# Reports

## Early Deglaciation of the Labrador Shelf

Abstract. *Two marine sediment cores from a basin on the southeastern Labrador Shelf penetrate a mud sequence extending back to 21,000 carbon-14 years before the present (B.P.). The benthic foraminifera are dominated by subartic nearshore species indicative of ice-free summer waters. The pollen record indicates the presence of a sedge-shrub tundra in eastern Labrador as early as 21,000 years B.P. Both sources of evidence suggest less extensive continental ice than has previously been reported for this subarctic region.*

Physiographic and sedimentary evidence for glaciation of the Labrador Shelf is well preserved, and it has been suggested that continental ice was present in the Late Wisconsinan (*1*). However, the excellent preservation of submarine glacial features could also be due to the water depth (several hundred meters) on the shelf, resulting in a limited reworking of sediment during periods of changing Pleistocene sea levels. On the basis of evidence from sediment cores, we believe that an ice-free ocean may have occurred as early as 22,000 years before the present (B.P.) and spanning the time of maximum ice extent on the Labrador Shelf off Hamilton Inlet in eastern Canada.

According to Pleistocene paleoceanographic models, the extent of open water in the Labrador Sea during various glacial stages is largely dependent on the circulation patterns of the North Atlantic (*2*). The present interglacial is characterized by the entrance of saline and warm Atlantic water into the Labrador Sea by way of the West Greenland Current (*3*). During the Wisconsin glacial maximum, a closed cyclonic polar water gyre dominated Atlantic latitudes north of 45°N (*4*), preventing the penetration of warm water to the north. On the basis of evidence in sediment cores from the North Atlantic, it has been proposed that the polar gyre existed as late as 9300 years B.P. (*5*). Climate: Long-Range Investigation, Mapping, and Prediction (CLIMAP) reports indicate that at 18,000 years B.P. the margin of the ice field in summer followed approximately a line from the southern tip of Greenland to the Grand Banks of Newfoundland (*6*). Although direct evidence is lacking, these reports (*6*) imply that the Labrador Sea was locked in year-round polar ice.

Indirect evidence from terrestrial records has also been used to describe a possible history of deglaciation on the Labrador Shelf in the area of Hamilton Inlet. On the basis of $^{14}C$ dates from raised marine deposits and estimates of postglacial revegetation of coastal Labrador, the time interval of 8000 to 10,000 years B.P. was suggested as the most likely for final deglaciation of the shelf (*1*). According to this model, basins on the Labrador Shelf remained blocked by thick lobes of grounded ice from coastal glaciers until shortly before deglaciation of the coastline.

This hypothetical chronology of the extent and rate of retreat of the Late Wisconsinan ice margin does not agree with our evidence in marine sediment cores collected from Cartwright Saddle, Labrador Shelf (54°37.7′N, 56°12.6′W) (Fig. 1). Two cores are discussed here; core 11 was taken at a water depth of 577 m and core 12 at 495 m. The distance between the cores is 5 km. Samples for pollen analysis were processed according to the recommended method for Holocene marine sediments, except that we used *Lycopodium* spore tablets instead of the weighing method for estimating "absolute" pollen concentrations (*7*). In order to facilitate comparison with terrestrial pollen stratigraphies for this region, pollen percentages were based on a sum of 200 grains excluding sedge, heath, and sphagnum. Relative pollen data are plotted in Fig. 2 as cumulative curves combining spruce, birch-alder, and sedge-willow-sphagnum, with the remainder representing for the most part herbs but also including minor amounts of exotic tree pollen. Figure 2 also displays the total pollen concentrations and the absolute numbers of willow (*Salix*) pollen in grains per gram of sediment (dry weight).

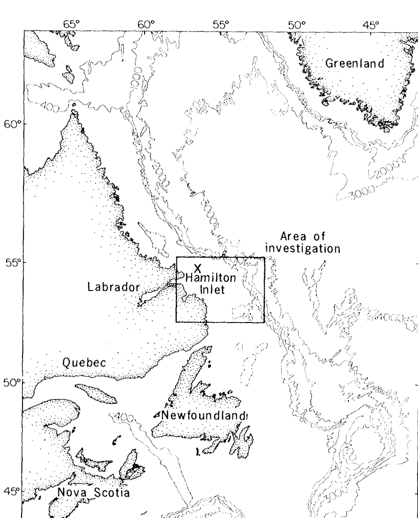


Fig. 1. Index map of the Labrador Shelf area; X, coring site. Bathymetry is in meters.

Radiocarbon dates were obtained from the total organic matter preserved in the sediments (Table 1). The line of linear regression between $^{14}C$ dates and core intervals at which these dates were determined (Fig. 2) is considered to represent the best estimate of the age of the sediment between 800 cm and the surface (*8*). The age at about 720 cm below the surface in both cores is estimated as 22,000 years B.P.

The sediment consists of fine silty clay throughout the cores. Below 500 cm, representing approximately 13,000 years B.P., the benthic foraminifera are dominated by *Elphidium clavatum* (Williamson) with a few other inner-shelf species, such as *Islandiella islandica* (Norvang). The rate of sedimentation in this interval is approximately 25 cm per 1000 years.

Two sandy beds between 125 and 500 cm have a greater benthic foraminiferal diversity and a decreased percentage of *E. clavatum*. This material was deposited between about 13,000 and 5000 years B.P., suggesting a twofold to threefold increase in sedimentation rates. During the last 4000 to 5000 years, the sedimentation rate is uncertain because of the possible loss of up to 25 cm of surface sediment during coring.

Planktonic foraminifera in these cores are represented only by the sinistrally coiled *Neogloboquadrina pachyderma* with very few occurrences of *Globigerina bulloides* and *G. quinqueloba*. The number of planktonic tests per sample decreases at the same level at which the benthonic species decrease in diversity.

*Elphidium clavatum* is an arctic-subarctic nearshore species that is found in waters free of summer ice (*9, 10*). *Neogloboquadrina pachyderma* occurs in reduced numbers under polar pack ice (*10*) and in waters of intermittent ice cover of the Canadian Arctic Archipelago (*11*).


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The production of *N. pachyderma* may be high seasonally in waters outside the nearshore influence of the Labrador Current and along the margins of polar pack ice (*11, 12*).

The dominance of *E. clavatum* in our sediments indicates the presence of open water, at least during the summer. The marine environment was marginal with a limited offshore influence, according to the low diversity of benthic species and low numbers of *N. pachyderma*. The total number of benthic foraminifera is not lower than at present, and large concentrations of methane in sediment below about 600 cm (*13*) suggest a high production of organic matter during that time. The modern equivalent sub-ice environment under the Ross Sea Shelf in Antarctica does not show evidence of living invertebrates (*14*).

The location of Cartwright Saddle is highly favorable for the accumulation of a continuous regional pollen record for central Labrador because of its proximity (70 km) to the coastal entrance of a large river, Churchill River, with a drainage area of 79,000 km$^2$ (*15*). Palynomorphs are well preserved throughout core 12, and, although the pollen concentrations are typically one to two orders of magnitude lower than those of Labrador lake sediments, the numbers are sufficiently high to permit a meaningful interpretation of changing relative pollen frequencies.

Table 1. Carbon-14 dates for cores 11 and 12; GX sample numbers were analyzed by Geochron, and GSC sample numbers were analized by the Geological Survey of Canada.

| Interval (cm) | Age ($^{14}$C years B.P.) | Laboratory number |
|---|---|---|
| | *Core 11* | |
| 65–100 | 3,370 ± 160 | GX-4942 |
| 465–475 | 11,700 ± 490 | GSC-2560 |
| 500–535 | 13,140 ± 440 | GX-5074 |
| 700–735 | 21,050 ± 1050 | GX-4944 |
| | *Core 12* | |
| 50–85 | 3,320 ± 165 | GX-4935 |
| 490–500 | 13,300 ± 770 | GSC-2565 |
| 615–650 | 19,660 ± 710 | GX-5075 |

Three major floral episodes are recognized in core 12. First, northern boreal forest during the last 6500 years is recorded in the upper 175 cm by high relative frequencies of spruce (*Picea*) pollen, 40 to 70 percent, and large absolute pollen concentrations (APC). This episode can be matched with the development and expansion of spruce forest or woodland recorded in Labrador lake sediments, beginning about 5000 years B.P. (*16, 17*). The decline in spruce and the concomitant expansion of forest tundra (*Betula* plus *Alnus*) recorded in the upper 50 cm of core 12 appear to be coeval with the reversal toward colder, drier climatic conditions shown for the past 3000 or 2000 years at lake sites north of Hamilton Inlet (*17*).

The second major floral episode is marked by a shrub-tundra association, recorded in the dominance of birch and alder pollen (40 to 60 percent) between 175 and 300 cm. This event begins about 8000 years B.P. and can be correlated with a similar episode recorded in coastal lake sites during the same time interval (*16, 17*).

The third floral episode is a sedge-shrub-tundra period recorded in the lower part of core 12 by a dominance of dwarf shrub and herb elements, predominantly *Salix*, Cyperaceae, and *Sphagnum*, with variable amounts of Gramineae, Rosaceae, Saxifragaceae, and Ericaceae. This episode corresponds with a fivefold decrease in APC compared to the shrub-tundra episode and indicates the continuous regional presence of tundra vegetation from as early as 21,000 years B.P. This episode matches that recorded in coastal lakes between 10,300 and 7000 years B.P. (*16, 17*), but the marine tundra record differs from the terrestrial record in its much greater duration.

Thus, there is a strong correlation between the marine and upland pollen

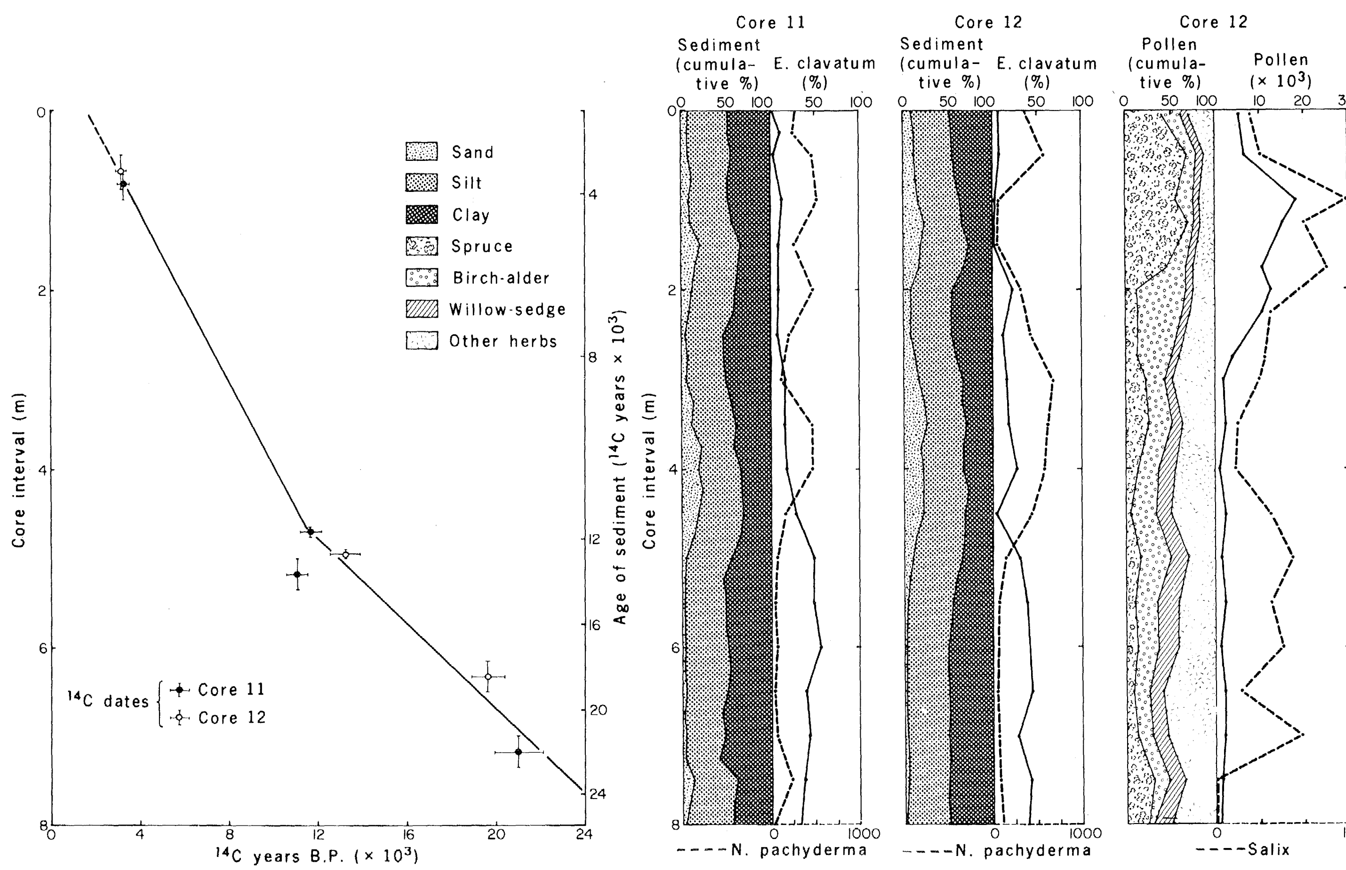


Fig. 2. Carbon-14 dates, sediment texture, percentage of *Elphidium clavatum*, and the total numbers of *Neogloboquadrina pachyderma* per 35 cm$^3$ of sediment in cores 11 and 12. Pollen profiles are from core 12 only.

stratigraphies for this region throughout the time interval represented in the upland sites. In the lake cores, the tundra episode is only clearly recorded down to the top of highly inorganic sediments dated about 10,300 years B.P., although it is possible that longer lake cores would yield older tundra records. In contrast, the lower part of the marine stratigraphy registers the continuous presence of sedge-shrub-tundra vegetation to at least 21,000 years B.P. The fact that the total pollen concentration during this floral episode rarely falls below one-third of the modern values of 5000 grains per gram (dry weight) suggests the proximity of densely vegetated areas. Good evidence for a regional vegetation source of pollen is the persistently high amounts of *Salix* pollen at the marine site; this pollen type is not adapted for long-distance transport by air and is one of the least corrosion-resistant pollen types (*18*); hence, it is unlikely to survive reworking from older sediment. Thus there is strong evidence in the marine pollen stratigraphy to support the following hypothesis. Cartwright Saddle remained a seasonally open-water depositional environment during the Late Wisconsinan. Extensive areas of tundra vegetation were located within 100 km of the marine basin throughout this time, probably including much of the inner continental shelf above 100 m (present water depth) as well as the Labrador mainland nunatak and coastal refuges proposed by Ives (*19*).

Thus, foraminiferal evidence in the Cartwright Saddle sediment indicates open-water conditions during the past 22,000 years and the pollen spectrum indicates the continuous regional presence of terrestrial vegetation during this time. The almost exclusively arctic-subarctic foraminifera suggest that the open water was not due to the influx of warmer currents. Therefore, seasonal removal of the sea ice probably took place by processes similar to present-day conditions; that is, the ice cover broke in summer and was driven by winds toward the Atlantic. Lack of ice-rafted sediment in the cores precludes local melting. The fact that fast continental ice was not present in the basin suggests that the last glacial event in this region was not extensive.

The limit of the Wisconsinan ice along the northeast Canadian coast is controversial. An extended limit along the coast [for example, (*20*)] is disputed on the basis of field studies, which indicate that some of the coastal highlands on Baffin Island and Labrador were not overrun by the last episode of continental ice (*21*). Marine sediments contain well-preserved evidence of glacial history, as demonstrated by the CLIMAP team (*22*) in the North Atlantic and our cores on the continental shelf. It is possible that sediments in small basins of the shelf contain the necessary information to settle the controversy of the Wisconsinan ice limits and to assist the work of CLIMAP by providing boundary information for paleoclimatic synthesis in the North Atlantic.

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8. The possibility that the $^{14}C$ dates from the lower sections of our cores may be spuriously old as a result of dilution by ancient carbon cannot be ignored, as a 10 percent error in an age of about 20,000 $^{14}C$ years is not uncommon in marine sediments. However, recent testing of the $^{14}C$ time scale against magnetic and $^{230}Th$ dating methods [M. Stuiver, *Nature (London)*, in press] points toward an enhancement of atmospheric $^{14}C$ between 9000 and 25,000 years B.P., yielding a maximum error of 2000 years (too young) for the radiocarbon dates. Thus it appears that, in the time range of our older $^{14}C$ dates, the two major sources of error (old carbon versus enhanced atmospheric $^{14}C$) should approximately cancel out. Recently we have obtained additional $^{14}C$ dates that gave a correlation coefficient between core intervals and ages of .884 ($N = 9$) and a date close to 21,000 years B.P. Good correlation indicates limited reworking of old organic matter and improves one's confidence in the $^{14}C$ dates.
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## Carbon Flow in Four Lake Ecosystems: A Structural Approach

Abstract. *Direct and indirect carbon fluxes in lakes Marion (British Columbia), Findley (Washington), Wingra (Wisconsin), and Mirror (New Hampshire) are compared, using budgets and input-output analysis. Overall differences in carbon flow between the lakes are shown with cycling indices of .031, .108, .572, and .661, respectively. The results suggest that lake ecosystems may be considered unique aggregations of similar components.*

Lakes receive inputs from surface runoff, groundwater, and airborne materials. Their trophic status may fluctuate in response to changes in inputs of carbon and nutrients from their watershed due to disturbances such as those caused by logging, fertilization, or urbanization (*1*). These changes in carbon and nutrient input have traditionally been considered in terms of their effects on the primary trophic level—in particular on phytoplankton photosynthetic activity, planktonic community structure, and physiochemical factors influencing the biota. However, comprehensive analyses tracing inputs and subsequent metabolic effects throughout a lake ecosystem are rare (*2*). In this report we compare four such studies in an effort to evaluate differences in carbon cycling between lakes. The purpose of this comparative analysis is to gain insights unavailable in site-specific research and to provide a basis for developing hypotheses concerning factors that regulate ecosystem structure.

The lakes included in this comparison are Findley Lake, an oligotrophic subalpine lake in the coniferous forest of the Cascade Mountains, Washington; Marion Lake, an oligotrophic lake on the mild wet Pacific coast of southern British Columbia; Mirror Lake, an oligotrophic lake surrounded by deciduous and coniferous forests in New Hampshire; and Lake Wingra, a marl-eutrophic lake receiving urban drainage in Madison, Wisconsin (Table 1). The lakes are similar in size, climate, and altitude, except Findley Lake, which is at a higher elevation


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