Paleohydrology of a Canadian Shield lake inferred from $^{18}$O in sediment cellulose

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Oxygen- and carbon-isotope analyses on cellulose in the postglacial sediment of Weslemkoon Lake, southern Ontario, show that the cellulose came mainly from aquatic plants or algae, rather than from terrestrial sources. If a wholly aquatic source is assumed, the oxygen-isotope content permits inferences of lake-water $\delta^{18}$O values over the past 10 000 years by accounting for the isotopic fractionation that occurs during cellulose synthesis. Chronological control is provided by pollen analysis and six $^{14}$C dates. Our reconstruction shows lake-water $\delta^{18}$O fluctuated from about 5% more negative than present in the early postglacial to 5% or more above present values during the mid-postglacial. These broad, secular shifts reflect a combination of fluctuating mean annual $\delta^{18}$O of local precipitation, evaporative isotopic enrichment of surface waters, and snowmelt-bypass effects. The first two factors reflect the changing paleotemperature and paleohydrology, respectively, whereas the third factor is a more speculative interpretation of isotope effects during snowmelt delivery to the lake. The snowmelt-bypass mechanism is supported by parallel changes in the overall abundance and seasonal distribution of precipitation. This effect is probably responsible for pronounced isotopic enrichment of the water throughout the moist climate of the past 6000 years.

Les analyses des isotopes de l’oxygène et du carbone dans la cellulose contenu dans les sédiments postglaciaires du lac Weslemkoon, dans le sud de l’Ontario, montrent que la cellulose provient principalement de plantes aquatiques ou d’algues, plutôt que de sources terrestres. Si on supposait une origine essentiellement aquatique, la teneur en isotopes de l’oxygène permet alors de déduire les valeurs de $\delta^{18}$O durant les derniers 10 000 ans, si on tient compte du fractionnement isotopique qui se produit durant la synthèse de la cellulose. Un contrôle chronologique est fourni par l’analyse des pollens et six dates au $^{14}$C. Notre reconstruction atteste que les $\delta^{18}$O, au début de la période postglaciaire, fluctuaient d’environ 5% plus négatives que les valeurs actuelles, jusqu’à 5% ou plus au-dessus des valeurs actuelles au milieu de la période postglaciaire. Ces grands changements sèculaires reflètent la combinaison d’une fluctuation moyenne annuelle des $\delta^{18}$O de la précipitation locale, de l’enrichissement isotopique par évaporation des eaux de surface et des effets de détourment des eaux de fonte. Les deux premiers facteurs sont les témoins du changement de paléotempérature et de paléohydrologie, respectivement, tandis que le troisième facteur peut être expliqué, d’une manière plus speculative, par les effets isotopiques créés durant la livraison des eaux de fonte au lac. Le mécanisme de détourment des eaux de fonte est corroboré par les changements parallèles dans l’abondance globale et la distribution saisonnière de la précipitation. Cet effet est probablement responsable de l’enrichissement isotopique de l’eau durant tout l’intervalle de climat humide des derniers 6000 ans.


Introduction

Cellulose, a nearly ubiquitous constituent of plant tissues, is frequently preserved in fossil deposits. In addition to being present in macroscopic plant matter, such as peat and wood, cellulose occurs as a finely disseminated residue within organic-rich lake sediment (Bourbonniere and Meyers 1983). Previous paleoenvironmental studies of lake sediment using isotope techniques focused on carbon-isotope variations within undifferentiated organic material (e.g., Stuiver 1975; Oana and Deevey 1960; Hakansson 1985). Improving documentation of the oxygen-isotope relations between cellulose and the water and carbon dioxide from which it forms suggests potential for obtaining paleoenvironmental information from this specific fraction of sedimentary organic matter. This thesis is borne out by the following interpretation of oxygen- and carbon-isotope results for cellulose extracted from cores of the gyttja underlying a lake in southern Ontario.

Study area

Cores were obtained from Weslemkoon Lake (45°02’N, 77°26’W), a 1955 ha, irregularly shaped lake lying in the southern extension of the Laurentian Highlands (Fig. 1). The lake is enclosed within the outcrop area of a granitic batholith that is part of the Grenville Province of the Canadian Shield. The surrounding area is discontinuously mantled by sandy, calcareous drift of Wisconsinan age that includes outwash and esker deposits at the south end of the lake and a small esker segment at the north end. The lake is underlain by substantial accumulations (in places over 25 m thick) of stratified glaciolacustrine sediments deposited during deglaciation, when northward drainage was impeded by remnant ice in the valleys of Little Mississippi, York, and Madawaska rivers. These sediments are partly covered by postglacial gyttja that is locally over 4 m thick (Shilts and Farrell 1982).

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The main body of the lake comprises several interconnected basins with maximum depths of 10–36 m (Fig. 2). The altitude of the lake surface (at 316 m asl) is maintained 1–2 m above the natural level by a weir at the outlet to Little Mississippi River. Most of the lake is bounded by steep, bare outcrop, aside from the shallow, island-filled bay at the south end, where sandy outwash deposits were flooded by the higher water level. Limnological surveying in the summers of 1983 and 1984 showed thermal stratification but almost negligible hypolimnetic oxygen depletion. Surface lake-water pH is 7.5–8.0, owing to the buffering effect of the surrounding and underlying calcareous glacial deposits.

The climatic normals for Bancroft (327 m asl), which is 40 km west of Weslemkoon Lake, are as follows: mean daily temperature, 4.8°C; mean January temperature, −10.4°C; mean July temperature, 18.6°C; and mean annual precipitation, 880 mm (Environment Canada 1982a, 1982b). The regional mixed forest consists of conifers (Pinus strobus, 9%; Pinus resinosa, 1%; Thuja, 7%; Abies, 5%; Tsuga, 4%; Picea, 3%) and hardwoods (Acer saccharum, 19%; Populus, 15%; Betula, 10%; Ulmus, 7%; Quercus, 5%; Fraxinus, 4%; Fagus, 3%; Tilia, 3%; miscellaneous, 5%) (Ontario Department of Lands and Forests 1957).

Previous research

Research in southern Ontario using stable isotopes includes study of fossil wood cellulose from the Brampton site (Edwards et al. 1985; Edwards and Fritz 1986) and reexamination of isotopic data from marl cores from Little Lake (near Cambridge) and Inglesby Lake (near Tamworth) (Edwards and Fritz 1988) (Fig. 1). The wood-cellulose studies related cellulose δ18O and δD values to the isotopic composition of the groundwater taken up by the plant (local meteoric water) and the relative humidity at the time of the plant’s growth by accounting for the isotopic fractionations due to evaportranspiration and cellulose synthesis. Fossil wood samples spanning most of the postglacial period in southern Ontario yielded “paleoisotope” and “paleohumidity” profiles that show systematic secular variations in temperature and moisture. Correlation of the changing meteoric water isotopic composition and inferred temperature changes with oxygen-isotope data from marl cores provides additional support for the cellulose-based paleoclimate reconstructions (Fig. 3).

The paleotemperature and paleohumidity curves shown in Fig. 3 divide postglacial climate history in the eastern Great Lakes region into four zones: zone I from local deglaciation to about 7400 years ago was characterized by ameliorating conditions that were colder and drier than present; zone II from ca. 7400 to 5800 years ago was mainly warmer, but still drier, than present; zone III from ca. 5800 to 1500? years ago was warmer and moister than present; and zone IV from ca. 1500? years ago to present was characterized by the relatively cool and moist climate that prevails today. Although based on a simple two-dimensional expression of past conditions, the zonation is consistent with the classical interpretation of postglacial climatic change from biotic evidence (e.g., Bryson and Wendland 1967), including a period of higher than present mean annual temperatures (the “hypsithermal”: zones II and III) (cf. Webb et al. 1987).

Independent evidence for postglacial climate is derived from simulations, fossil pollen, and plant macrofossils. Simulations at 3000, 6000, 9000, and 12 000 years ago (Webb et al. 1987) indicate that until 9000 years ago mean annual temperature was about 5°C below the present, whereas at 9000 and 6000 it was 1–2°C above the present. Up to 6000 years ago, precipitation minus evaporation was lower than today, indicating a dry as well as warm hypsithermal. This reconstruction is
broadly confirmed by the application of modern pollen-climate response functions to the fossil pollen record. The hypsithermal is further supported by fossil white pine and hemlock needles in lakes above the modern altitudinal limits of these trees in the mountains of New York and New Hampshire (Davis 1983). This suggests that climate 9000–5000 years ago was 2°C warmer and that precipitation was 125 mm lower than today. Much of the post-hypsithermal temperature decline has occurred over the past 2000 years; Gajewski (1988) used fossil pollen-climate functions to demonstrate a 1.5°C decline in summer temperature in New York State over this interval. These lower temperatures were accompanied by fluctuating but slightly increased precipitation.

**Sampling and analysis**

The three cores used for isotopic study (Fig. 2) were obtained by divers as continuous sections using a 75 mm diameter piston corer. Gyttja samples of the uppermost 20 cm were taken by hand. Core 1 contained the most complete stratigraphic sequence. The basal unit in this core consisted of firm, grey, silty clay. Judging by sediment recovered in other cores and the acoustic subbottom profiling results of Shilis and Farrell (1982), this silty clay is the thick glaciolacustrine deposit underlying much of the lake. The silty clay graded (over several millimetres) into an 8 cm thick unit of silty, olive-green gylttja that was overlain abruptly by a second 31 cm thick unit of silty clay. This second clay unit graded upward to olive-green, silty gylttja that graded into watery, olive-black gylttja at the core top. Cores 2 and 3 both contained repetitions of the silty, olive-green to watery, olive-black gylttja sequence but fell short of penetrating the underlying clay because of the thicker accumulations of organic-rich sediments at these sites.

The chronological correlation between cores 1 and 2 was established by radiocarbon dates on organic matter extracted from the gylttja and was confirmed by the results of thermal (loss-on-ignition (LOI)) and pollen analyses (Fig. 4). Correlation between cores 2 and 3 was based on lithologic similarity, LOI, and relative rates of sedimentation at the two sites.

Gyttja was collected for isotopic analyses as bulk samples in 5 cm (core 1) and 10 cm (cores 2 and 3) stratigraphic increments, which were freeze dried and thoroughly homogenized prior to further subsampling. Cellulose was extracted from the <149 µm fraction of the sediment following the procedure of Green (1963) for purification of wood cellulose. An additional step was included to separate organic matter from mineral detritus (mainly silt-size quartz) by flotation with zinc chloride solution, following the initial solvent extraction and before subsequent bleaching (delignification) and alkali hydrolysis. Core 3 was used for carbon-isotope analysis of the total organic fraction in comparison with the cellulose; these gyttja samples received only a simple pretreatment with dilute hydrochloric acid to remove carbonate material (as described by Stuiver 1975).

The nickel-pyrolisys technique (Thompson and Grey 1977) and a standard combustion procedure were used to generate carbon dioxide for mass spectrometric determination of the $^{18}O/^{16}O$ and $^{13}C/^{12}C$ ratios respectively, within the sediment cellulose and organic matter. The results are expressed in the conventional “δ” notation, representing the per mil deviation from the international standards for δ$^{18}O$ (standard mean ocean water (SMOW)) and δ$^{13}C$ (Pee Dee belemnite (PDB)). Cited values have an analytical uncertainty of ±0.2‰ for both δ$^{18}O$ and δ$^{13}C$.

**Results and discussion**

**Pollen data**

The pollen stratigraphy from cores 1 and 2 is typical of other postglacial sites in southern Ontario (McAndrews 1981).
There are four main pollen zones, with only the narrow pre-settlement zone 3d missing from the top of core 2. The Weslumko Lake record contains an unusually detailed early postglacial spruce pollen zone 1, permitting differentiation of subzones 1a and 1b (cf. McAndrews and Jackson 1988). Comparable pollen sequences include Foun Lake (McAndrews 1981), which lies 95 km northwest of Weslumko, and Inglesby Lake (Fritz et al. 1987b), which lies 65 km south-southeast, although neither of these sequences resolve subzones 1a and 1b. The zone boundaries at Weslumko Lake are constrained by radiocarbon dates.

Subzone 1a within the lower clay of core 1 is dominated by Pinus, Betula, and Cyperaceae, together with small peaks of Alnus, Salix, and Artemisia. Trees were likely absent at this time; tree pollen was probably either blown from southern forests (and therefore contemporaneous with the sediment) or released from melting glacial ice nearby (McAndrews 1984). The other pollen suggest a local tundra dominated by Betula glandulosa, Alnus crispa, and Salix.

Subzone 1b, contained within the lower gyttja layer and part of the overlying clay in core 1, shows a succession to forest in the watershed, with initial dominance by Populus (probably P. balsamifera) followed by Picea. In lake sediments from Ottawa valley, the Populus peaks dated at about 10 600 BP (GSC-1956) (Mott 1978), which is somewhat earlier than our 9370 BP (TO-836) date (on a poplar twig). The layer of gyttja could reflect an interval of relatively high algal productivity in the lake, perhaps in response to nutrient input from abundant leaf litter provided by the deciduous poplar. The subsequent succession to Picea, which has a relatively nutrient-poor litter, could explain the return to mineral sedimentation in the upper part of the subzone.

We suggest an interpolated date for the lower boundary of zone 2, the Picea–Pinus transition, of about 9000 BP. Zone 2 is dominated by Pinus, initially P. banksiana–resinosa type (subzone 2a), and then by P. strobos (subzone 2b), with the subzone boundary having an interpolated age of about 8400 years. The zone passes from clay at the base into gyttja, presumably in response to increasing limnic productivity. The upper boundary with zone 3 is marked by the rise of Tsuga and Fagus; the sediments straddling this boundary are dated at 6750 BP (WAT-1110) in core 2.

Zone 3 is dominated by P. strobos, which declines upward to be partly replaced by Betula. Subzones 3a and 3c are defined by peaks of Tsuga, whereas the intervening subzone 3b has a Tsuga minimum bounded by dates of 4810 BP (WAT-1151) and 3270 BP (WAT-1112). The Tsuga minimum is geographically widespread in east-central North America and is consistently dated to begin at 4800 BP; the decline in Tsuga trees may have been triggered by a pathogen rather than climatic change (Davis 1981). At Weslumko Lake, Tsuga is initially succeeded by Betula, followed by P. strobos and Fagus. With the rise of Tsuga in 3c, P. strobos continues its long-term decline. Carbonate has a slight but consistent minimum during subzone 3b, perhaps reflecting decreased leaching of soil carbonates with reduction of the acidic litter produced by Tsuga during this interval. Most pollen diagrams from southern Ontario have a subzone 3d, beginning with the interval 1500–500 BP, in which P. strobos increases sharply. Weslumko Lake sediment containing this subzone may have been lost from core 2 during collection.

Zone 4 is recorded by a slight rise in Gramineae and Ambrosia and an increase in noncombustible residue in the sediment. This reflects the proliferation of weeds and soil erosion due to Euro-American disturbance in the past century.

The lithologic and pollen stratigraphies reflect the general pattern of environmental change during deglaciation and climatic amelioration in the Weslumko Lake area. Tundra was followed by successive migrations of forest trees until about 7000 years ago. Since then, forest succession has probably responded mainly to the postulated Tsuga pathogen and Euro-American settlement.

A feature of note is the gradual long-term decline of P. strobos and rise of Betula during the past 7000 years, sug-
Table 1. Radiocarbon dates from Weslemkoon Lake cores 1 and 2, corrected to δ13C = -25‰ (PDB)

<table>
<thead>
<tr>
<th>Core</th>
<th>Interval (cm)</th>
<th>Material</th>
<th>Apparent age (δ14C years BP ± 1σ)</th>
<th>Laboratory No.</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>105–110</td>
<td>Bulk organics</td>
<td>5 770 ± 130</td>
<td>WAT-1106</td>
</tr>
<tr>
<td>1</td>
<td>170–174</td>
<td>Bulk organics</td>
<td>8 820 ± 250</td>
<td>WAT-1103</td>
</tr>
<tr>
<td>1</td>
<td>205–206</td>
<td>Wood</td>
<td>9 370 ± 120</td>
<td>TO-836</td>
</tr>
<tr>
<td>1</td>
<td>210–213</td>
<td>Bulk organics</td>
<td>12 640 ± 795c</td>
<td>WAT-1104</td>
</tr>
<tr>
<td>2</td>
<td>90–100</td>
<td>Bulk organics</td>
<td>3 270 ± 150</td>
<td>WAT-1112</td>
</tr>
<tr>
<td>2</td>
<td>170–180</td>
<td>Bulk organics</td>
<td>4 810 ± 110</td>
<td>WAT-1115</td>
</tr>
<tr>
<td>2</td>
<td>280–290</td>
<td>Bulk organics</td>
<td>6 750 ± 130</td>
<td>WAT-1110</td>
</tr>
</tbody>
</table>

NOTE: Laboratories: WAT, University of Waterloo; TO, University of Toronto.

*This result is considered unreliable, based on palynological evidence and the much younger date subsequently obtained from accelerator dating of a poplar twig (TO-836) within the same gyttja layer.

Isotopic data

The isotopic analyses on the three cores are plotted relative to a linear time scale in Fig. 5a. The δ18O and δ13C profiles for cellulose from cores 1 and 2 display contrasting characters. The close agreement between δ18O values for both cores in the period of overlap (verified by additional replication of analyses in this zone) indicates that a single composite profile for cellulose δ18O is compatible for both cores. The equivalent carbon-isotope data are consistently offset, arguing against an analogous common profile. The δ13C of whole organic matter in core 3 is lower and less variable than that of the cellulose fraction in the first two cores, reflecting overprinting of the cellulose isotopic signature by other organic constituents. The range of values for δ13C (−26.5 ± 1‰) is typical of the whole organic fraction of gyttja in other lakes in southern Ontario (T. W. D. Edwards and J. H. McAndrews, unpublished data) and in midlatitude lakes elsewhere (Stuiver 1975; Hakansson 1985).

Interpretation of oxygen-isotope data from Weslemkoon Lake is complicated by the possible existence of both aquatic and terrestrial plant cellulose in the fine fraction of the sediments, since the two sources are expected to have differing isotopic signatures. Direct measurement (De Niro and Epstein 1979, 1981; Sterberg et al. 1984a, 1984b) and inference (Edwards et al. 1985; Edwards and Fritz 1986) show that during cellulose synthesis there is a nearly invariant oxygen-isotope separation between the cellulose and the associated leaf water of about 28 ± 1‰. Leaf water of aquatic plants shares the isotopic composition of the surrounding water, thus permitting direct estimation of ambient water δ18O from the oxygen isotopes of the cellulose. The cellulose of terrestrial plants, on the other hand, inherits the additional isotopic enrichment of leaf water (relative to the groundwater taken up by the roots) that occurs because of evapotranspiration. Modern climatic conditions during the growth season in southern Ontario result in isotopic differences between plant cellulose and local groundwater of about 34–36‰ (Edwards et al. 1985); drier conditions of the past led to enrichment of over 41‰ (Edwards and Fritz 1986).

The δ18O values for Weslemkoon Lake water at surface and at depth ranged from −9.0 to −7.7‰ in the summers of 1983 and 1984. (Although pronounced thermal stratification develops seasonally in the lake, the water mass was essentially isotopically homogeneous during individual sampling episodes.) The average fractionation (α) of 1.0282 between cellulose and leaf water reported by Edwards et al. (1985), where αcell-water = (δcell + 1000)/(δwater + 1000), suggests that aquatic plants now living in the lake should have cellulose δ18O values between 18.9 and 20.3‰. This range brackets the sediment-cellulose values of 19.8 and 20.2‰.

Modern terrestrial-plant cellulose near the lake is unlikely to be depleted in 18O to the same extent, despite uptake of local meteoric water that is isotopically light relative to lake water (meteoric water δ18O = −12.2‰; T. W. D. Edwards and J. H. McAndrews, unpublished data; see also Fritz et al. 1987a). The relation between leaf-water enrichment and photosynthetic humidity observed by Edwards et al. (1985), using the above δ18O value and photosynthetic humidity of 0.72 ± 0.02 (abstracted from data in Canada Department of Transport 1968), provides an estimate of 23.2 ± 0.7‰ for the δ18O of terrestrial-plant cellulose likely to be deposited in the lake. This agrees with the 22.9‰ average value for cellulose obtained from two trees living in local microclimatic extremes: a pine tree growing in a sheltered leeward location (where minimum evapotranspirative enrichment effects are expected) had cellulose δ18O of 21.5‰, and a spruce tree growing in an exposed location (where maximum enrichment effects should occur) had δ18O of 24.3‰.

Mass-balance considerations permit assessment of aquatic- and terrestrial-cellulose proportions in the sediments. Sediment-cellulose δ18O of 19.8–20.2‰, aquatic-cellulose δ18O of 18.9–20.3‰, and terrestrial-cellulose δ18O of 21.5–24.3‰ indicate an absolute range for the aquatic fraction of 0.50–1.13; mean δ18O values for each category yield an estimate of 0.88, which is similar to the central value of 0.89 obtained by substituting the inferred terrestrial-cellulose δ18O value of 23.2 ± 0.7‰. Hence, based on isotopic data, aquatic plants likely contribute about 90% of the fine-grained sediment cellulose under modern conditions.

The oxygen- and carbon-isotope data from the underlying sediment provide indirect evidence that aquatic cellulose formerly predominated in Weslemkoon Lake. Notable is the
close alignment of the cellulose $\delta^{18}O$ profiles during the 1500 year period common to both cores. Maintenance of highly similar oxygen-isotope signatures during this interval at two widely separated sites (and at a time of relatively rapid change in $\delta^{18}O$) would be expected for the cellulose of aquatic plants living within the same water body. Influx of significant terrestrial cellulose is unlikely, since the observed signature would require continuous deposition of equal proportions of terrestrial-plant matter of the same isotopic composition at the two sites over this extended period.

The lack of overlap between the two carbon-isotope profiles (which has perhaps persisted to the present, judging by the similar difference between the surface samples) is also most compatible with predominance of aquatic-plant cellulose. The $^{13}C$ content of all plants is controlled by the isotopic composition of ambient carbon dioxide and the photosynthetic pathways employed by the plants. Variability in the carbon-isotope composition of local terrestrial plants would have been constrained by the relatively invariant isotopic composition of atmospheric carbon dioxide and preeminence of the C$_3$ photosynthetic pathway in likely source vegetation (Smith and Epstein 1971). As a result, terrestrial-plant cellulose would tend to minimize carbon-isotope differences between sites. The distinct offset between the $\delta^{13}C$ profiles is more consistent with the broad range of possible carbon-isotope compositions expected for aquatic plants. Persistent variations between sites could reflect the characteristic spatial and temporal variability in the isotopic composition of ambient carbon in lakes and the differing photosynthetic pathways found in submergent plants and algae (Oana and Deever 1960; Hoefs 1980; Sternberg et al. 1984a, 1984b).

Weslemkoon Lake oxygen-isotope record

Previous isotopic studies in southern Ontario aid the interpretation of the Weslemkoon Lake oxygen-isotope data. Because precipitation is the ultimate source of all water in the catchment area, inferred meteoric-water $\delta^{18}O$ data (Fig. 5b) can be used to resolve fluctuations in cellulose oxygen-isotope content that occurred independently of changes in the isotopic composition of local precipitation. Thus, the core data are replotted in Fig. 6 as inferred deviations from contemporary meteoric-water composition ($\Delta^{18}O_{\text{cell-water}}$ values) that express isotopic variations in the sediment cellulose not inherited from meteoric water $\delta^{18}O$.
values between 6500 and 7000 BP, which approach 28‰ (the biochemical fractionation associated with cellulose synthesis). These sediment samples likely contain nearly pure aquatic cellulose, since contemporaneous terrestrial cellulose was richer in 18O. Most of the samples from 9600 to 6500 BP fall along a trend that probably approximates the evaporative-enrichment line for the lake, judging by the evaporative-enrichment response of nearby Inglesby Lake over this interval (Edwards and Fritz 1988, Fig. 5).

The 7900 BP sample, which falls well to the right of line B in Fig. 5, is the only sample older than 6500 BP likely to contain significant terrestrial cellulose. Less evaporative enrichment of the lake water than suggested by line B would be required to account for terrestrial input in other samples, which is unlikely, given the climate of the early Holocene. Conversely, more-pronounced evaporative enrichment is not reconcilable with the sediment-cellulose δ18O values, since the leaf water of aquatic plants cannot be isotopically lighter than the surrounding lake water. Simple two-component mixing of aquatic and terrestrial cellulose in a 66:34 ratio explains the Δ18O value for the 7900 BP sample.

The pronounced divergence of the Weslemkoon data from line B after 6500 BP indicates that something other than evaporative enrichment of the lake water began to influence the isotopic separation between the cellulose in the sediments and meteoric water. Although mixing effects (with some samples containing up to 100% terrestrial cellulose) could account for most of the elevated values of Δ18Ocell–water, such a radical shift to predominance of terrestrial cellulose is not supported by other data. (Note that this explanation would not account for the outliers sample at ca. 3300 BP, without invoking an extremely high aquatic-cellulose Δ18O value.” The more likely alternative is that abundant aquatic cellulose persisted, leading to a simpler interpretation of the Δ18O data in terms of secondary isotopic effects on the lake water, which has implications for interpreting the paleohydrology of Weslemkoon Lake.

Paleohydrology of Weslemkoon Lake

Isotopic composition of lake water is determined by the composition of local meteoric water and from secondary factors such as evaporation and snowmelt mixing. Although evaporative enrichment is well documented, the effect of snowmelt mixing (or more aptly “snowmelt bypass”) on the isotopic composition of lake water has received little notice. Recent isotopic studies by Schiff and English (1988) confirm various chemical investigations (e.g., Jeffries et al. 1979; Hendrey et al. 1980; Bergman and Welch 1985) showing that the precipitation stored in the winter snowpack in a lake catchment may pass rapidly through the system as a more or less discrete sub-ice layer prior to breakup. Because winter precipitation is isotopically light compared with that originating in other seasons, this selective loss of snowmelt causes apparent enrichment of the lake water in 18O (and 2H) with respect to precipitation.

The combined influence of snowmelt bypass and evaporative enrichment on the isotopic composition of lake water can be illustrated on a crossplot of δ18O versus δ2H (Fig. 7). Snowmelt bypass causes apparent enrichment relative to local meteoric water along a trajectory of slope 0 (i.e., along the meteoric-water line), whereas evaporation causes offset along a line of shallower slope. Changes in climatic and hydrologic conditions in a lake catchment will affect the relative and abso-
olute magnitudes of the isotope effects from these two processes.

The pronounced offset between postulated evaporative-enrichment effects (line B, Fig. 6) and total cellulose—meteoric-water separation for core samples from Weslemkoon Lake suggests the existence of strong snowmelt-bypass effects in this lake over the past 6000 years. A speculative reconstruction of changing snowmelt-bypass effects versus time together with changing evaporative enrichment (Fig. 8) corresponds to inferred climatic changes in southern Ontario.

According to this reconstruction, maximum bypass occurred during the moistest climatic interval (zone III), when higher water levels and maximum spring discharge would contribute to the most efficient throughflow of meltwater. Conversely, minimal bypass effects apparently occurred during the dry early postglacial (zone I), when low water levels and discharge rates in the spring ensured greater representation of winter precipitation in the total lake budget.

Changing seasonal distribution of precipitation may also have influenced snowmelt-bypass effects. The absence of such effects during the early postglacial could have stemmed, in part, from relatively sparse winter precipitation, owing to a more southerly arctic front compared with the present. Incorporation of a larger proportion of annual precipitation in the winter snowpack would have had the opposite effect in the middle to late Holocene as a consequence of greater moisture availability.

The modern isotopic separation between Weslemkoon Lake water and local meteoric water and the magnitudes of evaporative enrichment and snowmelt-bypass effects are probably influenced by human intervention. The raising of the lake level by construction of the outlet weir could have variable impacts owing to changing lake volume and seasonal rate of discharge.

![Fig. 8. Generalized fluctuations in evaporative enrichment and snowmelt bypass in Weslemkoon Lake during the postglacial. Evaporative enrichment is inferred mostly from previous isotopic studies in southern Ontario. Snowmelt bypass is estimated from the residual offset between line B and the core data plotted in Fig. 6 (with the exception of the data point at 7900 BP). The climatic zonation is from Edwards and Fritz (1988) (also see Fig. 3).](image)

This imparts some additional uncertainty to the reconstruction of the modern situation in Fig. 8 but has no affect on the paleohydrologic interpretation.

**Summary and concluding comments**

Cellulose in the sediment of Weslemkoon Lake originated primarily from aquatic plants or algae, and thus the cellulose $\delta^{18}O$ provides a history of the oxygen-isotope content of the lake water (see lower scale in Fig. 5a). Other isotopic studies allow speculative disentanglement of the signatures of changing meteoric-water composition, evaporative enrichment, and snowmelt-bypass effects from the lake-water $\delta^{18}O$ record.

The inferred paleohydrologic changes also compare favourably with the local vegetation history. In the time of tundra and subsequent coniferous forest, evaporation had the dominant secondary influence on lake-water composition. Snowmelt-bypass effects became important at about the time when modern-type mixed forest appeared in the watershed, possibly in part related to changes in runoff characteristics (induced by albedo change?), soil development, or other factors in addition to climate. Because snowmelt bypass depends on lake stratification during spring runoff, perhaps the thermal characteristics of the lake (which may also reflect climate) are significant.

These investigations are one of a series on the paleoclimatic history of southern Ontario using isotope techniques. The first studies by Edwards et al. (1985) and Edwards and Fritz (1986) showed that the relation between the oxygen-isotope composition of wood cellulose and the groundwater taken up by the plant could be expressed by the generalized equation

$$\delta^{18}O_{\text{cell}} = \delta^{18}O_{\text{water}} + \epsilon_{\text{cell-water}} + \epsilon_{\text{evap}}$$

where $\delta^{18}O_{\text{water}}$ is the isotopic composition of local meteoric water, $\epsilon_{\text{cell-water}}$ is the net biochemical fractionation between leaf water and cellulose, and $\epsilon_{\text{evap}}$ is the isotopic enrichment resulting from kinetic and equilibrium effects during evapo-
transpiration. Coupling this equation with the equivalent relation for hydrogen isotopes and the global meteoric-water line relating oxygen and hydrogen isotopes in meteoric water permitted time-series reconstructions of paleo-isotope and paleo-humidity estimates (Edwards and Fritz 1986).

The second stage of the investigations compared oxygen-isotope data from marl cores with those from the wood cellulose (Edwards and Fritz 1988) and showed that the oxygen-isotope relation between marl and meteoric water could be summarized by the equation

\[ \delta^{18}O_{\text{marl}} = \delta^{18}O_{\text{water}} + \epsilon_{\text{marl-water}} + \epsilon_{\text{hydro}} \]

where \( \epsilon_{\text{marl-water}} \) is the temperature-dependent equilibrium fractionation between marl and lake water, and \( \epsilon_{\text{hydro}} \) represents the isotopic separation between meteoric water and lake water due to hydrologic factors. For the lakes studied, \( \epsilon_{\text{hydro}} \) was dominated by the evaporation effects and was thus very similar to \( \epsilon_{\text{evap}} \) in [1].

Our sediment-cellulose studies suggest that an entirely analogous equation describes the oxygen-isotope relation between sediment cellulose and local meteoric water for Weslemkoon Lake:

\[ \delta^{18}O_{\text{cell}} = \delta^{18}O_{\text{cell-water}} + \epsilon_{\text{cell-water}} + \epsilon_{\text{hydro}} \]

where \( \epsilon_{\text{cell-water}} \) is the fractionation associated with cellulose synthesis (identical to \( \epsilon_{\text{cell-water}} \) in [1]), and \( \epsilon_{\text{hydro}} \) is the isotopic separation between meteoric water and lake water (akin to \( \epsilon_{\text{hydro}} \) in [2]). For Weslemkoon Lake, \( \epsilon_{\text{hydro}} \) reflects both varying evaporative-enrichment effects and the apparent isotopic enrichment imparted by snowmelt bypass. Aside from a possible anomaly at about 7900 BP, admixture of terrestrial cellulose has probably not had a significant influence on the paleo-isotope record of this lake; however, false enrichment effects mimicking evaporative enrichment or snowmelt bypass could occur in other situations because of terrestrial-cellulose input.

As the above equations indicate, all three systems inherit the fundamental signature of meteoric-water isotopic composition (which is a close proxy for mean annual temperature). Superimposed on the meteoric-water signature are varying isotopic signals deriving from the climatic-moisture regime. A remarkably consistent characteristic of the paleotemperature and paleohydrologic changes in southern Ontario since deglaciation has emerged from these efforts. Such isotopic techniques offer potential for additional refinement of the paleoenvironmental history in this area and elsewhere.

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