Water levels in Lake Ontario 4230–2000 years B.P.: evidence from Grenadier Pond, Toronto, Canada

Francine M. G. McCarthy¹ & John H. McAndrews²

¹ Department of Geology, University of Toronto, Toronto, Canada, M5S 1A1; ² Department of Botany, Royal Ontario Museum, 100, Queen’s Park Crescent, Toronto, Canada, M5S 2C6, and Departments of Geology and Botany, University of Toronto, Toronto, Canada, M5S 1A1; Present address: Department of Geology, Dalhousie University, Halifax, Canada, B3H 3J5

Received 25 February; accepted 24 May 1988

Key words: Great Lakes water levels, Lake Ontario, pond sedimentation

Abstract

Lake Ontario water levels have been rising for the past 11 500 years due to differential isostatic rebound of the St. Lawrence outlet. Small scale fluctuations in water level superimposed on this general trend have received little study, with the exception of the ‘Nipissing Flood’.

The transgression of a Grenadier Pond was studied from cores along a transect from the bar that separates the pond from Lake Ontario to the marsh on the north shore. Radiocarbon dates of the transition from swamp peat to pond marl in five cores provide estimates of the rate of water level rise since 4230 years B.P. These estimates are supported by changes in sediment type and in abundance of pollen and seeds of aquatic plants. There were three short intervals of accelerated water level rise in Grenadier Pond, around 4200, 3000, and 2000 years B.P., when water levels rose up to 2 m instantaneously, within the resolution of radiocarbon dating. Sedimentological and paleobotanical data suggest that Grenadier Pond was an open embayment of Lake Ontario until 1970–1850 years B.P., when it was isolated by the bar, and therefore sediments deposited prior to this time reflect water levels in Lake Ontario.

Short term departure of up to 2 m from the average rate of water level rise over the past 4000 years, as observed in the record at Grenadier Pond, is of the same range as historically observed departures from the mean lake stage of Lake Ontario. This implies that a threshold discharge exists above which broadening of the outflow channel occurs to accommodate further increase in discharge with little rise in lake level. The intervals of accelerated water level rise in Lake Ontario broadly coincide with periods of cool, wet climate, suggesting that increased moisture may have caused the short term fluctuations in water level.

* This is the second of a series of papers to be published by this journal that was presented in the paleolimnology sessions organized by R. B. Davis and H. Löffler for the XIIth Congress of the International Union for Quaternary Research (INQUA), which took place in Ottawa, Canada in August 1987. Drs. Davis and Löffler are serving as guest editors of this series.
Introduction

The level of Lake Ontario was long assumed to have risen at an exponentially decreasing rate solely in response to differential isostatic rebound of the St. Lawrence outlet since the Admiralty Phase (or Early Lake Ontario) 11 500 years B.P. (Muller & Prest, 1985). Recent work indicates that the Holocene water level history of Lake Ontario is more complex than the simple rebound model suggests. Sutton et al. (1972) and Anderson & Lewis (1982, 1985) indicate that periods of accelerated water level rise followed by temporary stabilization occurred around 5000 to 4000 B.P. The accelerated water level rise, called the ‘Nipissing Flood’, was attributed to the capture of Upper Great Lakes drainage.

Larsen (1985) in his stratigraphic study of shorelines of Lakes Michigan and Huron showed that water level fluctuations occurred in the late Holocene. The high water levels lasted 200–300 years and were 1–2 m above the historic mean of the lakes. He suggests that the fall in water level from the Nipissing to the Algoma and later Holocene levels, as well as the fluctuations in the late Holocene, were climate-related, citing pollen, archeological, and neoglacial evidence. Our objective is to describe small-scale, post-Nipissing Flood water level fluctuations in Grenadier Pond and to show how these fluctuations reflect the late Holocene water-level history of Lake Ontario.

This study

Evidence for small-scale fluctuations in water level in Lake Ontario can be found and dated in embayments containing organic authigenic sediments (Fig. 1), as was done by Otto & Dalrymple (1983) in the St. Catherines area. Rates of transgression can be measured by 14C dating of the inception of pond sediments at successively higher elevations in the embayment away from the lake.

The sediments in embayments contain pollen and plant macrofossils that provide additional data for estimating water depths, record progradation of fringing marshes during intervals of stable or falling water levels, and permit differentiation between gradual and sudden transgression of the shoreline. Vegetational succession reflects shoreline transgression and increasing water depth as upland species are replaced by emergent aquatic marsh species. If transgression continues, these are in turn replaced by floating and submerged aquatic species, commonly found in water to 4 m depth in Ontario lakes, below which there is a sharp decline in species richness and biomass (Crowder et al., 1977). This depth varies with physical limnological conditions in each basin. Because aquatic pollen and plant macrofossils are locally deposited, an abundance of emergent aquatic fossils reflects sedimentation in the littoral zone, the part of the basin shallow enough to support rooted vegetation.

Agitated water and high energy conditions would be expected to accompany rapid water level rise in Lake Ontario. Increased clastic deposition resulting from accelerated longshore drift and shoreline erosion is easily noted in marl-dominated embayments.

Grenadier Pond (Fig. 2) was chosen to study the transgression of Lake Ontario embayments due to its long sedimentary record, its long, narrow morphology perpendicular to Lake Ontario, and its location in one of the five areas of sand concentration in Lake Ontario (Thomas et al., 1972).

The pond is isolated by a bar and its level in May, 1985, was 1.3 m above the level of Lake Ontario. The bar has been widened in historic times by landfiling, but maps and records indicate that the pond was isolated before European exploration (Robinson, 1933). The level of the pond is maintained by a culvert today, and so does not necessarily reflect natural conditions. Prior to this artificial stabilization, the elevation of the pond relative to Lake Ontario depended on the elevation of the natural outlet stream.

Methods

Five cores were taken using a modified Livingstone piston sampler (Wright, 1967) along
Fig. 1. The Lake Ontario shoreline in the Toronto area, showing several embayments.
a transect from the bar that separates the pond from Lake Ontario to the cat-tail marsh on the north shore (Fig. 3). The upper metre of sediment at each coring site was sampled with a Rowley-Dahl sampler (Rowley & Dahl, 1956) to retain the sediment-water interface, preserve stratigraphy of upper watery sediments, and allow water depths to be accurately measured.

Sediments were described visually and analysed using differential thermal analysis (Dean, 1974). Absolute chronology was provided by radiocarbon dating. Both accelerator dates on picked terrestrial plant macrofossils and beta emission dates on bulk sediment samples were obtained.

Sediment samples were prepared for pollen
Fig. 3. Lithological cross-section along S-N transect in Grenadier Pond. North is to the right. Numbers 0 to 5 refer to coring sites. Note the peat/marl contact which represents transgression and the four clastic units in the marl-dominated embayment.
analysis using standard procedures (Faegri & Iversen, 1975). Coarse clastics and peats were sieved through 0.15 and 0.015 mm mesh in addition to the chemical treatment. Spores of Lycopodium clavatum (Stockmarr, 1971) were used as marker particles, permitting pollen density to the estimated. The pollen and spores were identified using the key of McAndrews et al., (1973). A sum of over 200 pollen grains per sample was used to generate pollen diagrams.

Selected 10 cm core intervals were sieved through 0.5 mm mesh to concentrate macrofossils. Seeds were identified using Montgomery (1977) and Martin & Barkley (1961) and by comparison with the reference seed collection of the Royal Ontario Museum.

Results

The stratigraphic succession typical of Lake Ontario lagoons is from basal glaciolacustrine sediments to peat, peaty marl, and marl (Anderson & Lewis, 1982). The marl is overlain by a dark silty organic marl which persists to the present. The change in sedimentation to foul-smelling silty organic marl is detectable in all cores taken from Lake Ontario bays and lagoons, and corresponds to the rise in Ambrosia pollen, about A.D. 1850 (McAndrews & Boyko-Diakanow, in press). The Ambrosia rise was $^{14}$C dated in the Humber Marsh, about 1 km west of Grenadier Pond, at 150 ± 50 years B.P. (Weninger & McAndrews, submitted).

A similar stratigraphy exists in Grenadier Pond, where a humic, woody peat is overlain by peaty (organic) marl, marl, coarse organic detritus, and silty organic marl. Three intervals of clastic sedimentation, clastic units A, B, and C in order of decreasing age, occur below the Ambrosia zone, clastic unit D (Fig. 3). Two factors make the identification of these clastic units difficult without thermal analysis (Fig. 4): the decrease in grain size away from the shoreline, and the dilution by authigenic marl production, generally highest at intermediate water depths (ca. 1–3 m) where carbonate-secreting organisms are most abundant.

Radiocarbon dates are listed in Table 1. Note that accelerator mass spectrometry (AMS) dates on terrestrial plant samples date approximately 3% younger than bulk sediment dates from the same interval in Grenadier Pond.

The contact between woody peat and marl records transgression. Transgression is diachronous, dating at 4230 ± 60 years B.P. (AMS 4094 ± 60 years B.P.) in core 0, 2980 ± 60 years B.P. in core 1, 2930 ± 80 years B.P. (AMS 2830 ± 50 years B.P.) in core 2, 1970 ± 100 years B.P. in core 3 and 1850 ± 60 years B.P. (AMS) in core 4 (Figs. 3, 4). Dates at successively higher elevations along the transect provide quantitative estimates of the rates of water level rise between the transgression of each core site along the transect (Table 2). The accuracy of the rate estimates depends on the dating error (± 50 to 100 years) and on the accuracy of measurement of the peat/marl contact, which is ± 5cm.

The vegetational succession was determined in cores 0, 1 and 2 from pollen and plant macrofossils (Fig. 5). Pollen zones 4 and 3 of McAndrews (1981) were identified in each core (McCarthy, 1986). In addition to these regional pollen zones a local pollen zone, containing a high percentage of pollen of emergent aquatic plants, was identified in the lower part of each core. Above this 'emergent aquatic pollen zone', the sediment contains low background concentrations of emergent aquatic pollen grains.

The top of the emergent aquatic pollen zone parallels the transgressive contact between humic peat and marl (Fig. 3). In core 2, the top of this zone occurs just below a date of 1270 ± 50 years B.P., suggesting that the water level at this site became too deep for emergent aquatics about 1500 years after its initial transgression. Figure 5 shows that the pollen and macrofossils of emergent aquatic species generally decrease upcore, and further, that there is a succession from emergent aquatic species (e.g. Cyperaceae, Typha, Sparganium) to floating aquatic species (Nuphar and Nymphaea) and then to submerged aquatic species (e.g. Potamogeton and Myriophyllum). In general, this succession occurs steadily upward in the sequence, reflecting rising water level in the
littoral zone due to the continuous isostatic uplift of the St. Lawrence outlet. Periods of accelerated water level rise are reflected by abrupt decreases in emergent aquatic pollen and macrofossils, whereas periods of stable water level are marked by an increase in emergent aquatic pollen and macrofossils as marsh plants grow outward into the pond.

Clastic unit A was dated in core 0 at 3110 ± 80 years B.P. using accelerator dating. It occurs as a fine sand in peat in cores 1 and 2. It was dated at 2980 ± 60 years B.P. in core 1 and lies just below a date of 2930 ± 80 years B.P. (AMS 2830 ± 50 years B.P.) in core 2. Given the errors involved, these dates are essentially of the same age, suggesting that clastic unit A was deposited synchronously at all three sites. The base of clastic unit C was accelerator dated in core 2 at 1070 ± 100 years B.P. A bulk C\textsuperscript{14} date of 2370 ± 60 years B.P. at the base of clastic unit C in core 0 was rejected as being too old based on sedimentological and pollen density data (McCarty, 1986). This is probably due to recycling of older sediments suggested by high percentages of Picea and Cyperaceae in the pollen record of clastic unit C (Fig. 5), since these pollen types dominate the late Pleistocene Glacial Lake Iroquois sediments. The clastic units parallel isochrons, i.e., the surface and base of the Ambrosia zone, and cut across diachronous facies boundaries reflecting transgression (i.e., the lithological boundary between woody peat and marl and the top of the aquatic pollen and plant macrofossil zone). The deposition of each clastic unit thus appears to have been synchronous throughout the basin, and these units represent relatively short periods of increased clastic input.
Fig. 5. Summary of water level indicators in cores 0, 1, and 2. An abbreviated upland pollen diagram is also shown for core 0, zoned following McAndrews (1981). Pollen percentages of individual aquatic taxa are shown for cores 1 and 2. On plant macrofossil and aquatic pollen diagrams, black represents submerged aquatic plant species. Dashed lines indicate sudden changes in water depth reflected by pollen and plant macrofossils; stipple represents percentages of grass (wild rice) pollen, excluded from the emergent aquatic pollen sum. Percentages of grass pollen in clastic unit A in core 0 range from 334% at 500 cm to 2010% at 448 cm.
Table 1. Radiocarbon dates from Grenadier Pond cores. Dates with TO- lab numbers are accelerator dates on terrestrial plant macrofossils, while dates with WAT- lab numbers are beta emission dates on bulk sediment samples.

<table>
<thead>
<tr>
<th>Core</th>
<th>Lab No.</th>
<th>Depth</th>
<th>14C date</th>
<th>Material dates</th>
<th>Significance</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>In core (cm)</td>
<td>Below datum* (cm)</td>
<td>(years B.P.)</td>
<td></td>
</tr>
<tr>
<td>0</td>
<td>WAT-1332</td>
<td>771-781</td>
<td>1171-1181</td>
<td>4230 ± 60</td>
<td>marl</td>
</tr>
<tr>
<td>0</td>
<td>TO-160</td>
<td>780</td>
<td>1180</td>
<td>4094 ± 60</td>
<td>twig</td>
</tr>
<tr>
<td>1</td>
<td>WAT-1330</td>
<td>500-510</td>
<td>760-770</td>
<td>2980 ± 60</td>
<td>marl</td>
</tr>
<tr>
<td>2</td>
<td>WAT-1328</td>
<td>608-618</td>
<td>668-678</td>
<td>2930 ± 80</td>
<td>marl</td>
</tr>
<tr>
<td>2</td>
<td>TO-164</td>
<td>618</td>
<td>678</td>
<td>2830 ± 50</td>
<td>Angiosperm wood</td>
</tr>
<tr>
<td>3</td>
<td>WAT-1334</td>
<td>380-390</td>
<td>375-385</td>
<td>1970 ± 100</td>
<td>marl</td>
</tr>
<tr>
<td>4</td>
<td>TO-165</td>
<td>299</td>
<td>216</td>
<td>1850 ± 60</td>
<td>marl</td>
</tr>
<tr>
<td>0</td>
<td>TO-159</td>
<td>480</td>
<td>880</td>
<td>3110 ± 80</td>
<td>pine needles, birch seeds, wood fragments</td>
</tr>
<tr>
<td>0</td>
<td>WAT-1591</td>
<td>290-300</td>
<td>690-700</td>
<td>2370 ± 60</td>
<td>silty mud</td>
</tr>
<tr>
<td>2</td>
<td>TO-162</td>
<td>200</td>
<td>260</td>
<td>1070 ± 100</td>
<td>pine needles, leaf petiole</td>
</tr>
<tr>
<td>2</td>
<td>TO-163</td>
<td>275</td>
<td>335</td>
<td>1270 ± 50</td>
<td>pine needles, cedar needles</td>
</tr>
</tbody>
</table>

* Modern level of Lake Ontario.

Table 2. Rates of water level rise based on 14C dates of transgression. The rate of rise is considered instantaneous where three times the standard errors of the dates overlap.

<table>
<thead>
<tr>
<th>Interval (cm)</th>
<th>years B.P.</th>
<th>rate (cm/y)</th>
<th>minimum rate</th>
<th>maximum rate</th>
</tr>
</thead>
<tbody>
<tr>
<td>420</td>
<td>4230-2980</td>
<td>0.336</td>
<td>0.307</td>
<td>0.373</td>
</tr>
<tr>
<td>90</td>
<td>2980-2930*</td>
<td>instantaneous</td>
<td></td>
<td></td>
</tr>
<tr>
<td>300</td>
<td>2930-1970**</td>
<td>0.313</td>
<td>0.288</td>
<td>0.441</td>
</tr>
<tr>
<td>170</td>
<td>1970-1850*</td>
<td>instantaneous</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

* dates indistinguishable using 14C dating
** sediment and vegetational succession indicates that most of this water level rise occurred in the last few hundred years of this interval. Water level appears to have been stable until ca. 3200 B.P.; the rate of water level rise from 2300 to 1970 B.P. was nearly instantaneous.

Discussion

The dates of the transgression in cores 0, 1, 2, 3, and 4 are plotted (Fig. 6), and are compared with the dates predicted by the water level curve of Sly & Prior (1984) (Fig. 7). There are two anomalies: 1) water levels rose 90 cm as the shoreline retreated about 250 m from site 1 to site 2 instan-

taneously, within the resolution of radiocarbon dating, and 2) the date for transgression in core 4 lies 1.7 m above the predicted value for Lake Ontario.

The second anomaly is attributed to isolation of Grenadier Pond. Rapid transgression from site 3 to site 4 was not accompanied by clastic sedimentation, suggesting that bar buildup and ponding
may have been responsible for the sudden quiet rise in water level. The 1.7 m water level rise is consistent with the present elevation of Grenadier Pond of 1.3 m above Lake Ontario.

The first anomaly cannot be attributed to pond isolation because high energy conditions are indicated by the contemporaneous deposition of clastic unit A during the rapid transgression. Nor
Fig. 7. Postglacial water levels in the western Lake Ontario basin, redrafted from Sly & Prior (1984).

can it be attributed to dating error because of independent paleobotanical evidence of rapid transgression at this time.

In core 0, the organic content of the marl decreased around 3300 years B.P. and emergent aquatic pollen fell abruptly (Fig. 5), implying rapid water level rise. Clastic unit A was deposited simultaneously, or shortly afterward, 3110 ± 80 years B.P. This unit contains very high percentages (up to 2000%) of grass pollen. Based on pollen morphology and size, this is probably the pollen of wild rice (Zizania aquatica). This aquatic grass grows in moving or agitated water, usually in streams and in the bays of large lakes,
such as Long Point Bay of Lake Erie, suggesting agitated water in Grenadier Pond during the deposition of clastic unit A. Around 2950 years B.P., clastic deposition ('residue' in Fig. 5) in core 0 was succeeded by marl, and grass pollen fell sharply to background levels of less than 1%.

The site of core 1 was transgressed 2980 ± 60 years B.P. at an elevation of 7.6 m below datum (the modern elevation of Lake Ontario), and the transgression is contemporaneous with the deposition of clastic unit A (Fig. 5). The silty peat is immediately succeeded by marl with relatively low percentages of emergent aquatic macrofossils and pollen, which remain relatively stable until just prior to the deposition of clastic unit B.

Clastic unit A also intersects the transgression in core 2, which dates at 2930 ± 80 years B.P., 6.7 m below datum. In this core, however, the humic peat is succeeded by silty, peaty (organic) marl, indicating the persistence of very shallow water, shoreline conditions at this site for eight hundred years, until about 2100 years B.P., when water levels again rose abruptly, depositing clastic unit B. The percentage of emergent aquatic and pine pollen in the silty peaty (organic) marl is very high, relative to that of all arboreal taxa excluding pine (McCarthy, 1986). This suggests that this site was at the edge of the shoreline, because marshes differentially trap Pinus pollen. The fluctuation in percentages of organic matter and CaCO$_3$ and the high percentage of clastics supports this interpretation.

The evidence for anomalously high energy conditions contemporaneous with paleobotanical and lithological evidence for rapid transgression between 3300 and 2900 years B.P. indicates that Grenadier Pond was an open embayment of Lake Ontario at the time. Water levels therefore rose 90 cm nearly instantaneously in Lake Ontario around 3000 years B.P. as the shoreline retreated about 250 m from site 1 to site 2 in Grenadier Pond.

Because clastic unit A indicates high energy conditions and transgression in the embayment, we suggest that other clastic units in the pond reflect intervals of rapid transgression, at least prior to pond isolation around 1900 years B.P.

Clastic sediments in lagoons, however, could also result from increased erosion and runoff from the upland due to deforestation. To distinguish between clastics of shoreline erosion and slopewash origin on sedimentological grounds McCarthy (1986) found that the grain size distribution of clastic unit C, deposited after pond isolation, was similar to that of clastic unit D which resulted from slopewash accompanying European land clearing. The grain size distribution of clastic unit B, however, resembled that of clastic unit A, which we have shown above was the result of accelerated shoreline erosion accompanying rapid transgression.

Pollen and plant macrofossil data also support accelerated shoreline erosion due to rapid transgression as the origin of clastic unit B, deposited about 2100 years B.P. Marl rapidly succeeded silty organic marl just prior to the deposition of clastic unit B at site 2, and an abrupt decrease in the pollen and macrofossils of emergent aquatic plants accompanied the increase in clastics at sites 1 and 2 (Fig. 5).

High clastic sedimentation contemporaneous with paleobotanical evidence for rapid transgression is also found at the base of core 0. Site 0 was transgressed 4230 years B.P., and the woody peat was succeeded by silty marl rich in pollen and macrofossils of submerged aquatic species. This indicates rapid water level rise from terrestrial to deep water conditions, without the intermediate stage of emergent aquatic plants. Around 3700 B.P., the organic content of the marl increased and peaty layers rich in pollen and seeds of emergent aquatic species alternated with marl. This succession probably records the end of the 'Nipissing Flood' followed by stabilization of the water level, permitting the progradation of a shoreline-fringing, sedge-dominated marsh to site 0 (McCarthy, 1986).

The periods of accelerated water level rise in Lake Ontario 3000 and 2100 years B.P. broadly coincide with periods of cool, wet climate in northeastern North America. Figure 8 compares regional climatic interpretations for the late Holocene with water level reconstructions for Lake Ontario. The climatic interpretations were
Fig. 8. Correlation between regional climate and water levels and clastic sedimentation in embayments of Lake Ontario. The two intervals of rapid transgression, accompanied by the deposition of clastic units A and B in Grenadier Pond, correlate with moist climates around 2000 and 3000 years B.P., as reconstructed from pollen, plant macrofossil, charcoal, and peat inception data.

Based on pollen, plant macrofossil, charcoal, and peatland inception data. In addition, the pollen assemblage in Grenadier Pond changed from pine dominance to mesic deciduous tree dominance around 3400 years B.P., implying increased moisture (Fig. 5). Pinus comprised an average of 45% of the pollen assemblage between 4230 and 3400 years B.P., then fell to about 20% as percentages of mesic taxa such as Fagus, Acer saccharum and Betula approximately doubled, just prior to the deposition of clastic unit A in Grenadier Pond. Maximum percentages of Fagus, Acer saccharum, and Betula coincide with the deposition of clastic unit B, suggesting highest moisture during this interval (McCarthy, 1986).

Increased inflow resulting from wetter climate could account for the fluctuations documented for Lake Ontario around 3000 and 2000 years B.P. Short term departure of up to 2 m from the average rate of water level rise over the past 4000 years, as observed in the record at Grenadier Pond, is of the same range as historically observed departures from the mean lake stage of Lake Ontario. Water levels in Lake Ontario have fluctuated about a mean elevation of 246.5 ft. (75 m) with a range of ± 3 ft. (1 m) from 1860 to 1958 (US Army Corps of Engineers, 1956). Apparently, water levels cannot rise much beyond this limit, for any additional increase in input beyond this threshold discharge will be accommodated by
broadening of the outflow channel with little rise in lake level. Because of continued differential isostatic rebound of the outlet, this outflow channel-widening process must be repeated for discrete increases in inflow, resulting in the step-like pattern of lake level rise observed in the record at Grenadier Pond.

Summary and conclusions

Radiocarbon dates of transgression along a transect in Grenadier Pond suggest that water levels rose quickly for short periods (up to 300 years) around 3000 and 2100 years B.P. This resulted in accelerated shoreline erosion and turbid water depositing clastic sediments, and rapid transgression displacing the shoreline flora. These intervals were followed by longer periods of stable or slowly rising water levels and low energy conditions, when marshes grew out into the pond, and marls and peaty marls low in clastics were deposited.

The deposition of clastic sediments in marly embayments, and moderate to very high percentages of wild rice pollen, a grass that grows abundantly only in flowing or agitated water, suggest that high energy conditions accompanied the intervals of rapid transgression prior to ca. 1900 years B.P. This argues against barrier construction and pond isolation as a viable cause for the rise in water level. Grenadier Pond was probably isolated by barrier construction between 1970 and 1850 years B.P. when rapid transgression occurred, unaccompanied by evidence for high energy conditions, suggesting a quiet rise in water level. The 1.7 m water level rise is consistent with the present elevation of Grenadier Pond of 1.3 m above Lake Ontario.

The periods of accelerated water level rise in Lake Ontario correlate with periods of wetter, cooler climate, inferred from pollen and peat inception data. Short term departure of up to 2 m from the average rate of water level rise over the past 4000 years, as observed in the record at Grenadier Pond, is of the same range as historically observed departures from the mean lake stage of Lake Ontario. This implies that a threshold discharge exists above which broadening of the outflow channel occurs to accommodate further increase in discharge with little rise in lake level. Because of continued differential isostatic rebound of the outlet, this outflow channel-widening process must be repeated for discrete increases in inflow, resulting in the step-like pattern of lake level rise observed in the record at Grenadier Pond.

Acknowledgements

This work formed part of a thesis supported by an NSERC scholarship to F. McCarthy. Part of the work was also supported by NSERC grant A5699 to J. McAndrews. Discussions with N. Eyles, G. Norris, and A. Zimmerman of the University of Toronto provided important insights. The helpful suggestions of R. B. Davis and two anonymous reviewers are gratefully acknowledged. We also thank the staff of the Department of Botany of the Royal Ontario Museum for assistance in the field and in the laboratory.

References


