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

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Occurrences of Balanus hameri-bearing diamicts described in this paper and pertinent (Balanus plates and pelecypods shells) ¹⁴C 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.

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The presence of till-like diamicton 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 diamicton 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 ± 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 [In Parent & Occhietti (1988: 230), Occhietti is quoted as the collector for GSC-1476 and the date is also quoted as unpublished (Lowdon & Blake 1979)].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 diamicton (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 diamicton 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 ± 160 BP (LaSalle et al. 1972; Lowdon & Blake 1976); (2) Lapointe (Fig. 1) GSC-1295, 11,200 ± 160 BP (LaSalle et al. 1972; Lowdon & Blake 1976). Two new sites exposing Balanus-bearing diamictons 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 ± 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 (diamicton 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 diamictons 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 diamictons contain abundant fossil fragments and striped 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 diamictons 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 Hiarella 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 diamicton 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 diamicton 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 diamicton 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 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 Valders 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 Valders 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 Valders 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 diamictons (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 diamictons interpreted as till and was visited by numerous geoscientists around the time of the International Geological Congress in Montreal in 1972. At this site a date of 11,200 ± 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 ± 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 macro-fossils. 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 ± 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-Édouard-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 Édouard moraine (Figs. 2 and 3). East and southeast 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-Édouard-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 ± 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).
diamicton exposed at this site. As at other nearby sites, the diamicton 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 Balamus 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 Balamus-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 *Hiatella arctica*. Those shells have been radiocarbon dated at 10,300 ± 90 BP (GSC-4997). This is obviously a minimum age for the emplacement of the *Balamus*-bearing diamicton. 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 diamicton at two of three pits that expose it along Ruisseau Bourret. Erratics in the diamicton comprise c. 75% local Paleozoic carbonate clasts and about 25% Precambrian metamorphic rocks that crop out 25 km north of the sections. The diamictons 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 *Balamus*-bearing diamicton 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 ± 100 BP (GSC-4996), which is also a minimum age for the emplacement of the *Balamus*-bearing diamicton.

*Summary section: Rivièr du Chêne, Section 3.* – Section 3 (Fig. 5) is located about 3 km southwest of Saint-Edouard, on the west bank of Rivièr du Chêne (Fig. 2). It shows a sequence that is a good summary (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 Rivièr 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 Rivièr 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 Rivièr 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 δ13C value have been brought to a δ13C 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 ± 160 BP (McNeely 1989: 20) and GSC-4804, 11,000 ± 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 ± 160 BP) is consistent with the accelerator date obtained on the Clayton collection (TO-245, 12,180 ± 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 ± 100 BP, inner fraction; 12,800 ± 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 21J/12), but is apparently absent west of the point along the
Table 1. Published radiocarbon dates obtained on *Balanus haueri* collected from Champlain Sea sediments, except where mentioned otherwise in the Laboratory No. column.

<table>
<thead>
<tr>
<th>Name of site</th>
<th>Elevation m a.s.l.</th>
<th>Laboratory No.</th>
<th>¹⁴C age BP</th>
<th>δ¹³C</th>
<th>Reference</th>
</tr>
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<tbody>
<tr>
<td>Bearbrook</td>
<td>67</td>
<td>GSC-3983</td>
<td>10,700 ± 130</td>
<td>−0.9</td>
<td>Rodrigues 1988; Rodrigues 1987;</td>
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<td></td>
<td></td>
<td>TO-698</td>
<td>10,800 ± 90</td>
<td>−0.2</td>
<td>Rodrigues &amp; Richard 1985</td>
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<tr>
<td>Chevalier</td>
<td>106</td>
<td>GSC-1232</td>
<td>10,300 ± 90</td>
<td>−0.9</td>
<td>Rodrigues 1992</td>
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<tr>
<td>Crysler</td>
<td>69</td>
<td>GSC-4043</td>
<td>10,200 ± 110</td>
<td>0.0</td>
<td>Rodrigues 1988; Blake 1988</td>
</tr>
<tr>
<td>Herbert Corners</td>
<td>93</td>
<td>GSC-4113</td>
<td>10,200 ± 120</td>
<td>0.8</td>
<td>Rodrigues 1988; Blake 1988</td>
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<tr>
<td>Issoudun</td>
<td>80</td>
<td>GSC-4998</td>
<td>11,400 ± 90</td>
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<tr>
<td>Lapointe</td>
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<td>GSC-1295</td>
<td>11,200 ± 160</td>
<td>0.6</td>
<td>This paper</td>
</tr>
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<td>GSC-4804</td>
<td>11,000 ± 120</td>
<td>+0.6</td>
<td>Lowdon &amp; Blake 1976</td>
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<tr>
<td>Saint-Césaire</td>
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<td>TO-704</td>
<td>10,970 ± 60</td>
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<td>Rawdon</td>
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<td>−0.1</td>
<td>Prichonnet 1988</td>
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<td>Saint-Alban</td>
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<td>McNeely 1989;</td>
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<tr>
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<td>11,200 ± 170</td>
<td>0.7</td>
<td>Lowdon &amp; Blake 1979</td>
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<td>Morigeau</td>
<td>70</td>
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<td>10,900 ± 150</td>
<td>0.6</td>
<td>Barrette <em>et al.</em> 1981</td>
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<tr>
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<td>9.580 ± 80</td>
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<td>Navan</td>
<td>93</td>
<td>GSC-3706</td>
<td>11,000 ± 90</td>
<td>1.4</td>
<td>Rodrigues &amp; Richard 1986; Blake 1984</td>
</tr>
<tr>
<td>Dorn(e) I</td>
<td>106</td>
<td>GSC-4468</td>
<td>10,900 ± 120</td>
<td>−0.9</td>
<td>McNeely &amp; McCuaig 1991</td>
</tr>
<tr>
<td>Sainte-Thérèse-en-haut</td>
<td>64</td>
<td>GSC-1805</td>
<td>11,300 ± 140</td>
<td>0.7</td>
<td>Lowdon &amp; Blake 1975</td>
</tr>
<tr>
<td>Twin Elm</td>
<td>97</td>
<td>GSC-4052</td>
<td>10,800 ± 110</td>
<td>0.7</td>
<td>Rodrigues 1988</td>
</tr>
<tr>
<td>Rivière Beaudette</td>
<td>56</td>
<td>GSC-3702</td>
<td>11,000 ± 90</td>
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<td>Rodrigues &amp; Richard 1985</td>
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<tr>
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<td>80</td>
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<td>11,200 ± 150</td>
<td>−0.6</td>
<td>McNeely &amp; McCuaig 1991</td>
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<td>Rigaud</td>
<td>28</td>
<td>GSC-4112</td>
<td>11,100 ± 130</td>
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<td>Rodrigues 1988</td>
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<td>−1.1</td>
<td>Rodrigues 1988</td>
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<tr>
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<td>GSC-1712</td>
<td>11,100 ± 150</td>
<td>+2.2</td>
<td>Lowdon &amp; Blake 1979</td>
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<td>Moulin à Baude</td>
<td>100</td>
<td>GSC-1500</td>
<td>9,820 ± 150</td>
<td>0.0</td>
<td>Lowdon &amp; Blake 1973</td>
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<td>Saint-Nicolas</td>
<td>44</td>
<td>GSC-1500</td>
<td>9,820 ± 150</td>
<td>0.0</td>
<td>Lowdon &amp; Blake 1973</td>
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<td>Pointe Saint-Nicolas</td>
<td>57</td>
<td>UQ-98</td>
<td>11,340 ± 180</td>
<td>0.7</td>
<td>Parent &amp; Occhietti 1988</td>
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<td>11,120 ± 220</td>
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<td>Parent &amp; Occhietti 1988</td>
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<td>Deschaillons</td>
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<td>GSC-4996</td>
<td>10,200 ± 90</td>
<td>0.7</td>
<td>Parent &amp; Occhietti 1988</td>
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<td>Rousseau Bourret</td>
<td>68</td>
<td>GSC-4996</td>
<td>10,300 ± 90</td>
<td>0.7</td>
<td>Parent &amp; Occhietti 1988</td>
</tr>
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<td>Issoudun</td>
<td>90</td>
<td>GSC-4997</td>
<td>10,400 ± 90</td>
<td>−2.3</td>
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<tr>
<td>Saint-Edouard</td>
<td>38</td>
<td>GSC-4752</td>
<td>10,400 ± 90</td>
<td>−2.3</td>
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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 haueri*, 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. haueri* was the only species present in the Champlain Sea in numbers large enough to dominate the fossil record in glacially re-worked 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. haueri* 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. haueri* 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 Quebec 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 Quebec 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 Quebec 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 Quebec 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 ± 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 ± 160 BP (GSC-1235) and 12,400 ± 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 pectenoids (e.g. TO-245, 12,180 ± 90 BP) collected in littoral sediments near the marine limit also in the western part of the Champlain Sea. Northwest of Quebec 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 Quebec City area, the oldest dates (LaSalle et al. 1977; Chauvin et al. 1985) obtained on shells of pectenoids (GSC-1235, 11,600 ± 160 BP and GSC-1533, 12,400 ± 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 ± 350; Gif-424, 10,350 ± 350 BP). Maximum ages were those obtained on B. hameri, 11,200 ± 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 ± 350; Gif-424, 10,250 ± 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 ± 100 BP), GSC-4752 (10,400 ± 90 BP) and GSC-4997 (10,300 ± 90 BP) are from offshore marine sediments overlying the Balanus-bearing diamicrt. 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 ± 230 BP (1-3489) 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 \( ^{14} \text{C} \)) 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.

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