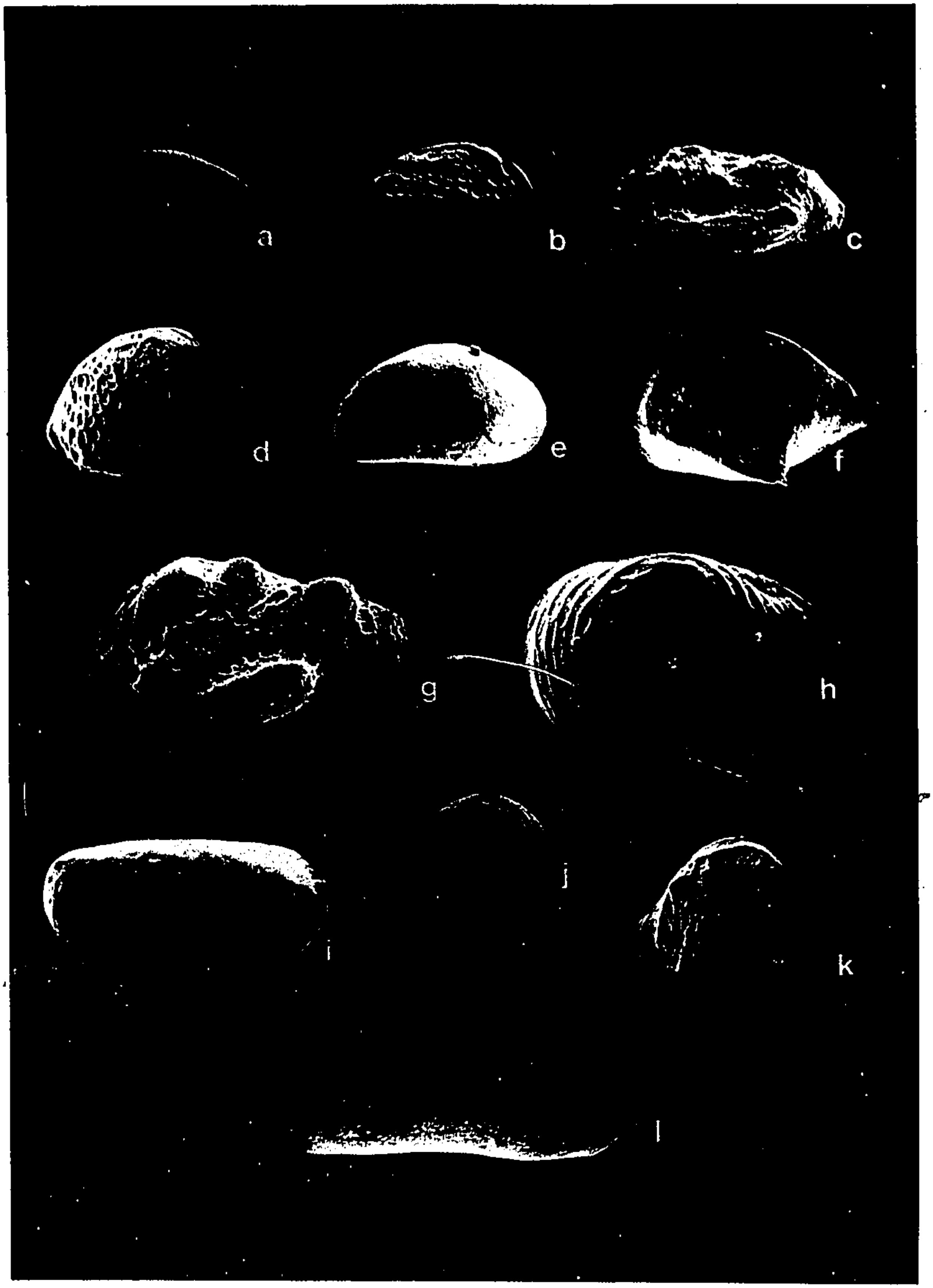
k: Cytheropteron nodosum Brady
RV x 100, Sarsfield

l: Candona subtriangulata Benson and MacDonald
RV x 100, F071

LV = left valve

RV = right valve

Figure 34: Plate IV


a
b
c
d
e
f
g
h
i
j
k
l

a: Oolina hexagona (Williamson)
x 100, Sarsfield

b: Oolina melo d'Orbigny
x 120, Sarsfield

c: Oolina williamsoni (Alcock)
x 100, Sarsfield

d: Pseudopolymorphina novanglie (Cushman)
x 120, F076

e: Quinqueloculina seminulum (Linne)
x 100, F038

f: Guttulina sp.
x 120, F041

g: Islandiella helenae Feyling-Hansen and Buzas
x 100. GSC 76-22-155

h: Cibicides lobatulus (Walker and Jacob)
x 200, F041

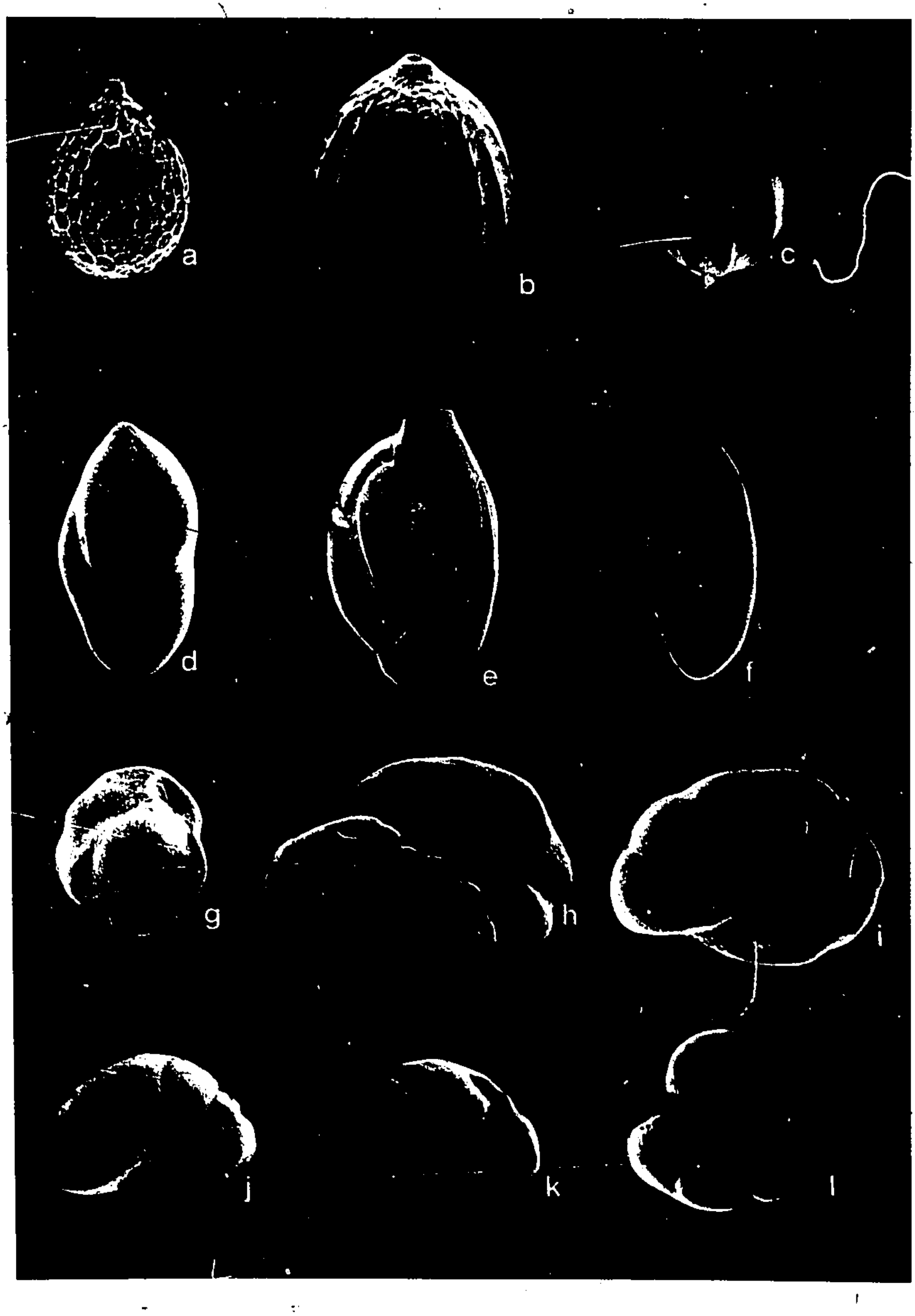
i: Protelphidium sp.
x 200, F041

j: Elphidium sp. 1
x 120, F041

k: Cassidulina crassa d'Orbigny
x 120, GSC 76-22-155

l: Elphidium sp. 2
x 120, F041

Figure 35: Plate V


a
b
c
d
e
f
g
h
i
j
k
l

careful consideration of the morphological variation of populations from different areas. If intergradation among species of Elphidium could be understood enough to properly identify taxa, then their frequencies might be used to indicate varying paleoecological conditions. These problems could only be solved with more extensive analyses of samples, and comparisons with Elphidium from other regions.

A number of variants of the Elphidium genus were recognized, but time did not permit full breakdown of the group, since extensive SEM use is required. The following were identified: E. excavatum Terquem forma clavata Cushman; E. subarcticum Cushman; E. incertum (Williamson); E. bartletti Cushman and Protelphidium orbiculare (Brady). More accurate identification of Elphidium is beyond the scope of the present study. Wherever possible, Elphidium was identified to the species level, or placed in the Elphidium/ Protelphidium complex group.

As noted in previous studies, the most abundant fauna was found in silty sand facies, with most of the sand and clay facies barren. To simplify discussion, faunal assemblages found in each of five sedimentary facies will be discussed in stratigraphic order from the base of the sections upward.

The five facies are identified as follows. (1) sand and gravel; (2) laminated silt and clay; (3) massive silty clay; (4) interbedded sand, silt and clay; and (5) sand. These facies have already been described in detail in Chapter 3, and are used here as a framework for discussion of faunal assemblages and interpretation of depositional environment.

Facies (1) samples F021-F024 at section F01 and F050-F055 at section F02 were all barren. This facies is found at the base of exposed sections and is interpreted as subaqueous outwash deposited in a proglacial lake (see Chapter 3). Similar facies have been identified in the GSC boreholes; recovery is poor because the non-cohesive sediment is lost from drill tubes. Microfaunal growth was prevented by the high sediment load and turbulence of the depositional environment, as shown by the coarse, well sorted nature of the sands.

Facies (2) sediments comprise the rhythmites directly overlying facies (1). Samples F025-32 at site F01 and F056-60, and F070-72 at site F02 were examined. These sediments are generally barren, but contain small numbers (4-5/200 g sample) of *Candona* cf. C. subtriangu*lata* Benson and MacDonald in the upper portion (F071, F031).

The presence of the ostracode *Candona* cf. *C. subtriangulata* in association with other ostracodes such as Cythereis lacustris and *Limnocythere friabilis* has been used by Anderson et al. (1985) to indicate deep lacustrine conditions. Cronin (1981) noted *Candona* in Transitional phase Champlain Sea sediments where fresh and marine waters mixed to produce a brackish environment. *Candona*, therefore, must be salinity-tolerant to some extent. Delorme (pers. comm., 1986) noted the genus will not live exclusively in a marine environment, and is now most commonly found in the Great Lakes. It is very tolerant of sulphate rich brackish water, and less tolerant of brackish water with high chlorinity. It seems, therefore, that the presence of Candona is a useful indicator of fresh water, but can tolerate brackish water under certain conditions.

The possibility of ostracode valves being washed into the depositional area was considered and rejected, since the surface texture of Candona showed no evidence of transport. It is thus assumed that all ostracodes, even though disarticulated, are found in place.

Candona abundance in the Ottawa surface samples corresponds with numbers found in other studies. 4-5 individuals/200 g sample were found in the Foster pit samples, compared to 4-5/100 g sample in the eastern townships of Quebec (Parent, 1986). Anderson et al. (1985) found from 1-50/sample, with average of 8/sample and sample size up to 500 g (Anderson and Delorme, pers. comm., 1986).

The sparcity of the Candona fauna indicates harsh conditions. In the Foster pit samples, Candona was only recovered from the upper portion of the rhythmites (samples F071 and F031), and it is assumed that conditions prior to that were too extreme for survival. The lower 2/3 of the rhythmites show abundant slump, ice contact and ice-rafted debris evidence (see Chapter 3), indicating the importance of ice interactions to early lake conditions. Possibly this factor was partially responsible for the faunal sparsity, and prevented the survival of Candona until conditions ameliorated.

Facies (3) is massive silty clay directly overlying facies (2). Samples F034-F038 at site F01 and F073-F075 at site F02 were examined. Three faunal zones appear in facies (3). The lowest is barren, and does not contain macro or microfossils. The middle zone contains small bivalves possibly Portlandia sp. or Yoldia sp.. Identification is tentative since shells were only observed in outcrop and their highly weathered state caused disintegration upon touch, precluding further investigation. The upper zone contains spat-killed Portlandia arctica (see Figure 26) and a foraminiferal assemblage dominated by Islandiella helenae, Cassidulina crassa, and Elphidium/ Protelphidium complex (sample F038, Table 9). As commonly occurs with other arctic assemblages, dominance is strong and diversity low, with dominant species comprising 90-94% of the individuals present.

The barren lower portion of the facies indicates the difficulty organisms had in coping with fluctuating salinity. Portlandia arctica is usually the first macrofossil present in a glaciomarine sequence, but spat-kill indicates that Portlandia could not survive the earliest Transitional Champlain Sea environment in spite of its normal hardiness. As conditions stabilized, the Islandiella-Cassidulina-Elphidium/Protelphidium association was able to survive.

Comparison with similar biozones identified by Fillon and Hunt (1974) in the Champlain Valley of New York indicates minimum salinity of 22-28 ppt based on the presence of the Elphidium/Protelphidium assemblage, and maximum salinity of 30-33 ppt based on the presence of *Islandiella helenae* (= *I. teretis* of Fillon and Hunt). The assemblage is also similar to the *Cassidulina crassa*, *Islandiella helenae* and *Elphidium excavatum* forma *clavata* assemblage that Cronin (1979a, b) noted represents offshore, deep (30-100 m) water.

Facies (4) is interbedded to interlaminated sand, silt and clay directly overlying facies (3). These sediments represent the mixed bedding described as nearshore or tidal facies in Chapter 3. Samples F039-F043 at section F01 and F076-F079 at section F02 were examined.

As indicated in Table 11, roughly half of the samples were barren, but no faunal zonation is apparent. Microfossils were found from the base to the top of the facies. Barren samples are interpreted as resulting from patchy distribution as was observed in test sample F038.

Species found in samples F041, F043, F076 and F078 are listed in Table 11. All other samples were barren. Dominant taxa include *Elphidium* sp. and *Protelphidium* sp. with minor numbers of *Cibicides lobatulus* and *Guttulina* sp., *Pseudopolymorphina novanglie* and *Cassidulina crassa*.

The environment represented by this assemblage is a nearshore, shallower environment relative to that of facies (3). Cronin (1979a) noted *Elphidium* sp. and *Protelphidium orbiculare* dominated assemblages represent nearshore environments less than 30 m deep. This interpretation is supported by the presence of *Balanus* fragments and small (juvenile ?) *Macoma balthica*. *Balanus* prefers high energy environments, and Macoma balthica prefers shallow water less than 10 m deep (see Figure 27). The extensively damaged ostracode valves found in all samples also indicate a high energy of deposition. Every ostracode valve recovered was disarticulated, and 55-60% of valves showed some physical damage.

The assemblage indicates salinities of 18-28 ppt. Fillon and Hunt (1974) noted Elphidium clavatum (= E. excavatum) as dominant in water with salinity 18-24 ppt. E. clavatum and P. orbiculare dominate in water of 22-28 ppt salinity. Summer water temperatures for this assemblage probably were less than or equal to 12 °C.

This facies is apparently that in which Romanelli (1970) reported Elphidium bartletti Cushman, Psudopolymorphina novanglie, Protelphidium orbiculare (Brady), and Cassidulina islandica. He noted the foraminifera as belonging to the laminated clay, which here is termed facies (2), and underlies facies (4). The assemblage is not consistent with the assemblage found in facies (2), and seems to agree with that found in facies (4).

Sandy facies (5) directly overlies facies (4) and was sampled at F080 and F081 at section F02. Sample F080 was barren, and F081 contained the Elphidium dominated foraminiferal assemblage indicated in Table 11b. The sparse nature of facies (5) probably results from the high energy of the environment the sands represent. Sediment is well sorted, clean sand having a low mud content. This is not a preferred substrate for benthic foraminifera, so diversity and number of dominant species are low. More comprehensive identification of the microfauna and depositional environment for facies (5) was not attempted, since it represents the littoral facies of the Champlain Sea, and so is beyond the scope of the present study. In order to more accurately determine the salinity range the Elphidium group represents, a clear distinction between E. bartletti, E. excavatum and Protelphidium orbiculare is required.

4.4 SUBSURFACE EVIDENCE

In contrast to surficial studies, subsurface studies of massive and laminated clay facies are rare. In order to add to the coverage provided by surface samples and previous subsurface studies, samples from GSC cores taken in the Ottawa and Gatineau valleys (Figures 31-33) were analyzed. Because of prior commitment, not all core taken was available for examination, and core selected for faunal analysis was restricted. Of the available core, that having the greatest interval of laminated clay was chosen. Samples from the Venosta and Touraine cores were thus chosen as being the most useful for study.

Table 12 lists samples examined, their depth below ground surface, and grain size of sample material. Approximate position of samples may be fixed by measurement from the top of the borings shown in Figure 33.

The Venosta core was barren in all samples studied. Foraminifera and ostracodes were found in samples from the Touraine boring, as indicated in Table 13. As in Guilbault's

TABLE 12

Subsurface Sample Depths and Grain Size

Sample	Depth (ft.)	Grain Size
Venosta		
74-8-81	50.1-51.9	clay-sandy clay-sand
74-8-83	59.6-61.4	interstratified clay/sand
74-8-86	72.4-74.2	dark/light clay cycles
74-8-88	79.6-81.4	massive grey clay
74-8-90	89.8-91.6	sensitive clay
74-8-92	100.0-101.8	sand at base; massive clay
74-8-94	109.8-111.6	(t) massive (b) lam. clay
74-8-96	121.9-123.7	clay/silt rhythmite
74-8-98	130.0-131.8	banded clay/silty clay
74-8-100	140.0-141.8	sensitive clay
74-8-102	149.7-151.5	interstratified silt/clay
74-8-103	159.8-161.6	interbedded sand/silt/clay
Touraine		
76-22-137	80.0-82.1	coarse silt
76-22-139	90.0-92.1	fine silt-silty clay
76-22-141	100.0-102.1	silty clay
76-22-143	110.0-112.1	silt
76-22-145	120.0-122.1	interstrat. red/grey clay
76-22-147	130.0-132.1	red/grey banded clay
76-22-149	140.0-142.1	massive dark grey clay
76-22-151	150.0-152.1	massive grey clay
76-22-153	155.0-157.1	massive grey-black clay
76-22-155	171.1-173.2	compact dk. grey-black clay
76-22-156	175.0-177.1	silt and silty clay
76-22-157	180.0-182.1	silt and clay rhythmites
76-22-158	184.0-189.0	gravel

(1980) study, freshwater or oligohaline ostracodes (*Candona*) were found at the base of the core.

As shown on the correlation chart in Figure 33, the rhythmite facies (2) is thin as in other borings. Microfossil examination of the rhythmites from core samples is therefore somewhat of a hit and miss process, since the

TABLE 13

Foraminifera and Ostracoda from GSC 76-22 Core Touraine

Species/Sample Number	139	141	143	145	147	149	151	153	155	156	157	158
Elphidium incertum												
Elphidium excavatum	?12		1			9	18	10				
Elphidium bartletti												
Elphidium subarcticum												
Protelphidium orbiculare			1			12	14	8				
Islandiella islandica												
Islandiella helenae									30	28		
Cassidulina crassa									360	69		
Pseudopolymorphina novangliae							6	1				
Guttulina sp.												
Dentalina pauperata												
Oolina melo												
Oolina hexagona												
Oolina williamsoni												
Oolina squamosa-sulcata												
Quinqueloculina seminulum												
Triloculina trihedra									3			
Cibicides lobatulus												
Eucytheridea bradii												
Eucytheridea macrolaminata												
Cytheropteron inflatum								6		4		
Cytheropteron latissimum			3							5		
Cytheropteron pseudomontrosiense												
Cytheropteron paralatissimum								2				
Cytheropteron nodosum							20	4				
Heterocyprideis sorbyana												
Sclerochilus contortus												
Candona cf. *C. subtriangulata*											7	
Roundstonia globulifera												
Finmarchinella logani												
Palmenella limicola												
Number of Specimens	12	0	5	0	0	21	58	39	393	106	7	0

sample interval of five feet is approximately the same thickness as the rhythmites. In many cases, only a small portion of the rhythmites was penetrated in the sample interval.

In the Touraine core, marine foraminifera dominated by Protelphidium orbiculare, Elphidium clavatum and Elphidium incertum occur in all fossil-bearing samples including 76-22-153 and above. The presence of Balanus fragments in these samples confirms a marine environment for the overlying sediments. As was found in the surface samples, the facies (1) sample was barren, and facies (2) samples show a sparse Candona population indicative of freshwater, or salinity not exceeding 18 ppt (Cronin, 1981).

Guilbault (1980) examined selected samples from GSC cores at Treadwell, Touraine and Plaisance (Figure 31). Sample size and number of individuals recovered were not noted. Summaries of these previous analyses are given below.

Treadwell:

4 samples sent by N.R. Gadd, each representing one of the 4 facies described by Gadd (1977). Top of boring 55 m asl. Sample 46 (6.5 m) contained no macrofossils; foraminifera- a few specimens of E. excavatum probably redeposited unless contaminant. Sample 51 (37 m) contained no macrofossils. 19 specimens of unnamed foraminifera, possibly redeposited; too abundant to be contaminants. Sample 55 (61.5 m) contained no macrofossils and unnamed foraminifera. Sample 58 (84 m) contained many small

specimens of Portlandia arctica and unnamed foraminifera.

Touraine:

A single sample sent by N.R. Gadd from "varved" clay facies. Top of boring 60 m asl; sample 157 (55 m) contained valves and fragments of valves of oligohaline ostracodes (unnamed).

Plaisance:

7 samples sent by N.R. Gadd for foraminiferal study. Boring started between 45 and 60 m asl. Sample 164 (9.5 m) taken above Gadd (1977) lithofacies 4. No macrofossils; a few specimens of E. excavatum possibly redeposited in (fluvial ?) sediments. Sample 167 (18.5 m) unspecified foraminifera. Sample 173 (37 m) no macrofossils; single specimen of E. excavatum, possibly a contaminant. Sample 175 (42 m) unnamed foraminifera. Sample 177 (55 m) unnamed foraminifera. Sample 178 (58 m) a few macrofossil shell fragments, unnamed foraminifera. Sample 179 (64.5 m) many macrofossil shell fragments, unnamed foraminifera.

The most significant aspect of Guilbault's work is the recognition of transported foraminifera and the identification of oligohaline ostracodes in sample T 157.

Anderson et al. (1985) give faunal analysis of several cores taken from the Ottawa area through the Rideau Lakes area and into Lake Ontario. As with many other studies, sample size and number of individuals recovered was not stated.

The majority of ostracodes were immature, making identification difficult. The *Candona subtriangulata-Cytheissa lacustris-Limnocythere friabilis* assemblage found in these cores represents a lake having few dissolved solids and a depth of at least 180 m, based on the presence of *C. subtriangulata* and *C. lacustris* (Delorme, 1970c). This assemblage is similar to modern Great Lake assemblages (Anderson et al., 1985).

In the upper portion of the Ottawa Valley site core, the foraminiferal assemblages represent a high salinity environment near the base of the marine sequence followed by decreasing salinity upwards in the core. The lowermost marine interval contains high salinity indicators such as *Islandiella helenae* in association with the freshwater ostracode *Candona* cf. *C. subtriangulata*. Anderson et al. (1985) attributed this to a transitional interval between an initial freshwater phase at the base of the core and marine conditions inferred for the overlying sediments. Presumably, this interval corresponds to the Transitional phase of Cronin (1979a, b). The association of high salinity foraminifera with low salinity ostracodes suggests that the ostracodes have some tolerance for varying (low) salinity.

4.5 INSECTS AND ASSOCIATED FAMILIES

Documented cases of insects in Champlain Sea deposits are rare. The first case was reported by Dawson (1893), who reported the elytron of the beetle *Fornax ledensis* Scudder.

The first insects described and figured by Scudder (1895) and Ami (1895) were three beetles (Coleoptera) and a caddisfly (Neuroptera) found in Leda clay nodules at Green Creek, near Ottawa.

The only recent report of Champlain Sea insects is by Mott et al. (1980), who found organic deposits at two sites in Quebec which bordered the Champlain Sea at different times: 11,050+130 BP (QU 448) for the site near St. Eugene, and 10,100+150 BP (GSC 2200) for the site near Mont St. Hillaire. At the St. Eugene site, a lens of organic debris containing fossil leaves, minute woody twigs to small woody fragments and insect remains in sandy deltaic gravel was found. Twigs with bark intact indicated a nearby source, but the small wood fragments had a rounded, water-worn appearance suggesting a distant source. Most of the debris probably came from the adjacent coastal area, whereas the wood fragments must have washed into the sea from some distance from the site. Marine pelecypods were not found associated with the deposits, but fragments of a marine hydrozoan were noted.

An apparently similar deposit was found at the Foster pit section FO1 (shown in Figure 26c). The bed consists of current rippled, well sorted medium grained silt with detrital wood fragments, insect and foraminiferal remains. No bivalve remains were found, and the marine foraminifera (Elphidium sp.) was highly abraded, suggesting transport over some distance.

The insect and plant remains were studied by J.V.

Mathews, Jr., Geological Survey of Canada Terrain Sciences Division. Results of these studies are shown in Appendix E and Appendix F.

Fauna found in the sample does not appear to match the suggested age of approximately 10,000 BP. Radiocarbon dates (see section 3.1.4) on sediment overlying the silt bed have produced dates in the range of 11.200-10,000 BP. The fauna which appears in the silt bed, however, is extremely well preserved, and contains fragments of cedar, which would not have been present in the Ottawa area at 10,000 BP. In addition, sow bugs and millipeds were found: these are not northern arthropods, and would not have been present during cold climate periods.

These facts point to the "fossil" material as possible modern contaminants, or at the oldest, late Holocene material.

The appearance of a significant amount of modern material in the bed representing the disconformity between the pre-Champlain Sea lake episode and the Transitional phase Champlain Sea is problematic, because there appears to be little opportunity for contamination. The material above and below the silt bed is clay, which is not preferred by insects. In addition, the bed sampled is thin in comparison to the surrounding clay beds, and so does not seem a likely place for modern insects to live, given the more suitable nature of the overlying sand. The climatic preference for the arthropods found and their excellent preservation does point to modern species. Clearly, more investigation is needed since some material appears to be of the correct age (eg Elphidium sp.) and some does not.

4.6 DISCUSSION

Comparison of microfossil abundance and diversity of a sample taken on the flank of the Sarsfield ridge with studies of similar deposits indicates the sample processing and recovery technique to be satisfactory. Examination of duplicate surface samples indicates that although strong faunal variation in small lateral distances (0.5-1.0 m) may occur as a result of patchy microfossil distribution, dominant species are consistent between samples and adequately represent the environment of deposition for any given facies.

On the basis of sedimentary structures, depositional style, and biozonation, five facies are recognized which document the change from post-glacial lake to early glacio-marine conditions of the Champlain Sea.

The coarsening upward sequence formed by facies 3-5 forms an off-lap sequence recognized by Gadd (1977). Results of the present study confirm this interpretation. They also indicate a change from the freshwater conditions of facies 1-2 to the brackish conditions of facies 3-5. Using the dominant microfossil assemblages as a guide, Champlain Sea salinity decreased from an initially high and possibly fluctuating value of up to 33 ppt to a low value of 18 ppt or less.

Faunal analysis and sedimentology of facies (1) shows an initial period of subaqueous outwash relatively close to the glacier margin. The presence of till flow and well sorted coarse sands shows the proximity of glacier ice, and the sorting power of the mass flows responsible for sediment deposition.

Faunal evidence from facies (2) suggests the existence of a deep lake prior to the Champlain Sea. Presence of Candona and other freshwater ostracodes in surface and subsurface samples suggests water depths of up to 180 m. This depth agrees with the high water level proposed for the Belleville-Ft. Ann phase water body, which could have had elevations up to 216 m asl in the Lake Ontario basin (Clark and Karrow, 1984), and flooded the large area shown in Figure 5.

The initial proglacial lake period was dominated by rapid sedimentation and by sediment/ice interaction which produced slump and ice-contact features as well as common lenses of ice-rafted debris. Harsh conditions prevented the establishment of either a micro or macrofaunal community until conditions ameliorated. Towards the end of rhythmite deposition, conditions had improved to the point where the freshwater ostracode Candona could survive.

With the removal of the ice dam blocking the lower St. Lawrence River, trapped glacial lake water could then escape, and marine water rush in, mixing with the remaining fresh water. Lowering of the water level resulted until an elevation of approximately 160 m asl was achieved (Clark and Karrow, 1984) producing water depths in the early Transitional Champlain Sea of 30-100 m. This is supported by the presence of the Islandiella-Cassidulina-Elphidium/Protelphidium assemblage found in facies (3). Salinity range for this assemblage is from 22-33 ppt.

Facies (4) foraminifera are dominated by the Elphidium/Protelphidium complex, which indicates a shallower, nearshore environment relative to that of facies (3). This assemblage and the presence of Balanus and Macoma balthica indicate water depths in the range of 10-30 m. On the basis of the same fossil assemblage, salinity would be 18-28 ppt, and summer water temperature less than or equal to 12 °C.

Facies (5) contains an almost exclusively Elphidium assemblage. No significant ostracodes were found. Salinity may have been 18 ppt or less: exact determination of the Elphidium species is required to be more specific, and is not within the scope of the present study.

Chapter V

DISCUSSION AND CONCLUSIONS

5.1 DISCUSSION

5.1.1 Sedimentary Evidence

Surface exposures of rhythmites do not show any trend in silt or clay thickness going upsection: couplet thicknesses show considerable variation and do not thin upwards. Normally, annual rhythmites (varves) thin upwards, reflecting the increasingly ice-distal position. Unlike true varves, the rhythmites do not show a consistent clay layer thickness since the clay was not deposited as a result of winter fallout. Each couplet is the product of a turbidity current type flow, with decreasing energy depositing successively finer units. Thus, the clay layer thickness is proportional to the silt layer thickness for each couplet, but does not show a consistent thickness over the basin. This shows the independant nature of the flows forming the rhythmites. This phenomenon, along with evidence discussed following, suggests that the Ottawa Valley rhythmites are the result of episodic (surge) currents, and represent sporadic, not annual events.

Other supportive evidence is the lack of winter and summer pollen species in "winter" and "summer" layers; the consistent carbonate content of the couplet pairs, showing that finer grained material is not always deposited in winter months when solution rate of detrital carbonate is higher, and the lack of trace fossil evidence in the coarser grained portion of the rhythmites.

While none of these lines of evidence is conclusive by itself, the combination of several independant lines of investigation clearly demonstrates the origin of the Ottawa Valley rhythmites to be episodic rather than annual.

The major problem in assigning rhythmites to the episodic or annual type is that variation of sediment input and transport from basin to basin may result in varying sedimentation rates if the large proglacial lake is in fact composed of a number of smaller basins. If this were the case, there is no reason to assume that the basins would have identical or even similar sedimentation rates or patterns of deposition.

It may be that the variation seen in rhythmites is naturally occurring, and reflects differing conditions in smaller basins or depocentres. This type of sedimentation is most likely in areas overlying the Shield, where thinning ice would decay over an irregular topography, and cause a disruption of water movement, and possible variations in sedimentation rates and pattern of deposition.

Although the sedimentation may be influenced by seasonal processes, there is no clear evidence to suggest the rhythmites are annual. Other studies of pre-Champlain Sea proglacial lake sediments (eg Parent, 1986) have shown good evidence for annual rhythmites (varves) in the eastern townships of Quebec, but their relationship to the glacio-lacustrine sediments of the Ottawa Valley is unclear.

Disconformably overlying the rhythmites is the massive clay facies of the Transitional Champlain Sea. In the Foster pit section, this disconformity is marked by the top of a rippled silt bed which is interpreted to be the result of mixing water bodies resuspending the previously deposited rhythmite sediment. This accounts for the well sorted nature of the silt bed, since the source material was restricted to the rhythmite silt and clay, and then the clay fraction left in suspension when the silt was deposited. In other localities, the low proportion of coarse material in the rhythmites precluded the formation of such silty beds, and rhythmite material remained in suspension, settling out at a later time. This accounts for the absence of the rippled silt marker bed in many of the GSC cores. This interpretation is problematic since the silt does not appear throughout the basin. The asymmetry of the ripples suggests current transport. Rapid lowering of lake level probably would have initiated slumps in what were previously stable lake-bed sediments; these would become turbidity currents as they travelled toward the basin centre. It would therefore be expected that the silt would have been deposited basin-wide, but it does not appear to be that extensive.

The denser brackish water prevented the continuation of sediment underflow currents. Any salinity greater than 3-4 ppt would also cause flocculation of the fine grained sediment, increasing the occurrence of massive clay bodies. Sporadically, sediment concentrations were high enough to produce underflows, but these high concentrations could not be maintained for an extended period of time. Assuming salinity of 15-20 ppt, sediment load required to produce underflow currents would be at least 25-30 g/l. Thus, occasional rhythmite-like couplets occur at the beginning of the brackish series, and become rarer as sediment supply diminished.

5.1.2 Regional Implications

Pre-Champlain Sea glaciolacustrine rhythmites have now been identified as far west as the Lake Ontario basin, as far east as the eastern townships of Quebec, and as far north as the Ottawa Valley. The extent and distribution of the rhythmites in the southern area (United States) is not known.

If the rhythmite bodies identified in these areas are correlated with elevations equivalent to the Ft. Ann phase of Lake Vermont and the Belleville phase of Lake Iroquois, the elevation of this lake (216 m) would be high enough to flood all of the land from the Champlain basin into the Lake Ontario basin, across the Rideau Lakes area and into the Ottawa Valley, as shown in Figure 5. The great extent of this lake discounts Gadd's (1980) digitate ice front hypothesis unless the inflowing water could somehow submerge or float the ice lobes. If the digitate ice lobes were present, the lake would most likely be divided into a number of smaller basins with restricted circulation. The effect of a digitate ice margin would be difficult to prove since the bottom topography of such a large lake would be irregular. The undulatory bedrock in the Shield areas and the irregular ice topography would break up the lake into smaller segments, influencing water circulation and sediment dispersal patterns. Thus, a single, large water body might have been created, but local sedimentation conditions would have been controlled by bedrock and ice topography which in turn control the distribution and dispersal of sediment underflow currents within the basin.

Although the high elevation of the lake would have flooded a large area, the underlying lake bottom was probably irregular, and caused the division of the lake into several smaller basins. Distinction between obstructions such as bedrock and small portions of isolated ice or digitate ice lobes still connected to the glacier would be difficult to make. Since the ice bodies would eventually melt, withdrawing support from the surrounding sediments, there should be evidence in the form of sediment deformation structures from collapse, slumping, faulting, fluid escape and similar mechanisms. Where bedrock is responsible for the separation of smaller basins, sediment distribution should roughly conform to the present bedrock topography. It is therefore possible that although the lake consisted of one continuous body of water, individual sedimentation events were localized and controlled by lake-bottom topography.

It is interesting to note that the highest Champlain Sea deposit found in the Ottawa Valley occurs at Kingsmere at an elevation of 210 m asl. This indicates the Champlain Sea was present at roughly the same elevation as the preceding glacial lake. The identification of glaciomarine deposits on the basis of marine macrofossils shows a fauna that probably would not have existed during the earliest period of the Champlain Sea when, water elevations were highest.

This problem points to the possibility of a second, higher level Champlain Sea episode occupying the Gatineau highlands. Unfortunately, because of the apparent error associated with radiocarbon dates (section 1.5), it is unlikely that shell dates from this locality would be useful in determining the precise age of the deposits. This leaves the question of a second, high level Champlain Sea episode unanswered. Further investigation would be required to clarify this point.

5.2 CONCLUSIONS

Results of the present study indicate the presence of a proglacial lake in the Ottawa Valley immediately preceding the Champlain Sea episode. The presence of ostracode Candona cf. C. subtriangulata and the laminated nature of the rhythmites indicate freshwater deposition.

The dominant mechanism for rhythmite deposition was by turbid density current underflow. Examination of couplet thickness trend, grain size distribution, carbonate and trace fossil content indicates the rhythmites to be episodic rather than annual.

Two rhythmite types have been identified: continuous types (I) and (II) and discontinuous. Continuous type (I) represents the simplest case of a single sedimentation event. The rhythmite consists of a continuous fining upwards series beginning with traction load (indicated by grooves and sole markings) and rapidly changing to saltating load and suspended load as flow competence diminished.

Continuous type (II) was most commonly observed. The series is similar to series (I) with the addition of random, sporadic bursts of coarser sediment to the finer interval. Ungraded and poorly sorted laminae result from these smaller episodic flows.

The discontinuous series shows a hiatus in sedimentation between a continuous rhythmite series and a layer of coarser material containing clasts 1-2 grade classes larger, interpreted to be ice-rafted debris dropped as a result of a (summer ?) melting event.

The sparse microfauna and absence of macrofauna point to a short-lived, harsh environment for the proglacial lake. The presence of slump structures and apparent ice-contact folds at the base of the rhythmites supports the concept of ice obstructions blocking free water flow in the lake, and creating smaller restricted basins in conjunction with the uneven bedrock topography. The ubiquitous ice-contact features also show the importance of floating and partially grounded ice at early stages of rhythmite deposition.

The exact size and duration of the lake are still unknown. Surface and subsurface evidence indicates the presence of a lake occupying the Ottawa and Rideau River Valleys, for which exposures located at the Foster pit are suitable type sections. The lake occupying this area is informally called Lake Rideau, after the type locality.

Correlation of Lake Rideau with other water bodies such as the Ft. Ann phase of Lake Vermont and the Belleville phase of Lake Ontario produces a lake covering the area from the Champlain Valley to the Lake Ontario basin and up the Rideau Valley into the Ottawa Valley. Until more work is done, the exact extent of the lake will not be known. Whether a single lake or several smaller lakes are involved is not known conclusively, but evidence seems to point to the formation of a single, high level lake at an altitude of approximately 216 m asl, with bedrock and ice obstructions restricting flow and creating smaller, transient basins. Ostracode evidence points to a lake up to 180 m in depth.

The transition to the early Transitional phase of the Champlain Sea is marked by a decrease in clay lamination and an increase in massive clay. The lower portion of the massive clay (facies 3) is barren, and the upper portion contains spat-killed Portlandia arctica, a typically early glaciomarine bivalve. A foraminiferal assemblage of Islandiella-Cassidulina-Elphidium/Protelphidium indicates early Champlain Sea salinity of 22-33 ppt, with water depth in the range of 30-100 m. This transition from deep, freshwater conditions to shallower brackish conditions apparently was short-lived, and a harsh environment for the invertebrates, as shown by the Portlandia arctica spat kill, and the barren nature of the lowermost massive clay facies. When conditions improved, the common faunal succession of foraminifera, foraminifera and ostracodes, and then microfauna and macrofauna developed.

Since there is no datable material within the rhythmites, and the first datable material in overlying sediments would be somewhat younger, the exact timing of the pre-Champlain Sea freshwater episode is speculative. The relatively thin package of rhythmites, the sparse to barren fauna, and soft sediment deformation and slump features suggests rapid deposition in a freshwater environment followed in quick succession by mixing with marine water.

The stratigraphic position of the rhythmites shows them to directly overlie facies interpreted as subaqueous outwash, and the presence of till flow units suggests a nearby glacial source. Rhythmite deposition is thus placed closely after ice retreat in the Ottawa area, and immediately prior to, and possibly continuing into the earliest Champlain Sea phase.

5.3 FUTURE WORK

Possible future work falls into three areas of study: 1) sedimentology and stratigraphy; 2) micropaleontology; and 3) regional deglaciation. These are discussed in order in the following sections.

5.3.1 Sedimentology and Stratigraphy

Although the sedimentology and stratigraphy of the rhythmite and massive silty clay facies are fairly well known in the Ottawa Valley area, the exact extent, thickness and distribution of these deposits in the upper Ottawa Valley, Rideau Lakes and Lake Ontario basin areas is unknown. The most promising line of study is the continuation of the Geological Survey of Canada coring. Coring in the Rideau Lakes are (Anderson et al., 1985) and in the Ottawa Valley (Gadd, 1986) has already been described. Excavation of sections along the Rideau and Ottawa Rivers would provide useful surface exposures for comparison to those already documented.

In the past, it has not been possible to determine the exact thickness of the rhythmites or the specific nature of their deposition since core logging and section description have been done subjectively and by more than one investigator. Interpretation of the Geological Survey of Canada core from the Ottawa Valley is particularly difficult since no objective lithostratigraphic logging technique has been used. Terms such as "varve", "rhythmite" and "interbedded or interlaminated silt and clay" have been used without precise definition, so that distinction between annual rhythmites (varves) and episodic (surge) rhythmites is problematic. In order to avoid this problem in future studies, a lithostratigraphic logging system which records only grain size, bedding style and other objectively noted descriptive parameters is needed. In addition, for consistent interpretation of core logs, the number of investigators should be kept to a minimum to avoid the use of conflicting or ambiguous terminology.

Core material should be logged objectively by (1) photography; (2) x-radiography; (3) preservation by impregnation so that future workers will have "hard" material to work with (not just a description).

Sedimentological analyses of the rhythmite laminations in all areas should aid in correlation of the rhythmites and the interpretation of the depositional mechanism(s) involved. It is believed that such a study may reveal pulses over a wide area of the basin which were previously unidentified. It is unlikely that a bed by bed correlation is possible, because of the rapid and abrupt facies changes involved, but several depositional packages may be traceable through the basin, or between smaller basins.

Measurement of individual rhythmite thickness and the number of rhythmites in a sequence at each locality should aid in better interpreting rhythmite deposition and history.

5.3.2 Micropaleontology

With the exception of the present study and that of Guilbault (1980), little or no work on ice-marginal microfauna has been done using adequate stratigraphic control. The systematic paleontology of ice-marginal brackish and fresh water fauna is well known; what remains to be done is to study the fauna in stratigraphic and paleoenvironmental context.

Faunal investigation in the present study was restricted to two groups: the foraminifera and the ostracoda. Sample processing was restricted to the 100-mesh fraction to save time. Preliminary tests of the 200-mesh fraction indicate juveniles of roughly equal proportion to the dominant species present in the coarser fraction.

Processing the finer sediment fraction may yield new and unforseen information- certainly, smaller microfossils such as the diatoms, if present, should give more information on paleoenvironments.

Enlargement of the present work into the upper Ottawa Valley, Rideau Lakes and Lake Ontario basin should greatly aid in establishing the extent of various biofacies.

In order to better understand the mixing of water bodies in ice-marginal areas, a more complete knowledge of the faunal assemblages is required. Determination of whether assemblages represent a biocoenosis or thanatocoenosis, and the extent of any post-mortem changes in the assemblage is necessary. For example, the delicate nature of some ostracode valves makes their preservation problematic. SEM study of valve mineralogy and surface texture should indicate the effect and extent of carbonate solution, and whether the valves are naturally thin-walled.

The Champlain Sea environment represented by the Ottawa Valley microfauna is dominated by meltwater input rather than by marine water. In contrast, the Goldthwait Sea represents an environment which, although glaciomarine, was influenced little by meltwater input. Comparison of these two environments would greatly contribute to the present knowledge of fresh and marine water mixing in ice-marginal areas.

5.3.3 Regional Deglaciation

The present study indicates the presence of a large fresh water body in the Ottawa Valley at the time when the Belleville phase of Lake Iroquois and the Fort Ann phase of Lake Vermont coexisted. Further study is required to establish the extent and duration of this water body, and possible correlation with other water bodies. Subsequent study may reveal that the apparently large, single water body postulated here was in fact several smaller coexisting bodies.

An important aspect of this investigation may be the measurement of the elevation of any exposure of the freshwater clay body which may help determine the elevation of a depositional plane. Unfortunately, this may not be possible since the glacigenic clays were deposited by bottom-hugging density current underflows which closely followed the uneven glacial lake-bottom topography. Similar depositional mechanisms have been found for Lake Iroquois bottom sediments (Anderson, pers. comm., 1985), resulting in a very uneven distribution and topography. Establishment of the elevation of the large lake may aid in the correlation of this water body with other water bodies in the Lake Ontario basin and in the Champlain Valley. Development of better correlation with already known events may also help to clarify the chronology of the pre-Champlain Sea water body. Since the rhythmites are not annual, they may not be used for measurement of time, and since there is no dateable material contained within the sediments, the development of a chronology for the freshwater body must be done by indirect means.

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Appendix A

PALYNOLOGY SAMPLE PREPARATION

Each sample was treated with approximately 40 ml of cold HCl to remove carbonates, then washed with distilled water. Samples were then placed in nickel crucibles and treated with concentrated HF. Each sample was heated to boiling point at least three times and then allowed to cool. Samples were then washed with distilled water and 10% HCl added and samples heated to 90 °C and left at this temperature for five minutes. Samples were then washed with distilled water and treated with glacial acetic acid and finally with acetolysis solution.

Two (unstained) slides were prepared for each sample. These were counted using both 25 and 40 power objectives and 10 power wide-field eyepieces on a binocular Leitz S.M. biological microscope. The entire slide was traversed and pollen grains noted when found.

Appendix B

LOSS ON IGNITION (LOI) METHOD

The following method has been developed from several well-known methods of soil and sediment analysis. It has the advantage of being quick, reasonably accurate (± 1-2%) and done with commonly available equipment.

Equipment required: furnace to 875 °C, crucibles; tongs; desiccator; asbestos mat; high temperature marking pen; balance accurate to 0.01 g.

Method is as folows:

1. Place approximately 10 g air dried sediment in a numbered and accurately weighed crucible. Weigh to 0.01 g.
2. Heat to 110 °C overnight; put in desiccator and cool to room temperature (rt) and weigh.
3. Heat to 375 °C overnight; cool to about 150 °C on asbestos mat, then to rt in desiccator. Weigh. Let furnace cool to rt.
4. Heat to 550 °C for one hour after furnace reaches 550 °C. Cool to 150 °C on asbestos pad, then in desiccator to rt. Let furnace cool. Weigh.
5. Heat to 875 °C for 1.5 hours after furnace reaches 875 °C. Remove and cool to 150 °C on asbestos mat, then in desiccator to rt. Weigh.

Various components are burned off at different temperatures. These may be calculated as follows:

1. Loss due to gravimentric moisture is weight loss from rt to 110 °C.
2. Loss due to organic matter is weight loss from 110 °C to 375 °C.
3. Loss due to structural water is weight loss between 375 °C and 550 °C.
4. Loss due to carbonates is weight loss between 550 °C and 875 °C.

Weights may then be divided into the original sample weight and calculated as a percentage.

Appendix C

DETERMINATION OF CALCITE/DOLOMITE RATIOS

The following section describes the technique used to determine calcite/dolomite ratios in paired couplets of silt and clay.

Laminations of silt and clay rhythmites were separated using a single-edge razor blade into dark (D) and light (L) singlets. Five different couplets were separated and labelled A, B, C, D, E, so that individual laminations were termed, respectively, DA, LA, DB, LB, DC, LC, DD, LD, DE and LE. Grain size separation was tested by running the couplets on a Coulter Counter, producing grain size distribution curves. It was thus confirmed that the dark laminations are finer than the light laminations.

Sediment was air dried and ground with an agate mortar and pestle until it would pass (dry) though a 325-mesh screen. 32 mg of this powder was suspended in one ml of distilled water and pipetted onto a standard glass x-ray diffraction slide (25 x 30 mm).

Samples were scanned on a PAD II diffractometer using Co-k-alpha radiation at settings of 40 mA and 40 kV. The samples were scanned from 33 degrees to 38 degrees to identify the (104) reflections of calcite and dolomite.

Ratios were obtained using the intensities of the (104) peaks in counts per second, which is proportional to the mass of the mineral present.

Appendix D

FORAMINIFERA/OSTRACODA SAMPLE PREPARATION

Standard micropaleontological techniques are well known and documented (eg Brasier, 1980; Cronin, 1979a; Feyling-Hansen, 1958, 1964; Feyling-Hansen et al., 1971; Guilbault, 1980; Melgaard and Knudsen, 1978; and Rodrigues, 1980),

Most disaggregation and cleaning techniques involve use of hydrogen peroxide, commercial detergents (calgon or Quaternary-O) or water. Hydrogen peroxide is very efficient, and is often used in soil work, but is too strong and it was suspected it might destroy delicate or agglutinated foraminifera. Calgon is also used as a preparation agent, but is too slow when high clay contents are involved. Quaternary-O is a stronger industrial detergent which seems to work well. Guilbault (1980) suggested the use of water, but this is excessively slow, and should only be used where there is concern for damaging of specimens. In particularly clay rich samples, repeated slow drying and wetting disaggregates the clay well if done with water alone. Final cleaning may then be done using Quaternary-O.

The following method was developed by the author for processing foraminifera and ostracodes together. 200 g raw sample is heated on low heat for one to two hours (depending on clay content) in 2 l of water with 30 ml of Quaternary-O. The mixture is cooled and wet sieved with warm water (to prevent flocculation of clay) through 20-, 100- and 200-mesh sieves. The 20-mesh sieve retains some of the largest foraminifera and ostracodes, insects and macrosfossil fragments. The residue from the 100- and 200-mesh sieves is then washed two or three times with water to remove residual detergent and dried using acetone. If necessary, material finer than 200-mesh is retained for clay mineralogy and geochemical testing.

Once dry, the tests are picked from the mineral fraction using a wet 10/0 sable brush. Flotation methods were tried without success. Guilbault (1980) separated tests using a mixture of dibromoethane and methyl alcohol (density 1.8), and Brasier (1980) suggested using carbon tetrachloride (density 1.6), but these methods work only for tests of a given density and often a mixture of ostracodes and foraminifera with arenaceous tests, calcareous tests and tests containing large air spaces would require separation in several stages. It is believed that the scarcity of some species of foraminifera (Cronin, 1979a) such as the arenaceous forms, may be the result of concentration and recovery techniques. Thus hand picking, although very much slower, was chosen in order to ensure recovery of a complete and representative population.

Appendix E

GSC PLANT MACROFOSSIL REPORT NO. 84-25

Sample No.: FOP-33

Locality: Foster Gravel Pit, Rideau River, Ottawa

Province or Territory: Ontario

Collected by: D. Naldrett

Submitted by: D. Naldrett

Material Submitted: Picked fossils mounted on slides

Fossils:

Fungal Sclerotia		
Cupressaceae	"cypress family"	3,4
Thuja sp.	"cedar"	53,5,45
Unidentified plant fragments		48,49,50,51 52,25,27,2 40,46,47,35
Cemented sand tubules (formerly plant stems ?)		61-84

Comments:

The numbers following the named items in the list refers to the slide on which the object was seen.

The only identifiable plant fragments were a few fragments of cedar. Although the exact time of appearance of cedar in the Holocene of southern Ontario is poorly known (because the pollen is difficult to distinguish from other types), it is unlikely that it was a member of the flora of the Ottawa area 10,000 BP. Thus the plant fossils support the evidence of arthropod fossils that the sampled level is either younger than the date indicated or that it contains late Holocene (possibly modern) contaminants.

See also Fossil Arthropod Report 84-24.

Identification and Comments by:

J.V. Mathews, Jr.

September 3, 1984

Appendix F

GSC FOSSIL ARTHROPOD REPORT NO. 84-24

Sample No.: FOP-33

Locality: Foster Gravel Pit, Rideau River, Ottawa

Province or Territory: Ontario

Collected by: D. Naldrett

Submitted by: D. Naldrett

Material Submitted: Picked fossils mounted on slides

Fossils:

MIRAPODA		
DIPLODA	"millipeds"	30(p+)
ARTHROPODA		
INSECTA		
Unidentified ff		55,19,20,31, 35,38,39,41 13,60
COLEOPTERA	"beetles"	
Cicindelidae	"tiger beetles"	21,37,3(p+)
Hydrophilidae	"water scavenger beetles"	
Helophorus sp.		7,42
Genus ?		14(p+)
Curculionidae	"weevils"	
Genus ?		6,9,10,11(p+)
DIPTERA	"flies"	
Family		49
HYMENOPTERA	wasps and ants"	
Family		4

Formicidae	"ants"	
Genusnd ants"		
Family Formicidae	"ants"	4
Genus ?		? 36
CRUSTACEA		
Isopods	"sow bugs"	16(p+),17,18
		24(p+),28,29
		? 26,22

Comments:

The number following the identified fossil in the above list refers to the slide on which the fossil is mounted.

Some of the arthropod fossils are very well preserved (designated by "+" in the above list). A few of the sow bug "fossils" are articulated even though they are poorly sclerotized and thus more fragile than most insect fossils. In addition the unidentified weevil fragments possess the scales that normally cover the animal when living.

The fossils come mainly from sand (silt) which normally does not allow such excellent preservation of insect fossils. Thus the state of preservation of the fossils suggests that they are either very young or modern contaminants.

Sow bugs and millipeds are not northern arthropods, and based on what is known of the early Holocene fauna of southern Ontario and Quebec, are definitely not in accord with the 10,000 BP date of the sampled level. If the fossils are not contaminants that were living in the exposure face, they must indicate a date no older than than the late Holocene. The excellent preservation of the fossils and the tiger beetle larvae (presumed fossils were larval fragments) live in sand suggests that the "fossils" may well be modern.

In addition to arthropod and plant fossils, slide 32 contains what appears to be the maxillae of a fish.

See also Plant Macrofossil Report 84-25.

Identification and Comments by:

J.V. Mathews, Jr.

September 8, 1984