

# Younger Dryas-age readvance of Laurentide ice into the Champlain Sea

PIERRE LASALLE AND WILLIAM W. SHILTS

## BOREAS



LaSalle, P. & Shilts, W. W. 1993 (March): Younger Dryas-age readvance of Laurentide ice into the Champlain Sea. *Boreas*, Vol. 22, pp. 25-37. Oslo. ISSN 0300-9483.

Occurrences of *Balanus hameri*-bearing diamicts described in this paper and pertinent (*Balanus* plates and pelecypods shells)  $^{14}\text{C}$  dates suggest that there was glacial activity in the Champlain Sea basin between 11,000 BP and 10,400 BP and that this activity can be ascribed to a climatic cooling episode correlative with the Younger Dryas of the late-glacial sequence of northeastern Europe.

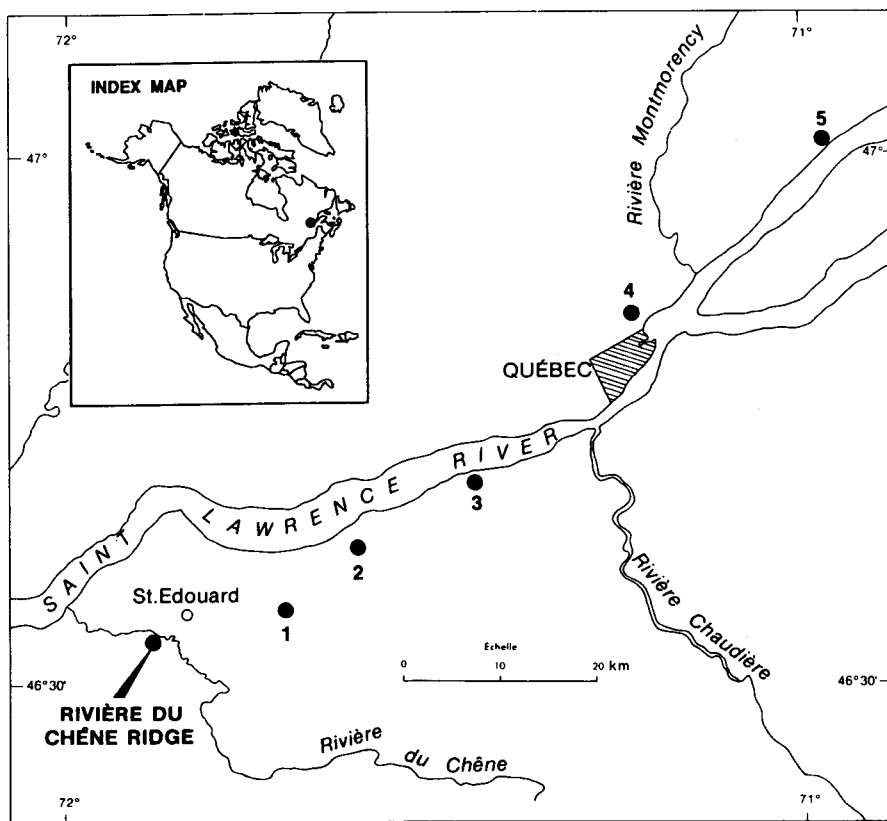
Pierre LaSalle, *Énergie et Ressources*, 5700 4<sup>e</sup> Avenue Ouest, Charlesbourg, Québec, G1H 6R1, Canada; William W. Shilts, *Geological Survey of Canada*, 601 Booth St., Ottawa, Ontario, K1A 0E8, Canada; 25th, January, 1991 (revised 26th October, 1992).

The presence of till-like diamict bearing plates or fragments (opercular, wall and basal plates) of *Balanus hameri* in the Québec City area was reported for the first time in 1972 (LaSalle *et al.* 1972). The first collections of *Balanus hameri* plates obtained from glacio-marine diamict were made at Pointe St Nicolas, about 20 km west of the Québec bridge (Fig. 1) on the south shore of the St Lawrence River. They were

radiocarbon-dated at  $11,200 \pm 170$  BP (GSC-1476, LaSalle *et al.* 1972; Lowdon & Blake 1979). [In Parent & Occhietti (1988: 230), Occhietti is quoted as the collector for GSC-1476 and the date is also quoted as unpublished (Lowdon & Blake 1979)].

Two other exposures of *Balanus*-bearing diamict (LaSalle *et al.* 1972) were discovered at about the same time at sites located northeast of Québec City,

Fig. 1. Occurrences of *Balanus hameri*-bearing glacio-marine diamict in the Québec City area: (1) Issoudun; (2) Ruisseau Bourret; (3) Pointe Saint-Nicolas; (4) Chevalier; (5) Lapointe.



on the north side of the St Lawrence Channel: (1) Chevalier (Fig. 1), GSC-1232,  $11,000 \pm 160$  BP (LaSalle *et al.* 1972; Lowdon & Blake 1976); (2) Lapointe (Fig. 1) GSC-1295,  $11,200 \pm 160$  BP (LaSalle *et al.* 1972; Lowdon & Blake 1976). Two new sites exposing *Balanus*-bearing diamictos have been added recently: Issoudun and Ruisseau Bourret, both located southwest of Québec City (Fig. 1).

Plates of *Balanus hameri* also have been found in shallow-water marine sediments at St Nicolas (GSC-1712,  $11,100 \pm 150$  BP) and in early post-marine fluvial sediments. They are obviously reworked from their original growth site. [The housing of *Balanus hameri* is made of wall plates, opercular plates, and one basal plate (Bousfield 1954). In the text, broken plates are fragments. Basal plates have not been included in the fragments dated.]

The purposes of this paper are to describe these *Balanus*-bearing and associated sediments and landforms and to propose a sequence of glacial events and environments that can account for them. The conclusion that will be advanced is the following: the maximum radiocarbon age of the *Balanus* plants and the minimum external radiocarbon ages obtained on pelecypods suggest that these sediments (diamictos and associated subaqueous outwash) were emplaced during a glacial readvance in the Champlain Sea attendant upon a cooler climate episode correlative with the Younger Dryas of the late-glacial sequence of northeastern Europe. As the recognition of this sequence in lake sediments in eastern North America has been challenged and has remained doubtful since approximately 1950, a résumé of the evolution of the late-glacial stratigraphy in North America will be presented.

## Definitions

### Glacio-marine environment

Molnia (1989) has reviewed the terminology used by workers in the glacio-marine domain. It is complex and seems to vary from author to author. To discuss these deposits without adding any new, unnecessary terms, glacio-marine has been retained here to designate the environment in which glacier ice is in contact with seawater and subjected to tides. Sediments that are deposited in the environment are also called glacio-marine and the glacier 'tide-water'.

In the case discussed here, the glacier appears to have been at least in part grounded in the Champlain Sea. Where the glacier was grounded, glacial diamictos were deposited either directly from the ice at its front in the sea, or beneath the ice in the form of till. The glacier must have reworked already deposited marine sediments by advancing over them because the diamictos contain abundant fossil fragments and stri-

ated and faceted clasts and have all the common attributes of till, such as massiveness and compactness.

In the present environment around Antarctica (Anderson & Molnia 1989), sediments derived from the ice sheet and deposited around it can be classified as glacio-marine, either because of their location with respect to the ice sheet (geographical association) or because of their texture, structures, and the nature of their erratics, whether ice rafted or emplaced directly from grounded ice.

In the case discussed here, the diamictic sediments are called glacio-marine largely because of the marine shell clasts in them and the fact that they are overlain by shallow-water Champlain Sea sediments containing *Mya arenaria* and *Hiatella arctica* in growth position. Also, they are underlain commonly by stratified sand and gravel thought to have been deposited as subaqueous outwash in the Champlain Sea. Assuming that the Champlain Sea episode was continuous and without an interval of subaerial erosion within the limit of the marine basin, the *Balanus*-bearing diamictos had to be deposited from ice standing in the sea, because fossiliferous waterlain marine sediments are also present stratigraphically beneath it and beneath the stratified subaqueous outwash.

The presence of *Balanus* plates or fragments of plate in the diamictos is not in itself a criterion for glacio-marine origin, as they could have been picked up on dry land by a glacier advancing over isostatically raised sediments containing *Balanus hameri*. Similarly, the fact that the *Balanus* plates are sometimes observed together in growth position, argues neither for nor against a glacio-marine origin, since blocks of fossiliferous sediments may have been picked up by the glacier as frozen clasts and transported and incorporated in the glacio-marine diamictos at a later time. However, there is no known combination of fluctuation isostatic and eustatic sea-levels during Champlain Sea time that would allow ice to have advanced over isostatically uplifted marine sediments on dry land, picking up the *Balanus* plates.

### Subaqueous outwash

In this paper the term 'subaqueous outwash' is used in the sense of Rust & Romanelli (1975) and Rust (1977). It designates stratified sand and gravel outwash sequences deposited below wave base. Individual beds in these sedimentary sequences are well sorted and are cut by channels that are filled with stratified to massive sand. No fossils have been observed in these sediments, probably because the meltwater-enriched marine environment and associated rapid sedimentation at the submerged ice front was inimical to the survival or colonization of marine organisms. In the geological context of the Québec City area and for reasons just given above, the absence of marine fossils in these sediments cannot be used as an argument to say they

have  
envi  
Su  
note  
30-m  
catin  
stoo  
by 1  
com  
mari  
depc  
McC  
Lac  
fans  
devc

The

The  
nort  
time  
(194  
Low  
Dry:  
(194  
othe  
and  
Plei:  
You  
You  
to 1  
octo  
corr  
Tun  
& 1  
Ear:  
and  
sedi  
pap  
Twe  
Wis  
T

on  
(19:  
repi  
grai  
clin  
tho:  
woi  
(19  
glac  
(19  
ana  
195  
the  
app  
sug

have been deposited in a freshwater glaciolacustrine environment.

Such a paucity of marine macro-organisms has been noted even in the silty clay facies at the base of a 30-m-thick sediment sequence that has structures indicating rapid deposition directly from an ice front that stood in the Champlain Sea, in the basin now occupied by Lac Deschênes, in Ottawa (C. Rodrigues, pers. comm., 1988). Very high ratios of sediment volume to marine microfauna confirm marine conditions during deposition of similar sequences elsewhere (Eyles & McCabe 1989). Likewise, in the Ottawa Valley near Lac Deschênes the classic marine subaqueous outwash fans described by Rust and co-workers, are similarly devoid of marine fossils (Rust & Romanelli 1975).

### The Younger Dryas in North America

The late-glacial vegetation and pollen sequence of northern and western Europe is mentioned for the first time in the North American literature by Deevey (1949). The terms used by him were the following: Lower Dryas flora, Allerød oscillation, and Upper Dryas flora. Deevey (1949: Table 2) refers to Movius (1942) as his main source but he also mentions several other authors, among them Jessen & Milthers (1928) and Jessen (1935). In Deevey's summary of the late-Pleistocene stratigraphy of Maine (Deevey 1951), the Younger tundra zone, L3, is correlated with the Younger Tundra of northern Europe. This zone was to become later the Younger Dryas (after *Dryas octopetala* L.). Zone L2 of northern New England was correlated with the Allerød and zone L1 with the Older Tundra which was to become the Older Dryas. Faegri & Iversen (1964: 92-93) used the following terms: Early Dryas, Allerød and Late Dryas. Zones L1, L2 and L3 are based on the pollen content of lake sediments from Aroostook County, Maine. In the same paper, Deevey (1951) correlates the Allerød with the Two Creeks (Thwaites & Bertrand 1957) horizon of Wisconsin (see also Flint & Deevey 1951).

To the east of Maine, in the sediments of Gillis Lake, on Cape Breton Island, Livingstone & Livingstone (1958) reported a well defined Zone 3. Ogden (1959) reported the presence of tundra zones in pollen diagrams from southern New England, but pollen and climatic zones did not appear to be as well defined as those of Deevey (1951) for northern Maine. Other workers, among them Leopold (1956) and Davis (1956) contributed to the establishment of the late-glacial pollen stratigraphy of New England, but Davis (1963) became very critical of the very basis of pollen analysis. At this point, we shall quote her paper (Davis 1956: 393): 'In view of the uncertainties surrounding all the evidence of a climatic oscillation in the Northeast approximately 11,000 years ago, I am inclined to suggest that the pollen data from the Herb Pollen Zone

and Spruce Pollen Zone, both in southern and northern New England, can also be interpreted merely as the record of a progressive increase in the numbers of trees on the landscape. There is no definitive proof for this viewpoint, but it should be considered as an alternative to the previous interpretations that involve climatic oscillations. I think the possibility should be kept in mind that climatic changes (if any) associated with the advance of Valdres ice, and the climatic change recorded by the Younger Dryas deposits in Europe, might have failed to cause detectable changes in the vegetation of New England. In maritime regions or in regions very close to the ice margin the situation may have been very different, as indicated by the late-glacial pollen diagram from Nova Scotia.'

This skepticism had been reinforced by the failure to identify evidence for the Valdres readvance in lake sediments in the American Midwest in the very area where this advance occurred (Jelgersma 1962; Wright *et al.* 1963). This seemed to buttress the hypothesis that pollen zones were well defined only in maritime areas and that continental areas were not favorable for the recording of herb zones (West 1961; Davis 1965). However, recent work shows the pollen records from the Great Lakes area (Anderson & Lewis 1990) indicate a cool period from 11,000 to 10,500 BP. Broecker & Farrand (1963) on the basis of new radiocarbon dates, revised the position of the Two Creeks and suggested that it was more likely correlative of the Bølling than the Allerød. The Valdres then would more likely be correlative with the Older Dryas. LaSalle (1966) suggested that the St Narcisse moraine and associated features were correlative of the Younger Dryas on the basis of external radiocarbon dates and pollen stratigraphy of the St Hilaire bog.

Recent work by Peteet *et al.* (1990) has revealed other evidence for the occurrence of a climatic fluctuation in northeastern USA between 10,000 BP and 11,000 BP. They (Peteet *et al.* 1990) have correlated it with the Younger Dryas. Work by Mott *et al.* (1986) has shown that the Younger Dryas oscillation is recorded in lake sediments of the Atlantic Provinces of Canada, the same area where Livingstone & Livingstone (1958) had reported a well defined Zone 3 in sediments of Gillis Lake on Cape Breton Island. Stea & Mott (1988, 1989) have also shown that terrestrial glacial sediments record glacial activity in Nova Scotia that appears to be correlative with the Younger Dryas. Also, the sedimentary sequence in sections of unconsolidated sediments in bluffs on the North shore of the St Lawrence Estuary, suggests that the St Narcisse Ice Front, which can be traced on land as far as St Simeon, west of Tadoussac, was standing in the Goldthwait Sea, east of Tadoussac, around 11,000 BP. Data from the Sulu Sea recently published (Kudrass *et al.* 1991) tend to suggest that the climatic cooling associated with the Younger Dryas occurred simultaneously in many parts of the world (Kudrass *et al.* 1991), and its effects

were not restricted to the Northern Hemisphere or even the north Atlantic. Finally, the cause of the Younger Dryas climatic oscillation has been the subject of recent stimulating discussions (Broecker *et al.* 1988a, b; Berger 1990; Lehmann & Keigwin 1992; Veum *et al.* 1992).

### Description of critical sites

Exposures of marine diamictos (Fig. 1) have changed continuously since first observed and reported in 1972 (LaSalle *et al.* 1972). The summary of each site presently known is based on serial observations or on single observations made when a pit was particularly well exposed.

*Pointe Saint-Nicolas site (St Nicholas in Lowdon & Blake 1979).* – This was the discovery site (site 3 on Fig. 1) for *Balanus*-plate-bearing diamictos interpreted as till and was visited by numerous geoscientists around the time of the International Geological Congress in Montréal in 1972. At this site a date of  $11,200 \pm 170$  BP (GSC-1476) was obtained on plates or fragments of plates of the barnacle *Balanus hameri* separated from a gray, compact, calcareous diamicton. Basal plates of the barnacles were observed still attached to erratic boulders. The plates were on all sides of the stones. Although clasts representing local bedrock lithologies are most abundant in the diamicton, some precambrian erratics from north of the St Lawrence are also present. Northward-dipping, low-angle thrust planes in the sediment indicate glacial movement from the north for depositing or overriding ice. Therefore, it can be concluded that despite the significant depth ( $> 150$  m) of marine water in which the glacier edge must have been submerged, ice was grounded at one time. At Pointe Saint-Nicolas, wall plates of *B. hameri* are occasionally observed still attached to basal plates. This suggests that they may have been incorporated in blocks of frozen sediment. Foraminifera tests are also present in the diamicton. At Pointe Saint-Nicolas, the fossiliferous diamicton in places is underlain by sediment interpreted as sandy subaqueous outwash with minor gravel in cut-and-fill structures.

*Chevalier site (Beauport in Lowdon & Blake 1976).* – A date of  $11,100 \pm 160$  BP (GSC-1232) was obtained for *B. hameri* plates or plate fragments retrieved from the diamicton exposed at this site (site 4 on Fig. 1). The diamicton here is clayey and calcareous and is much less stony than that at the Pointe Saint-Nicolas site. The clayey diamicton was originally observed to be underlain by a sand unit which contained no macrofossils. The original site is no longer exposed because of construction.

*Lapointe site (Sainte-Anne-de-Beaupré in Lowdon & Blake 1976).* – A date of  $11,200 \pm 160$  BP (GSC-1295)

was determined on large plates or plate fragments of *B. hameri* collected from a gray, compact, calcareous diamicton (site 5 on Fig. 1). No visible structure was observed in the diamicton, which was interpreted to be a till. The diamicton is directly underlain by bedrock which forms the edge of the upper rock terrace found in the Beaupré area. This terrace, of unknown age and significance, stands above the Micmac terrace (Goldthwait 1911).

*Saint-Edouard-de-Lotbinière site.* – At this site (Fig. 1) an unfossiliferous, sandy diamicton with few large erratics lies on coarse sandy sediments with flaser bedding, interpreted to be subaqueous outwash. The diamicton is believed to be a till that caps or forms a low, east–west trending ridge named formally here the St Edouard moraine (Figs. 2 and 3). East and south-east of this location, the ridge passes into rolling topography. In the vicinity of the pit that exposes the internal structure of the ridge, its south side is marked by a 4-m-high escarpment thought to mark the most southerly position of ice from the readvance during which the *B. hameri*-bearing diamicton that crops out in several nearby exposures was deposited. At and downstream from the point that Rivière du Chêne cuts the ridge, its banks expose several sections with the same general stratigraphy as in the pit, i.e. sandy diamicton overlying gravel-poor sandy subaqueous outwash with flaser bedding.

At the Saint-Edouard-de-Lotbinière site as well as at several other sites where fossiliferous or unfossiliferous diamicton lies over subaqueous outwash, the contact shows evidence of erosion and shearing, presumably due to drag of an overriding glacier, and inclusions of the underlying sand are found as discrete clasts in the diamicton. The sandy nature of the diamicton at this site is attributed to more intense glacial reworking of the underlying outwash sands here than was the case elsewhere. Here, as elsewhere, the upper surface of the diamicton shows the effects of having been isostatically uplifted through wave base; the upper 1–2 m of the exposures consist of sandy, nearshore sediments with macrofauna indicative of a shallow water depositional environment. Fine-grained, deep-water sediments have not been observed to intervene between the diamicton and sandy, reworked sediments on its surface.

*Issoudun site.* – At this site (site 1 on Fig. 1), plates and plate fragments (Fig. 4) of *B. hameri* were found in a gray, calcareous, compact diamicton with structures, striated and faceted stones, and all the compositional characteristics of tills typical of this region. Basal plates of *Balanus* can be seen still attached to cobble-sized Precambrian erratics. Well-preserved wall plates of *Balanus* are found scattered throughout the till matrix. A date of  $11,400 \pm 90$  BP (GSC-4998) was obtained for *B. hameri* plates collected from the

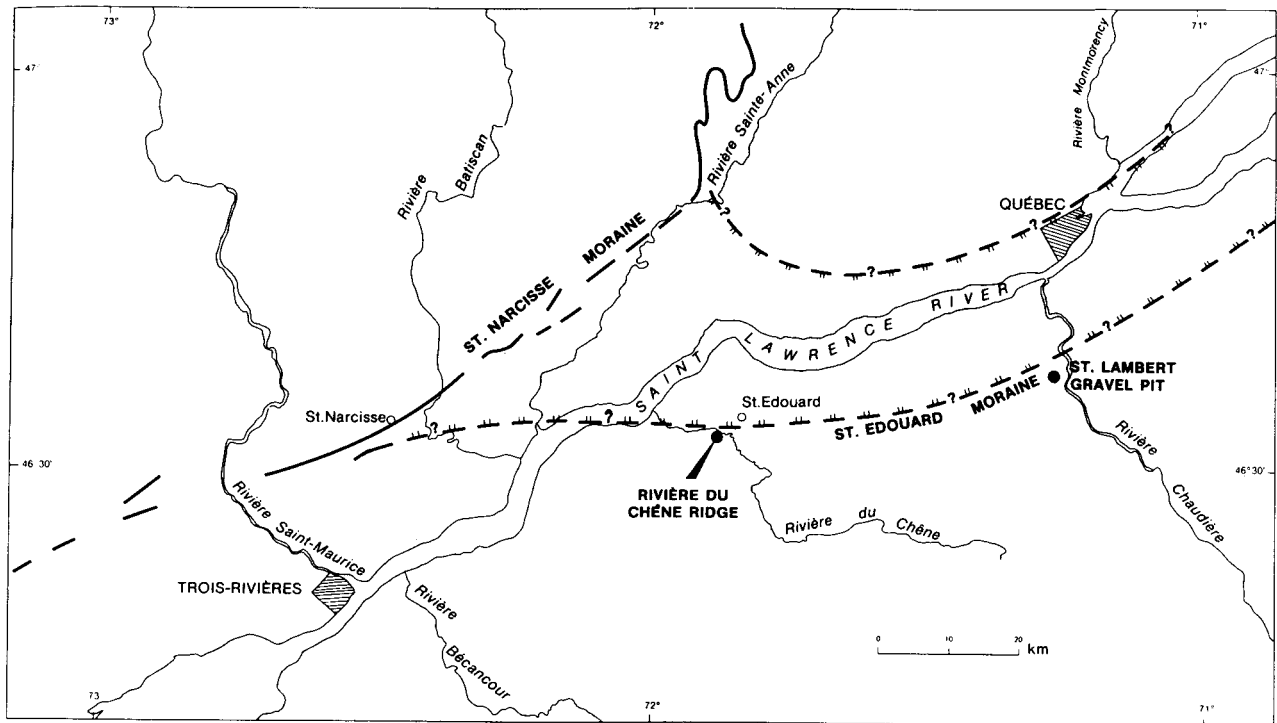


Fig. 2. Map showing the St Narcisse Moraine and the position (in part hypothetical) of the ice front at the time of the emplacement of the St Edouard Moraine.

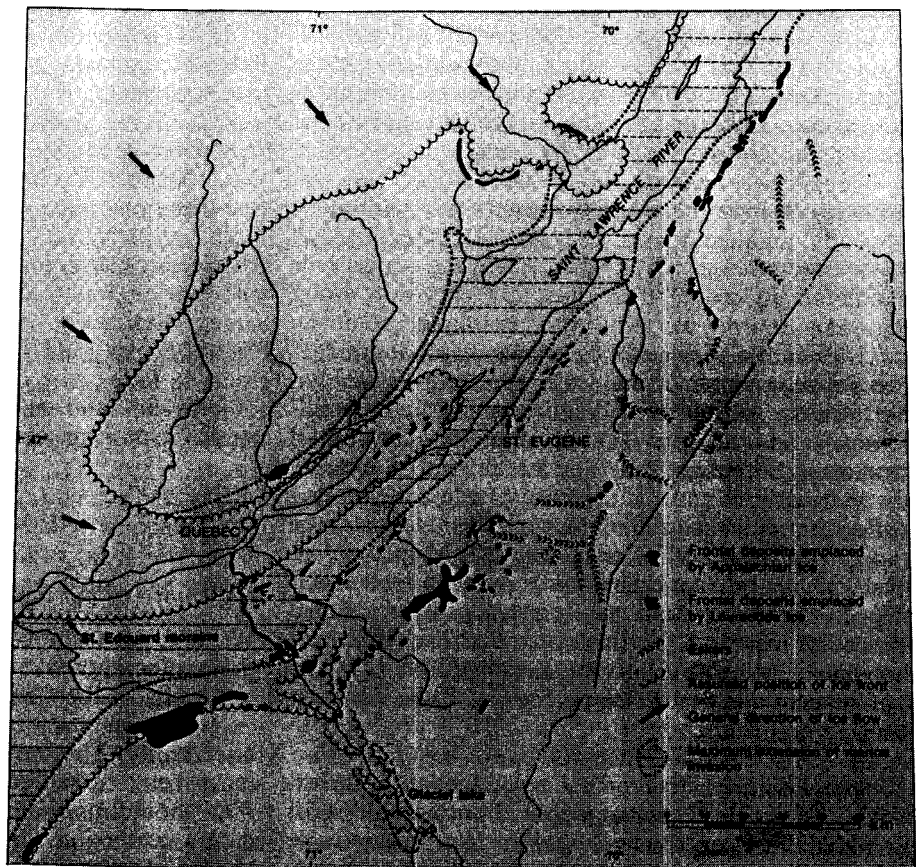


Fig. 3. Late-glacial ice-frontal deposits and position of the ice at about 11,000 BP. Location of St Eugene deposit with respect to the ice front is also shown (modified after LaSalle & Chapdelaine 1990).

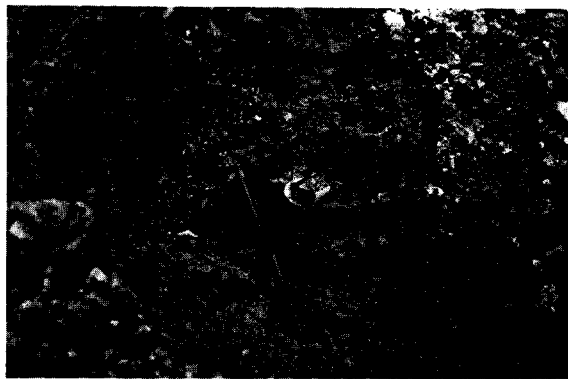


Fig. 4. Plates of *Balanus hameri* in till, Issoudun site.

diamiction exposed at this site. As at other nearby sites, the diamiction overlies sandy subaqueous outwash, which is the material being extracted from this and other recently active gravel pits in the region. Only at this site were rare *Balanus* plates observed in the subaqueous outwash. South of the pit, (0.5 km), a 20-m-high, east–west trending escarpment is thought to mark the southernmost limit of a readvance that deposited the *Balanus*-rich till. At Issoudun, as elsewhere, a thin sandy unit deposited as the receding Champlain Sea shoreline passed across this site contains abundant shells of *Hiattella arctica*. Those shells have been radiocarbon dated at  $10,300 \pm 90$  BP (GSC-4997). This is obviously a minimum age for the emplacement of the *Balanus*-bearing diamiction. Similar deposits and fauna cap the numerous exposures of Champlain Sea sediments in the area.

**Ruisseau Bourret site.** – At this site (site 2 on Fig. 1), presently undated plates and plate fragments of *B. hameri* were found in a gray, compact, calcareous diamiction at two of three pits that expose it along Ruisseau Bourret. Erratics in the diamiction comprise c. 75% local Paleozoic carbonate clasts and about 25% Precambrian metamorphic rocks that crop out 25 km north of the sections. The diamictions overlie unfossiliferous sand and gravel with abundant cut-and-fill structures. Because of its setting more than 100 m below the marine limit and the evidence of rapid, aggrading sedimentation, the underlying sorted sediments are thought to have been deposited in a subaqueous fan. The *Balanus*-bearing diamiction is overlain by a sandy deposit containing *Mya arenaria* shells still articulated with some in growth position. They have been radiocarbon dated at  $10,200 \pm 100$  BP (GSC-4996), which is also a minimum age for the emplacement of the *Balanus*-bearing diamiction.

**Summary section: Rivière du Chêne, Section 3.** – Section 3 (Fig. 5) is located about 3 km southwest of Saint-Edouard, on the west bank of Rivière du Chêne (Fig. 2). It shows a sequence that is a good summary

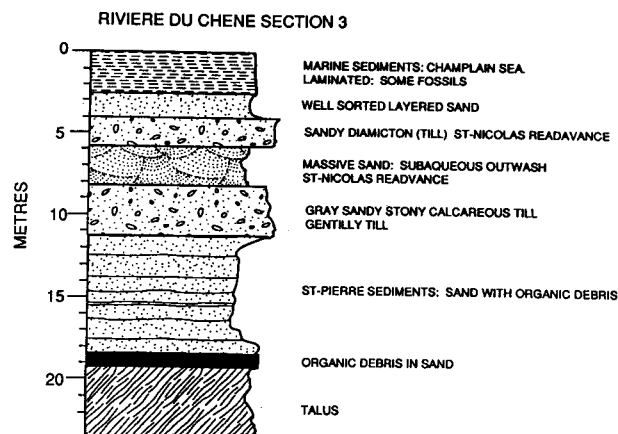


Fig. 5. Rivière du Chêne, Section 3.

(though incomplete) of the stratigraphic record of the unconsolidated sediments in the area. The four upper units (Fig. 5) that are the subject of this paper, are well defined in that section. It becomes obvious now that wherever till is observed at the surface of the land in this area southwest of Québec City and within the limit of the Saint-Nicolas readvance, the surface till is not necessarily the 'Gentilly' till but could as well belong to the Saint-Nicolas drift. Also, the absence of freshwater pre-Champlain Sea but post-Gentilly sediments in Section 3, on Rivière du Chêne, must be noted. Glacial lake sediments are present at the base of the Champlain Sea sequence in the Montréal area. Their first appearance west of Québec City is recorded in the Drummondville area. This suggests that in the intervening area, between Rivière du Chêne and Drummondville, the Champlain Sea waters were in contact with the ice and that there was no freshwater episode between the time of disintegration of the ice sheet and the arrival of the marine waters. Further south, in other sections along Rivière du Chêne but outside the limit of the Saint-Nicolas readvance, the Saint-Nicolas drift units seem to fade away or are represented only by a layer of gravelly sand as the distance from the presumed ice-front position increases.

## Discussion

### *Reliability of the radiocarbon dates*

We have no absolute standard with which to compare the radiocarbon dates of the shells collected in the sediments of the Champlain Sea. Radiocarbon dating in such circumstances carries a certain amount of uncertainty. The best that we can hope for is consistency between radiocarbon dates obtained for events that should normally appear in sequence. In some cases, corrections have been suggested or applied to radiocarbon dates. Examples of corrections for

remains of marine organisms are given by Bard (1988). He has shown that in order to correct accelerator mass spectrometry (AMS) (Grootes 1983: 97–99) dates obtained on Foraminifera from deep-sea cores, we have to establish the variations of the apparent age of ocean surface waters (reservoir age) through time up to c. 40,000 BP. To do that, we have to date contemporaneous terrestrial organic material and Foraminifera tests found together in deep-sea cores.

Another and certainly better way to establish the reservoir age variations through time (Bard 1988: 642) would be to date the Foraminifera tests associated with a well-dated volcanic ash layer in the ocean cores, and organic matter associated with the same ash layer in a terrestrial stratigraphic setting. Corrections, based on present reservoir age (Mangerud & Gulliksen 1975) and applied to ancient shell dates are arbitrary and, at best, approximations (Königson & Possnert 1988: 142).

All GSC radiocarbon dates obtained on *B. hameri* and other marine shells and quoted in this paper with a  $\delta^{13}\text{C}$  value have been brought to a  $\delta^{13}\text{C}$  of 0.0‰. Details can be found in McNeely (1989). Other dates on *B. hameri* and other dates quoted in this paper have been used as they have appeared in the literature. Rodrigues (1988: 170–173) has pointed out several discrepancies and inversions of shell dates in the western part of the Champlain Sea basin. To explain those anomalies, the hypothesis has been advanced (Hillaire-Marcel 1981; Rodrigues 1988) that fresh meltwaters at shallow depth contained old carbon glacially derived from bedrock surrounding the Champlain Sea basin while the high salinity marine waters (with higher density) occupied the deeper part of the basin. Those invading marine waters from the Atlantic are believed to be low in old carbon. It must be recalled that 'dead' carbon was also a prime suspect as the cause for anomalies among the first radiocarbon dates obtained on Champlain Sea faunas (MacClintock & Terasmae 1960). In the eastern part of the Champlain Sea basin and especially in the Québec City area, there does not seem to be any major discrepancy or inversion of numbers as those reported by Rodrigues (1988) for the western part of the basin.

If we use the range of individual dates (because the true radiocarbon age may statistically be located anywhere within that range), the dates obtained on *B. hameri* plates from the western part and the eastern part of the Champlain Sea Basin overlap. At St Alban (Table 1) in the St Anne River sections two dates have been obtained on *B. hameri*: GSC-2090,  $10,600 \pm 160$  BP (McNeely 1989: 20) and GSC-4804,  $11,000 \pm 120$  BP). However, there are two horizons of *Balanus* remains in those sections and certainly GSC-4804 (sample collected by LaSalle 1988) was obtained on plates from the lower horizon. Presumably, GSC-2090 was obtained on plates from the upper one. Dates obtained on *B. hameri* plates collected in Goldthwait

Sea sediments are younger (Table 1) but one should expect that, as marine waters migrated to the east during the shoaling of the Champlain and Goldthwait seas.

The oldest date obtained on marine shells in the Québec City area (GSC-1533,  $12,400 \pm 160$  BP) is consistent with the accelerator date obtained on the Clayton collection (TO-245,  $12,180 \pm 90$  BP) since shell dates should be progressively younger as one moves from east to west in the Champlain Sea basin. Obviously, GSC-1533 is not consistent with the older conventional data (GSC-2151,  $12,700 \pm 100$  BP, inner fraction;  $12,800 \pm 100$  BP for the outer fraction) obtained on shells from the same Clayton collection. Small differences can be expected between laboratories using different methods but no one has offered any explanation for the discrepancy between the accelerator date and the conventional date in this case (Hoefs 1987: 21 and 25). Anomalies have also been reported with AMS dating of *Ancylus* phase faunas of the Baltic Sea (Königson & Possnert 1988).

In summary, as has been stated above, there are no absolute standards with which to compare radiocarbon dates (not true age) of shells of the Champlain Sea in order to evaluate their validity. However, we can make comparison between results obtained on shells of the same species between the western part and the eastern part of the Champlain Sea basin. We can also compare radiocarbon dates of the Champlain Sea with those for events not directly related to it but which should appear in sequence with it, such as the marine invasion of the Lac-Saint-Jean Lowlands (see below). For *B. hameri*, which is a deep-water species (Bousfield 1954; Wagner 1970), there are no apparent discrepancies or inversions, and dates obtained on remains of that species should be reliable.

#### Sedimentary environments

Most of these sites have been exposed recently by excavations made to mine, in a nearly flat marine plain, the sorted subaqueous sediments that underlie the fossiliferous diamicton. Most sites show evidence of incorporation of clasts of the underlying sand and gravel into the diamicton. It is probable that the fossiliferous diamicton is continuous between sites. Its southwest limit is bordered by a low escarpment or ridge. At all sites the surface of the diamicton is oxidized to about 1 m depth and is overlain by 1–2 m of sandy, fossiliferous nearshore deposits, formed by wave reworking during regression of the Champlain Sea. Because of the sparsity of *Balanus* fragments in the diamicton (till), particular care was taken at all exposures to ensure that fragments slumped or infiltrated from deposits above where not collected inadvertently.

Subaqueous outwash in present as far west as the northeast corner of the Bécancour sheet (NTS 21L/12), but is apparently absent west of the point along the



Table 1. Published radiocarbon dates obtained on *Balanus hameri* collected from Champlain Sea sediments, except where mentioned otherwise in the Laboratory No. column.

Name of site	Elevation m a.s.l.	Laboratory No.	<sup>14</sup> C age BP	δ <sup>13</sup> C	Reference
Bearbrook	67	GSC-3983	10,700 ± 130	-0.9	Rodrigues 1988; Rodrigues 1987;
		TO-698	10,800 ± 90	-0.2	Rodrigues & Richard 1985
Chevalier	106	GSC-1232	10,860 ± 70		Rodrigues 1992
Crysler	69	GSC-4043	11,100 ± 160		Lowdon & Blake 1976
Herbert Corners	93	GSC-4113	10,900 ± 90	-0.9	Rodrigues 1988
			11,200 ± 110	0.0	Rodrigues 1988; Blake 1988
			11,200 ± 120	0.8	
Issoudun	80	GSC-4998	11,400 ± 90	+1.0	This paper
Lapointe	67	GSC-1295	11,200 ± 160		Lowdon & Blake 1976
Rivière Sainte-Anne	60	GSC-4804	11,000 ± 120	+0.6	This paper
Saint-Césaire	40	TO-704	10,970 ± 60		Rodrigues 1992
Rawdon		UQ-1262	11,100 ± 200	-0.1	Prichonnet 1988
Saint-Alban	71	GSC-2090	10,600 ± 160		McNeely 1989;
Pointe Saint-Nicolas	61	GSC-1476	11,200 ± 170		Lowdon & Blake 1979
Morigeau	70	QU-492	10,900 ± 150		Barrette <i>et al.</i> 1981
Saint-Bernard-sur-Mer		GSC-5133	9,580 ± 80	+0.6	This paper
		Goldthwait Sea			
Les Trois-Fourches	60	GSC-4769	10,500 ± 120	-0.5	This paper
Navan	93	GSC-3706	11,000 ± 90	1.4	Rodrigues & Richard 1986; Blake 1984
Dornie(I)	106	GSC-4468	10,900 ± 120	-0.9	McNeely & McCuaig 1991
Sainte-Thérèse-en-haut	64	GSC-1805	11,300 ± 140		Lowdon & Blake 1975
Twin Elm	97	GSC-4052	10,800 ± 110	0.7	Rodrigues 1988
		TO-700	10,970 ± 70		Rodrigues 1992
Rivière Beaudette	56	GSC-3702	11,000 ± 90	1.4	Rodrigues & Richard 1985
Très-Saint-Rédempteur	80	GSC-4258	11,200 ± 150	-0.6	McNeely & McCuaig 1991
Rigaud	28	GSC-4132	11,100 ± 130	-0.7	Rodrigues 1988
Watterson Corners	93	GSC-4070	11,200 ± 110	-1.1	Rodrigues 1988
			11,300 ± 110	-0.8	
Saint-Nicolas	64	GSC-1712	11,100 ± 150	+2.2	Lowdon & Blake 1979
Moulin à Baude	100	GSC-1500	9,820 ± 150		Lowdon & Blake 1973
		Goldthwait Sea			
Saint-Nicolas	44	UQ-39	10,890 ± 125		Parent & Occhietti 1988
Pointe Saint-Nicolas	57	UQ-40	11,340 ± 180		Parent & Occhietti 1988
Pointe Saint-Nicolas	60	QU-98	11,120 ± 220		Samson <i>et al.</i> 1977
Deschailons		UQ-651	11,130 ± 180		Lamothe 1985
Ruisseau Bourret	68	GSC-4996	10,200 ± 90		This paper
		( <i>Mya arenaria</i> )			
Issoudun	90	GSC-4997	10,300 ± 90		This paper
		( <i>Hiatella arctica</i> )			
Saint-Edouard	38	GSC-4752	10,400 ± 90	-2.3	This paper
		( <i>Portlandia arctica</i> )			

south shore of the St Lawrence River. Thus, it is most likely that an ice front stood in the Champlain Sea basin at the time of emplacement of the St Edouard moraine, as is shown in Fig. 2. East of the Chaudière River, the position of the ice front is more difficult to define.

*Balanus hameri*, an animal that lives preferentially in deep cold marine waters, is the only macrofossil present in the diamicton associated with the St Nicolas readvance to the St Edouard moraine. Apparently, at the time of the readvance *B. hameri* was the only species present in the Champlain Sea in numbers large enough to dominate the fossil record in glacially reworked sediments. Because of glacio-isostatic depression, marine water along the axis of the St Lawrence valley was deep, probably restricting the number of

species available for incorporation into the glacial load at about 11,000 BP.

Shell fragments of *B. hameri* also are found scattered through fossil assemblages of shallow-water marine sediments emplaced after 11,000 BP, as well as in early St Lawrence river fluvial sediments. Ages obtained on some of those obviously reworked shells (e.g. St Nicolas, GSC-1712, 11,100 ± 150 BP) appear to overlap with those found in the diamicton associated with the St Nicolas readvance and the St Edouard moraine. They tend to confirm the widespread presence of *B. hameri* in this part of the basin of the Champlain Sea around 11,000 BP.

The mode of emplacement of the fossiliferous diamicton remains an important question: 'Was the *Balanus*-bearing diamicton deposited by subglacial



processes or derived from supraglacial sediments? Since *B. hameri* is a deep-water organism and was probably living on the seafloor ahead of the ice front, it is most likely that it was incorporated at the base of the ice. In either case, the age of the organism approximates the age of a readvance of the ice front in the sea as both modes of incorporation require glacier ice in contact with or over the sea bottom as a floating shelf.

Several models have been proposed for the deposition of subglacial outwash and overlying diamicton (Rust & Romanelli 1975; Rust 1977; Gravenor *et al.* 1984; McCabe *et al.* 1984, 1987; Molnia 1989). At the time of emplacement of the St Nicolas drift, the readvancing ice front was submerged in water to depths of 100–150 m. Although the ice must have been floating in places, it must also have been grounded in other places, especially over bedrock ridges. The observation that the diamicton facies is compact and sandy in places where it overlies subaqueous outwash also suggests that the readvancing glacier was at least partially grounded. Like the subaqueous outwash, where the diamicton is sandy, it is not fossiliferous.

Where the diamicton is fossiliferous, some *Balanus* shells are still intact. They may have been enclosed in sediment clasts that were incorporated into the diamicton in a frozen state or they may have grown on clasts in a diamicton melting out of the base of the ice or from basal debris-rich bands along its submerged front. Sand laminations and lenses in the compact, finer grained fossiliferous diamicton suggests that they may have been deposited as basal melt-out till from sediment-rich, grounded ice on the sea floor. A similar origin has been proposed for much of the till covering the Appalachians south of the Champlain Sea (Shilts & Smith 1989). Finally, the time of emplacement of the St Nicolas drift (and the St Edouard morainic sediments) is also a maximum age for the emplacement of parts of the younger St Narcisse morainic sediments northwest of Québec City. If the St Narcisse moraine were older, it presumably would have been destroyed during the St Nicolas readvance to the south side of the St Lawrence.

Some parts of the St Narcisse morainic system may have been emplaced at the same time as the St Edouard moraine sediments and the St Nicolas drift, particularly where the ice front was pinned against topographic highs. Glacial striae oriented east–west, on both sides of the St Lawrence Channel, may have been made by an ice lobe extending downstream (Fig. 2) from points northwest of Québec City at the time of the St Nicolas readvance. It may have been grounded in many places on both sides of the St Lawrence Channel near Québec City and downstream from it (Fig. 2), and its south side may have been marked by the St Edouard moraine.

There is evidence that the ice front was also very close to the St Eugène site northeast of Québec City (Fig. 3; LaSalle *et al.* 1977) where an arctic beetle

fauna and an arctic flora were found in an organic layer interstratified with Champlain Sea deltaic sediments (Mott *et al.* 1981). Morgan (1987) associated the fauna and flora of the St Eugène site with an unspecified but nearby ice-front position at 12,000 BP. However, a date of  $11,050 \pm 130$  BP (QU-448) has been obtained on the organic beds. Thus the younger date makes it more likely that the St Eugène organic deposits are associated with rigorous conditions near the St Edouard ice front, 'possibly approaching present conditions in northern Quebec' (Morgan *et al.* 1983: 358).

The paleogeographic reconstruction shown in Figs. 2 and 3 is based largely on (1) east–west striations on both sides of the St Lawrence Channel; (2) the presence of the *Balanus*-bearing diamicton as far south as the geomorphic features that comprise the St Edouard moraine; (3) stratigraphic position of the diamicton over subaqueous outwash and/or fossiliferous Champlain Sea bottom sediments and below younger Champlain Sea nearshore sediments; and (4) dates on marine shells collected in growth position behind (north of) the St Edouard moraine:  $11,600 \pm 160$  BP (GSC-1235) and  $12,400 \pm 160$  BP (GSC-1533), which are significantly older than the dates that have been obtained on *B. hameri* collected from several sites in the diamicton. According to Rodrigues (1988: 183), the appearance of the high-salinity *B. hameri* faunal association (11,400–11,000 BP) marks the beginning of the deep-water marine sedimentation in the western part of the Champlain Sea. This is somewhat at variance (significantly younger) with dates obtained on marine pelecypods (e.g. TO-245,  $12,180 \pm 90$  BP) collected in littoral sediments near the marine limit also in the western part of the Champlain Sea. Northwest of Québec City, at the edge of the Shield, near the St Narcisse ice-frontal position, the ice may have occupied some areas until the appearance of the *B. hameri* association in deep-water sediments, before the St Nicolas readvance. Outside the area occupied by the St Nicolas lobe, these sediments have not been disturbed by overriding glacier ice. In the Québec City area, the oldest dates (LaSalle *et al.* 1977; Chauvin *et al.* 1985) obtained on shells of pelecypods (GSC-1235,  $11,600 \pm 160$  BP and GSC-1533,  $12,400 \pm 160$  BP) appear reasonable, at least for the time being, with respect to the dates obtained on shells of *B. hameri* from the same area, taking into account their respective topographic and stratigraphic position.

#### Relationship to Younger Dryas

LaSalle (1966), on the basis of pollen spectra and minimum and maximum radiocarbon dates, suggested that the emplacement of the St Narcisse moraine and associated sediments were related to the Younger Dryas climatic oscillation. At that time, minimum ages were obtained on marine shells collected in the

Lac-Saint-Jean Lowlands approximately 100 km behind (north of) the moraines (Gif-400,  $10,060 \pm 350$ ; Gif-424,  $10,350 \pm 350$  BP). Maximum ages were those obtained on *B. hameri*,  $11,200 \pm 170$  (GSC-1476), collected in the glacio-marine diamicton associated with the St Nicolas readvance and the St Edouard moraine (see above). It now appears that the St Edouard moraine is more likely to mark the maximum Younger Dryas readvance and that the St Narcisse moraine is related to the same climatic oscillation and marks a halt in the retreat of the Laurentide ice.

LaSalle & Elson (1975) have suggested that north of the St Lawrence, along the north shore of the Maximum Champlain Sea, large ice tongues occupied valleys at about 11,000 BP. In the same paper emplacement of sediments now associated with the St Edouard moraine was discussed briefly. LaSalle & Elson (1975) also suggested that both the St Nicolas readvance (which formed the St Edouard moraine) and the event that emplaced the St Narcisse moraine could have had a climatic significance and might have been associated with a climatic cooling of wide significance. In view of new observations of evidence of the Younger Dryas climatic oscillation in lake sediments in the Maritime Provinces (Mott *et al.* 1986; Anderson 1988; Stea & Mott 1988, 1989) and in New Brunswick (Lamothe *et al.* 1987), it is suggested that the St Nicolas readvance, with a maximum age of approximately 11,200 BP, is also related to the same climatic episode.

Since the Younger Dryas oscillation has been recorded only in Scandinavia and in eastern Canada, but has not been reported in the continental interior of the USA, it may well be related to changes in the circulation pattern of waters in the North Atlantic Ocean, as suggested by Broecker *et al.* (1988b) and Broecker & Denton (1989). Those changes could have been caused by the shifting of cold, freshwater discharge of Lake Agassiz from the Mississippi River basin to the Great Lakes and St Lawrence River system at about 11,000 BP (Lewis *et al.* 1988; LaSalle 1989a, b). This shift is postulated to have been a result of ice retreat from the Lake Superior basin and uncovering of low, isostatically depressed outlets through Lake Nipissing into the upper Ottawa River.

## Conclusions

Rind *et al.* (1986), Broecker *et al.* (1988b), Lewis *et al.* (1988), Lewis & Anderson (1989) and Berger (1990) have discussed the possible causes of the abrupt and short Younger Dryas cool episode. Rind *et al.* (1986) and Broecker *et al.* (1988b) included the Canadian Maritime Provinces within the area where they postulated the Younger Dryas climatic fluctuation was felt on the west side of the northern Atlantic Ocean. Recent work by Stea & Mott (pers. comm. and 1988, 1989) and younger organic debris found beneath till in

central New Brunswick (Lamothe *et al.* 1987; pers. commun. 1990) further support the inference that the Younger Dryas was marked by glacial activity in northeastern North America.

We suggest that the Younger Dryas climatic fluctuation was responsible for the St Nicolas readvance (and associated features including the St Edouard moraine) and that deposition of at least some parts of the St Narcisse morainic system (LaSalle & Elson 1975) is also related to the Younger Dryas climatic fluctuation. This statement is based partly on radiocarbon dates from marine shells and partly on the position of the St Nicolas sediments within the sedimentary sequence of the Champlain Sea. Both the St Narcisse moraine and the St Edouard moraine are older than 10,200 BP because of minimum dates obtained on marine shells (Gif-400,  $10,060 \pm 350$ ; Gif-424,  $10,250 \pm 350$ ; LaSalle 1966: 128) collected near the base of the marine sedimentary sequence in the Lac-Saint-Jean Lowlands, located approximately 100 km behind (north of) the St Narcisse moraine (LaSalle 1966). It is assumed that it would take at least a few hundred years for the ice front to retreat from the position of the St Narcisse moraine to the Lac-Saint-Jean Lowlands (LaSalle 1965). Samples for GSC-4996 ( $10,200 \pm 100$  BP), GSC-4752 ( $10,400 \pm 90$  BP) and GSC-4997 ( $10,300 \pm 90$  BP) are from offlap marine sediments overlying the *Balanus*-bearing diamict. These also are minimum ages, from the Ruisseau Bourret, Saint-Edouard and Issoudun sites respectively, and tend to confirm the interpretation suggested above for the Lac-Saint-Jean shell dates. Wood collected in deltaic sediments at 12 m elevation has yielded a radiocarbon age of  $9940 \pm 230$  BP (I-3489) which is in agreement with the shell dates (Gif-400 and Gif-424) as a minimum age for the arrival of the marine waters in the Lac-Saint-Jean Lowlands. *Balanus hameri* plates collected from the diamicton associated with the St Nicolas readvance, and dating at approximately 10,900 BP (see above) provide a maximum age for the St Edouard and St Narcisse moraines. This interval of time between 10,900 and 10,300 BP fits very well with the ages conventionally assigned to the Younger Dryas climatic fluctuation as determined by Paterson & Hammer (ending at 10,750 BP; 1987: 100) and Broecker *et al.* (10,500 BP; 1988a).

The diamicton associated with the St Nicolas readvance and the St Edouard moraine has two principal textural facies: (1) a compact sand facies with a few large stones and some clay overlying sandy subaqueous outwash; (2) a dark gray, compact, calcareous facies that contains *Balanus hameri*. The compact diamicton has all the characteristics of a till sheet deposited by grounded ice and could not have been emplaced by floating icebergs. This facies also overlies sandy subaqueous outwash, but it is preferentially exposed in gravel pits where the outwash is exploited and probably overlies other sediment types elsewhere. Only at the Issoudun site have *Balanus* shell remains been observed

in the subaqueous outwash. The outwash also shows low-angle thrust faults assumed to have been caused by drag of a grounded glacier. The diamicton is assumed to be a till deposited from grounded ice by a melt-out process. The subaqueous outwash probably was deposited as fans built by meltwater debouching from tunnels at the edge of the ice front into deep, early Champlain Sea waters, but it is not possible to say whether it was deposited in front of a pre-St Edouard retreating ice front or in front of the readvancing glacier responsible for the emplacement of the St Edouard moraine. The fact that some rare *Balanus* plates have been found in the subaqueous outwash at one site (Issoudun), however, suggests that at least some of it was emplaced by the readvancing Saint-Edouard ice.

Finally, on a regional scale, in the Québec City area the surface distribution of the St Nicolas drift is poorly known because it is only well-exposed in gravel pits. However, where its presence can be demonstrated, the upper part of the Champlain Sea marine sequence above the St Nicolas drift, should start at around 11,000 BP; below it, the base of the entire Champlain Sea sequence should begin sometime around 12,400 BP (GSC-1533,  $12,400 \pm 160$  BP obtained on articulated shells of *Portlandia arctica* with periostraca still attached). The arrival of seawaters west of Québec City should then be younger than approximately 12,400 BP, when the ice barrier was still effective in the Québec City area, unless the present collection of oldest radiocarbon dates obtained on shells provides us with only minimum ages, as suggested by Karrow (1981).

Earlier readvances (Fig. 3) up the Chaudière and adjacent south shore valleys and to the Highland Front Moraine position (Blais 1989; Blais & Shilts 1989) apparently took place before the Champlain Sea penetrated as far west as the Québec City narrows. Deposits of this readvance, such as the massive subaqueous fan at Vallée-Jonction, lie above or near Champlain Sea limits but far south of the southernmost occurrence of *Balanus*-bearing diamicton. The climatic trigger for these earlier pre-12,400 BP readvances was evidently linked to a process that, while it caused a slight expansion of the eastern sector of the Laurentide ice mass, was not linked to influx of Lake Agassiz meltwaters into the North Atlantic.

**Acknowledgements.** – Discussions of some parts of the manuscript with R. McNeely of the Geological Survey of Canada and C. G. Rodrigues are gratefully acknowledged. The senior author would also like to thank the Geological Survey of Canada for radiocarbon dates obtained over the years on marine shells collected in the Québec City area. The authors are also grateful for critical and constructive comments by Dr Svante Björck.

## References

- Aitken, J. D. 1991: Two Late Proterozoic glaciations, Mackenzie Mountains, northwestern Canada. *Geology* 19, 445–448.
- Anderson, J. B. & Molnia, B. F. 1989: *Glacial-marine Sedimentation*. International Geological Congress, Washington, Short Course in Geology, 127 pp. American Geophysical Union, Washington.
- Anderson, T. W. 1988: Evidence for a late Wisconsinan climatic fluctuation in Newfoundland, Canada (abstract). *Program and Abstracts, AMQUA 10th meeting, Amherst, Massachusetts, USA* 52.
- Anderson, T. W. & Lewis, C. F. M. 1990: Stable isotope ( $\delta^{18}\text{O}$  and  $\delta^{13}\text{C}$ ) and pollen trends in sediments of eastern Lake Erie during the climatic reversal (11–10.5 ka). Abstracts, *International Symposium, Past and Present Climate Dynamics: Reconstruction of Rates of Change, Locarno, Switzerland*.
- Bard, E. 1988: Correction of accelerator mass spectrometry  $^{14}\text{C}$  ages measured in planktonic Foraminifera: paleoceanographic implications. *Paleoceanography* 3, 635–645.
- Barrette, L., LaSalle, P. & Samson, C. 1981: Québec radiocarbon measurements III. *Radiocarbon* 23, 241–251.
- Berger, W. H. 1990: The Younger Dryas cold spell – a quest for causes. *Palaeogeography, Palaeoclimatology, Palaeoecology* 89, 219–237.
- Blais, A. 1989: Lennoxville glaciation of the middle Chaudière and Etchemin valleys, Beauce Region, Québec. MSc Thesis, Carleton University, 137 pp.
- Blais, A. & Shilts, W. W. 1989: Surficial geology of Saint-Joseph-de-Beauce map area, Chaudière River Valley, Québec. *Geological Survey of Canada Paper* 89-1B, 137–142.
- Blake, W. Jr. 1984: Geological Survey of Canada radiocarbon dates XXIV. *Geological Survey of Canada Paper* 84-7, 35 pp.
- Blake, W. Jr. 1988: Geological Survey of Canada radiocarbon dates XXVII. *Geological Survey of Canada Paper* 87-7, 100 pp.
- Bousfield, E. L. 1954: The distribution and spawning seasons of barnacles on the Atlantic coast of Canada. *Bulletin of the National Museum of Canada* 136, 112–154.
- Broecker, W. S. & Farrand, W. R. 1963: Radiocarbon age of the Two Creeks forest bed, Wisconsin. *Geological Society of America Bulletin* 74, 795–802.
- Broecker, W. S. & Denton, G. H. 1989: The role of ocean-atmosphere reorganizations in glacial cycles. *Geochimica et Cosmochimica Acta* 53, 2465–2501.
- Broecker, W. S., Oppo, D., Peng, T.-H., Currey, W., Andree, M., Wolff, W. & Bonani, G. 1988a: Radiocarbon-based chronology for the  $^{18}\text{O}/^{16}\text{O}$  record for the last deglaciation. *Paleoceanography* 3, 509–515.
- Broecker, W. S., Andree, M., Wolff, W., Oeschger, H., Bonani, G., Kennett, J. & Peteet, D. 1988b: The chronology of the last deglaciation: implications to the cause of the Younger Dryas event. *Paleoceanography* 3, 1–19.
- Chauvin, L., Martineau, G. & LaSalle, P. 1985: Deglaciation of the Lower St. Lawrence region. Québec. In Borns, H. W., LaSalle, P. & Thompson, W. B. (eds.): *Late Pleistocene History of Northeastern New England and Adjacent Quebec*. Geological Society of America, Special Paper 197, 11–123.
- Colman, S. M., Pierce, K. L. & Birkeland, P. W. 1987: Suggested terminology for Quaternary dating methods. *Quaternary Research* 28, 314–319.
- Davis, M. B. 1956: Three pollen diagrams from central Massachusetts. *American Journal of Science* 256, 540–570.
- Davis, M. B. 1963: On the theory of pollen analyses. *American Journal of Science* 261, 897–912.
- Davis, M. B. 1965: Phytogeography and palynology of northeastern United States. In Wright Jr., H. E. & Frey, D. G. (eds.): *The Quaternary of the United States*, 377–401. Princeton Univ. Press, New Jersey.
- Deevey, E. S. Jr. 1949: Biogeography of the Pleistocene, Part 1, Europe and North America. *Geological Society of America Bulletin* 60, 1315–1416.
- Deevey, E. S. Jr. 1951: Late-glacial and postglacial pollen diagrams from Maine. *American Journal of Science* 249, 177–207.
- Eyles, N. & McCabe, A. M. 1989: Glaciomarine facies within subglacial tunnel valleys: the sedimentary record of glacio-isostatic down warping in the Irish sea basin. *Sedimentology* 36, 431–448.

- Faegri, K. & Iversen, J. 1964: *Textbook of Pollen Analysis*, 237 pp. Hafner, New York.
- Flint, R. F. & Deevey, E. S. Jr. 1951: Radiocarbon dating of late-Pleistocene events. *American Journal of Science* 249, 257–300.
- Goldthwait, J. W. 1911: The twenty-foot terrace and seaciff of the lower St. Lawrence. *American Journal of Science* 32, 291–317.
- Gravenor, C. P., Von Brunn, V. & DREAMANIS, A. 1984: Nature and classification of waterlain glaciogenic sediments, exemplified by Pleistocene, Late Paleozoic and Late Precambrian deposits. *Earth-Science Reviews* 20, 105–166.
- Grootes, P. 1983: Radiocative isotopes in the Holocene. In Wright, Jr., H. E. (ed.): *Late-Quaternary Environments of the United States, The Holocene*, 86–105. University of Minnesota Press, Minneapolis.
- Hillaire-Marcel, C. 1981: Palé-oceanographie isotopique des mers post-glaciaires du Québec. *Palaeogeography, Palaeoclimatology, Palaeoecology* 35, 63–119.
- Hoefs, J. 1987: *Stable Isotope Geochemistry*, 241 pp. Springer-Verlag, Heidelberg.
- Jelgersma, S. 1962: A late-glacial diagram from Madelia, South-central Minnesota. *American Journal of Science* 260, 522–529.
- Jessen, K. 1935: The composition of the forest in northern Europe in Epipalaeolithic time. *Kongelige Dansk Videnskabernes Selskab Biologiske Meddelelser* 12, No. 1, 64 pp.
- Jessen, K. & Milthers, V. 1928: Stratigraphical and palaeontological studies of interglacial fresh-water deposits in Jutland and North-west Germany. *Danmarks Geologiske Undersøgelse series 2*, No. 48, 380 pp.
- Karrow, P. F. 1981: Late-glacial regional ice-flow patterns in eastern Ontario: Discussion. *Canadian Journal of Earth Sciences* 18, 1386–1390.
- Königson, L.-K. & Possnert, G. 1988: Ancyclus faunas studied by accelerator  $^{14}\text{C}$  dating of single small shells. In Winterhalter, B. (ed.): *The Baltic Sea*. Geological Survey of Finland, Special Paper No. 6, 137–145.
- Kudrass, H. R., Erlenkeuser, H., Vollbrecht, R. & Weiss, W. 1991: Global nature of the Younger Dryas cooling event inferred from oxygen isotope data from Sulu Sea cores. *Nature* 349, 406–408.
- Lamothe, M. 1985: Lithostratigraphy and geochronology of the Quaternary deposits of the Pierreville and St-Pierre-les-Becquets area, Québec. Unpublished PhD thesis, University of Western Ontario, London, 240 pp.
- Lamothe, M., Plouffe, A. & Sacré, J. 1987: Stratigraphy, lithology and geochemistry of till in the vicinity of tin-bearing granites, Central New Brunswick, Canada (abstract). *INQUA, XIIth International Congress, Program with Abstracts* 206, Ottawa, Canada.
- LaSalle, P. 1965: Radiocarbon date from the Lake St. John area, Québec. *Science* 149, 860–862.
- LaSalle, P. 1966: Late Quaternary vegetation and glacial history in the St. Lawrence Lowlands, Canada. *Leidse Geologische Mededelingen* 38 91–128.
- LaSalle, P. 1989a: Subaqueous outwash deposits associated with the St. Nicolas glacial readvance (Younger Dryas) near Québec City, Qué., Canada. *Geological Society of America, Northeastern Section, 24th Annual Meeting, New Brunswick, New Jersey, Abstracts with Program*, 28 (abstract).
- LaSalle, P. 1989b: Stratigraphy and glacial history of Québec City Region. In LaSalle, P. (ed.): *Guidebook, Friends of the Pleistocene, 52nd Annual Reunion*, Québec City, Québec Department of Transport, 27–70.
- LaSalle, P. & Chapdelaine, C. 1990: Review of late-glacial and Holocene events in the Champlain and Goldthwait Seas areas and arrival of man in eastern Canada. In Lasca, N. P. & Donahue, J. (eds.): *Archaeological Geology of North America*. Boulder, Colorado, Geological Society of America, Centennial Special Volume 4, 1–9.
- LaSalle, P. & Elson, J. A. 1975: Emplacement of the St. Narcisse moraine as a climatic event in eastern Canada. *Quaternary Research* 5, 621–625.
- LaSalle, P., Hardy, L. & Poulin, P. 1972: An ice frontal position in the northwest part of the Parc des Laurentides, and northeast of Québec City. *Québec Department of Natural Resources Report S-135*, 8 pp.
- LaSalle, P., Martineau, G. & Chauvin, L. 1977: Morphology, stratigraphy and deglaciation in Beauce-Notre-Dame Mountains-Laurentide Park area. *Ministère des Richesses Naturelles du Québec DPV-516*, 74 pp.
- Lehman, S. J. & Keigwin, L. D. 1992: Sudden changes in North Atlantic circulation during the last glaciation. *Nature* 356, 757–762.
- Leopold, E. B. 1956: Two late-glacial deposits in southern Connecticut. *National Academy of Science Proceedings* 42, 863–867.
- Lewis, C. F. M., Anderson, T. W. & Miller, A. A. L. 1988: Lake, ocean and climate response to meltwater discharge, Great Lakes and western Atlantic Ocean (abstract). In *Program and Abstracts, AMQUA 10th Meeting, Amherst, Massachusetts*, 81.
- Lewis, C. F. M. & Anderson, T. W. 1989: Oscillations of levels and cool phases of the Laurentian Great Lakes caused by inflows from glacial Lakes Agassiz and Barlow-Ojibway. *Journal of Paleolimnology* 2, 99–146.
- Livingstone, D. A. & Livingstone, B. G. R. 1958: Late-glacial and post-glacial vegetation from Gillis Lake in Richmond County, Cape Breton Island, Nova Scotia. *American Journal of Science* 256, 341–359.
- Lowdon, J. A. & Blake, W. Jr. 1973: Geological Survey of Canada radiocarbon dates XIII. *Geological Survey of Canada Paper* 73-7, 61 pp.
- Lowdon, J. A. & Blake, W. Jr. 1975: Geological Survey of Canada radiocarbon dates XV. *Geological Survey of Canada Paper* 75-7, 32 pp.
- Lowdon, J. A. & Blake, W. Jr. 1976: Geological Survey of Canada radiocarbon dates XVI. *Geological Survey of Canada Paper* 76-7, 21 pp.
- Lowdon, J. A. & Blake, W. Jr. 1979: Geological Survey of Canada radiocarbon dates XIX. *Geological Survey of Canada Paper* 79-7, 58 pp.
- MacClintock, P. & Terasmae, J. 1960: Glacial history of Covey Hill. *Journal of Geology* 68, 232–241.
- Mangerud, J. & Gulliksen, S. 1975: Apparent radiocarbon age of Recent marine shells from Norway, Svalbard and Ellesmere Island. *Quaternary Research* 5, 263–273.
- McCabe, A. M., Dardis, G. F. & Hanvey, P. M. 1984: Sedimentology of a Late Pleistocene submarine moraine complex, County Down, northern Ireland. *Journal of Sedimentary Petrology* 54, 716–730.
- McCabe, A. M., Dardis, G. F. & Hanvey, P. M. 1987: Sedimentation at the margins of a late Pleistocene ice-lobe terminating in shallow marine environments, Dundalk Bay, eastern Ireland. *Sedimentology* 34, 473–493.
- McNeely, R. 1989: Geological Survey of Canada radiocarbon dates XXVIII. *Geological Survey of Canada Paper* 88-7, 93 pp.
- McNeely, R. & McCuaig, S. 1991: Geological Survey of Canada radiocarbon dates XXIX. *Geological Survey of Canada Paper* 89-7, 134 pp.
- Molnia, B. F. 1989: Definitions and controlling factors of glacial-marine sediment and the glacio-marine sedimentary environment. In *Glacial Marine Sedimentation*, 3–4. Short Course in Geology, American Geophysical Union, Washington.
- Morgan, A. V. 1987: Late Wisconsin and early Holocene paleoenvironments of east-central North America based on assemblages of fossil Coleoptera. In Ruddiman, W. F. & Wright, H. E., Jr. (eds.): *North America and Adjacent Oceans during the Last Deglaciation*, Volume K-3, 353–370. Geological Society of America, The Geology of North America, Boulder, Colorado.
- Morgan, A. V., Morgan, A., Ashworth, A. C. & Matthews, J. V. Jr. 1983: Late Wisconsin fossil beetles in North America. In Wright, Jr., H. E. (ed.): *Late-Quaternary Environments of the United States, the Late Pleistocene*, 354–363. University of Minnesota Press, Minneapolis.

- Mott, R. J., Anderson, T. W. & Matthews, J. V. Jr. 1981: Late-Glacial paleoenvironments of sites bordering the Champlain Sea based on pollen and macro-fossil evidence. In Mahaney, W. C. (ed.): *Quaternary Palaeoclimate*, 129–171. GeoAbstracts, Norwich.
- Mott, R. J., Grant, D. R., Stea, R. & Occhietti, S. 1986: Late-glacial climatic oscillation in Atlantic Canada equivalent to the Allerød/Younger Dryas event. *Nature* 123, 247–250.
- Movius, H. L. 1942: *The Irish Stone Age. Its Chronology, Development and Relationships*, 339 pp. Cambridge University Press, Cambridge.
- Ogden, J. G. III 1959: A late-glacial pollen sequence from Martha's Vineyard, Massachusetts. *American Journal of Science* 257, 366–381.
- Parent, M. & Occhietti, S. 1988: Late Wisconsinan deglaciation and Champlain Sea invasion in the St. Lawrence Valley, Québec. *Géographie Physique et Quaternaire* 42, 215–246.
- Paterson, W. S. B. & Hammer, C. V. 1987: Ice core and other glaciological data. In Ruddiman, W. F. & Wright, H. E. Jr. (eds.): *North America and Adjacent Oceans During the Last Deglaciation*, Volume K-3, 91–109. Geological Society of America, the Geology of North America, Boulder, Colorado.
- Peteet, D. M., Vogel, J. S., Nelson, D. E., Southon, J. R., Nickmann, R. J. & Heusser, L. E. 1990: Younger Dryas climatic reversal in northeastern USA? AMS ages for an old problem. *Quaternary Research* 33, 219–230.
- Prichonnet, G. 1988: Glacial marine facies of the late Wisconsinan Champlain Sea (southern Quebec). In Gadd, N. R. (ed.): *The Late Quaternary Development of the Champlain Sea Basin*. Geological Association of Canada, Special Paper 35, 91–105.
- Rind, D., Peteet, D., Broecker, W., McIntyre, A. & Ruddiman, W. 1986: The impact of cold North Atlantic sea surface temperatures on climate: implications for the Younger Dryas cooling (11–10 ka). *Climate Dynamics* 1, 3–33.
- Rodrigues, C. G. 1987: Late Pleistocene invertebrate macrofossils, microfossils and depositional environments of the western basin of the Champlain Sea. *Geological Survey of Canada Paper* 86-23, 16–23.
- Rodrigues, C. G. 1988: Late Quaternary invertebrate faunal associations and chronology of the western Champlain Sea basin. In Gadd, N. R. (ed.): *The Late Quaternary Development of the Champlain Sea Basin*. Geological Association of Canada, Special Paper 35, 155–176.
- Rodrigues, C. G. 1992: Successions of invertebrate microfossils and the late Quaternary deglaciation of the central St. Lawrence Lowland, Canada and United States. *Quaternary Science Reviews* 11, 503–534.
- Rodrigues, C. G. & Richard, S. H. 1985: Temporal distribution and significance of late Pleistocene fossils in the western Champlain Sea basin, Ontario and Quebec. In *Current Research, Part B, Geological Survey of Canada Paper* 85-1B, 401–411.
- Rodrigues, C. G. & Richard, S. H. 1986: An ecostratigraphic study of the late Pleistocene sediments of the western Champlain Sea basin Ontario and Quebec. *Geological Survey of Canada Paper* 85-22, 33 pp.
- Rust, B. R. 1977: Mass flow deposits in a quaternary succession near Ottawa, Canada: diagnostic criteria for subaqueous outwash. *Canadian Journal of Earth Sciences* 14, 175–184.
- Rust, B. R. & Romanelli, R. 1975: Late Quaternary subaqueous outwash deposits near Ottawa, Canada. In Jopling, A. V. & McDonald, B. C. (eds.): *Glaciofluvial and Glaciolacustrine Sedimentation*, Society of Economic Paleontologists and Mineralogists, Special Publication 23, 177–192.
- Samson, C., Barrette, L., LaSalle, P. & Fortier, J. 1977: Quebec radiocarbon measurements I. *Radiocarbon* 19, 96–100.
- Smith, S. L. & Shilts, W. W. 1987: Quaternary stratigraphy of Noire River cores, Beauceville area, Quebec. *Geological Survey of Canada Paper* 87-1A, 159–167.
- Stea, R. R. & Mott, R. J. 1988: Events of the late Wisconsinan–Holocene transition in Nova Scotia. *Geological Society of America, Northeastern Section, 23rd Annual Meeting, Portland, Abstracts with Program*, 72.
- Stea, R. R. & Mott, R. J. 1989: Deglaciation environments and evidence for glaciers of Younger Dryas age in Nova Scotia, Canada. *Boreas* 18, 169–187.
- Thwaites, F. T. & Bertrand, K. 1957: Pleistocene geology of the Door Peninsula, Wisconsin. *Geological Society of America, Bulletin* 68, 831–880.
- Veum, T., Jansen, E., Arnold, M., Beyer, L. & Duplessy, J.-C. 1992: Water mass exchange between the North Atlantic and the Norwegian Sea during the past 28,000 years. *Nature* 356, 783–785.
- Wagner, F. J. E. 1970: Faunas of the Pleistocene Champlain Sea. *Geological Survey of Canada Bulletin* 181, 104 pp.
- West, R. G. 1961: Late- and Postglacial vegetational history in Wisconsin, particularly changes associated with the Valdres readvance. *American Journal of Science* 259, 766–783.
- Wright, H. E. Jr., Winter, T. C. & Pattern, H. L. 1963: Two pollen diagrams from south eastern Minnesota; problems in the regional and postglacial vegetation history. *Geological Society of America, Bulletin* 74, 1371–1399.