Géographie physique et Quaternaire

# Climatic Influences of Deglacial Drainage Changes in Southern Canada at 10 to 8 ka Suggested by Pollen Evidence

# L'influence des changements de débit d'eau de fonte sur le climat du sud du Canada entre 10 et 8 ka, à partir des données polliniques.

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Résumé de l'article

L'augmentation du débit de l'eau de fonte provenant des lacs glaciaires Agassiz et Barlow-Ojibway de 9,6 à 8 ka BP a engendré des micro-climats froids au-dessus des nappes d'eau en aval : le Lac Minong, les lacs de la phase de Mattawa, dans les Grands Lacs, et la Mer de Goidtwaith, dans le golfe du Saint-Laurent. L'effet refroidissant du drainage de l'eau de fonte a entravé le réchauffement estival de la surface des eaux lacustres, écourté la saison végétative et ainsi modifié la composition de la végétation des terres environnantes. La réponse de la végétation a été variable comme l'indiquent les cinq types de déviation (anomalies polliniques) par rapport à la succession pollinique normale. Les anomalies sont plus importantes là où l'effet de l'augmentation du débit de l'eau de fonte a été plus prononcé, notamment près des limites des nappes d'eau touchés ou de leurs zones, surtout près des écotones. L'influence climatique a été très limitée ou nulle là où les surfaces aquifères étaient réduites, comme celles des cours de l'Outaouais et du Saint-Laurent. Le détournement de l'écoulement des lacs Agassiz et Barlow-Ojibway vers la mer d'Hudson après 8,4 ka BP a rétabli le réchauffement estival des eaux de surface du réseau des Grands Lacs et du Saint-Laurent, mettant ainsi fin à la période froide qui a prévalu de 9,6 à 8 ka.

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# CLIMATIC INFLUENCES OF DEGLACIAL DRAINAGE CHANGES IN SOUTHERN CANADA AT 10 TO 8 KA SUGGESTED BY POLLEN EVIDENCE*

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ABSTRACT Enhanced meltwater discharge from proglacial lakes Agassiz and Barlow-Ojibway at about 9.6 to 8.3 ka BP. created cold localized climates over downstream water bodies, specifically Lake Minong and Mattawa phase lakes in the Great Lakes and Goldthwait Sea in the Gulf of St. Lawrence. The cooling effect of the meltwater drainage suppressed summer warming of the surface lake waters, reduced the growing season and thus altered the vegetation composition in the surrounding land areas. The vegetation responded in different ways as evidenced by five variants from the normal pollen succession.The pollen anomalies are most pronounced where the effect of increased meltwater discharge had a strong influence, such as within or along the margins of Lake Agassiz, Mattawa phase lakes, and the Goldthwait Sea, or in their lee areas, especially where these water bodies intersected ecotonal boundaries. Climatic effects were minimal or non-existent where the water surface areas were restricted such as the channelized drainage routes of the Ottawa and St. Lawrence rivers. Diversion of Lakes Agassiz and Barlow-Ojibway drainage to Hudson Bay after about 8.4 ka BP reinstated summer warming of the surface water in the Great Lakes-St. Lawrence system bringing the 9.6-8.3 ka cool period to a close.

RÉSUME *L'influence des changements de débit d'eau de fonte sur le climat du sud du Canada entre 10 et 8 ka, à partir des données polliniques*. L'augmentation du débit de l'eau de fonte provenant des lacs glaciaires Agassiz et Barlow-Ojibway de 9,6 à 8 ka BP a engendré des micro-climats froids au-dessus des nappes d'eau en aval: le Lac Minong, les lacs de la phase de Mattawa, dans les Grands Lacs, et la Mer de Goldtwaith, dans le golfe du Saint-Laurent. L'effet refroidissant du drainage de l'eau de fonte a entravé le réchauffement estival de la surface des eaux lacustres, écourté la saison végétative et ainsi modifié la composition de la végétation des terres environnantes. La réponse de la végétation a été variable comme l'indiquent les cinq types de déviation (anomalies polliniques) par rapport à la succession pollinique normale. Les anomalies sont plus importantes là où l'effet de l'augmentation du débit de l'eau de fonte a été plus prononcé, notamment près des limites des nappes d'eau touchés ou de leurs zones, surtout près des écotones. L'influence climatique a été très limitée ou nulle là où les surfaces aquifères étaient réduites, comme celles des cours de l'Outaouais et du Saint-Laurent. Le détournement de l'écoulement des lacs Agassiz et Barlow-Ojibway vers la mer d'Hudson après 8,4 ka BP a rétabli le réchauffement estival des eaux de surface du réseau des Grands Lacs et du Saint-Laurent, mettant ainsi fin à la période froide qui a prévalu de 9,6 à 8 ka.

ZUSAMMENFASSUNG *Der Einfluß des Wechsels der Schmelzwassermenge auf das Klima im südlichen Kanada um 10 bis 8 ka anhand von Pollenbelegen*. Verstärktes Schmelz-wasserabfließen von den proglazialen Seen Agassiz und Barlow-Ojibway um etwa 9.6 bis 8.3 ka v.u.Z. bewirkte örtlich beschränktes kaltes Klima über den Wasserflächen stromabwärts, und zwar Minong-See und Seen der Mattawa-Phase in den Großen Seen, und das Goldtwaith-Meer im Golf des Sankt Lorenz. Die kühlende Wirkung des abfließenden Schmelzwassers verhinderte die sommerliche Erwärmung des Oberflächenwassers der Seen, reduzierte die Wachstumsperiode und veränderte so die Zusammensetzung der Vegetation in den umliegenden Landgebieten. Die Vegetation reagierte auf verschiedene Weisen, wie aus fünf Varianten der normalen Pollenabfolge ersichtlich wird. Die Pollen-Abweichungen sind am deutlichsten, wo die Wirkung des verstärkten Schmelzwasserabflusses am stärksten war, wie innerhalb oder entlang der Ränder des Agassiz-Sees, der Seen der Mattawa-Phase und des Goldtwaith-Meeres, oder in ihren windgeschützten Gebieten, besonders wo diese Wasserflächen Übergangszonengrenzen durchschneiden. Die Einwirkungen auf das Klima waren minimal oder inexistent, wo die Wasserflächengebiete begrenzt waren, wie die kanalisierte Dränage-Route des Ottawa- und Sankt Lorenz-Stroms. Die Ableitung des Abflusses des Agassiz- und Barlow-Ojibway-Sees zur Hudson-Bay hin nach etwa 8.4 ka v.u.Z., stellte die sommerliche Erwärmung der Oberflächenwasser im System der Großen Seen und des Sankt Lorenz wieder her und beendete die von 9.6 bis 8.3 ka dauernde kalte Periode.

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## INTRODUCTION

Two distinct episodes of eastward discharge (11-10.5 and 9.6-8.3 ka) from glacial Lake Agassiz in central North America increased meltwater flow to the Great Lakes basins and Gulf of St. Lawrence during deglaciation of the Laurentide Ice Sheet (Teller and Thorleifson, 1983; Teller, 1985 (Figs. 1 and 2). The first discharge at 11 ka increased inflow by four-fold to the large Main Lake Algonquin impounded in the basins of the Upper Great Lakes based on estimates of ice volume reduction and precipitation runoff by Teller (1990). A concurrent vegetation inversion has been observed in pollen profiles of the region (Shane, 1987; Lewis and Anderson, 1989). Isotopic evidence of enhanced meltwater presence of the same age has been discovered in the Great Lakes sediments, and we have proposed that this represents increased meltwater inflow which induced an extended seasonal cold lake surface and a "cool climate" of reduced growing season around the lake basins (Lewis and Anderson, 1989, 1992), possibly in the same way that a late spring ice cover on Hudson Bay "winterizes" the summer climate of the Hudson Bay lowlands today (Rouse, 1991). This cooling effect was terminated by the drainage of Lake Algonquin about 10.5 ka. Subsequently, the Agassiz discharge was diverted southward to Mississippi River about 10 ka when ice readvanced across the Superior basin (Clayton, 1983) (Fig. 1A).

The second eastward Aqassiz discharge, which began about 9.6 ka (Fig. 1B) when ice retreated again into northwestern Ontario, drained first into Superior basin (Lake Minong) and later into Lake Barlow-Ojibway of northern Ontario before the proglacial lakes were drained by breakup of the Laurentide Ice in Hudson Bay shortly after 8.4 ka (Dyke and Prest, 1987) (Figs. 1C, 1D). Both the Upper Great Lakes and Barlow-Ojibway routes drained via Ottawa and St. Lawrence valleys to Goldthwait Sea in the Gulf of St. Lawrence. The Agassiz discharge increased flow through the Great Lakes by 3 to 4-fold and more than doubled the fresh water inflow to Goldthwait Sea (Teller, 1990). The increased flow from Agassiz was resisted hydraulically in constrictions of the Ottawa Valley, causing water levels to rise to the expanded Mattawa phase in the Huron-Michigan and Georgian Bay-Nipissing basins (Lewis and Anderson, 1989) (Figs. 1B, 2). Meltwater intrusion into the southern Michigan basin during this Mattawa phase has been demonstrated by the discovery of ostracode shells with low $\delta^{18}O$ ratios dated 9.1 ka (Colman *et al.*, 1990). As for the first discharge, we infer that the extra flow of meltwater induced seasonally prolonged cold surfaces on downstream water bodies including Lake Minong, Lake Mattawa, and the Goldthwait Sea.

This effect is thought to have also induced a cool climate in lowlands around the Great Lakes and Gulf of St. Lawrence (Fig. 2). Indeed, preliminary examination of several pollen stratigraphies in and around Lake Huron and Georgian Bay basins showed the presence of a pollen anomaly (suggesting a climatic reversal or revertence according to the terminology and criteria presented by Cushing (1967)) that corresponds in time with the Mattawa phase of high and variable lake levels in the Great Lakes basin (Lewis and Anderson, 1989). The pollen anomaly represents a vegetation inversion of the unidirectional pollen sequence, in this case, a return to *spruce (Picea) from a pine (Pinus)-dominated stratigraphy*. It is interpreted as a climatic response to the presence and drainage of this cold meltwater-capped lake. Further investigations have suggested that a similar climatic response extended to the Gulf of St. Lawrence (Lewis *et al.*, 1988; Anderson and Lewis, 1992).

The purpose of this paper is to document and review further palynological evidence in relation to climatic response (or lack of it) to deglacial drainage changes for the period 10 to 8 ka throughout the Agassiz-Upper Great Lakes region and downstream to the Gulf of St. Lawrence and Atlantic Ocean. The palynological evidence consists primarily of early Holocene (10-8 ka) pollen records. Existing and new pollen records from sites both distant from and along this waterway are assessed for evidence of cold-tolerant vegetation and its possible correlation with eastward drainage of Lakes Agassiz and Barlow-Ojibway.

Documentation of paleoclimatic events such as meltwater-induced climate change enhances our knowledge of the feedback and sensitivity of the Earth's climate system. These events therefore serve as possible test cases in modelling paleoclimate to better understand global change.

## AVAILABLE DATA SETS AND METHODOLOGY

Pollen stratigraphies used in this synthesis are from sites in and around the Great Lakes, Ottawa Valley, St. Lawrence lowlands and Gulf of St. Lawrence. Sixty localities have been selected to display evidence (or lack of it) relating to the 10-8 ka meltwater drainage period (Fig. 1B, Table I). These key sites provide the main data base after a thorough examination and assessment of pertinent pollen records extending from central North America to Gulf of St. Lawrence. The sites fall into two groups, one that exhibits normal pollen succession, reflecting unidirectional warming, and another that shows perturbations in the normal succession which may be related to local climatic effects arising from deglacial drainage changes. Figures 3 to 6 show abbreviated pollen diagrams of sites representing these two groups. The diagrams show percent of pollen taxa that best reflect vegetation changes during the 10-8 ka period. Where possible the percentage data is supported by pollen influx estimates but, to date, few sites have been analyzed quantitatively in this way. Reference radiocarbon dates are shown where available: the dates are uncorrected except for those having $^{13}C$ adjustments. If unavailable, age estimates are derived from rates of sedimentation using 4.8 ka for the hemlock (*Tsuga*) pollen decline (Davis, 1981) and older dated levels.

## NORMAL REGIONAL POLLEN SUCCESSION

Several sites have been selected to illustrate the normal regional pollen successions of the Agassiz and Great Lakes basins, the St. Lawrence and Ottawa lowlands and the Atlantic Canada region (Fig. 3). Belmont Lake (No. 1), for example, shows an early Holocene spruce-mixed forest-grassland succession that is representative of the western sector of the Agassiz basin. Grassland was well established

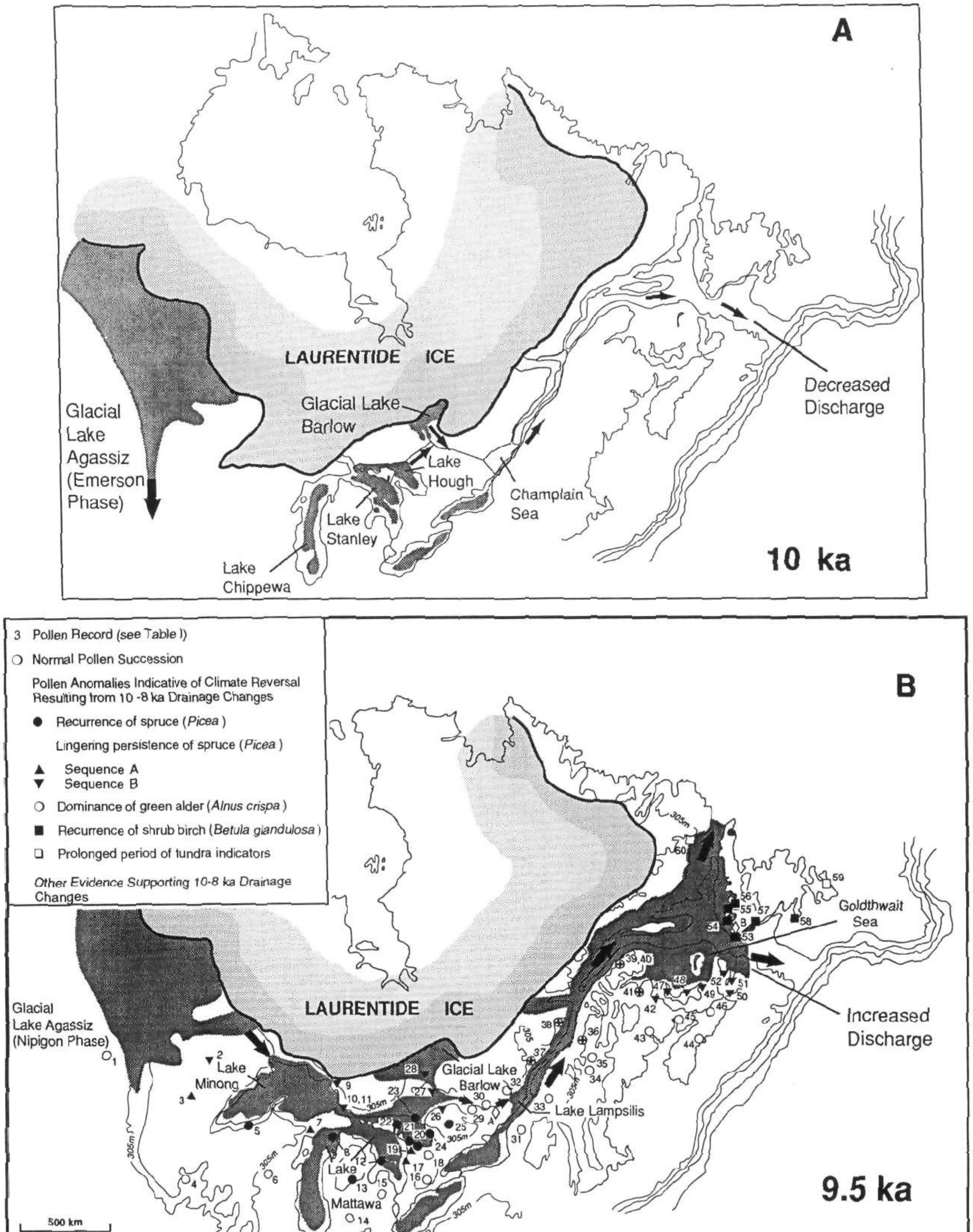


FIGURE 1. *Development of drainage along the southern margin of the retreating Laurentide Ice Sheet at 10-8 ka. A) Drainage at 10 ka; B) drainage at 9.5 ka, locations of sites discussed in text (see also Table I) and 305-m elevation contour (a.s.l.); Data for the Great Lakes from Lewis and Anderson (1989) and for other regions from Dyke and Prest (1987).*

*Évolution du drainage le long de la marge de l'Inlandsis laurentidien en retrait de 10 à 8 ka. A) Le drainage à 10 ka: B) le drainage à 9,5 ka, localisation des sites dont parle le texte (voir aussi le tabl. I) et courbe de 305 m; Les données sur les Grands Lacs proviennent de Lewis et Anderson (1989) et sur les autres régions, de Dyke et Prest (1987).*

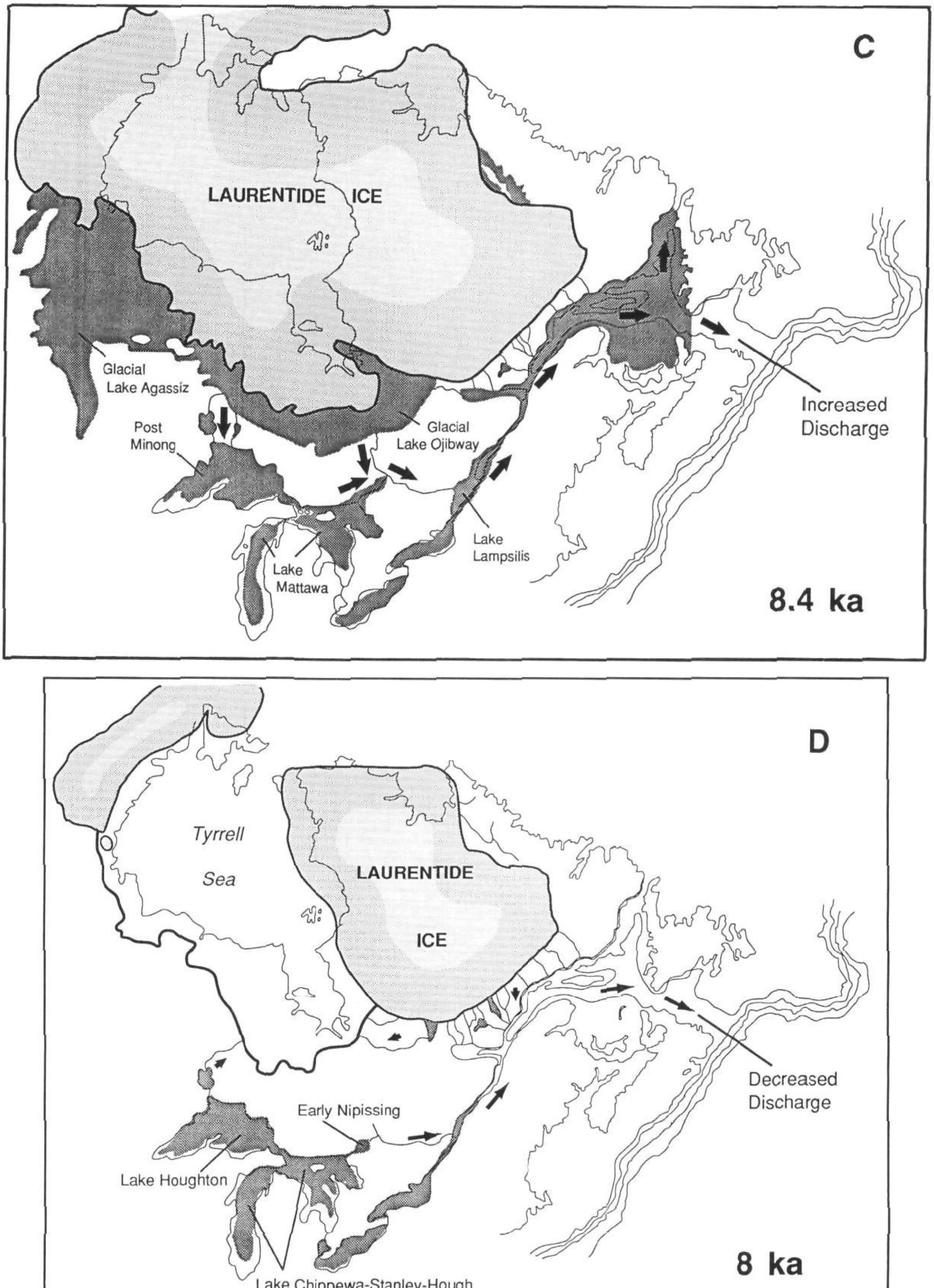


FIGURE 1. Development of drainage along the southern margin of the retreating Laurentide Ice Sheet at 10-8 ka. C) Drainage at 8.4 ka. D) Drainage at 8 ka. Data for the Great Lakes from Lewis and Anderson (1989) and for other regions from Dyke and Prest (1987).

*Évolution du drainage le long de la marge de l'Inlandsis laurentidien en retrait de 10 à 8 ka. C) Le drainage à 8,4 ka. D) Le drainage à 8 ka. Les données sur les Grands Lacs proviennent de Lewis et Anderson (1989) et sur les autres régions, de Dyke et Prest (1987).*

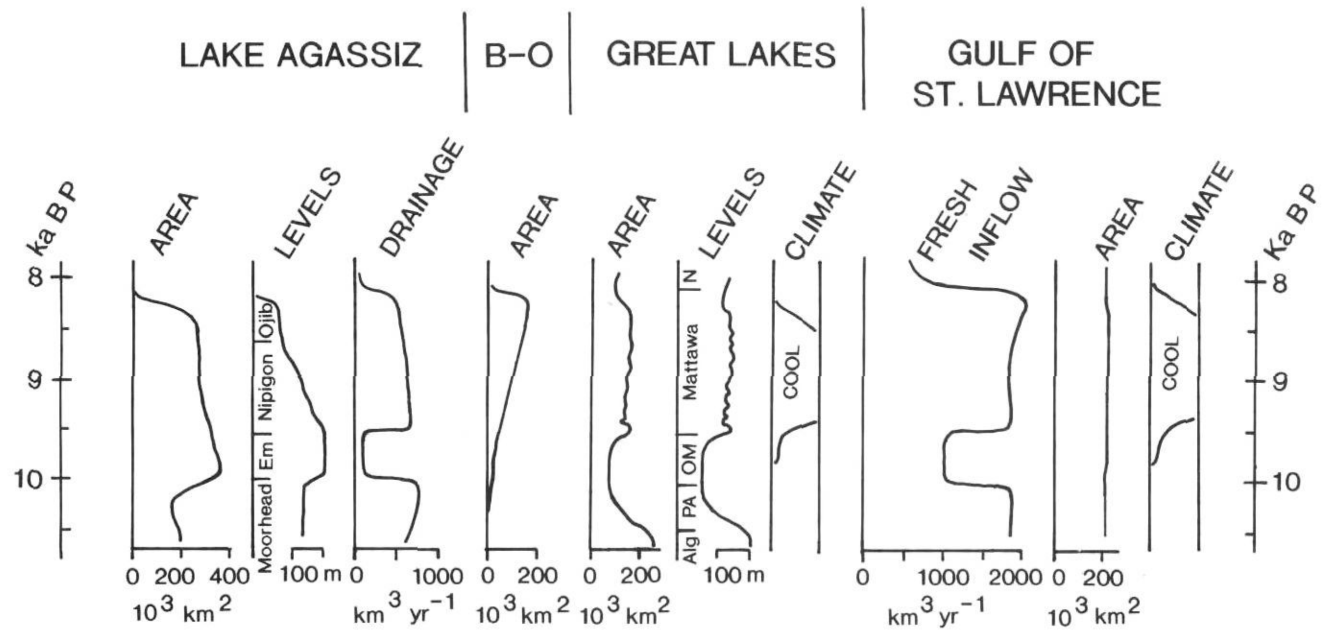


FIGURE 2. Correlation chart of drainage and climate events 10.5-8 ka across southern Canada from the Agassiz basin to Gulf of St. Lawrence. B-O = Lake Barlow-Ojibway; Em = Emerson phase; Ojib= Ojibway phase; Alg = Main Lake Algonquin phase; PA-Post-Algonquin phase; OM= Ottawa-Marquette phase; N = Nipissing phase. Agassiz basin data compiled from information in Clayton (1983), Dyke and Prest (1987), Teller (1985, 1987, 1990) and Teller and Thorleifson (1983). Lake Barlow-Ojibway data compiled from Dyke and Prest (1987) and Teller (1990). Great Lakes basin data compiled from Lewis and Anderson (1989), Dyke and Prest (1987) and Teller (1990). Gulf of St. Lawrence data compiled from Dyke and Prest (1987) and Teller (1990).

*Diagramme de corrélation entre le drainage et les événements climatiques survenus de 10,5 à 8 ka à travers le sud du Canada, à partir du bassin du Lac Agassiz jusqu'au golfe du Saint-Laurent. B-O = Lac Barlow-Ojibway: Em = phase Emerson; Ojib= phase Ojibway; Alg = phase du Lac Algonquin; PA - phase post-algonquine; OM= phase Outaouais-Marquette; N = phase Nipissing. Compilation des données sur le bassin du Lac Agassiz à partir de Clayton (1983), Dyke et Prest (1987), Teller (1985, 1987, 1990) et Teller et Thorleifson (1983). Compilation des données sur le Lac Barlow-Ojibway à partir de Dyke et Prest (1987) et Teller (1990). Compilation des données sur le bassin des Grands Lacs à partir de Lewis et Anderson (1989), Dyke et Prest (1987) et Teller (1990). Compilation des données sur le Saint-Laurent à partir de Dyke et Prest (1987) et Teller (1990).*

here by 9.4 ka. The Kirchner Marsh (No. 4) diagram may be considered representative of the eastern sector of the Agassiz basin and western Great Lakes region. Here spruce (*Picea*) is replaced by successive maxima in birch (*Betula*), fir (*Abies*), pine (*Pinus*), oak (*Quercus*) and elm (*Ulmus*) within the period 10 to 7 ka. Wintergreen Lake (No. 14), Chippawa Bog (No. 15) and Maplehurst Lake (No. 16) diagrams show a spruce-fir-pine-deciduous hardwoods succession typical of the central Great Lakes region. Pine is dominant as early as 10.2 ka at Wintergreen Lake and by 9.5 and 9.6 ka at Chippewa Bog and Maplehurst Lake, respectively. Similar successions exist in southern and southeast Québec (Ramsay Lake, No. 30; Mont Shefford, No. 33) and southern Atlantic Canada (Basswood Road Lake, No. 43 and Chance Harbour Lake, No. 46). Pine was the dominant taxon at Basswood Road and Chance Harbour lakes by 9.5-9.2 ka, giving way to hemlock (*Tsuga*) and deciduous hardwood assemblages by about 7.0-6.5 ka. Sites representing these successions are distant from lakes Agassiz and Mattawa and Goldthwait Sea; two of these sites (Ramsay Lake and Mont Shefford) are close to the restricted drainage channels of the Ottawa and St. Lawrence valleys.

These successions document a time sequence of progressively more thermophilous, cold-sensitive pollen assemblages. Total pollen influx estimates at selected sites in southeastern Canada are generally low prior to 10 ka but increase several-fold between 10 and 9 ka corresponding to a proliferation of the vegetation at about the same time everywhere (Anderson *et al.*, 1989).

## VARIANTS OF THE NORMAL POLLEN SUCCESSION

### Spruce (*Picea*) recurrence (Fig. 4)

Several sites (Nos. 5, 8, 12-13, 20-25) in the upper Great Lakes region show the typical spruce decline and pine rise followed by a second peak in spruce during the period of pine dominance. At the same time, pine shows a moderate decrease or, in the case of site 12, remains unchanged. The spruce recurrence is almost always accompanied by slight increases in fir. At Lake Mary (No. 5), Vestaburg Bog (No. 13), Charles Lake (No. 20) and Strain Lake (No. 24) the spruce recurrence is compensated by an equivalent decrease of pine. At Beaver Island (No. 8) high but declining spruce percentages depress pine and there is clear indication of a spruce return and pine fall prior to the main *Pinus* maximum. In southwestern Lake Huron (No. 12) spruce shows a pronounced increase starting about 10 ka and reaches up to 40 % maximum about 9.5 ka before giving way to pine. The Charles Lake diagram shows spruce increasing for a second

TABLE I

*List of sites showing normal pollen successions and variants (pollen anomalies) of these successions, Agassiz basin – Great Lakes – Gulf of St. Lawrence region*

| Site No. | Site Name and Elevation[1] (m a.s.l.) | Lat:[2] Long:[2] | Reference Dates[3] | Laboratory No. | Pollen Record 10-8 ka Period | Pollen Anomaly[4] | Reference(s) |
|---|---|---|---|---|---|---|---|
| 1. | Belmont Lake, Man. | 49° 26'<br>99° 26' | 9430 ± 160 | I-3157 | Spruce-mixed forest-grassland succession established by 9.4 ka | No | Ritchie and Lichti-Federovich, (1968) |
| 2. | Rattle Lake, Ont. (460) | 49° 21'<br>92° 42' | 8420 ± 90<br>10150 ± 100 | WIS-1398<br>wis-1328 | Persistence of spruce, delay of oak until ca. 7.8 ka (Sequence B) | Yes | Bjorck (1985) |
| 3. | Myrtle Lake, Minn. (393) | 47° 58'<br>93° 23' | 7850 ± 120<br>10150 ± 160 | Y-1780<br>Y-1781 | Persistence of spruce, delay of oak until ca. 7.8 ka (Sequence A) | Yes | Janssen (1968) |
| 4. | Kirchner Marsh, Minn. (254) | 44° 50'<br>93° 07' | 7120 ± 110<br>10230 ± 110 | Y-1140<br>Y-1141 | Successive maxima in spruce, birch, fir, pine, elm and oak at 10-8 ka | No | Wright et al (1963) |
| 5. | Lake Mary, Wis. (488) | 46° 15'<br>89° 54' | 8540 ± 90<br>9460 ± 100 | WIS-437<br>WIS-371 | Recurrence of spruce (just prior to 9.5 ka) corresponds to lithologic change from black to red sandy sediments | Yes | Webb (1974) |
| 6. | Disterhaft Farm Bog, Wis. (329) | 43° 55'<br>89° 10' | 8480 ± 85<br>11150 ± 160 | WIS-429<br>WIS-441 | Reference dates occur at onset of pine and oak dominance, respectively | No | West (1961)<br>Bender et al. (1971) |
| 7. | Winter's Sinkhole peat deposit, Mich. (201) | 45° 52'<br>86° 37' | | | Persistence of spruce (Sequence A) | Yes | Kapp and Means (1977) |
| 8. | Beaver Island, Algonquin Peat Bog, Mich. (230) | 45° 40'<br>85° 33' | 7280 ± 160 | I-1978 | Recurrence of spruce at 9.5 ka based on correlation with dated (7.3 ka) second core | Yes | Kapp et al. (1969) |
| 9. | Alfies Lake, Ont. (288.3) | 47° 53'<br>84° 52' | 8140 ± 190<br>9210 ± 100 | HEL-465<br>GSC-1851 | Persistence of spruce and birch and delay of pine (Sequence B) | Yes | Saarnisto (1975) |
| 10. | Upper Twin Lake, Ont. (302) | 46° 33'<br>84° 35' | 8760 ± 270<br>9940 ± 210 | HEL-476<br>HEL-477 | Persistence of spruce and birch and delay of pine (Sequence B) | Yes | Saarnisto (1974) |
| 11. | Prince Lake, Ont. (290) | 46° 34'<br>84° 33' | 9050 ± 110 | GSC-1913 | Persistence of spruce and birch and delay of pine until about 8.1 ka (Sequence B) | Yes | Saarnisto (1974) |
| 12. | Southwest Lake Huron (175.8) | 44° 30'<br>83° 08' | 8460 ± 180<br>8830 ± 410<br>9370 ± 180<br>9370 ± 220<br>9170 ± 140<br>9680 ± 110 | GSC-1966<br>GSC-1943<br>GSC-1935<br>GSC-1982<br>GSC-1965<br>GSC-1983 | Recurrence of spruce between 9 and 10 ka | Yes | Lewis and Anderson (1989) |
| 13. | Vestaburg Bog, Mich. (255) | 43° 25'<br>84° 53' | 7982 ± 250<br>10328 ± 436 | OWU-200A<br>OWU-201 | Recurrence of spruce during initial period of pine dominance | Yes | Gilliam et al. (1967) |
| 14. | Wintergreen Lake, Mich. (283) | 42° 24'<br>85° 23' | 5500 ± 175<br>8945 ± 90<br>9740 ± 600<br>11425 ± 110 | DAL-201<br>WIS-670<br>DAL-203<br>WIS-672 | Successive maxima in spruce, pine and oak between 11 and 8 ka | No | Manny et al. (1978) |
| 15. | Chippewa Bog, Mich. | 42° 07'<br>83° 15' | 8410 ± 80<br>9540 ± 100 | WIS-1080<br>WIS-1079 | Pine maximum occurs between reference dates | No | Bailey and Ahearn (1981) |
| 16. | Maplehurst Lake, Ont. (300) | 43° 13'<br>80° 39' | 7690 ± 170[3]<br>9650 ± 110[3] | GSC-1882<br>GSC-1870 | Pine maximum occurs between reference dates | No | Mott and Farley-Gill (1978) |
| 17. | Kincardine Bog, Ont. (196) | 44° 09'<br>81° 39' | 7620 ± 70[3]<br>10300 ± 200 | GSC-1816<br>GSC-1644 | Decrease in pine at about 9.6 ka; persistence of spruce until 7.6 ka; (Sequence A) | Yes | Karrow et al. (1975) |
| 18. | Edward Lake, Ont. (504) | 44° 22'<br>80° 15' | 7670 ± 150<br>10550 ± 180 | I-9979<br>I-9980 | Pine maximum occurs between reference dates | No | McAndrews (1981)<br>McAndrews, p.c. (1992) |
| 19. | Townline Lake, Ont. (238) | 44° 33'<br>81° 04' | | | Persistence of spruce and fir into period of pine dominance (Sequence A) | Yes | Anderson (1971) |

| Site No. | Site Name and Elevation[1] (m a.s.l.) | Lat:[2] Long:[2] | Reference Dates[3] | Laboratory No. | Pollen Record 10-8 ka Period | Pollen Anomaly[4] | Reference(s) |
|---|---|---|---|---|---|---|---|
| 20. | Charles Lake, Ont. (810) | 44° 45' 81° 01' | 8765 ± 295 | OWU-467 | Recurrence of spruce commencing prior to 8.8 ka | Yes | Bailey, p.c. (1973) |
| 21. | Hope Bay, Georgian Bay (175.8) | 44° 55' 81° 07' | 8785 ± 145<br>9930 ± 250 | I-7857<br>I-7858 | Spruce recurrences commencing 9.9 ka and about 9.6 ka | Yes | Lewis and Anderson (1989) |
| 22. | Greenbush Swamp, Ont. (312) | 45° 56' 82° 00' | 6790 ± 100<br>9930 ± 90 | WAT-574<br>WAT-579 | Recurrence of spruce between 9.9 ka and about 7.8 ka | Yes | Warner et al. (1984) |
| 23. | Georgian Bay, M Core (175.8) | 45° 37' 83° 23' | | | Recurrence of spruce | Yes | Zilans (1985) |
| 24. | Strain Lake, Ont. (206) | 45° 21' 80° 03' | 9720 ± 120[3] | GSC-5297 | Recurrence of spruce, decline in pine at spruce maximum just after 9.7 ka. | Yes | This study |
| 25. | Found Lake, Ont. | 45° 30' 78° 30' | 7790 ± 175<br>10400 ± 180 | I-7781<br>I-7782 | Recurrence of spruce between reference dates | Yes | McAndrews (1981)<br>McAndrews, p.c. (1992) |
| 26. | Boulter Lake, Ont. (345) | 46° 19' 72° 02' | | | Persistence of spruce and suppression of pine (Sequence B) | Yes | Mott, p.c. (1992) |
| 27. | Morel Lake, Ont. (194) | 46° 16' 78° 48' | 10100 ± 240 | GSC-1275 | Peristence of spruce and suppression of pine (Sequence B) | Yes | Mott, p.c. (1992) |
| 28. | Lac Louis, Ont. (300) | 47° 17' 79° 07' | 7280 ± 250<br>9090 ± 240 | GSC-1481<br>GSC-1432 | Persistence of spruce and delay of pine until about 8.3 ka (Sequence B) | Yes | Vincent (1973)<br>Lowdon and Blake (1973) |
| 29. | Perch Lake, Ont. (145) | 46° 02' 77° 32' | 7800 ± 300<br>9030 ± 220<br>9830 ± 250 | BGS-506<br>BGS-505<br>BGS-1516 | Pine maximum between reference dates | No | Terasmae (1980)<br>Terasmae and McAtee (1979) |
| 30. | Ramsay Lake, Que. (200) | 45° 36' 76° 06' | 6420 ± 140[3]<br>10200 ± 410[3] | GSC-2110<br>GSC-2122 | Successive maxima in spruce and pine between reference dates | No | Mott and Farley-Gill (1981) |
| 31. | Boyd Pond, New York (267) | 44° 23' 75° 05' | 8000 ± 90[3]<br>9840 ± 140[3] | GSC-4555<br>GSC-4236 | Pine maximum between reference dates | No | Anderson (1989) |
| 32. | Lac à St. Germain, Que. (473) | 45° 56' 74° 22' | 8060 ± 210<br>10005 ± 280 | GX-5230<br>GX-5232 | Successive maxima in spruce, birch and pine between reference dates | No | Savoie et Richard (1979) |
| 33. | Mont Shefford, peat bog, Qué. (282) | 45° 21' 72° 35' | 6345 ± 380<br>8715 ± 215<br>11100 ± 230 | I-8837<br>I-8838<br>I-8839 | Successive maxima in poplar, birch and pine between reference dates | No | Richard (1978) |
| 34. | Boundary Pond, Qué. (603) | 45° 35' 70° 41' | 7750 ± 150[3]<br>11200 ± 200 | GSC-1932<br>GSC-1248 | Successive maxima in birch, fir and pine between reference dates | No | Mott (1977) |
| 35. | Lac Dufresne, Qué. (650) | 45° 51' 70° 21' | 9600 ± 140[3]<br>11200 ± 160 | GSC-2345<br>GSC-1294 | Successive maxima in spruce and fir between reference dates followed by birch, minor green alder and pine | No | Mott (1977) |
| 36. | Lac Colin, Qué. (658) | 45° 43' 70° 18' | 8990 ± 100[3]<br>11100 ± 180 | GSC-2325<br>GSC-2282 | Post-spruce, pre-birch dominance of green alder between reference dates | Yes | Mott (1977) |
| 37. | Sud du lac du Noyer, Qué. (270) | 46° 47' 72° 50' | 8230 ± 270<br>9205 ± 385<br>9670 ± 190 | I-8825<br>I-8842<br>I-8497 | Post-spruce, pre-birch dominance of green alder between 9 and 8 ka | Yes | Richard (1977) |
| 38. | Lac à l'Ange, Qué. (640) | 47° 28' 70° 41' | 6410 ± 215<br>9605 ± 350 | GX-5324<br>GX-5326 | Dominance of green alder between reference dates | Yes | Labelle et Richard (1981) |
| 39. | Lac Turcotte, Qué. (456) | 49° 09' 65° 45' | 9010 ± 70<br>10360 ± 170 | BETA-3929<br>DIC-2165 | Dominance of green alder between reference dates | Yes | Labelle et Richard (1984) |
| 40. | Lac à Léonard, Qué. (17) | 49° 12' 65° 48' | 7910 ± 120<br>9040 ± 140 | GSC-3217<br>GSC-3210 | Dominance of green alder between reference dates | Yes | Labelle et Richard (1984) |
| 41. | Teagues Lake, N.B. (90) | 47° 37' 65° 25' | 8340 ± 260[3]<br>10500 ± 150[3] | GSC-3466<br>GSC-2751 | Post-spruce, pre-birch, dominance of green alder between reference dates | Yes | Mott p.c. (1992) |

| Site No. | Site Name and Elevation[1] (m a.s.l.) | Lat:[2] Long:[2] | Reference Dates[3] | Laboratory No. | Pollen Record 10-8 ka Period | Pollen Anomaly[4] | Reference(s) |
|---|---|---|---|---|---|---|---|
| 42. | Point Escuminac peat section, N.B. (6) | 47° 04' 65° 49' | 7250 ± 130<br>8970 ± 160<br>9460 ± 180 | Hel-1913<br>Hel-1790<br>Hel-1791 | Persistence of spruce and fir and depressed pine between reference dates (Sequence B) | Yes | Warner et al. (1991) |
| 43. | Basswood Road Lake, N.B. (106) | 45° 15' 67° 19' | 9460 ± 220[3]<br>11300 ± 180[3] | GSC-1643<br>GSC-1645 | Reference date, 9460 ± 220, provides age for transition from spruce to pine dominance | No | Mott (1975) |
| 44. | Silver Lake, N.S. (69) | 44° 33' 63° 38' | 7140 ± 140<br>9650 ± 150 | | Successive maxima in birch and pine between reference dates | No | Livingstone (1968) |
| 45. | Wood's Pond, N.B. (25) | 45° 54' 64° 22' | 9930 ± 350 | WAT-943 | Transition from spruce to pine dominance interpolated at 9.5 ka | No | Walker and Paterson (1983) |
| 46. | Chance Harbour, Lake N.S. (12) | 45° 40' 62° 36' | 7050 ± 100[3]<br>9220 ± 90[3]<br>11300 ± 190[3] | GSC-4382<br>GSC-4573<br>GSC-4274 | Transition from spruce to pine dominance interpolated at 9-9.5 ka | No | Jetté et Mott (1989) |
| 47. | Portage Bog, P.E.I. (8) | 46° 40' 64° 04' | 9880 ± 150 | GSC-773 | Persistence of spruce, birch and fir and delay of pine until about 8 ka (Sequence B) | Yes | Anderson (1980) |
| 48. | MacLaughlin Pond, P.E.I. (24) | 46° 22' 62° 50' | 8050 ± 100[3]<br>9670 ± 130[3] | GSC-2887<br>GSC-2891 | Persistence of spruce, birch and fir and delay of pine until 8 ka (Sequence B) | Yes | Anderson (1985) |
| 49. | East Baltic Bog, P.E.I. (45) | 46° 24' 62° 09' | 7000 ± 70[3]<br>8430 ± 150 | GSC-2473<br>GSC-775 | Persistence of spruce, birch and fir and delay of pine until about 8 ka (Sequence B) | Yes | Anderson (1980) |
| 50.(a) | Salmon River Lake, N.S. | 45° 38' 60° 46' | 8770 ± 150 | | Persistence of spruce, birch and fir and delay of pine until about 8 ka (Sequence B) | Yes | Livingstone (1968) |
| 50.(b) | Gillis Lake, N.S. (58) | 45° 39' 60° 46' | 10160 ± 160 | Y-524 | Persistence of spruce, birch and fir and delay of pine until about 8 ka (Sequence B) | Yes | Livingstone and Livingstone (1958)<br>Deevey et al. (1959) |
| 51. | McDougal Lake, N.S. (152) | 46° 03' 60° 25' | | | Persistence of spruce and birch and delay of pine until about 8.3 ka (Sequence B) | Yes | Livingstone (1968) |
| 52. | Wreck Cove Lake, N.S. (340) | 46° 32' 60° 27' | 9030 ± 170 | GSC-335 | Persistence of spruce and birch and delay of pine until about 8.3 ka (Sequence B) | Yes | Livingstone and Estes (1967) |
| 53. | Loch Lomond, NFLD. (84) | 47° 48' 59° 16' | | | Recurrence of shrub birch dominance replaces spruce shortly after 10 ka | Yes | This study |
| 54. | Joes Pond, NFLD. (42.5) | 48° 21' 58° 40' | 9445 ± 380<br>10130 ± 375 | GX-9963<br>GX-9964 | Recurrence of birch dominance replaces spruce at about 9.5 ka | Yes | McAndrews, p.c. (1992) |
| 55. | Romaines River marl section, NFLD. (6-7) | 48° 33' 58° 41' | 11500 ± 100 | GSC-4291 | Recurrence of shrub birch dominance replaces spruce shortly after 10 ka | Yes | This study |
| 56. | Southwest Brook Lake, NFLD. (145) | 48° 28' 57° 59' | 8550 ± 220[3]<br>11100 ± 120[3] | GSC-5041<br>GSC-4631 | Recurrence of shrub birch dominance replaces spruce shortly after 10 ka | Yes | This study |
| 57. | Woody Hill Brook Pond, NFLD. (165) | 47° 41' 57° 38' | 8460 ± 120[3]<br>9720 ± 110[3]<br>10400 ± 110[3] | GSC-5315<br>GSC-5309<br>GSC-4999 | Recurrence of shrub birch dominance replaces spruce at 9.7 ka. Spruce reappears at 8.5 ka. | Yes | This study |
| 58. | James Pond, NFLD. (115) | 46° 55' 55° 36' | 10700 ± 110[3] | GSC-3572 | Recurrence of birch dominance replaces spruce shortly after 10 ka | Yes | Anderson (1983) |
| 59. | Sugarloaf Pond, NFLD. (100) | 47° 37' 52° 40' | 7270 ± 200<br>9270 ± 150[3] | DAL-295<br>GSC-2601 | Persistence of tundra pollen assemblage indicators until 8.3 ka | Yes | Macpherson (1982) |
| 60. | Whitney's Gulch lake, Que. (98) | 51° 31' 57° 18' | 6275 ± 130<br>8965 ± 150<br>9820 ± 110 | SI-3135A<br>SI-3136<br>SI-3137 | Persistence of tundra pollen assemblage indicators until 8.3 ka | Yes | Lamb (1980) |

[1]Elevation refers to surface of lake, bog or section

[2]Location to the nearest minute

[3]Dates corrected to a $\delta^{13}C$ = -25‰ PDB; all other dates uncorrected

[4]Yes signifies pollen record is considered to be evidence of climatic effect

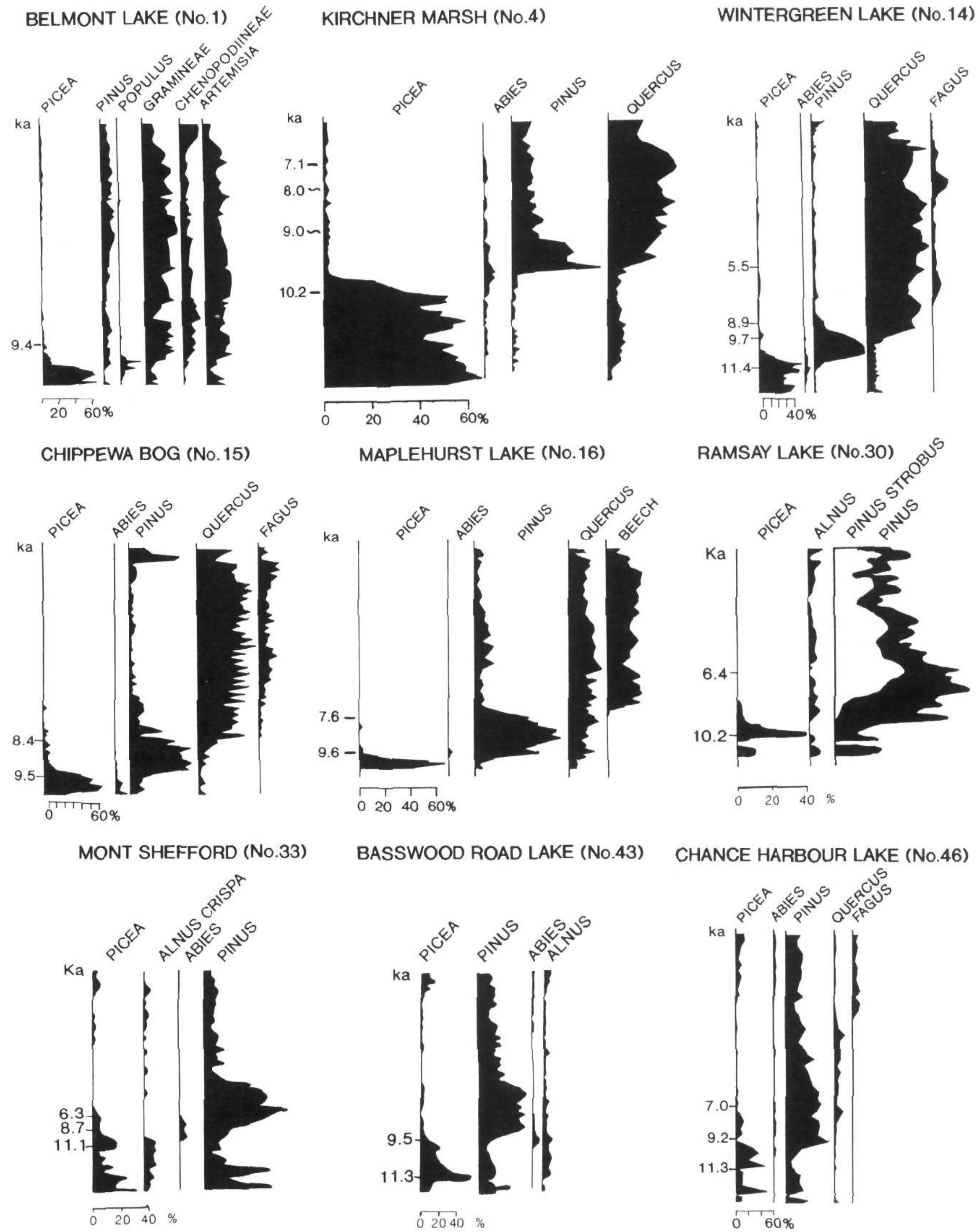


FIGURE 3. Pollen diagrams showing key taxa depicting normal (regional) pollen succession at selected sites.

*Diagrammes polliniques montrant les taxons clés illustrant la succession pollinique normale (à l'échelle régionale).*

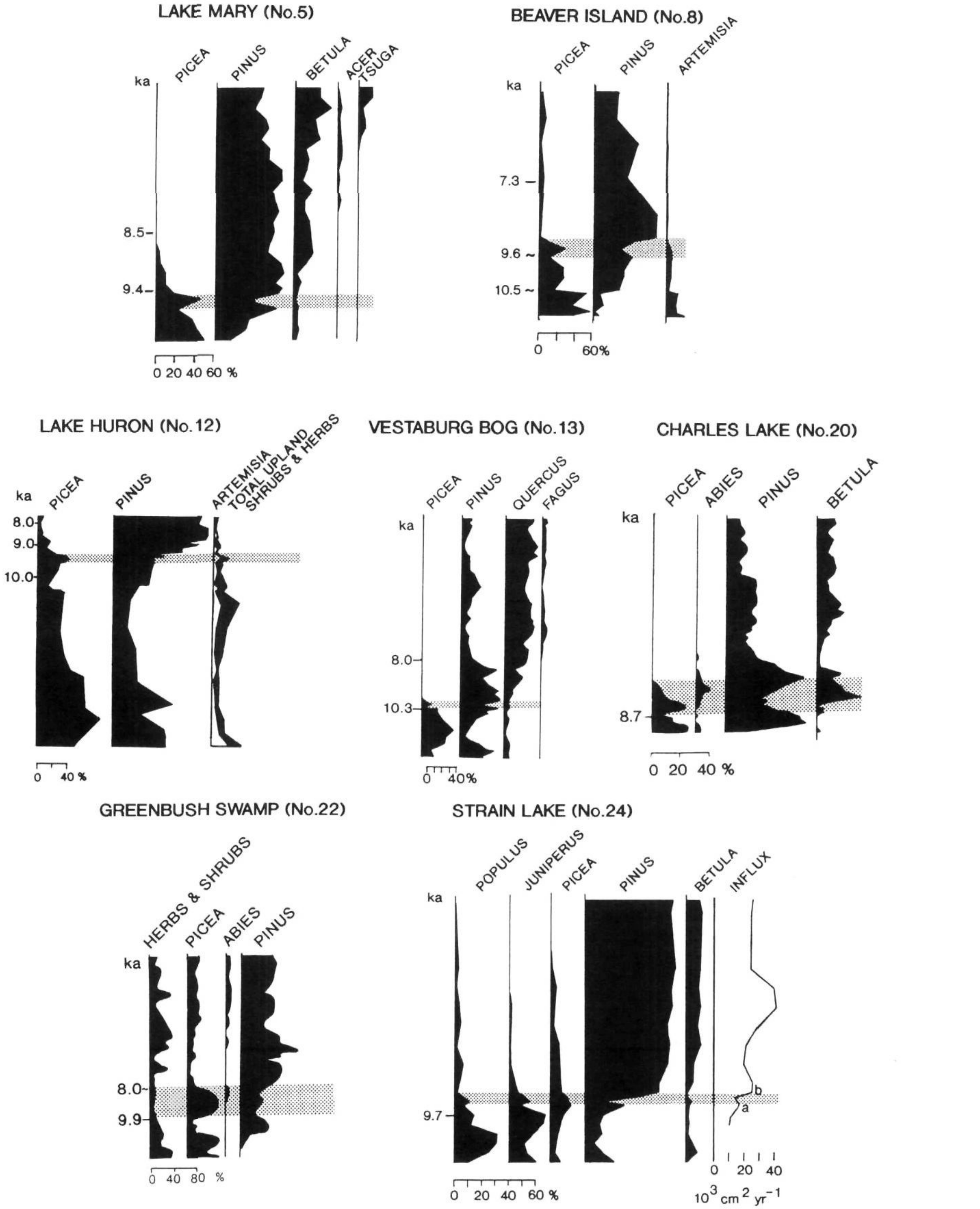


FIGURE 4. Pollen diagrams showing the spruce (*Picea*) recurrence pollen anomaly and other key taxa for selected sites. Stippled band denotes 10-8 ka cool phase.

*Diagrammes polliniques montrant l'anomalie de la récurrence de l'épinette* (Picea) *et certains autres taxons clés de sites choisis. La zone tramée identifie la période froide de 10 à 8 ka.*

time to maximum percentages of 30 % about 8.7 ka. A second increase in spruce at Greenbush Swamp (No. 22) is dated at 9.9 ka; spruce reaches 60 % maximum prior to being replaced by pine at about 8 ka. Strain Lake (No. 24) shows spruce attaining maximum percentages and pine decreasing some 17 % shortly after 9.7 ka. Total pollen influx estimates for Strain Lake decrease substantially at the same level (labelled a-b) implying a decrease in overall vegetation productivity corresponding to the spruce recurrence.

Lingering persistence of spruce (Fig. 5)

*Sequence A.* Sites 3, 7, 17 and 19 show relatively high but declining spruce percentages during the period of pine dominance. The lingering persistence of spruce is accompanied by generally depressed pine percentages and often maximum values of fir (to 8 and 10 % maximum at sites 17 and 19) and is succeeded by increases of deciduous taxa and/or hemlock. For example, at Myrtle Lake (No. 3) spruce declines after 10.1 ka but lingers on through the *Pinus*- dominated-

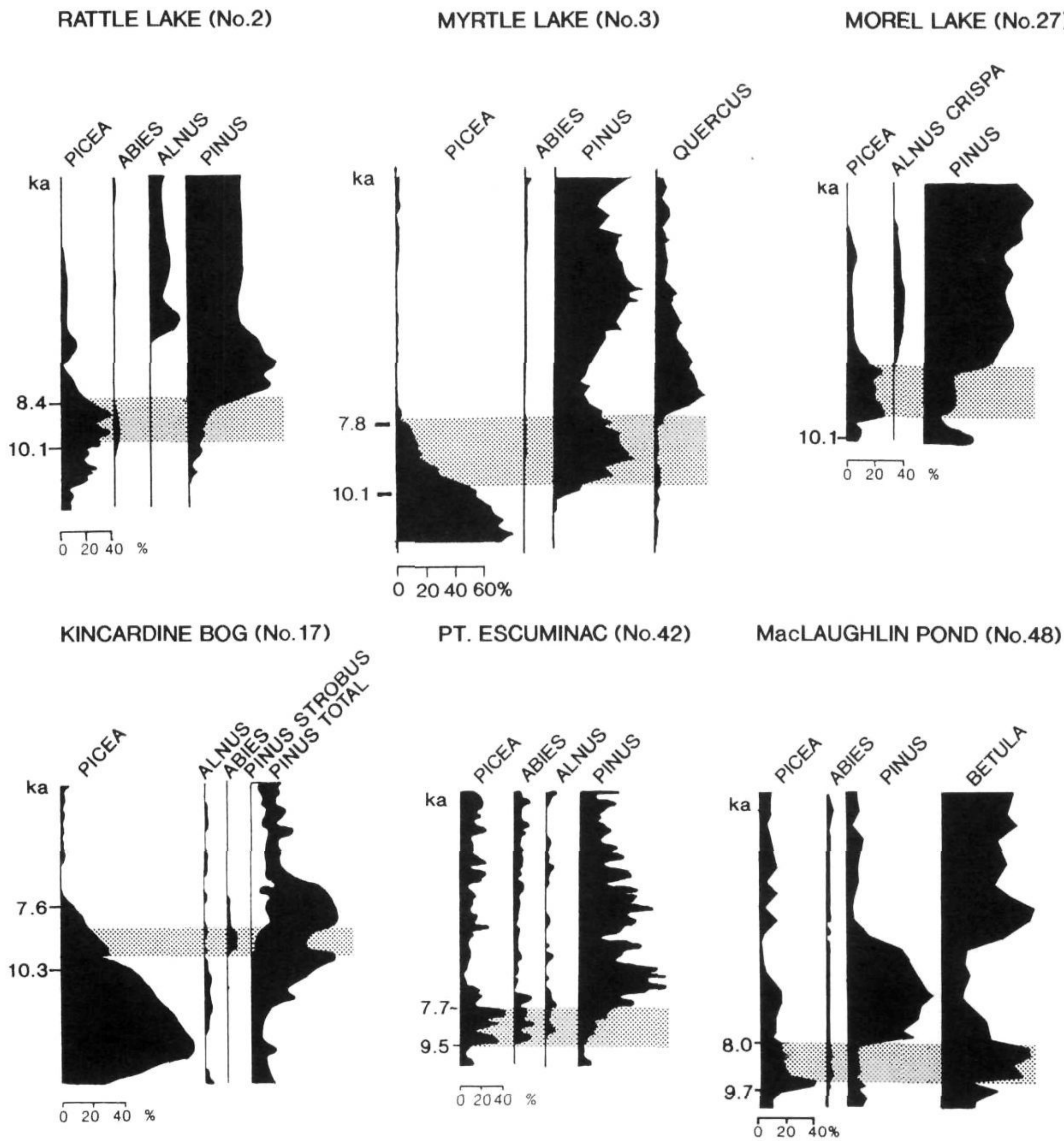


FIGURE 5. Pollen diagrams showing the lingering persistence of spruce (*Picea*) and other key taxa for selected sites. Myrtle Lake (No. 3) and Kincardine Bog (No. 17) are examples of Sequence A. Rattle Lake (No. 2), Morel Lake (No. 27) Pt. Escuminac (No. 42) and MacLaughlin Pond (N° 48) are examples of Sequence B. Stippled band denotes 10-8 ka cool phase.

*Diagrammes polliniques illustrant la persistance de l'épinette (*Picea*) et de certains autres taxons clés de sites choisis. Myrtle Lake (n° 3) et Kincardine Bog (n° 17) sont des exemples de la séquence A. Rattle Lake (n° 2), Morel Lake (n° 27), la pointe Escuminac (n° 42) et MacLaughlin Pond (n° 48) sont des exemples de la séquence B. La zone tramée identifie la période froide de 10 à 8 ka.*

interval to the *Quercus* rise. Likewise at Kincardine Bog (No. 17), spruce declines steadily upward from maximum values, increases slightly again shortly after 10 ka, and lingers on well into the *Pinus* period; pine shows a corresponding decrease prior to the main *Pinus* peak.

*Sequence B*. A lingering persistence of spruce and depressed pine percentages are particularly apparent at sites 2, 9-11, 26-28, 42, 47-52. Spruce dominated these records shortly after 10 ka but abruptly gave way to pine at about 8.4 ka at Rattle Lake (No. 2), at about 8.8 ka at Morel Lake (No. 27), at about 7.7 ka at Pt. Escuminac (No. 42) and at 8 ka at MacLaughlin Pond (No. 48). The lingering persistence of spruce in these sequences is almost always accompanied by high (in some cases maximum) percentages of birch and peak values of fir.

Dominance of green alder (*Alnus crispa*) (Fig. 6)

Certain sites (Nos. 36-41) document an early Holocene pollen succession dominated by spruce (or spruce with poplar and birch) giving way to green alder (*Alnus crispa*) which

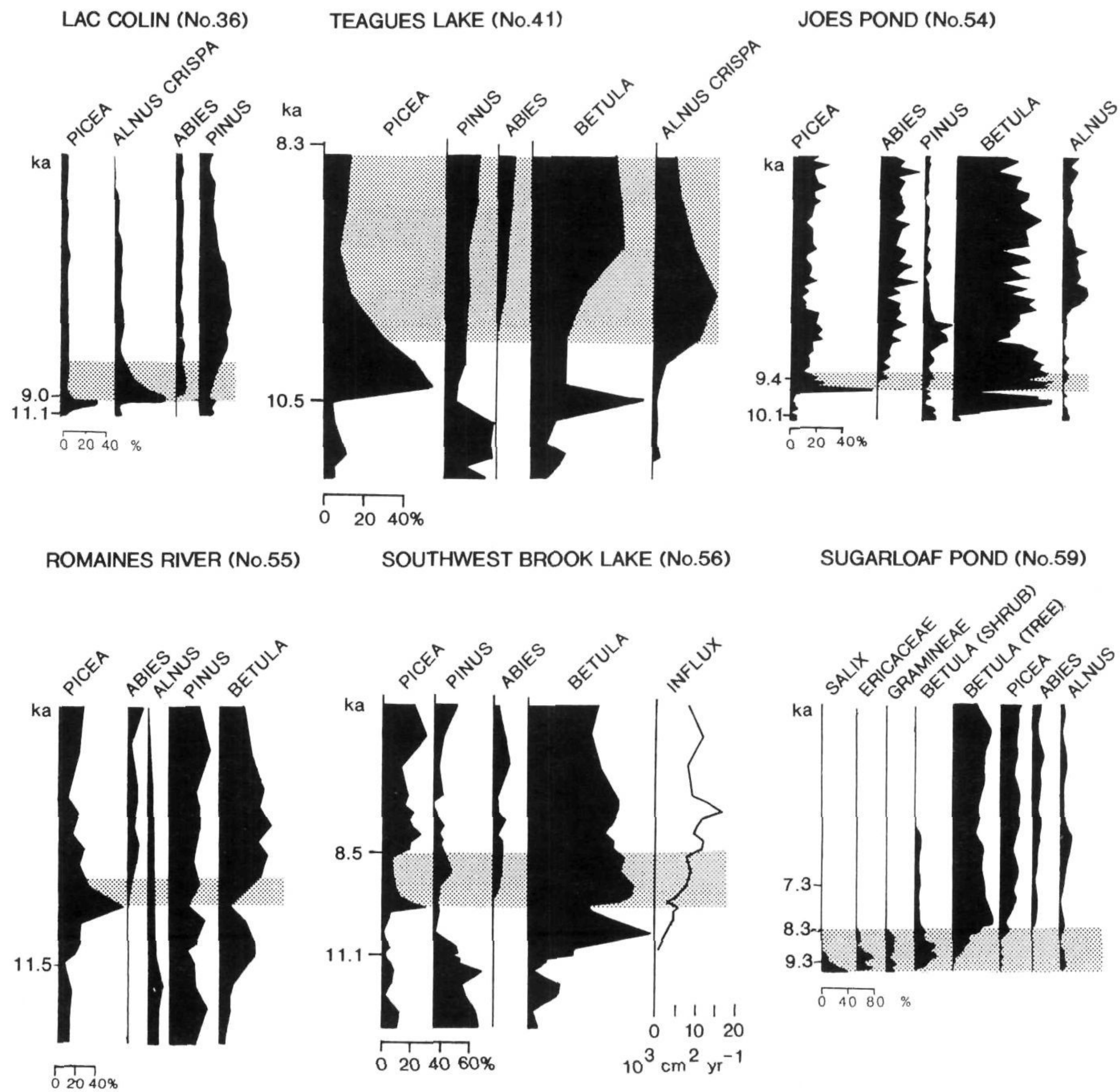


FIGURE 6. Pollen diagrams showing the green alder (*Alnus crispa*) dominance, birch (*Betula*) recurrence and prolongation of tundra indicators pollen anomalies and other key taxa for selected sites. Stippled band denotes 10-8 ka cool phase.

*Diagrammes polliniques illustrant la dominance de l'aulne crispé (*Alnus crispa*), la récurrence du bouleau (*Betula*) et la prolongation de la tundra, identifiée par des indicateurs d'anomalies polliniques, et autres taxons clés de sites choisis. La zone tramée identifie la période froide de 10 à 8 ka.*

yields to fir. At Lac Colín and Lac à L'Ange (Nos. 36 and 38) green alder increased dramatically at about 9.6 ka reaching maxima of 55 and 40 %, respectively. Increases of the same magnitude in green alder also prevailed between 10 and 8 ka at Teagues Lake (No. 41) following a period of spruce dominance.

Recurrence of shrub birch (*Betula glandulosa*) (Fig. 6)

Sites 53-58 show a succession from birch dominance to spruce dominance and back to birch between about 10 and 9.5 ka. For example, shortly after 10 ka but before 9.4 ka at Joes Pond (No. 54), birch (up to 75 % maximum) gives way to peak spruce values (of about 60 %) which fall abruptly while birch increases equally as abruptly again (to 70 % maximum) along with fir. Based on grain size measurements of birch pollen at Southwest Brook Lake (Fig. 7), shrub birch (*Betula glandulosa*) was clearly dominant during the periods of birch dominance but tree birch became more prevalent after about 8.5 ka. Total pollen influx estimates at Southwest Brook Lake decrease across the spruce-shrub birch transition and increase again during the period of shrub birch recurrence.

Prolonged period of tundra indicators (Fig. 6)

Herb/shrub-dominated pollen assemblages characterize some eastern and northeastern sites for a long period after deglaciation. For example, at Sugarloaf Pond (No. 59) a willow-heath-grass-sedge-shrub birch-juniper (*Salix*-Ericaceae-Gramineae-Cyperaceae-Betula *glandulosa-Juniperus*) succession existed soon after deglaciation and was replaced by increases of tree birch, spruce, fir and alder (*Alnus*) at about 8.3 ka. At Whitney's Gulch (No. 60) birch-willow-sedge assemblages gave way to others dominated by alder, birch and spruce between 10 and 8 ka.

## VEGETATIVE RESPONSE TO THE 10-8 KA DRAINAGE

Sites characterized by the pollen anomalies discussed above (Figs. 4 to 6) are located within or in proximity to Lake Agassiz, Mattawa-phase water bodies of the Upper Great Lakes and the contemporary Goldthwait Sea into which the lake phases drained at 10 to 8 ka. Increased meltwater inflow would have maintained cold surface water temperatures in these water bodies for much of this period, possibly either by increased vertical mixing or by rapid replacement of surface waters and advection of heat (Lewis and Anderson, 1992). It is hypothesized that the increased inflow created cold localized climates over these water bodies which had the effect of delaying seasonal warming, reducing the growing season and thus altering the vegetation composition in the surrounding land areas. The diverse nature of the pollen anomalies shows that vegetation responded in different ways to the climatic effect from increased meltwater drainage.

Great Lakes region

Sites in the upper Great Lakes region show three pollen anomalies that can be interpreted in terms of changes in the relative abundance of spruce and pine in the forests bordering Lake Mattawa at 10 to 8 ka. Sites characterized by

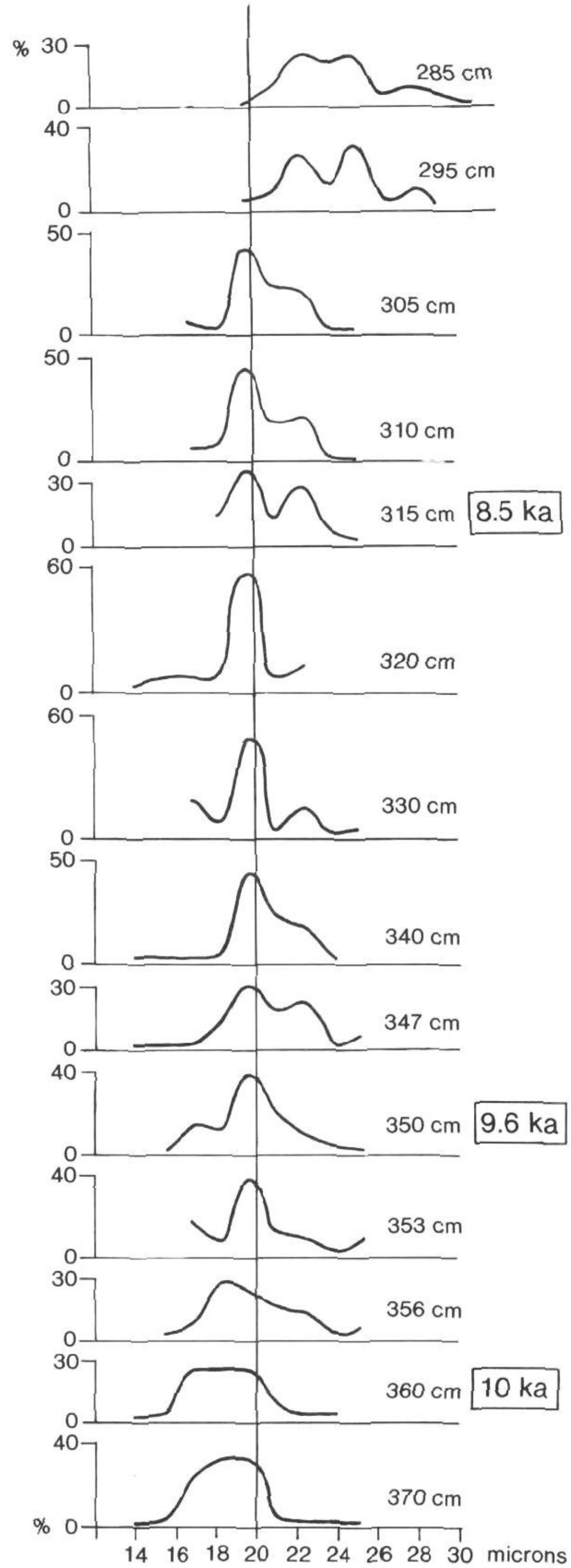


FIGURE 7. Grain size measurements for birch pollen, Southwest Brook Lake (No. 56). The transition from shrub to tree birch pollen is in the size range 20 to 22 μm.

*Granulométrie du pollen de bouleau, Southwest Brook Lake (n° 56). La transition du bouleau nain au bouleau arbustif se situe dans l'intervalle de 20 à 22 μm.*

recurrences of spruce occur within or close to Mattawa-phase water bodies of the Upper Great Lakes as on islands, coastal areas and to the lee (east) of the large lakes. The return of spruce at these sites during the period of pine dominance suggests climatic conditions became cool to cold and thus more favourable to spruce and fir growth than pine. Yet at greater distances (*e.g.* less than 150 km) from the large lakes, pine had permanently replaced spruce by 9.6 ka and became dominant thereafter (*e.g.* Maplehurst Lake, No. 16).

Sites showing a lingering persistence of spruce (sequence A) occur mainly in coastal areas just south of Lake Mattawa, with an isolated site (No. 3) located midway between lakes Agassiz and Minong. Sequence B sites, on the other hand, are concentrated in the more northerly areas within or in the lee (east) of these lakes. Both sequences indicate spruce lingered on as late as 8 ka (Kincardine Bog, No. 17; Myrtle Lake, No. 3) even though pine was dominant inland from (south of) the lakes. At Myrtle Lake, spruce persisted through most of the pine period giving way to oak shortly after 8 ka. Yet oak was prominent in the regional forest by 9.5 ka (Kirchener Bog, No. 4). Farther west (Belmont Lake, No. 1) forest gave way to grassland, implying progressive early Holocene warming. Sequence A shows that spruce and pine were probably co-dominants in the forests at the time whereas sequence B implies spruce was likely dominant. Fir also was prominent in certain areas especially at sites bordering the Lake Huron and Georgian Bay basins (Townline Lake, No. 19 and at Kincardine Bog, No. 17). Both sequences imply climatic conditions which favoured spruce and fir growth but which depressed or delayed migration of pine and oak to these areas.

### Ottawa and St. Lawrence valleys

Records from Ottawa Valley and St. Lawrence Lowlands exhibit no obvious pollen anomalies during the period 10 to 8 ka. This is consistent with the channelized drainage down Ottawa and St. Lawrence rivers. The limited water surface area would not have exerted any climatic effect at sites bordering these rivers. However, the higher Ottawa River levels at this time caused a delay in onset of organic deposition and vegetation development at flooded sites in and around Ottawa. For example, basal lake sediments (labelled A, Fig. 1B) from within the paleo-floodplain of Ottawa River yield radiocarbon dates in the range 7.6-8.8 ka (Mott and Camfield, 1969) compared to 10-11 ka at higher elevation sites in the same area (Mott and Farley-Gill, 1981).

Sites characterized by post-spruce, pre-pine peaks in green alder are restricted mainly to the lower St. Lawrence — Gaspé Peninsula area. The significance of increased frequencies of green alder pollen, however, is not clearly understood. Richard et Labelle (1989) interpreted the 9.6-7 ka maxima in green alder at Lac du Diable, Mont Albert, Gaspé Peninsula, to be indicative of dry climatic conditions and increased frequency of wild-fires. More recently, Richard *et al.* (1992) attributed increased frequencies of green alder to cooler conditions. Jetté et Richard (1992) also interpreted peaks in *Alnus crispa* in other Gaspésie sites to indicate prolonged cooling up to about 7 ka. We suggest that green alder flourished in the lower St. Lawrence - Gaspé Peninsula region at 10 to 8 ka because the climate had probably cooled and become more humid with increased frequency of fog than previously, due to the presence of cold, increased meltwater drainage in combination with proximity to the ice front. Similar conditions would have favoured fir growth. A similar climate prevails today along the embankments of the George River in northern Québec where green alder forms luxuriant growths (Rousseau, 1968).

### Gulf of St. Lawrence region

Sites bordering the Gulf of St. Lawrence record four types of pollen anomalies, indicating four different vegetation responses to a cold meltwater-capped Goldthwait Sea at 10 to 8 ka. Sites that best document a response are those located nearest to the Gulf or to the flow out of the Gulf.

The green alder anomaly of the lower St. Lawrence - Gaspé Peninsula region extends to site 41 suggesting that this shrub was widespread in the western Gulf of St. Lawrence region including Gaspé Peninsula and areas bordering Baie des Chaleurs. Thus climatic conditions favourable for green alder expansion characterized this broad region between 10 and 8 ka.

Elsewhere, spruce-fir-birch forests persisted in eastern New Brunswick (No. 42), Prince Edward Island (Nos. 47-49) and Cape Breton Island (Nos. 50-52) until about 8 ka even though pine was dominant in southwestern New Brunswick (No. 43, Fig. 3) and at sites bordering the Northumberland shore (Nos. 45 and 46) as early as 9-9.5 ka. The cold Goldthwait Sea (at 10-8 ka) had the effect of prolonging spruce, fir and birch and delaying migration of pine to sites in the lee (southern) areas of the Gulf of St. Lawrence.

In Newfoundland, the 10-8 ka drainage is reflected by two vegetative responses. Spruce trees immigrated into Newfoundland as early as 10 ka, and by 9.7 ka, spruce forests had replaced shrub birch-dominated tundra almost everywhere in southwest Newfoundland. Shortly afterwards, probably within centuries, the spruce forests had thinned out and were invaded by shrub birch. Shrub birch dominated again until about 8.5 ka when tree birch replaced it and spruce reinvaded the area. The migration of spruce into south-central Newfoundland was delayed until 8.5 ka (Macpherson and Dyer, 1987) and in easternmost Newfoundland (Sugarloaf Pond, No. 59) until 8.3 ka by the persistence of tundra. Likewise in southeast Québec (No. 60), tundra prevailed until about the same time giving way to spruce, alder and arboreal birch. The birch recurrence, persistence of tundra and delay in migration of spruce are attributed to climatic deterioration of regional proportions.

We suggest that the surface of the Goldthwait Sea was dominated by a cold, rapidly advecting freshened cap driven by increased meltwater and runoff when Agassiz basin drainage joined that of the Great Lakes - St. Lawrence basins. A cap of reduced salinity would enhance the seasonal presence of ice, and rapid advection would tend to remove the effects of seasonal solar heating, thereby maintaining the Goldthwait Sea as a heat sink and massive cooling surface for the overlying atmosphere. We propose that these cold surface waters caused a deterioration of climate in most parts of

Newfoundland and adjacent areas of southeast Québec. The colder local climate may have helped to prolong glacial-like conditions at higher elevations in western Newfoundland. For example, at the top of the Anguille Mountain range (site labelled B, Fig. 1B), elevation 414 m asl, organic accumulation did not start until about 8 ka, some 3 ka later than at low elevation sites.

## DISCUSSION

The 10-8 ka cold-tolerant pollen assemblages characterize a broad region extending from the western Great Lakes to Gulf of St. Lawrence (Fig. 8). The degree to which these assemblages are represented depends on several factors including: a) the position of any site relative to the 10-8 ka cold meltwater lakes and drainage route, b) the areal extent of the lake phases and c) site locations relative to ecotonal boundaries. Other criteria such as topographic relief, migration routes and migration rates for the various tree species, their tolerance limits, and competitive ability are also important.

Sites where the cold-tolerant assemblages are best documented are located on islands (*e.g.* Manitoulin Island in Huron basin) within the cold lakes, near the lake margins or in their lee areas. The wider-area Mattawa phase of the Great Lakes and Goldthwait Sea in Gulf of St. Lawrence exerted a greater climatic influence at sites bordering these water bodies than the much reduced Lampsilis Lake of the St. Lawrence valley and Ottawa River where the climatic effect was minimal or non-existant. The 10-8 ka drainage, however, resulted in higher levels of the Ottawa River which had the effect of suppressing organic deposition in several basins in the Ottawa area until close to 8 ka.

Early Holocene pollen records from eastern North America show that the period 11 to 9 ka was marked by rapid rates of vegetation change (Jacobson *et al.*, 1987). This was the time when pine populations advanced northward from the Appalachian region to the Great Lakes and areas eastward. By 9 ka pine had displaced spruce and dominated upland forests throughout the broad region extending from west of the Great Lakes to northern New England and southern parts of Atlantic Canada (Webb, 1981; Davis, 1983). The spruce-pine ecotone had an east-west orientation throughout the area from just north of the Great Lakes to southern Québec. The ecotonal boundary in the upper Great Lakes region would have been sensitive to fluctuations in climate. Thus the cooler climate generated by the 10-8 ka meltwater drainage, and resultant, larger lake-surface areas, shifted this boundary southward at that time. Pollen evidence, for example at Greenbush Swamp (No. 22), indeed indicates that spruce had become more prevalent at sites south of the ecotone, to the extent that it clearly had invaded previously established pine forests. North of the ecotone, spruce continued to have persisted and pine was not a factor until 8 to 8.5 ka, as at Rattle Lake (No. 2) and Upper Twin Lake (No. 10). Evidence from west of the Great Lakes and southeast of Lake Agassiz indicates that the cooling effect of the Nipigon phase allowed spruce to linger while suppressing northward migrations of some deciduous forest elements notably oak until about 8 ka, as at Myrtle Lake (No. 3). Similar effects from the Goldthwait Sea are thought to have delayed the northward migration of pine into parts of Atlantic Canada (*i.e.*, eastern New Brunswick, Prince Edward Island and Cape Breton Island) even though pine was present at contemporanous localities on the mainland (Nos. 43, 45 and 46).

The cooling effect of meltwater presence and drainage was influenced to a certain extent by topographic relief. The absence of a clear 10-8 ka pollen anomaly at Edward Lake (No. 18), for example, suggests that the Niagara Escarpment

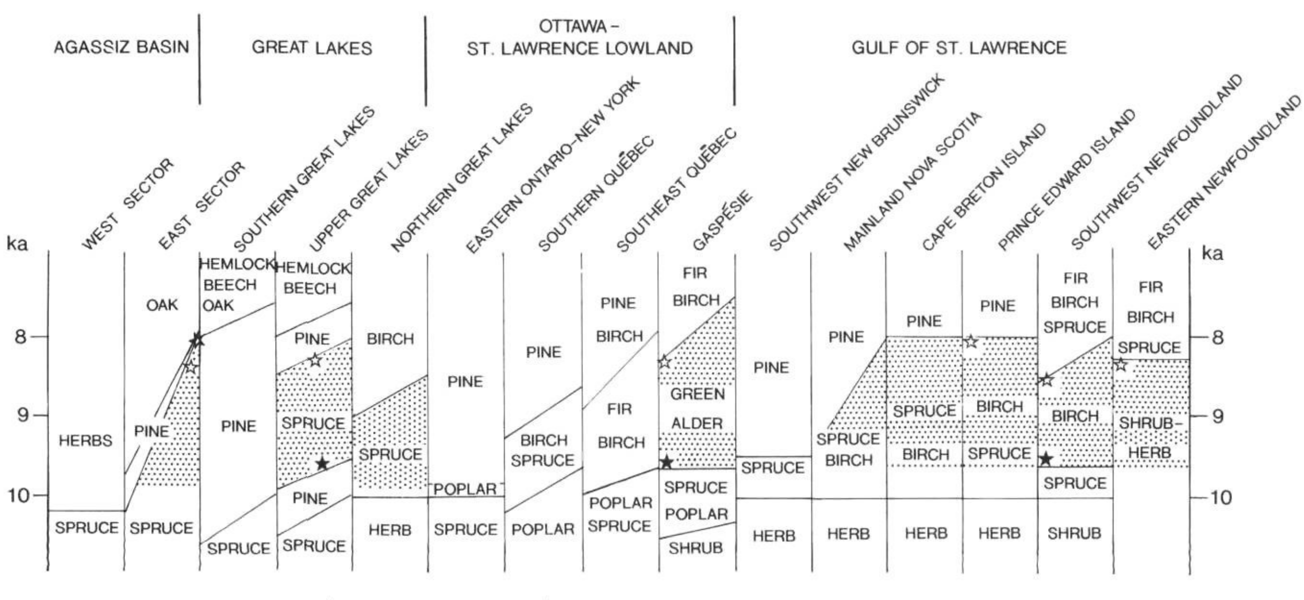


FIGURE 8. Correlation chart of cold-tolerant pollen assemblages (stippled band), central North America - Great Lakes - Gulf of St. Lawrence region.

*Diagramme de corrélation des assemblages polliniques supportant le froid (zone tramée), du centre de l'Amérique du Nord, des Grands Lacs et du golfe du Saint-Laurent.*

probably had acted as a barrier between this lake and the nearby cold Mattawa phase lake in Georgian Bay basin. However, the cooling effect of this lake was widespread in the depressed lowland northeast of Georgian Bay as evidenced by anomalies in records at sites 24-27.

The results of this paper and our study of the earlier eastward Agassiz discharge (Lewis and Anderson, 1992) suggest that the climate system, as it affects terrestrial vegetation, can be modulated by the growth and decay of wide-area, cold water surfaces. For the 10-8 ka period, these surfaces are the proglacial lakes themselves and downstream water bodies. The proglacial lakes Agassiz and Barlow-Ojibway were likely kept cold by the summer presence of melting icebergs delivered to the lakes by frequently surging icefronts (Teller, 1987). As these cold proglacial lakes expanded they would have cooled the overlying air masses more efficiently which would, in turn, have suppressed the summer climate in an enlarged area around and downwind of the lake basins. A cold Lake Agassiz surface is implicated in the climatic cooling by the coincidence in the rapid increase of the area of this lake (Fig. 2) and the onset of spruce downwind on Manitoulin Island (Warner *et al.*, 1984) at about 10 ka, prior to the resumption of eastward Agassiz drainage at about 9.6 ka. The downstream water bodies (Great Lakes and Gulf of St. Lawrence) were kept cool through suppression of seasonal surface heating by the large inflows of cold meltwater from the rapidly disintegrating Laurentide Ice margin and from runoff diverted from western Canada. The rapidity of this disintegration may have contributed to the rapid rise of sea level from 10.5-8.5 ka, termed meltwater pulse 1B by Fairbanks (1989). In the Great Lakes, the cooling mechanisms could have been rapid advection of surface water or deep vertical mixing during the summer growing season (Lewis and Anderson, 1992). The Gulf may have been cooled in summer by the lingering effects of increased sea-ice production on a freshened surface layer and by rapid advection of the fresh surface layer.

Once a large water surface is kept cool, it would facilitate the southward movement of cold air masses from the Laurentide Ice which would adversely affect the spring and summer climate of onshore areas. In addition, the differential heating between terrestrial lowlands and the large, cold water surfaces would likely have set up a strong, regional-scale pressure gradient and wind system dominated by cold onshore winds during the growing season, as presently occurs in the lowlands adjacent to Hudson Bay (Rouse, 1991).

Unlike the previous drainage at 11-10 ka which is possibly linked to the Younger Dryas cooling of the North Atlantic Ocean (Broecker *et al.*, 1989; Broecker, 1990), the 10-8 ka drainage is not reflected by any known ocean signal. Yet, it is worthy of note that a pollen anomaly consisting of declining percentages of hazel (*Corylus*) compensated by increased trends of grass (Gramineae), sorrel (*Rumex*), willow (*Salix*) and birch (*Betula*) occurred at a site in western Ireland at about 9.7 ka (Barnosky, 1988). Could the hazel crash, as Barnosky defines it, be climatically induced, *i.e.*, could the outflowing meltwater also have affected the eastern North Atlantic climate?

## SUMMARY AND CONCLUSIONS

1. Several types of pollen anomalies, some previously unexplained, characterize the period 10 to 8 ka in the central North America - Great Lakes - Gulf of St. Lawrence region.

2. The pollen anomalies represent episodes of onshore vegetation suppression that are attributed to the effects of increased deglacial drainage. That these anomalies occur along the Great Lakes - St. Lawrence drainage route supports our earlier hypothesis of meltwater-induced climate change. They are most pronounced where the effect of increased meltwater discharge had a strong influence such as within or along margins of wide-area, cold meltwater-capped water bodies (Glacial Lake Agassiz, Mattawa phase lakes of the Great Lakes and Goldthwait Sea), especially where these water bodies intersected ecotonal areas such as the spruce-pine ecotone.

3. In the Great Lakes, the cooling mechanisms could have been rapid advection of surface water or deep vertical mixing during the summer growing season. The Gulf of St. Lawrence may have been cooled in summer by the lingering effects of increased sea-ice production on a freshened surface layer and by rapid advection of the freshened surface layer.

4. The 10-8 ka period of meltwater drainage thus provides a framework for explaining variants of the normal, progressive pollen succession, and previously misunderstood anomalies in the migration rates of particular forest species, *i.e.*, the late arrival times for pine to certain areas (upper Great Lakes, eastern New Brunswick, Prince Edward Island, Cape Breton Island) even though pine was present regionally as early as 9.5 ka.

5. Documentation of paleoclimatic events, such as meltwater-induced climate change, increase our knowledge of the feedback and sensitivity of the Earth's climate system and help us better understand global change.

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