Early Holocene brackish closed basin conditions in Georgian Bay, Ontario, Canada: microfossil (thecamoebian and pollen) evidence

Francine McCarthy · Sarah Tiffin · Adam Sarvis · John McAndrews · Stephan Blasco

Abstract Microfossils have been critical in unravelling the complex postglacial history of Georgian Bay. Thecamoebians (testate amoebae/rhizopods) record paleolimnological conditions, and pollen stratigraphy allows correlation across the basin, where sedimentation has been spatially and temporally discontinuous. Because parts of Georgian Bay have been non-depositional or erosional since the end of the Nipissing transgression (∼5,000 (5,800 cal) BP), early Holocene features are exposed on the lakebed. Among these are shoreline features, such as submerged beaches and relict channels, associated with low-level Lake Hough that was driven far below the level of basin overflow. Cores taken throughout Georgian Bay record the existence of closed basin conditions that persisted several centuries around 7,500 (8,300 cal) BP, corresponding to the late Lake Hough lowstand. Evidence for hydrologic closure includes a low-diversity centropyxid-dominated thecamoebian fauna around the boundary between pollen subzones 2a and 2b in the Flowerpot Beach core, Flowerpot and Killarney basins, and in Severn Sound. This low-diversity centropyxid-dominated fauna is interpreted as recording the development of slightly brackish conditions as a result of a hydrologic deficit associated with relatively arid conditions in the Great Lakes basin during the early Holocene pine zone (∼8,800–7,200 (9,900–8,050 cal) BP). The rest of the Holocene record in Georgian Bay (where it is preserved) is more diverse and dominated by difflugiid thecamoebians: predominantly *Difflugia oblonga* prior to human settlement, and *Cucurbitella tricuspis* since high-density human occupation and agriculture (and resulting eutrophication) began with the Wendat First Nations people around Severn Sound about 750 years ago. The implication that water budget fluctuations leading to discernible variations in lake level and water chemistry occurred in the relatively recent geologic past is significant to studies of global climate change and resource management in the Great Lakes, one of the world's largest freshwater resources.

Keywords Great Lakes · Lake level · Paleohydrology · Paleoclimate · Thecamoebians · Pollen

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Introduction

The complex geological history of Lake Huron-Georgian Bay (Figs. 1, 2) has long been attributed to the effects of ice damming and retreat during deglaciation, drainage capture, and glacioisostatic rebound of outlets (Hough 1962; Lewis and Anderson 1989; Lewis et al. 1994; Dobson et al. 1995). More recently, a new analysis of isostatic adjustment coupled with reconstructed digital elevation models revealed hydrologically-closed lakes in the Huron and Michigan basins as well as in the Georgian Bay basin, between 8,000 and 7,400 BP (8,950 and 8,300 cal BP) (Lewis et al. 2005, 2007). Several phases of lake lowstands were separated by high-stands, termed the Mattawa lakes (Fig. 1). The unconformity created by the last lowstand, which Hough (1962) called Lake Stanley (here late Lake Stanley), has been identified in seismic reflection profiles as the basin-wide light blue reflector of Dobson et al. (1995). This unconformity was recently
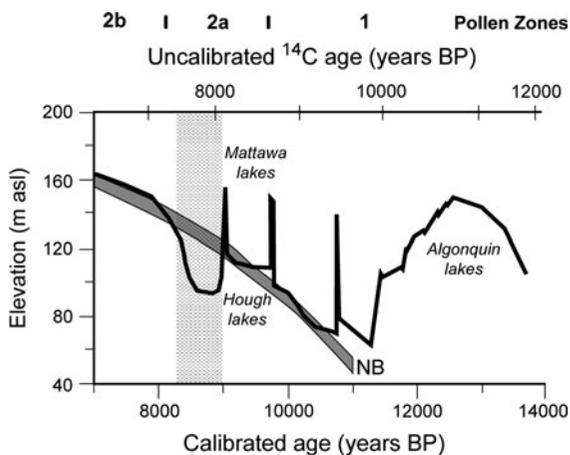

Fig. 1 Late Wisconsinan-early Holocene lake levels in the Georgian Bay basin (modified from Lewis et al. 2008) are a function of ice damming (e.g. Algonquin), hydraulic constriction (e.g. Mattawa highstands), glacioisostatic rebound determining the elevation of outlets (e.g. the sill at North Bay, marked NB), and climate (e.g. the closed basin of late Lake Hough, shaded in grey, when a negative hydrologic balance drove water levels below the level of the lowest outlet). Elevations are 'original' elevations computed by subtracting glacial rebound (relative to an area west of southern Lake Michigan beyond the maximum margin of the last glaciation, Lewis et al. 2005) from present uplifted elevations. Elevation is plotted against uncalibrated (radiocarbon) and calibrated age, and the ages of the pollen zone boundaries (zonation of McAndrews 1994) are also shown

cored and the zone eroded by lowstand wave abrasion was dated by paleomagnetic secular variation to about 7900 ± 350 (Lewis et al. 2007), an age supported by radiocarbon ages of drowned, in situ stumps of white cedar and tamarack as much as 53 m below the modern level of Georgian Bay in the Tobermory region (Blasco 2001; Lewis et al. 2005, 2008) and by the pollen stratigraphy (McCarthy et al. 2007). In the Georgian Bay basin, the last lowstand, correlative with late Lake Stanley in the Huron basin, is named for J.L. (Jack) Hough who identified the coeval Lake Stanley in the main basin of Lake Huron (Prest 1970). The implied lowstand shorelines in the Huron and Georgian Bay basins illustrate that late Lake Hough was well below the level of the lowest overflow outlets, at Dalles Rapids and North Bay, making it a closed basin (Fig. 2a, c). Cross-basin profiles reconstructed to 7,700 (8,490 cal) BP, based on calculations of isostatic rebound in Lewis et al. (2005), demonstrate the proposed hydrologic closure of late Lake Hough near the end of pollen zone 2a (Fig. 2).

Hydrologic closure resulting from a prolonged hydrologic deficit during the relatively arid early Holocene pine zone, particularly during subzone 2a (the red/jack pine zone), ~8,800–7,500 (9,900–8,200 cal) BP (McCarthy and McAndrews 2010), would have produced changes in water chemistry such as increased total dissolved solids that should be recorded in the paleolimnological record. Unfortunately, calcareous microfossils are surprisingly rare in sediments from Georgian Bay, so comparison with the ostracod records from Lake Huron (Lewis et al. 1994; Dobson et al. 1995) is not possible. Sarvis et al. (1999), however, suggested that the thecamoebian faunas associated with the late Lake Hough lowstand recorded slightly brackish conditions. Thecamoebians (also called testate rhizopods/amoebae or arcellaceans) are benthic protozoans related to the more familiar foraminifera, and are found in freshwater lakes and wetlands (Medioli and Scott 1988; Collins et al. 1990; Charman 2001; Scott et al. 2001; Patterson and Kumar 2002). Their agglutinated organic tests fossilize readily, and although they were first described in the nineteenth century, they have not been as extensively studied as other paleolimnological indicators like diatoms and ostracods. Although most of the lacustrine studies have been performed on small lakes, several thecamoebian

Fig. 2 Paleogeographic reconstructions of Lake Huron, Georgian Bay, and Lake Nipissing basins at 7,700 (8,490 cal) BP. **a** Map showing the late Lake Stanley and Hough lowstands in the Lake Huron and Georgian Bay basins, respectively, the locations of the points used to generate the cross-section profiles based on data in Lewis et al. (2005), and the locations of core sites in this study: Flowerpot Beach (Core LH04-800-200PC), "Killarney Basin" core 34 (Core LH95-800-034PC), Severn Sound Cores 26 and 35 (Cores LH97-802-026GC and LH97-802-035GC), and Flowerpot Basin ("FB") Core 41 (Cores LH95-800-041PC and -041TWC). The locations of Axe Lake and Porqui Pond are also shown. **b** The cross-section profile from Tobermory to Midland shows the shoreline at Flowerpot Beach (−53 m) and ∼20 m below sites 35 and 26 in Severn Sound during the latter part of pollen zone 2a. **c** The cross-section profile from the Stanley unconformity in NW Lake Huron to the North Bay sill shows the slightly lower elevation of late Lake Hough relative to late Lake Stanley. Vertical exaggeration of profiles is approximately 2000×. Cross-section profiles courtesy of C.F.M. Lewis
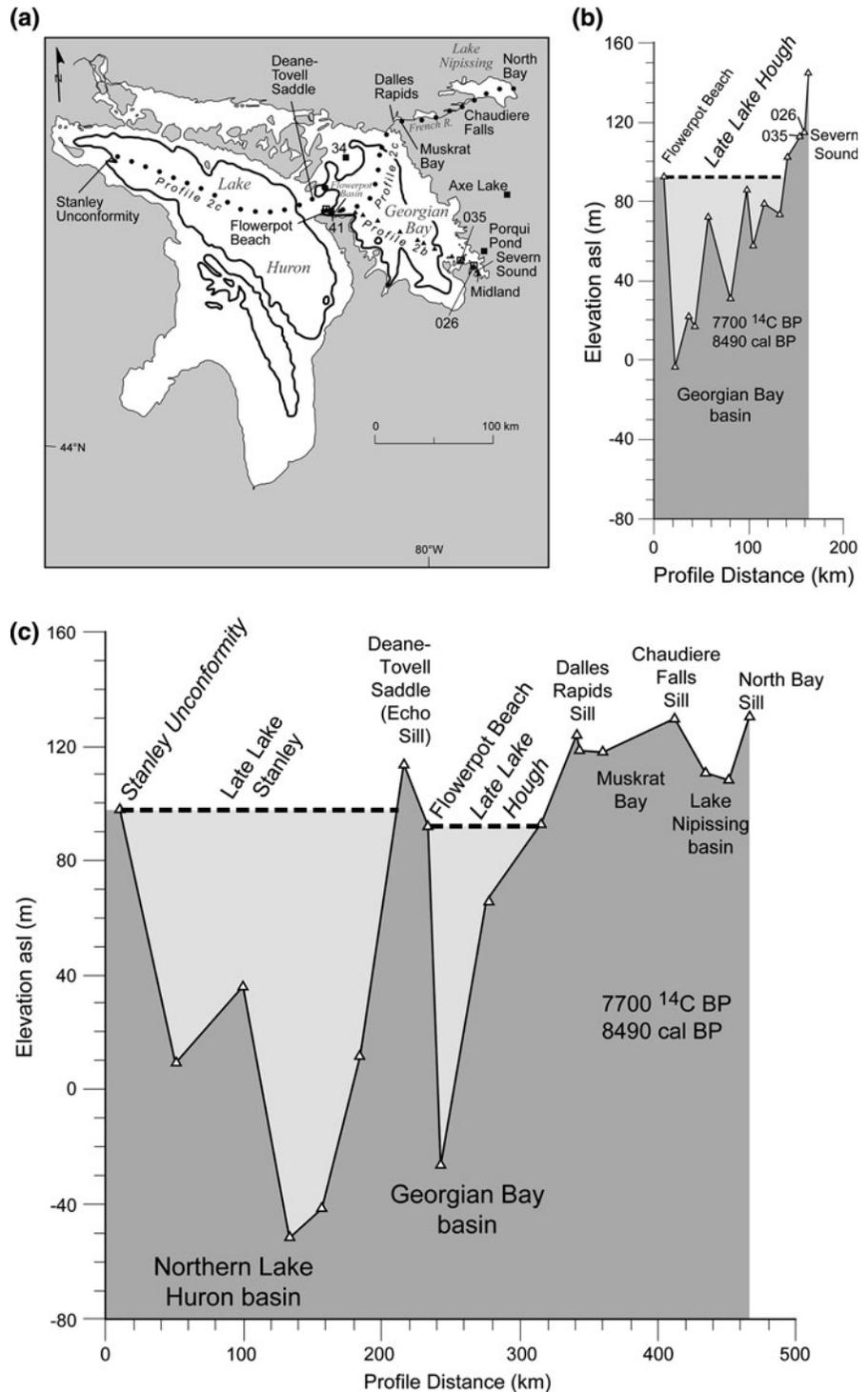
studies have been published on Great Lakes sites, including deep-water sediments from Lake Erie (Scott and Medioli 1983), a shallow embayment of Lake Ontario (Reinhardt et al. 2005), and a coastal wetland in the Lake Superior basin (Booth et al. 2002), as well as from other large lakes, such as Lake Winnipeg (Burbidge and Schröder-Adams 1998). Some taxa, notably the genus *Centropyxis*, can

tolerate slightly brackish conditions, so thecamoebians can be used together with foraminifera to zone marginal marine environments, such as estuaries, salt marshes, and even coastal caves (Scott and Medioli 1978; Scott et al. 2001; van Hengstum et al. 2009).

This paper examines Holocene thecamoebian assemblages from shallow and deep lake environments from five sites across the Georgian Bay basin, focusing on sediments deposited during pollen zone 2 of McAndrews (1994)—the early Holocene pine zone, ~8,800–7,200 BP (~9,900–8,050 cal BP). We revisit the suggestion, initially based on a small number of samples analyzed from Severn Sound and from the Flowerpot Basin (Sarvis et al. 1999; Sarvis 2000) that brackish conditions developed in late Lake Hough, the lowstand lake that occupied the Georgian Bay basin ~8,000–7,200 BP (~8,900–8,050 cal BP).

Methods

Cores were obtained from many parts of Georgian Bay, including a small sub-basin near Manitoulin Island north of the Flowerpot and French River basins of Thomas (1988), informally named the "Killarney Basin" in this work (Fig. 2; Table 1). Piston and trigger weight cores were collected from *R/V Laurentian* in 1995 from the Flowerpot Basin near Tobermory at 124 m water depth (Cores LH95-800-041PC and LH95-800-041TWC) and from the "Killarney Basin" in 54 m of water (Cores LH95-800-034PC and LH95-800-034TWC). Gravity cores were collected from the *Monitor VI* in 1997 from Severn Sound, and a number of cores, including LH97-802-035GC (~18 m water depth) and LH97-802-026GC (~17 m water depth), penetrated the early Holocene pine zone (McCarthy et al. 2007). These cores are curated at the Geological Survey of Canada- Atlantic, Bedford Institute of Oceanography, in Dartmouth, Nova Scotia. More recently, in May, 2004, sediments associated with the −53 m strand-line near Tobermory, inferred from sidescan sonar records and high-resolution seismic reflection profiles (Blasco 2001) were cored from the *CSS Limnos*. Early Holocene sediments are typically found on the lakebed in much of bedrock-bounded northern Georgian Bay, where sediment supply has been sparse between the end of the Nipissing transgression and anthropogenic land clearing (McCarthy et al. 2007). The "Flowerpot Beach" cores (Cores LH04-800-200GC and LH04-800-200-PC1 and -PC2) were taken from the submerged Niagara Escarpment near the main channel connecting Georgian Bay with Lake Huron, and the longest core (LH04-800-200-PC1) was subsampled for microfossil analysis. The Flowerpot Beach cores are curated at the University of Rhode Island.

Samples of 2.5–10 ml volume (depending on thecamoebian test concentrations) from the Georgian Bay cores were disaggregated using 10% Calgon and sieved to retain the >63 μm fraction for thecamoebian analysis; the 45–63 μm fraction was also examined for several samples analysed for this paper, although for consistency with earlier student theses that examined only the >63 μm fraction (Tiffin 1998; Sarvis 2000), only the coarser fraction is reported and

Table 1 Locations, core types, and water depths of Georgian Bay cores

Site	Core	Location (lat/long)	Core type	Water depth (m)
Flowerpot Beach	LH04-800-200-PC1	45°18′01″N	Piston	54
		81°35′52″W		
Flowerpot Basin	LH95-800-041PC	45°15.98′N	Piston	124
		81°34.41′W		
"Killarney Basin"	LH95-800-034PC	45°44.52′N	Piston	54
		81°20.39′W		
Severn Sound Outer Midland Bay	LH97-802-026GC	44°47′18″N	Gravity	17.3
		79°50′59″W		
Severn Sound	LH97-802-035GC	44°50′04″N	Gravity	18.2
		79°53′07″W		

discussed here. A few small thecamoebian taxa, such as *Difflugia urens*, are typically seen only in the 45–63 μm fraction, but these taxa are rare in Georgian Bay, and assemblages in the >63 μm fraction reflect total abundances in most studies (Neville 2009). The entire retained fraction was analysed wet at between 45 and 80× magnification. Alcohol was added as a preservative to sample vials only after analysis, to avoid the complications caused by evaporation during analysis. Identifications primarily followed the key of Kumar and Dalby (1998) and the monograph of Medioli and Scott (1983).

Samples of 2.5 ml volume from the cores were disaggregated using 0.02% Calgon for pollen analysis, sieved at 10 μm, and 10% HCl was added to dissolve carbonates. A tablet containing a known quantity of *Lycopodium clavatum* spores was added during HCl treatment to allow estimates of pollen density. Samples were then treated with hot 48% HF to remove silicates, sieved again at 10 μm, and the residue was mounted in glycerine jelly on a slide. At least 100 upland pollen grains were identified following McAndrews et al. (1973) from each sample at 400× magnification in order to zone the diagrams following the regional pollen stratigraphy of McAndrews (1994).

Chronology is based primarily on radiocarbon dates on material from the cores and on the well-dated regional pollen zones of McAndrews (1994) (Table 2). Unless otherwise stated, ages are reported in this paper as conventional (uncalibrated) radiocarbon years. To allow for easy comparison with other published works, calibrations of radiocarbon ages are provided. These were calculated using Oxcal software and the Intcal04 calibration curve (Reimer et al. 2004).

The major vegetational changes that produced the pollen stratigraphy used to correlate sediments across Georgian Bay (and with sediments from small lakes throughout southern Ontario) occurred quickly, mostly in response to climate changes. The transition from relatively arid conditions supporting a white pine dominated forest (pollen zone 2b) by more moist conditions supporting a mesic forest, for instance, produced the maple-beech-hemlock rich pollen zone 3 that can be widely correlated across mid-latitude eastern North America (McCarthy and McAndrews 2010). The pollen zone 2b/3a boundary has been dated ~7,200 (~8,050 cal) BP at Axe Lake (Table 2; Fig. 2) in the Georgian Bay catchment. Other causes of regional vegetation succession include anthropogenic land clearing, that produced pollen zone 4 that is rich in ragweed and other nonarboreal pollen, and disease, which may explain the decimation of hemlock that produced pollen zone 3b, although climatic interpretations have also been forwarded to explain the "hemlock crash" (Calcote 2003; Haas and McAndrews 2000). The radiocarbon ages of sediments at most pollen zone boundaries in small lakes in the Georgian Bay catchment are slightly younger than the climate-driven succession published for lakes farther south in McAndrews (1994), recording the later migration of thermophilous species compared with the lower Great Lakes region. Pollen zone 2 (the "pine zone") spans ~8,800–7,200 (~9,900–8,050 cal) BP in Axe Lake (McCarthy et al. 2007), and reflects aspen parkland vegetation that replaced the forest tundra (= pollen zone 1) after the Laurentide Ice Sheet retreated from the region (McCarthy and McAndrews 2010). The zone 2a/2b boundary records the succession from a dominance of northern pine (jack/red pine: *Pinus banksiana/resinosa*) to southern pine (white pine: *Pinus strobus*). The boundary between zones 2a and 2b in Porqui Pond dates around 7450 ± 90

Table 2 Pollen stratigraphic age control, small lakes in Georgian Bay catchment

Site	Depth in core (cm)	Event/zonation criteria	Radiocarbon age BP (calibrated)	Lab #
Axe Lake	365–380	Zone 3a/3b boundary/hemlock decline	4770 ± 120 (5,480 cal)	BGS 1684
Axe Lake	500–510	Zone 2b/3a boundary/increase in thermophilous trees	7200 ± 150 (8,030 cal)	BGS 1685
Axe Lake	630–640	Zone 1b/2a boundary pine rise (mainly red/jack pine)	8830 ± 220 (9,910 cal)	BGS 1686
Porqui Pond	230–240	Zone 3b/3c boundary/post-minimum hemlock rise	4300 ± 100 (4,880 cal)	BETA-3783
Porqui Pond	380–390	Zone 3a/3b boundary/hemlock decline	4450 ± 70 (5,100 cal)	BETA-3784
Porqui Pond	580–600	Zone 2a/2b boundary/increase in white pine	7450 ± 90 (8,279 cal)	BETA-3785

(∼8,300 cal) BP (Table 2). The Mixed Forest vegetation of pollen zone 3 spans ∼7,200–150 (∼8,050–140 cal) BP; McCarthy et al. 2007), with the hemlock minimum (zone 3b) spanning ∼4,500–4,300 (∼5,140–4,880 cal) BP in Porqui Pond, although the age of ∼4,800 (∼5,500 cal) BP in Axe Lake (McCarthy et al. 2007) is more consistent with the age of the base of zone 3b at nearby lakes (St. Jacques et al. 2000) and with the 1,000 year span from hemlock decline to recovery throughout eastern North America (Calcote 2003). Pollen zone 4 (the ragweed rise) spans ∼150 years in this region (McCarthy et al. 2007).

While small lakes in the Georgian Bay catchment, such as Axe Lake and Porqui Pond, allowed us to date pollen zone boundaries in this region, the taphonomic impact of poorer preservation and differential transport of pollen had to be taken into account (McCarthy et al. 2007). One of the biggest issues is with pine pollen, as its relatively small size and bisaccate morphology results in over-representation offshore (Mudie and McCarthy 1994) and also results in a very high fraction of broken grains, which are difficult to assign to white pine ("southern pine") versus red/jack pine ("northern pine"). Despite this problem, the portion of grains that could be confidently assigned to white or red/jack pine was used to determine the 2a/2b boundary, but the two types of pine are not plotted separately for the Georgian Bay cores.

Small lakes within the former basins of glacial Lake Algonquin and the Nipissing Great Lakes also record the large-scale transgressions and regressions that characterised Georgian Bay/Lake Huron throughout the postglacial. The informally named Porqui Pond (McCarthy and McAndrews 2010) occupies a small basin in the crystalline Precambrian rocks of the Canadian Shield in the southeastern portion of the Georgian Bay catchment (44.93 N, 79.78 W) (Fig. 2a). Siliciclastic sediments assigned to pollen zones 1p (produced by a spruce woodland vegetation) and 3a–3b (early hemlock peak and hemlock minimum produced by a maple-beech-hemlock forest) record relatively deep water "Great Lake" conditions in Porqui Pond when it was inundated by glacial Lake Algonquin as glacial ice blocked outlets, and later during the Nipissing transgression, as the surface of the pond is ∼7 m below the Nipissing Great Lake maximum

(McCarthy and McAndrews 2010). The organic-rich muds that accumulated beginning in pollen zone 2a and into the early part of pollen zone 3a (i.e. through the time characterized by aspen parkland vegetation) and from the middle of pollen zone 3b to the present (i.e. since the hemlock minimum) record the isolation of the shallow pond. The pond was first isolated during the Lake Hough lowstand (the pollen zone 2a/2b boundary) and subsequently in post-Nipissing time (pollen zones 3c–4), as lake level in Lake Huron/Georgian Bay fell when drainage was transferred to the southern outlets at Port Huron and Chicago (Eschman and Karrow 1985).

Holocene paleolimnology of Georgian Bay

Tobermory region: Flowerpot Beach and Flowerpot Basin

The longest piston core from the Flowerpot Beach site (Core LH04-800-200-PC1) recovered fine-grained sediments flanked by coarse sediments: a lower unit fining upwards from pebbles at the base of the core to sandy mud and coarsening upcore to the coarse sand lens at 155 cm, overlain by one fining upcore from the coarse sand lens to clay and coarsening to orange-brown muddy sand (Fig. 3). The orange-brown sand is also at the top of the nearby gravity core (Core LH04-800-200-GC, not shown). These sands are exposed on the lakebed, forming the beach ridges imaged by sidescan sonar (Blasco 2001; Blasco et al. 2010). The stiff grey mud above the coarse sand lens in Core LH04-800-200-PC1 is assigned to pollen zone 1 of McAndrews (1994) based on the abundance of spruce and herb pollen (Fig. 3). The overlying less stiff grey clay was assigned to pollen zone 2a, based on the increase in pine pollen, dominantly jack/red pine, at the expense of spruce and herb pollen. The boundary between pollen zones 2a and 2b, based on an increase in abundance of white pine (∼7,500 BP, or 8,300 cal BP, by comparison with the Porqui Pond stratigraphy; Table 2), approximately coincides with the organic-rich grey mud underlying the upper muddy sand. This provides an age equivalent to late Lake Hough for the muddy oxidized sand, supporting the date of about 7900 ± 350 BP obtained using paleomagnetic secular variation on the correlative late Lake Stanley
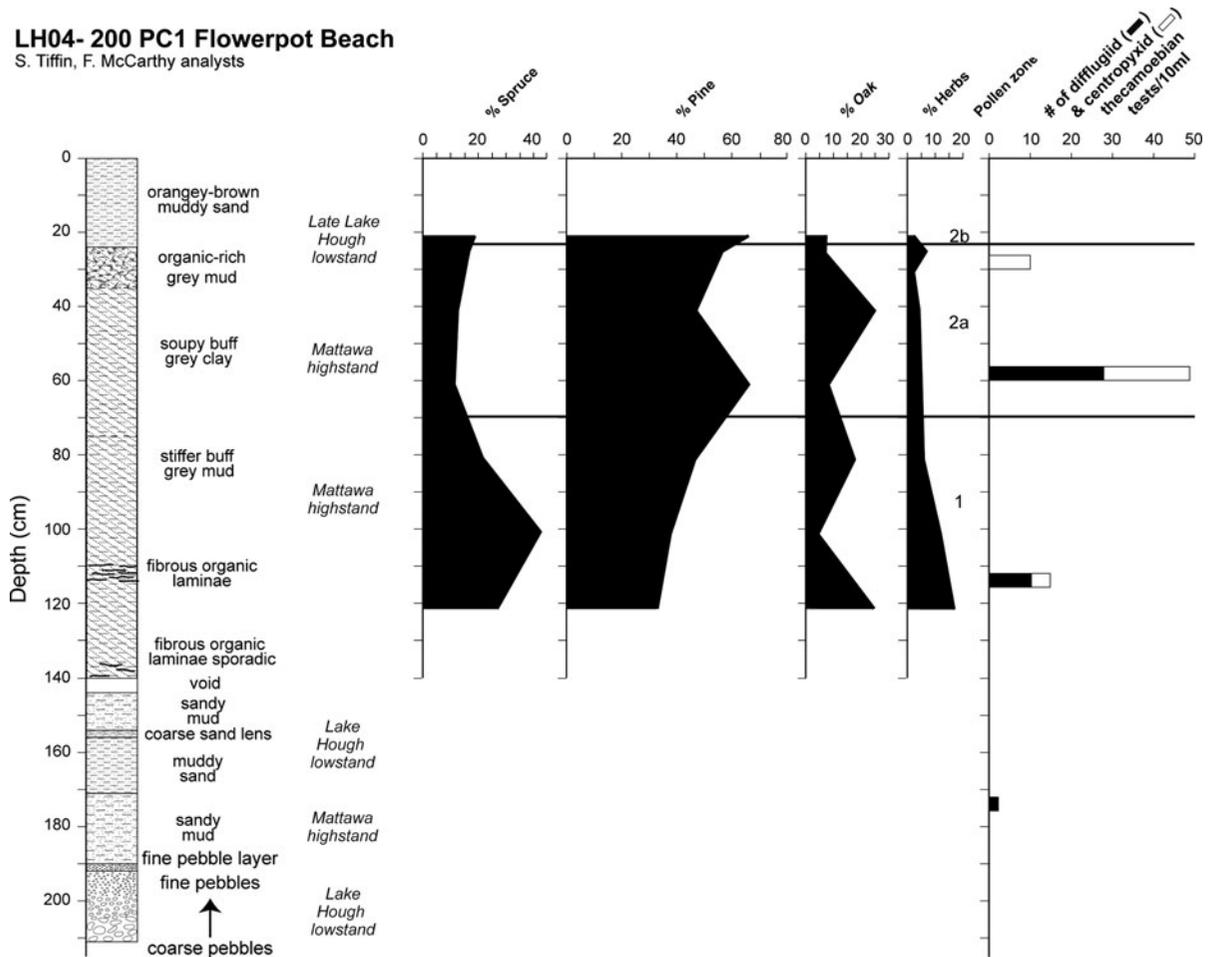
Fig. 3 Coarse siliciclastic units are separated by lacustrine muds in Core LH04-800-200PC1. Oxidized sands just below the surface of the piston cores and at the top of the gravity core can be seen forming prograding beach ridges in sidescan sonar records (Blasco 2001). These beach sands, equivalent to the late Lake Stanley unconformity in Huron basin were dated by paleomagnetic secular variation to about 7900 ± 350 BP (Lewis et al. 2007) and are just above the pollen 2a/2b boundary (∼7,500 (8,200 cal) BP) in the underlying organic-rich grey mud. They formed during the late Lake Hough lowstand (Blasco et al. 2010), and their preservation on the lakebed is the result of sediment starvation over most of Georgian Bay since the middle Holocene (McCarthy et al. 2007). The pollen in the soupy buff grey mud from 35 to 70 cm was assigned to zone 2a, and the lower stiff mud below 70 cm

in Core LH04-800-200PC1 is assigned to zone 1p. The sandy/pebbly sediments around 155 cm and below 190 cm in the core are possibly shoreline deposits deposited during earlier Lake Hough lowstands, separated by deep-water sediments deposited during Mattawa highstands, but the chronology remains uncertain because sediments examined for pollen in the lower 65 cm of the core were virtually barren. Thecamoebian abundances are very low, but the recovery of only centropyxids (mainly *Centropyxis aculeata*) in the organic-rich grey mud just below the late Lake Hough shoreline sands suggests harsh, probably slightly brackish conditions. In contrast, only *Difflugia oblonga* was found in the grey-brown sandy mud at 174 cm, presumably deposited during an earlier Lake Hough lowstand. The lowest unit of pebbly sediment might also be a deposit of subglacial meltwater flows

lowstand in the Huron basin (Lewis et al. 2007). The lower coarse sand and pebbly units appear to have been deposited during the middle and early Lake Hough lowstands, respectively, or possibly earlier by subglacial meltwater flow; without better chronological control these hypotheses remain speculative.

Analysis of the Flowerpot Beach core at 4 levels revealed a very sparse, low-diversity thecamoebian assemblage with only 0.2–5 tests/ml and 4 species: *Centropyxis aculeata*, *C. constricta*, *Difflugia oblonga*, and *D. protaeiformis* (Fig. 3). Only a single specimen of *Difflugia oblonga* was found in the sandy

mud sample from 174 cm, which is effectively barren. The stiff buff grey gyttja sample at 114 cm contained 11 difflugiid thecamoebians (6 *D. oblonga* and 5 *D. protaeiformis*) and 4 centropyxid thecamoebians (1 *C. aculeata* and 3 *C. constricta*), while the richest sample, clay-rich grey mud at 58 cm, contained 28 difflugiid thecamoebians (all *D. oblonga*) and 21 centropyxid thecamoebians (16 *C. aculeata* and 5 *C. constricta*). The organic-rich grey mud sample at 28 cm, just below the oxidised orange-brown muddy sand on the lakebed, contained only centropyxid thecamoebians (8 *C. aculeata* and 2 *C. constricta*). The relatively diverse, difflugiid-rich thecamoebian assemblages in the fine-grained Mattawa sediments ~115 and 60 cm, in contrast, resemble typical modern Georgian Bay thecamoebian assemblages (McCarthy et al. 2007).
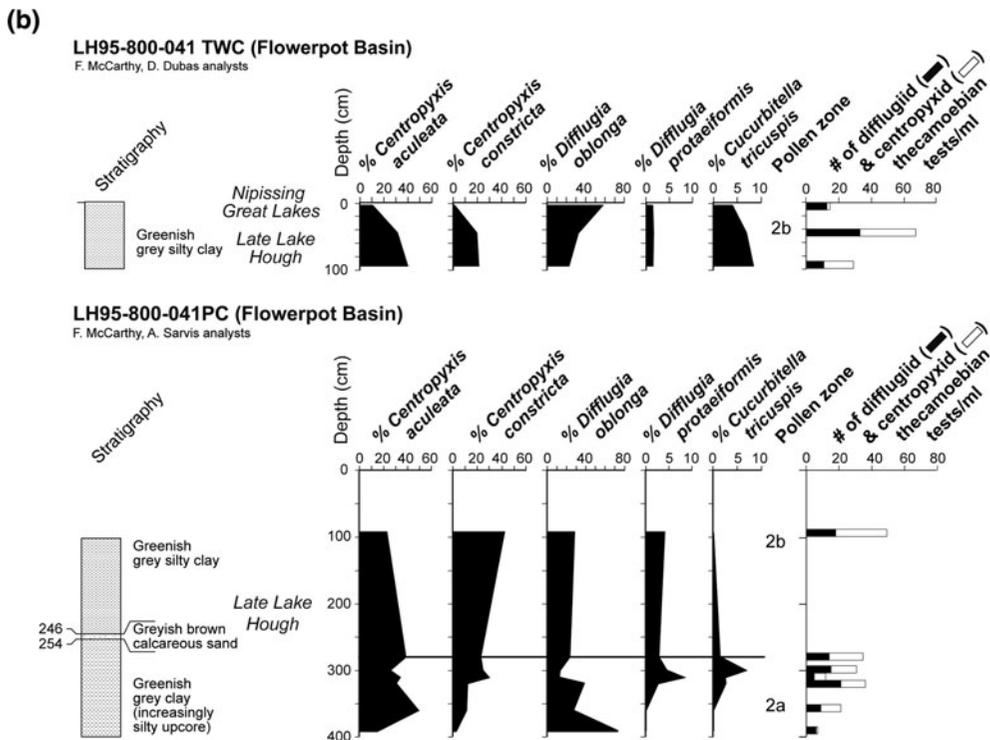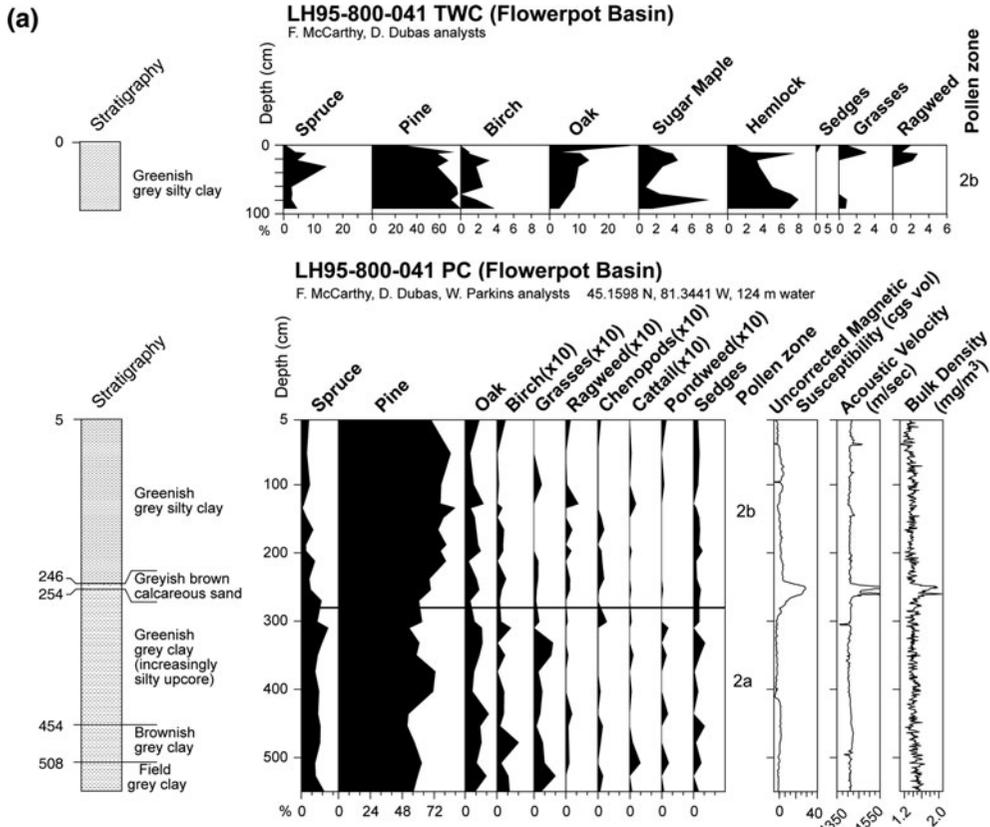
Piston core LH95-800-041PC, taken from ~124 m water depth in the Flowerpot Basin (Thomas 1988) off Tobermory (Fig. 2a), is assigned entirely to pollen zone 2 based on the dominance of pine pollen (Fig. 4a).The boundary between zones 2a and 2b was placed around 275 cm in the piston core, coinciding with an increase in coarse silt and sand in the greenish grey clay that is typical of this deep basin, culminating upward in a layer of relatively clean greyish brown calcareous sand at 254–246 cm (Fig. 4a). The subtle increase in grain size around 280 cm is recorded by the physical properties—a sharp increase in magnetic susceptibility, acoustic velocity, and bulk density implying increased sand content (Fig. 4a). The pollen of emergent and submerged aquatic plants (e.g. sedges, cattail, pondweed, water-milfoil, and water lily) is consistently present throughout the piston core, as is herb pollen, such as grasses, ragweed, and chenopods. Slightly higher than expected abundances of herb pollen (e.g. ragweed) and pollen of thermophilous trees, e.g. hemlock, sugar maple, and oak in sediments at the top of the trigger weight core (LH95-800-041TWC) probably represent the incorporation of modern sediments into early Holocene sediments by bioturbation or current action (McCarthy et al. 2007).

Thecamoebians are relatively sparse in the sediments that accumulated rapidly in the Flowerpot Basin during the early Holocene, ranging from 7 to 49 tests/ml in the piston core and 15–67 tests/ml in the trigger weight core (Fig. 4b). The lowermost sample analysed in the piston core and the uppermost

Fig. 4 Summary of sediment, pollen and thecamoebian data ▶ from the Flowerpot Basin site (LH95-800-041; "41") off Tobermory. **a** The entire piston core (LH95-800-041PC) in the Flowerpot Basin is assigned to pollen zone 2 (McCarthy et al. 2007), recording a minimum sediment accumulation rate of 3 mm/year. An increase in silt/sand flux to the site identified in the physical properties beginning ~280 cm culminates in a layer of greyish brown calcareous sand at 254–246 cm. The boundary between pollen zones 2a and 2b allows us to correlate the sand layer with upper sand unit in the Flowerpot Beach (Core LH04-800-200PC). **b** The thecamoebian fauna above ~390 cm in the piston core (Core LH95-800-041PC) and below the uppermost sample in the trigger weight core (Core LH95-800-041TWC) is dominated by centropyxid thecamoebians (*Centropyxis aculeata* and *Centropyxis constricta*). *Difflugia oblonga* strongly dominates the assemblage at 390 cm in the piston core and in the uppermost sample in the trigger weight core

sample analysed in the trigger weight core were dominated by *Difflugia oblonga*, while *Centropyxis aculeata* and *Centropyxis constricta* dominated the rest of the samples, particularly above 318 cm in the piston core. Peaks in abundance of *Cucurbitella tricuspis* and *Difflugia protaeiformis* between 318 and 299 cm in the piston core coincide with the establishment of the centropyxid-dominated fauna that persists until just below the modern lakebed. This change in fauna is accompanied by an increase in sand ~280 cm in the clay-rich greyish green muds, culminating in a well-sorted sand layer between 254 and 246 cm in the piston core. Several ostracod valves were noted in the sample processed for thecamoebians at 279 cm in the core, a rare observation in Georgian Bay sediments. Other thecamoebian species noted in the cores from this site are *Difflugia bidens*, *Difflugia globulus*, *Difflugia urceolata*, *Difflugia urens*, *Pontigulasia compressa*, *Lagenodifflugia vas*, and *Heleopera sphagni*.

The increase in sand at ~280 cm in the Flowerpot Basin piston core from 124 m water depth correlates with the dramatic increase in organic matter at ~35 cm in the nearby Flowerpot Beach piston core in muds deposited at 53 m water depth, based on the boundary between pollen zones 2a and 2b in both cores. The greyish brown calcareous sand at ~254–246 cm in the Flowerpot Basin piston core thus appears to correlate with the oxidized sands at the top of the Flowerpot Beach piston core. The upward-coarsening of grain size in both cores off Flowerpot Island is interpreted as recording falling water levels culminating around 7,500 BP (~8,300 cal BP), first

(a)

LH95-800-041 TWC (Flowerpot Basin)
F. McCarthy, D. Dubas analysts

LH95-800-041 PC (Flowerpot Basin)
F. McCarthy, D. Dubas, W. Parkins analysts   45.1598 N, 81.3441 W, 124 m water

(b)

LH95-800-041 TWC (Flowerpot Basin)
F. McCarthy, D. Dubas analysts

LH95-800-041PC (Flowerpot Basin)
F. McCarthy, A. Sarvis analysts

allowing aquatic vegetation to take root at the Flowerpot Beach site, then with a further drop in water level, producing a sandy beach whose prograding ridges can be seen in sidescan-sonar imagery (Blasco 2001; Blasco et al. 2010). Falling water levels likely accelerated down-slope transport of terrigenous material such as sand and pollen of aquatic plants like sedges and cattails to the Flowerpot Basin. At both the beach and basin sites near Flowerpot Island, the late Lake Hough lowstand is associated with the transition from a sparse *Difflugia oblonga*-dominated thecamoebian fauna to a very sparse assemblage co-dominated by *Centropyxis aculeata* and *Centropyxis constricta* (Figs. 3, 4).

Manitoulin Island Region: "Killarney Basin"

Piston core (LH95-800-034PC) sediments from a small sub-basin east of Manitoulin Island, informally named the "Killarney Basin" are assigned to pollen zones 2a–3c (Fig. 5). This age assignment is consistent with a high-resolution shallow seismic reflection profile taken along a transect showing the local presence of younger sediments above the late glacial to early postglacial lag that characterizes most of the lakebed in this part of Georgian Bay (McCarthy et al. 2007). An increase and subsequent consistent presence of pollen of thermophilous trees allows us to place the boundary between zone 2 and 3 around 350 cm in the core (~7,200 BP, or ~8,050 cal BP, by comparison with the Axe Lake stratigraphy; Table 2). The transition from the dominance of red/jack pine to white pine occurs around 480 cm in the core, corresponding to an increase in silt content in the grey clay that characterizes this site at the pollen zone 2a/2b boundary, as was found in core LH95-800-041PC at the Flowerpot Basin site (Fig. 4). The disappearance of hemlock pollen between ~210 and 170 cm is interpreted as the hemlock decline (zone 3b), spanning ~4,800–4,300 BP (5,800–4,880 cal BP) in this region (Table 2). Although no increase in ragweed or other herb pollen was noted at the top of the piston core (Fig. 5), pollen zone 4 was identified in the upper 10–20 cm of the trigger weight core from this site (McCarthy et al. 2007).

Thecamoebian concentrations are low in pollen zone 2 (~41–304 tests/ml) and substantially higher in pollen zone 3 (~94–462 tests/ml) in the Killarney Basin piston core. *Difflugia oblonga* dominates the upper 365 cm of the piston core together with other
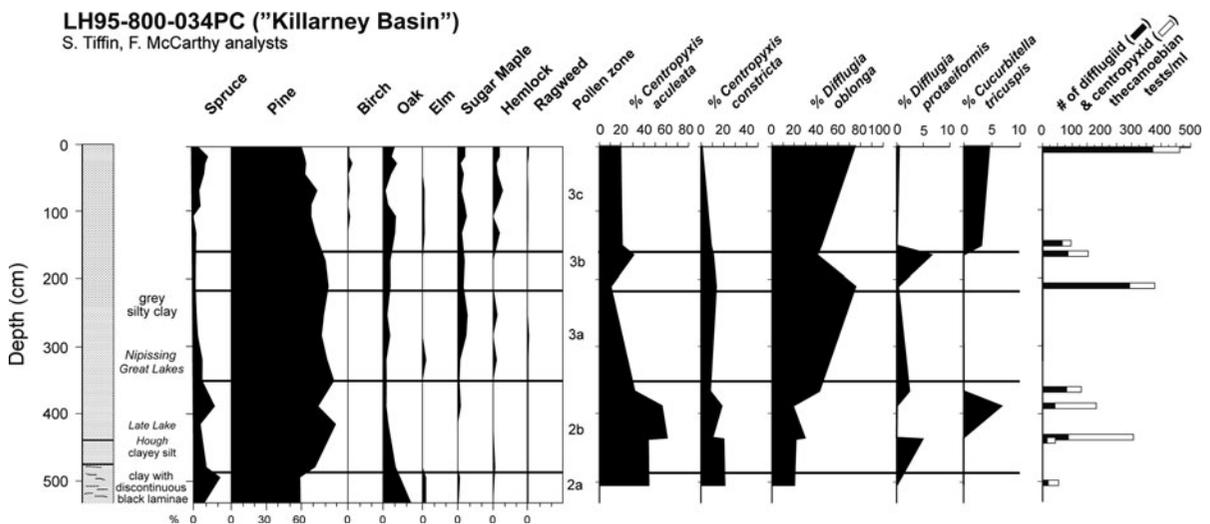

Fig. 5 Summary of sediment, pollen and thecamoebian data from the "Killarney Basin" piston core (LH95-800-034PC; "34"). The core recovered sediments assigned to pollen zones 2a to 3c, recording more continuous postglacial deposition than at most other sites in northern Georgian Bay. Siltier, more organic muds below ~440 cm in the core record low water levels during the late Lake Hough phase. The transition from a centropyxid to diffugiid dominated fauna occurs toward the top of pollen zone 2b. Centropyxid thecamoebians (*Centropyxis aculeata* and *Centropyxis constricta*) dominate the assemblage below ~365 cm, while *Difflugia oblonga* strongly dominates the assemblage in the rest of the piston core except in the sample at 165 cm, where a slight resurgence of centropyxids is noted at the top of pollen zone 3b (the "hemlock minimum")

difflugiid thecamoebians (Fig. 5). *Centropyxis acule-ata* dominates below this, together with *Centropyxis constricta* (although there is a slight resurgence in centropyxid species together with *Difflugia protaei-formis* associated with the hemlock minimum, in the sample from 165 cm). Other thecamoebian taxa identified in this core are *Cucurbitella tricuspis*, *Difflugia urceolata*, *Difflugia bidens*, *Difflugia glob-ulus*, and *Pontigulasia compressa*.

Severn Sound

Severn Sound is a relatively shallow bay in south-easternmost Georgian Bay. It is connected to Georgian Bay via a relatively narrow channel between Beausoleil Island and the Penetanguishene Peninsula (Fig. 2a), but would have been isolated from late Lake Hough (Fig. 2b, c). This region appears to have a highly discontinuous record of Holocene sedimentation, which is consistent with the shallowness of the basin. Only a thin veneer of hemlock-rich sediments assigned to pollen zone 3 (probably zone 3a—McCarthy et al. 2007), and a highly variable cover of ragweed-rich sediments attributed to anthropogenic siltation overlies these sediments. Where the modern sediment cover was thin, such as at sites LH97-802-026 in Outer Midland Bay and LH97-802-035 in a deep basin in the channel between Beausoleil Island and the Penetanguishene Peninsula, the gravity corer just penetrated red/jack pine rich sediments of subzone 2a (McCarthy et al. 2007). The abundance of nonarboreal pollen (e.g. sedges and grasses) in relatively peaty organic-rich muds assigned to pollen zone 2a records shallow water conditions at site LH97-802-035, which is now at >18 m water depth (McCarthy et al. 2007). The virtual absence of pollen in a sample from 70 cm, and of thecamoebians in samples examined from 62, 71, 84 and 86 cm in the gravity core, suggests that site LH97-802-035 dried out during the early Holocene. The recovery of a thin sequence assigned to pollen subzone 2a above refusal, and the recovery of the subzone 2a/2b boundary, is consistent with the lake level reconstruction of Lewis et al. (2008) that predicts subaerial exposure of sites 026 and 035, and the subsequent transgression of Severn Sound from a lowstand ~90 m asl ~7,700 BP, or 8,490 cal BP (Figs. 1, 2b).

Thecamoebian concentrations in the cores from Severn Sound are slightly higher than those in

sediments deposited in the Flowerpot and Killarney basins (Fig. 6). Concentrations are low in pollen zone 2 (~8–113 tests/ml in core LH97-802-035GC and ~49–177 tests/ml in core LH97-802-026GC), and substantially higher in pollen zone 3 (~415 522 tests/ml in core LH97-802-035GC and ~55–376 tests/ml in core LH97-802-026GC). Pollen zone 4 contains moderate thecamoebian concentrations (~72 tests/ml in core LH97-802-035GC and ~104 tests/ml in core LH97-802-026GC) strongly dominated by *Cucurbitella tricuspis* (Fig. 6). In both cores, a sharp transition from an assemblage dominated by *Centropyxis aculeata* to one dominated by *Difflugia oblonga* occurs within pollen zone 2b: between 34 and 21 cm in core LH97-802-035GC, and between 86 and 71 cm in core LH97-802-026GC. Other thecamoebian species identified include *Difflugia bidens*, *Difflugia urceolata*, *Difflugia globulus*, *Pontigulasia compressa*, *Difflugia urens*, and *Lesque-reusia spiralis*.

Discussion

Pollen and thecamoebian data record the evolution of Georgian Bay as climate and lake levels fluctuated through the Holocene (Fig. 7). During the late glacial, forest-tundra vegetation produced pollen zone 1 of McAndrews (1994) and Lake Algonquin occupied the Georgian Bay basin, transgressing well beyond the modern shoreline, especially over the low-lying Canadian Shield to the east (Lewis et al. 2008). Sparse *Difflugia oblonga*-dominated thecamoebian populations characterize the varved clays that were rapidly deposited in Lake Algonquin as the Laurentide ice sheet melted (Tiffin 1998; Sarvis 2000). Retreat of the ice sheet eventually exposed the much lower North Bay outlet in northeastern Georgian Bay, and lake level fell sharply, forming the Lake Hough lowstands that were punctuated by highstands (the Mattawa Lakes). The warming climate produced a vegetational succession to a boreal parkland/forest that produced pollen zone 2, whose base was dated ~8,800 (9,800 cal) BP in Axe Lake (McCarthy et al. 2007). *Difflugia oblonga* remained the dominant thecamoebian taxon until around the pollen zone 2a/2b boundary, ~7,500 (8,300 cal) BP, when a centropyxid-dominated thecamoebian assemblage (*Centropyxis aculeata* and
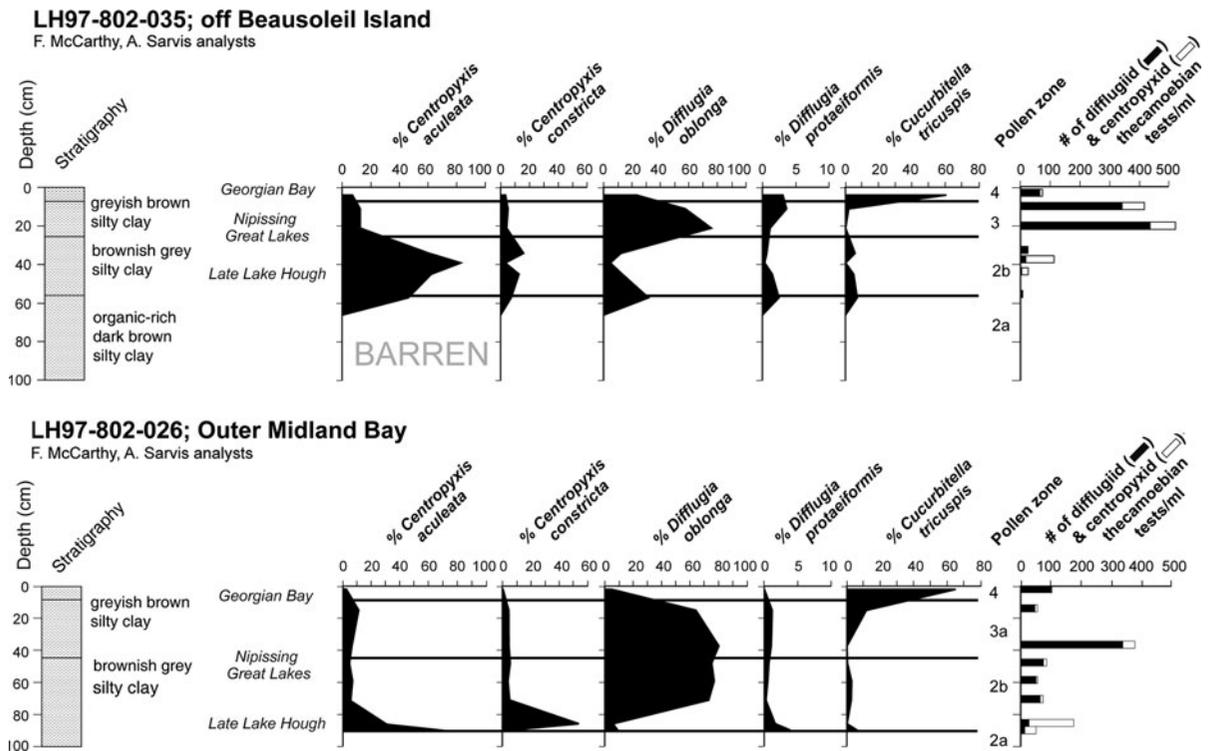
Fig. 6 Summary of sediment and thecamoebian data from Severn Sound. Muds in the gravity cores LH97-802-035GC ("035") and LH97-802-026GC ("026") in Severn Sound are assigned to pollen zones 2a through 4, recording known low net accumulation rates in Severn Sound (McCarthy et al. 2007). Stiff sediments barren of pollen below 70 cm at Site LH97-802-035 (currently in >18 m water; McCarthy et al. 2007) suggest subaerial exposure and oxidation in organic-rich (peaty) clays deposited during pollen zone 2a, ~8,800–7,500 (9,900–8,200 cal) BP. Centropyxid thecamoebians dominate sediments deposited around the pollen zone 2a/2b boundary, ~7,500 (8,200 cal) BP, at both sites LH97-802-026 and LH97-802-035

Centropyxis constricta) replaced the difflugiid-dominated assemblage. *Centropyxis* species are considered to be opportunists, better able to tolerate cold temperatures and oligotrophy (Collins et al. 1990; McCarthy et al. 1995; Neville 2009), high concentrations of heavy metals and toxic organic compounds (Reinhardt et al. 1998; Patterson and Kumar 2000. Neville 2009), and brackish conditions in marginal marine environments (Scott and Medioli 1978; Patterson et al. 1985; Honig and Scott 1987; Miller et al. 1982).

The establishment of a low-diversity assemblage dominated by centropyxid species records the existence of harsh conditions in late Lake Hough that ended with the establishment of the mesic mixed forest that produced pollen zone 3. The succession of a diverse thecamoebian assemblage dominated again by *Difflugia oblonga* replacing the centropyxid-dominated interval is consistent with the ubiquitous presence of this taxon in high numbers in relatively unstressed lakes throughout North America (Collins et al. 1990). The only other major change in the Holocene thecamoebian record of Georgian Bay resulted from another type of stress: anthropogenic impact. The dramatic increase in number of tests of the difflugiid thecamoebian *Cucurbitella tricuspis* seen in the Severn Sound cores (Fig. 6 and McCarthy et al. 2007) associated with the increase in ragweed and other non arboreal pollen is consistent with the association of an abundance of this taxon accompanying eutrophication (Medioli and Scott 1988; Reinhardt et al. 2005).

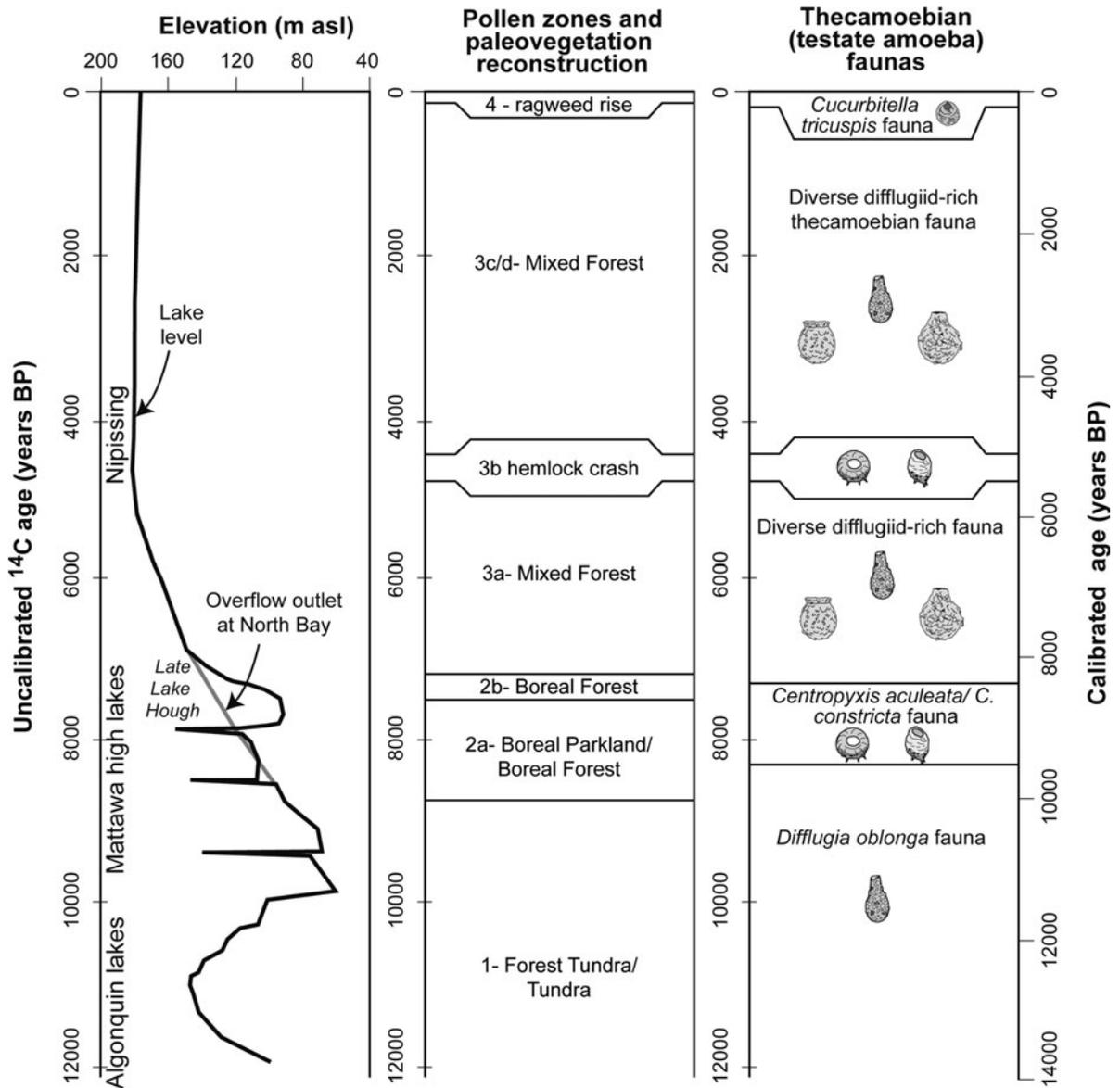The dominance of centropyxid thecamoebians in early Holocene sediments coincides with geological

Fig. 7 Summary diagram showing changes in lake level, pollen zones, paleovegetation, and thecamoebian fauna with time from ~11,800 (~13,700 cal) BP to present in the Georgian Bay basin. Lake level elevations are 'original' elevations with glacial rebound removed as described in the Fig. 1 caption. Thecamoebian assemblages appear to record paleoclimatic and paleolimnological changes in the Georgian Bay basin since deglaciation. Centropyxid thecamoebians (*Centropyxis aculeata* and *Centropyxis constricta*) were abundant between ~8,300 and 7,300 (9,300 and 8,100 cal) BP, apparently in response to the development of slightly brackish conditions in the closed basin of late Lake Hough during the relatively arid early Holocene pine zone: pollen zone 2, ~8,800–7,200 (9,900–8,050 cal) BP. The establishment of a diverse difflugiid-dominated thecamoebian fauna slightly before the transition to pollen zone 3a records the establishment of the mixed forest following the onset of warmer and wetter conditions. The subsequent increase in centropyxid thecamoebians during pollen zone 3b supports climate as a case for the hemlock crash. The dominance of *Curcurbitella tricuspis* in ragweed-rich sediments records eutrophication associated with anthropogenic activity

evidence of the Lake Hough lowstand, such as the prograding ridges of oxidized sand at the Flowerpot Beach site (Blasco 2001; Blasco et al. 2010), the increase in coarse silt and sand culminating in the calcareous sand layer in the Flowerpot Basin (Fig. 4) and clayey silt in the Killarney Basin (Fig. 5), and the

oxidation of pollen in peaty sediments in Severn Sound (Fig. 6). There is a clear geological record of a lowstand ∼30 m below the level of the lowest outlet, i.e. closed basin conditions (Fig. 2). We thus interpret the centropyxid-dominated thecamoebian fauna as recording the development of slightly brackish conditions in late Lake Hough due to a negative water budget (McCarthy and McAndrews 2010), supporting the earlier interpretation of Sarvis et al. (1999). A deficit in effective moisture in the Georgian Bay basin is consistent with pollen evidence of early Holocene drought throughout mid-latitude eastern North America during the early Holocene, including pollen and other microfossil and stable isotope data (McAndrews 1966; Webb et al. 1983, 1993a, b, 2004; Baker et al. 1992; Prentice et al. 1991; Newby et al. 2000; Shuman et al. 2002). Transfer function analysis of pollen data from small lakes in the Georgian Bay catchment reconstructs low annual precipitation (around 65–72 cm year^{-1}) and greater seasonality (more evaporative summers and less snowy winters) during the pine zone (McCarthy and McAndrews 2010). This is less than 70% of the modern value for this region (McCarthy and McAndrews 2010), and less than the ∼75 cm year^{-1} required for a healthy water budget (Schertzer et al. 1979).

Even greater aridity, producing eastward expansion of prairie and oak savanna in the American Midwest, is thought to have forced Lake Superior to hydrologic closure, eliminating ∼90% of the surface water input into Georgian Bay (McCarthy and McAndrews 2010). Warry (1978) showed that isolating Georgian Bay, under present conditions, would substantially increase the concentration of potassium and sulfate ions relative to the main basin of Lake Huron. The dramatic reduction in surface water input to Lake Hough would have increased the relative importance of base flow, the contribution of groundwater to surface water bodies, which is currently high in the drainage basin of Georgian Bay (Neff et al. 2005). Groundwater seeps are characterized by elevated high levels of conductivity (1,700 μS/cm in contrast to 140 μS/cm in modern Lake Huron), as well as high concentrations of chloride, sulfate, phosphorus and organic matter, as well as warmer temperature (Ruberg et al. 2005). Centropyxid-dominated thecamoebian assemblages in modern wetlands and lakes with high concentrations of chloride, sulfate and organic matter associated with oil sands

extraction in northern Alberta (Neville 2009) are similar to assemblages found in sediments deposited in late Lake Hough. The preservation of ostracod valves in a sample near the pollen zone 2a/2b boundary in the core from the deep Flowerpot Basin is evidence of greater concentration of ions around 7,500 (8,300 cal) BP. These microfossils are normally absent in Georgian Bay sediments, unlike early Holocene sediments in the main basin of Lake Huron (Lewis et al. 1994; Dobson et al. 1995). Their absence is attributed to the low availability of ions needed for the precipitation and postmortem preservation of the calcareous valves, except during the late Lake Hough evaporative lowstand.

Centropyxid-dominated thecamoebian faunas do not appear to have developed during the earlier phases of Lake Hough. This is attributed to the continued flow of Laurentide ice sheet meltwater into the Great Lakes basin until ∼8,000 (8,890 cal) BP (Lewis et al. 2008). Within ∼500 years of the diversion of meltwater from the Great Lakes, there are multiple lines of evidence pointing to hydrologic closure of Georgian Bay, and possibly Lake Superior (McCarthy and McAndrews 2010). The implication that water budget fluctuations leading to discernible variations in lake level and water chemistry occurred in the relatively recent geologic past is significant to studies of global climate change and resource management in the Great Lakes, one of the world's largest freshwater resources.

The positive water budget associated with the milder winters and higher mean annual precipitation that produced regional pollen zone 3 of McAndrews (1994) rapidly lowered the concentration of dissolved ions in Georgian Bay to modern values (McCarthy and McAndrews 2010). The re-establishment of "normal" fresh water conditions is recorded by the resurgence of difflugiid taxa (primarily *Difflugia oblonga*) slightly below the pollen zone 2/3 boundary where sufficient sampling resolution exists (e.g. such as Core LH95-800-034 from the Killarney Basin and in cores LH97-802-026 and -035 from Severn Sound). Tentatively, this resurgence in advance of the arrival of the mesic Mixed Forest suggests that these short-lived asexually-reproducing protists with rapid generation times are more sensitive to environmental change than pollen records that record vegetation changes that can lag climate change by many decades, as was shown in small Atlantic Canada lakes

by McCarthy et al. (1995). The subsequent increase in centropyxids at the expense of difflugiids in subzone 3b (the hemlock minimum) in the Killarney Basin core (Fig. 5) is also consistent with evaporation-driven changes in water chemistry in Georgian Bay, as several workers have attributed the mid-Holocene hemlock decline to aridity (Yu and McAndrews 1997; Haas and McAndrews 2000; Booth et al. 2002; Calcote 2003).

Conclusions

The centropyxid-dominated thecamoebian fauna identified in sediments deposited throughout the Georgian Bay basin around 7,500 (8,300 cal) BP are interpreted to record the development of slightly brackish conditions in the closed basin of late Lake Hough. This interpretation is consistent with geological evidence that lake level fell well below the level of the lowest outlet controls (at Dalles Rapids and North Bay) during the late Lake Hough phase. The more arid continental climate, with higher summer evaporation and colder, less snowy winters that characterised the Great Lakes basin during the early Holocene pine zone, particularly subzone 2a, the jack pine/red pine zone, ~8,800–7,500 (9,900–8,200 cal) BP (McCarthy and McAndrews 2010) could explain the development of slightly brackish conditions in the closed basin of late Lake Hough following the diversion of Laurentide Ice Sheet meltwater from the Great Lakes, ~8,000 (8,900 cal) BP (Lewis et al. 2008). The increase in mean annual precipitation and in winter temperatures that replaced the more arid pine zone over the span of several centuries all over eastern North America (Webb T et al. 2004; McCarthy and McAndrews 2010) produced a positive hydrologic budget that rapidly restored freshwater conditions to Georgian Bay, which favoured the difflugiid thecamoebians over the relatively euryhaline and eurythermal centropyxid thecamoebians. The subsequent establishment of a typical mid-latitude pre-anthropogenic thecamoebian fauna dominated by *Difflugia oblonga* appears to slightly precede the regional change in vegetation that produced the Mixed Forest (Laurentian-Great Lakes) vegetation in the Georgian Bay catchment, suggesting that these protists responded quickly to climate-driven changes in water quality. The changes in lake level and water quality which are registered in the sediments of late Lake Hough about 7,500 (8,300 cal) BP in the Georgian Bay basin as a result of a past dry climate are a clear indication of the sensitivity of Georgian Bay to changes in climate, an important consideration in the assessment of the effects of future climate change.

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