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Changing sedimentation patterns due to historical land-use change in Frenchman's Bay, Pickering, Canada: evidence from high-resolution textural analysis

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Abstract This study examines the anthropogenic alteration of sedimentation in Frenchman's Bay in Lake Ontario, using high-resolution particle size analysis in two 200 cm cores. Lithofacies were determined using the particle size data of both the terrigenous sediment and terrigenous sediment + diatom fractions. Terrigenous particle size data from the centre of the lagoon provided the most representative record of anthropogenic impacts. Three distinctive lithofacies were recognized: (1) a Natural Wetland (NW) lithofacies (106–200 cm) had an average mean particle size of 49.4 μm, a mode of 29.4 μm and an average standard deviation of 119.1 μm; (2) an Agricultural and Deforestation (AD) lithofacies (40–105 cm) had a statistically significant lower average mean (30.8 μm), mode (13.5 μm), and standard deviation (48.5) μm; (3) an Urbanized (U) lithofacies (0–40 cm) showed a continued trend towards smaller particle sizes with an average mean of 21.2 μm, a mode of 9.4 μm, and an average standard deviation of 32.7 μm. The lithofacies correlated with previously identified trends in thecamoebian biofacies and magnetic

susceptibility data showing post-colonial lagoon eutrophication and increased overland soil erosion. The up-core trend towards finer and less variable particle sizes is attributed to erosion of fine-grained watershed sediments (glacial Lake Iroquois silts and clay) during land-clearance and modification of natural drainage patterns. The influx of silts and clays into the lagoon is also recorded by increased sediment accumulation rates and a reduction in seasonal sediment variability in the wetland. Based on the ^{210}Pb dates, sedimentation rates increased at 1850 ± 56 AD (AD lithofacies) and suggest an exponentially increasing trend in accumulation rates. Increasing sedimentation rates can be attributed to the progressive loss of native vegetation and intensified erosion of Lake Iroquois deposits via stream and hillslope erosion. Ecologically, the increased input of fine-grained sediments into the wetland has resulted in reduced water clarity and has altered the wetland substrate contributing to wetland loss in Frenchman's Bay.

Keywords Land-use change · Wetlands · Particle size distributions · Deforestation

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Introduction

Frenchman's Bay is a small freshwater lagoon located on the north side of Lake Ontario about

40 km east of Toronto (Fig. 1). The lagoon once hosted a flourishing wetland system that provided an important habitat for fish, reptiles, and migrating birds (Ball et al. 2003). However, due to anthropogenic impacts starting with colonization in the mid-18th century, the natural wetland (NW) system has been severely affected by eutrophication, vegetation loss, and excessive suspended sediment input (Eyles and Chow-Fraser 2003; Eyles et al. 2003; Clark 2004; Reinhardt et al. 2005). Urbanization of the watershed in the 1950s caused rapid decline in the water quality within the lagoon due to discharge of municipal sewage into the bay. In response to these problems, the Township of Pickering has initiated remediation efforts to eliminate effluent discharges and to restore the natural ecosystem of Frenchman's Bay (Eyles and Chow-Fraser 2003). In order to guide the restoration efforts, several studies have been conducted to investigate the extent of human modification of the lagoon and its wetland system (Eyles and Chow-Fraser 2003; Eyles et al. 2003). The lagoon has experienced significant wetland fragmentation and vegetation

loss during the last 100 years but the exact cause of the wetland degradation has yet to be identified.

In this study, the impacts of land-use changes and urbanization on wetlands and sedimentation patterns in Frenchman's Bay were investigated through detailed particle size analyses of lagoon sediments. A number of studies have investigated the influence of land-use change on sedimentation rates (Warwick 1980; Baptista Neto et al. 1999; Cisternas et al. 2001; McDonald et al. 2002; Nelson and Booth 2002; Nakamura et al. 2004) and have shown that sediment influx and sediment accumulation rates increase dramatically during land clearance. In southern Ontario, Canada, the whole-scale clear-cutting of large tracts of forest around Lake Ontario that began in the 1840s resulted in dramatic impacts from erosion and a 10-fold increase in sediment accumulation in coastal lagoons and rivers (i.e., Humber River; Wenninger and McAndrews 1989). However, little is known about the subtle changes in sediment texture and alterations in coastal depositional environments that have accompanied these

Fig. 1 Bathymetric map of Frenchman's Bay (modified from Eyles et al. 2003) showing the locations of cores FMB1 and FMB2. Water depths in metres relative to the International Great Lakes Datum (74.0 m elevation). Horizontal datum NAD83 (UTM zone 17). Contour interval is 0.5 m
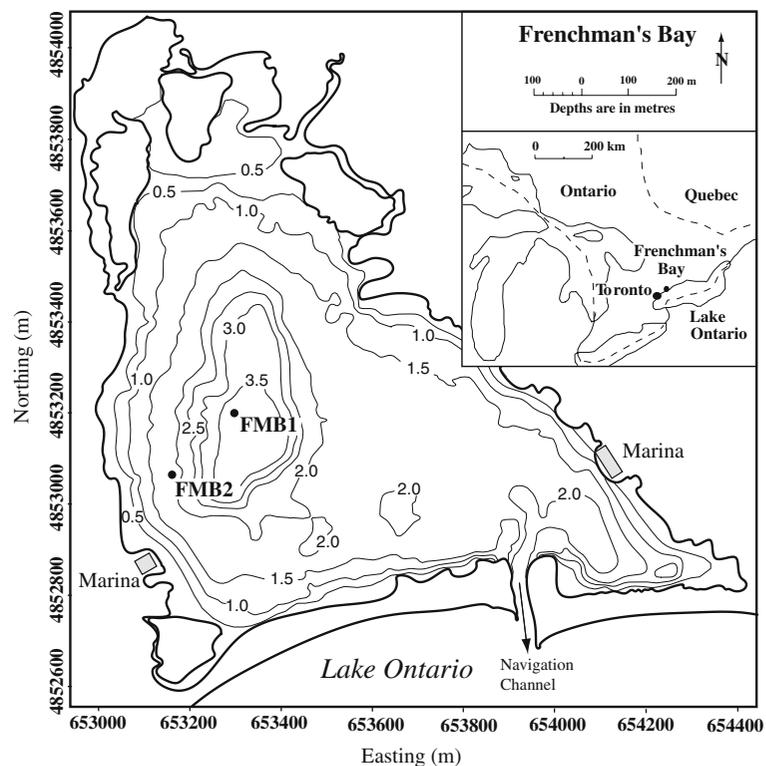
land-use changes. An understanding of changes in sediment yield and particle size is of particular importance for remediation and management of coastal wetlands because water turbidity and growth substrate strongly affect the health of emergent and submergent marsh vegetation (Chow-Fraser 1998; Chow-Fraser et al. 1998). Particle size is also important for understanding the historic sources of contaminants and their distribution in bottom sediments (e.g., Clark 2004), as many pollutants preferentially sorb onto finer-grained sediment particles. Particle size analysis has also been applied in other paleolimnological applications, such as tracking past climate change (e.g., Bird and Kirby 2006), lake-level fluctuations (e.g., Dieffenbacjer-Krall and Nurse 2005) and to monitor Antarctic ice shelf loss (e.g., Smith et al. 2006).

The results of this study demonstrate that the land clearance and urbanization within Frenchman's Bay were associated not only with an increase in erosion and sediment delivery to the lagoon, but also with subtle changes in sediment texture and composition. These shifts in particle size were not visible in the core and were detectable only with high-resolution particle size analysis. These results provide important insights into the consequences of landscape modification on coastal lakes and wetlands and show that wetland health is strongly influenced by changes in sedimentation patterns. The land-use impacts documented in Frenchman's Bay are likely representative of many other Great Lake watersheds that have experienced extensive deforestation and development following European colonization. The textural analysis methods presented here have a broader application to the study of these impacts and other types of land disturbance that may be archived in lake sediments.

Physical setting of Frenchman's Bay

The Frenchman's Bay watershed covers an area of ~20 km^2 and is drained by four streams (Amberlea, Dunbarton, Pine, and Krosno creeks) that empty directly into a small coastal lagoon (Fig. 2). The lagoon covers about 85 ha, comprising ~55 ha of open water and ~30 ha of fringing marsh (Eyles et al. 2003). The lagoon connects to Lake Ontario via a navigation channel at its south end that was constructed in 1843 to allow the passage off steamships into the harbour (McKay 1961). The watershed is heavily urbanized (>80%) and all of the streams have been heavily modified to varying degrees by channelization and integration with the municipal storm sewer system (Eyles et al. 2003).

Fig. 2 Drainage system and surficial geology of Frenchman's Bay watershed (modified from Eyles et al. 2003; Clark 2004)
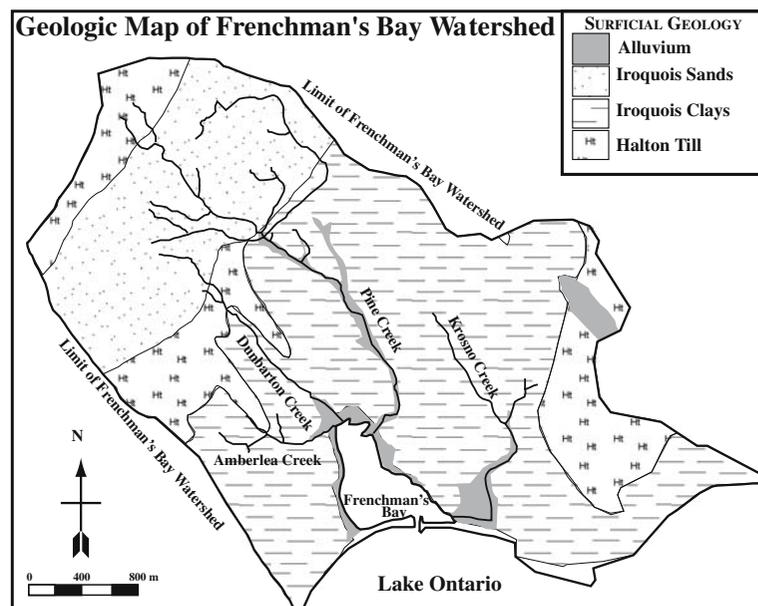
The watershed geology consists of late Pleistocene glacial sediments (Fig. 2) overlying Ordovician shale bedrock (Whitby Formation, Eyles et al. 2003). The surficial deposits include the Halton Till, which was deposited during the last re-advance of the Laurentide Ice Sheet (ca. 13000 BP) and overlying Lake Iroquois glaciolacustrine deposits (Clark 2004). Glacial Lake Iroquois stood up to 30 m above the present lake-level and was formed (ca. 12500 BP) by the damming of the St. Lawrence outlet as the Laurentide Ice Sheet retreated to the northeast. The predominant deposit is the Lake Iroquois Clay, comprised of silts and laminated clayey-silt textured sediment and is present across the lower two-thirds of the watershed. The former Lake Iroquois shoreline is marked in the upper-third of the catchment by sands and gravels (Fig. 2). The Halton Till, consisting of silt to silty-sand diamicton, is exposed only in the upland headwater areas of the catchment (Eyles et al. 2003).

Within the lagoon, the Lake Iroquois deposits are overlain by a thin (< 3 m) sequence of marls and peaty silt deposits recording the formation and land-ward transgression of the lagoon (McCarthy and McAndrews 1988; Eyles et al. 2003). Peat that was radiocarbon dated from the base of the sequence suggests that the lagoon was formed about 2,700 years ago, under conditions of rising water levels in Lake Ontario (McCarthy and McAndrews 1988). The coastal transgression has resulted in the preservation of a continuous record of late Holocene and recent environmental changes within the lagoon sediments.

Land-use changes

Huron and Five Nations Iroquois first inhabited Frenchman's Bay watershed about 4,000 years ago. The first European traders began arriving in 1669; however, a permanent European presence was not established until the early 1800s with immigrant arrivals from Ireland, England, and Scotland (McKay 1961; Skibicki 1991). By 1850, over half of the township of Pickering was deforested for agriculture and 26 saw mills were operating in the direct periphery of the present day lagoon shoreline (Skibicki 1991). Land-use in the watershed remained dominantly rural and agricultural until the 1960s (Fig. 3), when the construction of the Pickering Nuclear Generating Station (fission power plant) stimulated urban residential and commercial growth around Frenchman's Bay. By the late 1980s more than two-thirds of the watershed was urbanized and agricultural land-use had decreased to less than 5% of the total land area. This trend continues today as the population (ca. 92, 400) continues to grow with the rapid expansion of the Greater Toronto Area.

Previous work

Several recent studies have been conducted in Frenchman's Bay to gather baseline environmental

Fig. 3 Land-use in Frenchman's Bay watershed as a percentage of the total land area (1935–1995) (after Skibicki 1991; Clark 2004)
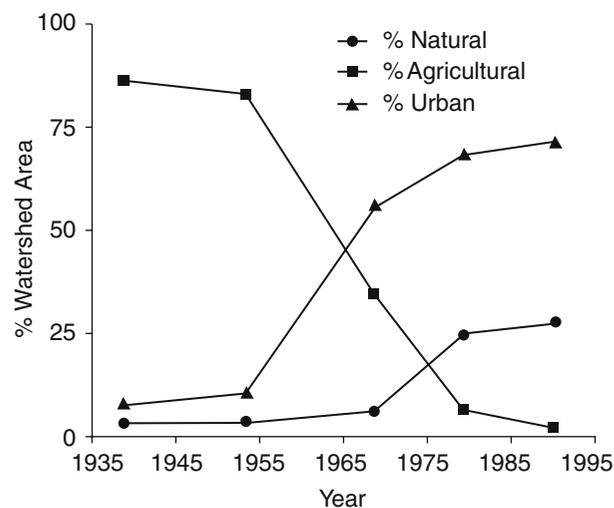
data prior to development of a remediation plan for the wetlands. Eyles et al. (2003) and Eyles and Chow-Fraser (2003) conducted a comprehensive study of the geological and biological conditions in the lagoon and documented the impacts of recent urban developments on the lagoon's sediment, water quality, and wetland habitats. Clark (2004) examined the magnetic properties of the lagoon bottom sediments and was able to identify a more magnetized upper layer of sediment recording European settlement and the onset of the industrial period in the watershed. The increased magnetic susceptibility of the layer was attributed to titano-magnetites derived from erosion of soils during land clearance and magnetic spherules produced by coal-burning (e.g., Beckwith et al. 1986; Petrovsky et al. 2000; Boar and Harper 2002).

Most recently, Reinhardt et al. (2005) investigated the thecamoebian diversity in the lagoon sediments. Thecamoebians (arcellaceans) are single-celled, testate rhizopod amoebas that occupy specific ecological niches in freshwater environments and are useful environmental indicators (Patterson and Kumar 2002; Patterson et al. 2002). The trends determined in thecamoebian biodiversity identified the onset of eutrophic conditions in the lagoon following European colonization in the mid-19th century. The eutrophication was marked by a large increase in the abundance of thecamoebian tests and the thecamoebian eutrophication indicator *Cucurbitella tricuspis*. The thecamoebian trends determined by Reinhardt et al. (2005) were closely correlated with the magnetic susceptibility trends documented by Clark (2004).

Methods

Vibracoring was conducted in Frenchman's Bay during September 2002 and two cores (FMB1 and FMB2; Fig. 1) were used in the present study. A 3.35 m core (FMB1) was extracted from the central portion of the lagoon at a water depth of 3.5 m and a 2.3 m core (FMB2) in a water depth of 1.7 m from the western lagoon periphery. The upper 200 cm of both cores were analyzed, as this interval had been determined by Clark (2004) to contain a complete sediment record of the

pre-colonial to recent conditions in the lagoon. The lagoon bathymetry (Fig. 1) had been mapped in detail in a previous study using a 200 kHz echosounder with differential GPS positioning and 10 m survey line spacing (Eyles et al., 2003).

Sediment samples (5 cm^3) were collected from FMB1 at 1-cm intervals over the entire 2 m length of the core (200 samples). FMB1 is considered a more complete record of the temporal changes in sedimentation patterns as it was from the deepest part of the lagoon. Core FMB2 was included for comparative purposes and sampled at a lower resolution (5–10 cm).

A Beckman–Coulter LS 230 (BC LS 230) was used for lazer diffraction particle size analysis on each sample and mathematical computations were completed using the Fraunhofer optical model (Murray 2002). The sediment samples were subjected to sequential chemical digestions to remove biological components (i.e., shell—HCl, OM—H_2O_2, diatoms—Na_2CO_3) leaving only siliciclastic sediment for analysis (Murray 2002; Conley and Schelske 2001). Samples were first treated with 10% HCl for digestion of the carbonate fraction followed by a rinse in de-ionized water (Murray 2002). A 30% H_2O_2 digestion was then used to remove the organic matter.

Following the HCl and H_2O_2 chemical digestions, sediment samples were centrifuged and supernatant decanted. The paste of sediment was then mixed with a spatula to homogeneity and then sub-sampled for particle size analysis. The sub-samples were mixed with a 1% sodium hexametaphosphate solution and ultrasonically disaggregated to disperse the individual sediment grains and particles before textural analysis (Murray 2002).
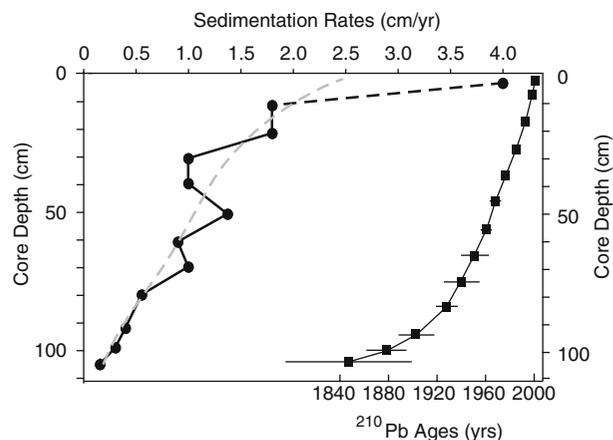
Samples from FMB1 were subjected to a further digestion in Na_2CO_3 in a hot 85°C bath for ~3 h to remove the biologic silica fraction (mainly diatoms). The samples were examined for completeness of dissolution and then re-analyzed for particle size as outlined above (Conley and Schelske 2001). The purpose of the additional digestion for FMB1 was to statistically and graphically visualize the influence of diatoms on a specific case study to determine its significance for high-resolution paleolimnological studies.

Summary statistical measures (mean, mode, and standard deviation) were calculated for the particle size distributions (PSD) and plotted depth-wise. A surface plot was produced for the FMB1 high-resolution PSD data using the methods outlined in Beierle et al. (2002). The surface plot provides details of the skewness and subtle modal characteristics of the PSDs that are difficult to visualize in the simple down core plots of the summary statistics. The raw particle size data were first reformatted as an x, y, and z file (depth, particle diameter, and % volume) and the particle size classes log transformed to the Wentworth Phi Scale. The log transformed data were then interpolated and gridded using a triangular irregular network (TIN) algorithm (Sambridge et al. 1995) and plotted as a colour surface plot using Geosoft Oasis™ software (Beierle et al. 2002). A surface plot was not generated from FMB2 PSDs as the lower sample resolution would have resulted in a large degree of interpolation of the particle size data.

Geochronology

FMB1 sediment ages were determined using ^{210}Pb dating provided by MyCore Scientific Inc. Deep River, Ontario, Canada (Clark 2004). The depth-age profile was calculated using the constant rate of supply model, which assumes that the sediment transport parameters are independent of the sedimentation rate and there is a constant influx of unsupported ^{210}Pb to the sediments (Oldfield and Appleby 1984; Blais et al. 1995).

The ^{210}Pb ages indicate that the upper 1-meter of sediment was deposited within the last 100–200 years (Fig. 4). The core ages were also constrained by small glass sherds found in both FMB1 and FMB2 (below 201 cm and 182 cm, respectively). The glass sherds were angular and non-abraded—indicating they had not undergone significant post-depositional reworking or transport. The sherds constrain the maximum possible age of the upper 200 cm of sediment in FMB1 and upper 180 cm of sediment in FMB2 to 1669, the date of earliest European settlement (Reinhardt et al. 2005).

Results

The results of the particle size analyses are shown in Figs. 5 and 6 together with core lithology and other environmental indicators (thecamoebian biofacies, loss on ignition (LOI), $CaCO_3$ content and magnetic susceptibility profiles) summarized from Reinhardt et al. (2005) and Clark (2004).

The generalized lithostratigraphy in both cores consisted of fining-upward sequences of sandy-silt to clayey-silts. In core FMB1 two lithostratigraphic units were visually recognized: an uppermost unit of massive to crudely bedded clayey-silt (0–106 cm) with low to moderate organic content (LOI 5–15%) overlying an organic-rich (LOI >50%) silt unit containing bark and leaf fragments. The FMB2 stratigraphy was also broadly sub-dividable into two units: an upper unit of fine to coarse silt (0–60 cm) with moderate

Fig. 4 ^{210}Pb ages (squares) and estimated sedimentation rates (circles) for core FMB1. Error bars not shown on ^{210}Pb ages where error less than ±4 years

organic content (LOI < 18%) followed by an organic-rich (LOI > 50%) silt unit interbedded with peat, clays, and sands (60–200 cm).

Natural wetland lithofacies

The NW lithofacies was identified at 106–200 cm in FMB1 and 82–200 cm in FMB2 (Figs. 5, 6). In FMB1, this lithofacies was characterized by alternating centimetre-scale beds of fine silt and coarse silt to fine sand and was recognizable in both the terrigenous + diatom and the terrigenous fractions. The particle size oscillations defined subtle interbedding that was not visible in the split core, which appeared largely massive with only crude laminations. The terrigenous sediment had a mode (dominant particle size) that varied between ~20 μm (fine silt) and ~60 μm (coarse silt) with an average modal value of 33.2 μm (Fig. 5). The mean particle size showed similar trends but was more variable, as it is more sensitive to changes in particle size distribution than the mode. The terrigenous + diatom fraction showed less variability in the mean and modal values and overall coarser particle sizes as a result of the large diatom component. The standard deviation (degree of sediment sorting) showed that the coarser-grained sand interbeds were more poorly sorted in comparison to the fine silt units that were moderate to well sorted. The mean, mode, and standard deviation for the NW lithofacies was distinctly different than the overlying facies both in FMB1 and FMB2, having both a coarser texture and poorer sorting (except the Anomalous Land Disturbance lithofacies; Tables 1, 2).

The PSD surface plot (Fig. 7) of FMB1 clearly shows the alternation of fine and coarse silt horizons defining interbedding with the NW lithofacies. The plot also provides additional details of the particle size modes, peakedness, and the skewness of individual samples. The majority of samples are uni- to multi-modal and have high peakedness. The top of the NW lithofacies is clearly defined by a shift to higher modal values at
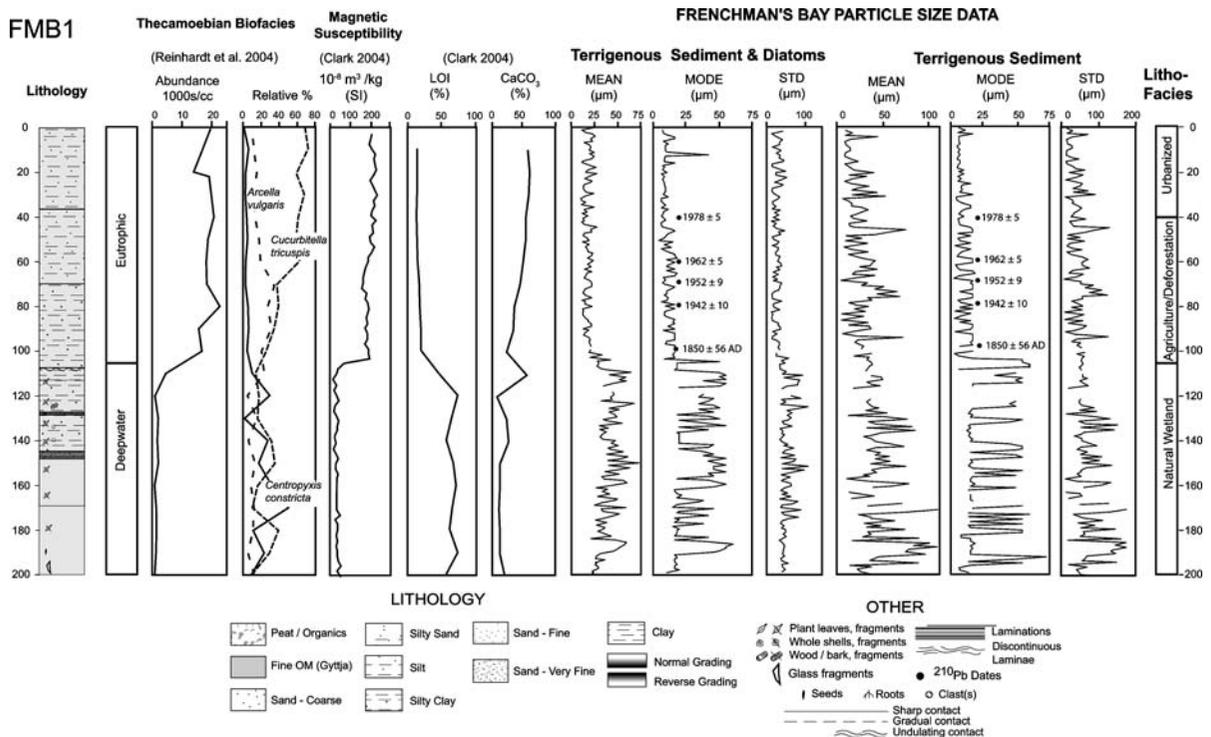

Fig. 5 FMB1 core lithology and particle size parameters (mean, mode, and standard deviation) for both grain-size sample preparations. Down core changes in thecamoebian biofacies, magnetic susceptibility, LOI, and carbonate content from previous studies also shown (Clark 2004; Reinhardt et al. 2005). Breaks in data represent sample loss on digestion
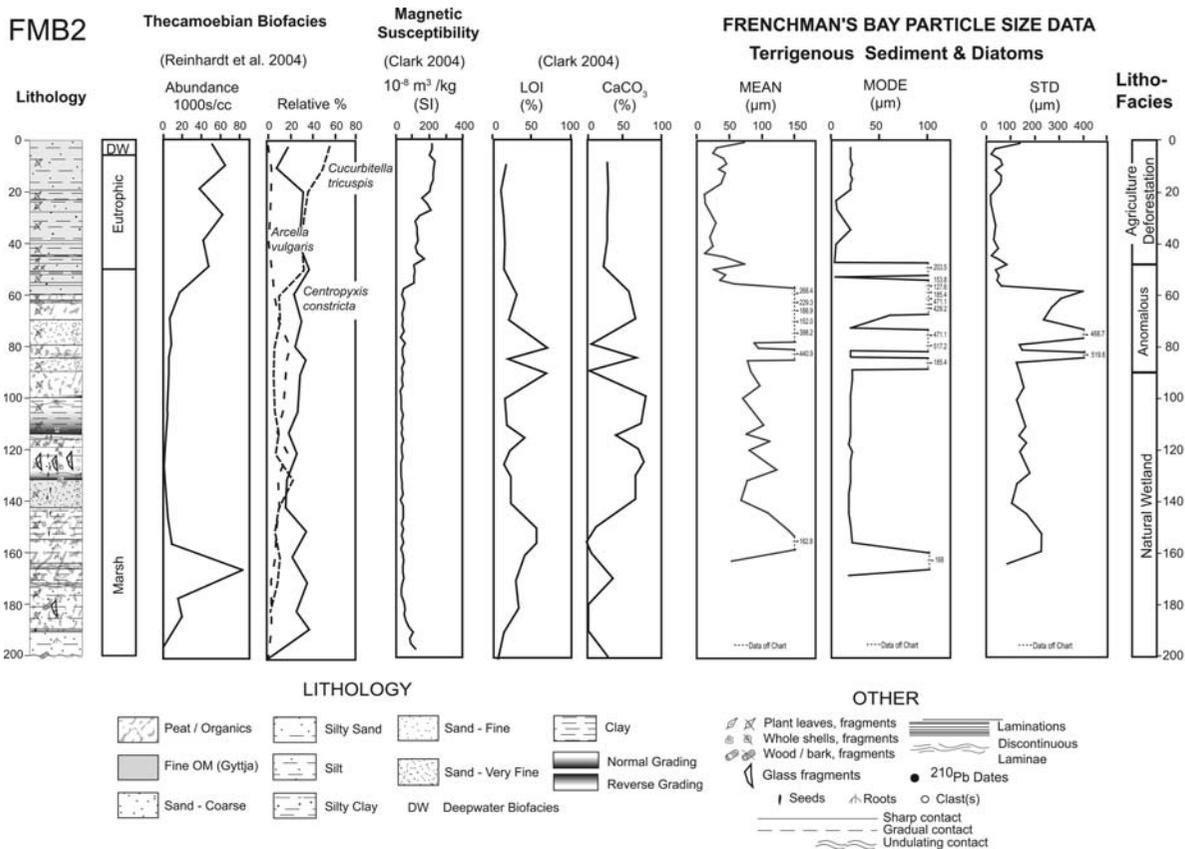
Fig. 6 FMB2 core lithology and particle size statistics (mean, mode, and standard deviation). Downcore changes in thecamoebian biofacies, magnetic susceptibility, LOI, and carbonate content from previous studies also shown (Clark 2004; Reinhardt et al. 2005)

106 cm depth. The PSD surface plot also shows that within the dominant texture range (4–8ϕ, 4–63 μm) the particle size variation (~2ϕ, 45 μm) agrees with the summary statistical parameters.

Comparison of the NW lithofacies with the thecamoebian biofacies showed that it corresponded closely with the Deepwater and Marsh biofacies in FMB1 and FMB2. The biofacies were characterized by relatively low thecamoebian abundance and were interpreted by Reinhardt et al. (2005) as a record of a minimally impacted wetland. The NW lithofacies also corresponds with a zone of low magnetic susceptibility (Figs. 5, 6) identified by Clark (2004).

Agriculture and Deforestation lithofacies

The Agriculture and Deforestation (AD) lithofacies was identified in FMB1 from 40 cm to 106 cm and from 0 cm to 46 cm in FMB2. In FMB1, the terrigenous + diatoms fraction showed a distinct shift to finer particle sizes with a decrease in the average mean (41.3–17.9 μm), mode (33.2–12.7 μm), and standard deviation (53.6–27.6 μm) between the AD and underlying NW lithofacies (Table 1). A similar shift was noted in the terrigenous sediments (average shift in mean 49.4–30.8 μm, mode 29.4–13.5 μm and standard deviation 119.1–28.5 μm). Using the mean values, a two-tailed z-test indicated that the FMB1 AD lithofacies is different from the NW lithofacies at the 95% confidence level, both with and without the diatoms. In FMB2, the AD lithofacies is characterized by a similar shift towards finer particle sizes with a decrease in the average values of the mean (95.6–33.9 μm), mode (36.1–15.7 μm), and standard deviation (152.5–59.8 μm). However, the anomalous land disturbance (ALD)

Table 1 FMB1 summary particle-size statistics for each lithofacies for terrigenous sediment + diatoms and the terrigenous sediment (diatoms removed)

FMB1		Terrigenous sediment + diatoms			Terrigenous sediment			Lithofacies
Core Depth	^{210}Pb Dates (Clark 2004)	Mean (μm)	Mode (μm)	SD (μm)	Mean (μm)	Mode (μm)	SD (μm)	
0–40 cm	1970 AD— Present	17.9	9.8	29.1	21.2	9.4	32.7	Urbanized lithofacies
40–105 cm	1850 + 56—1970 AD	17.9	12.7	27.6	30.8	13.5	48.5	Agricultural & Deforestation lithofacies
106–200 cm	<1840 AD	41.3	33.2	53.3	49.4	29.4	119.1	Natural Wetland lithofacies

Table 2 FMB2 summary particle size statistics for each lithofacies

FMB2	Terrigenous sediment + diatoms			Lithofacies
Core depth	Mean (μm)	Mode (μm)	SD (μm)	
0–46 cm	33.9	15.7	49.8	Argicultural & Deforestation lithofacies
46–82 cm	152.6	201.5	201.1	Anomalous disturbance
82–200 cm	95.6	36.1	152.5	Natural Wetland lithofacies

between 46 and 82 cm in FMB2 had significantly larger particle sizes (Table 2, Fig. 6).

In FMB1, the AD lithofacies showed less inter-sample variability than the NW lithofacies. However, small particle size oscillations were present, indicating crude interbedding of the sediment. Interbedding was defined in the terrigenous fraction by centimeter-scale alternation in the mode between ~20 μm (medium silt) and ~60 μm (coarse silt), whereas in the NW lithofacies the mode varied between ~8 μm (very fine silt) and ~20 μm. As with the NW lithofacies, the alternations were only detectable in the particle size data and the split core appeared mostly massive or crudely bedded.

The PSD surface plot for FMB1 provides a more complete picture of the range of particle size variability in the samples than the summary statistics (Fig. 7). In the NW lithofacies very fine silt to very fine sand samples dominate (4–8ϕ, 4–63 μm); whereas the AD lithofacies is dominantly clay to coarse silt (4–10ϕ, 1–63 μm) with some samples alternating with very fine silt to fine sand. The shift in the dominant texture (mode) is approximately 3ϕ (15 μm) between the NW and AD lithofacies and the skewness alternates from fine to more coarsely skewed when compared to the NW lithofacies, which is mostly coarse-skewed. It should be noted that the logarithimic scale of the phi particle-size plot emphasizes the

changes at the lower size ranges of the particle size spectrum (Fig. 7) and shows more distinctly the alternation in texture in the silt and clay range in the AD versus the NW lithofacies.

The transition between the NW and AD lithofacies coincides with a shift in both the thecamoebian abundance and the magnetic susceptibility (Figs. 5, 6). On the basis of the eutrophication indicator *Cucurbitella tricuspis*, the thecamoebian data indicate a shift to eutrophic conditions within the lagoon that is synchronous with a shift to higher values of magnetic susceptibility. The increase in magnetization of the sediment was found by Clark (2004) to result from increased titano-magnetite derived largely from erosion of top soil during land clearance (Clark 2004; Fig. 5). Based on the ^{210}Pb dates, the base of the AD lithofacies corresponds to $1,850 \pm 56$, a time by which whole-scale deforestation and agriculture had begun in the watershed. The vertical sediment accretion rate during this initial period of land clearance was ~0.3 cm/year, but rapidly increased to more than 1 cm/year with the onset of major urbanization in the early 1960s (Fig. 4).

Although core FMB2 was not dated, we have used the transition in thecamoebian assemblages and magnetic susceptibility as a reference point for the onset of European colonization. In FMB2, the NW lithofacies and the AD lithofacies were less distinct than in FMB1, reflecting the close proximity of core FMB1 to the shoreline and the
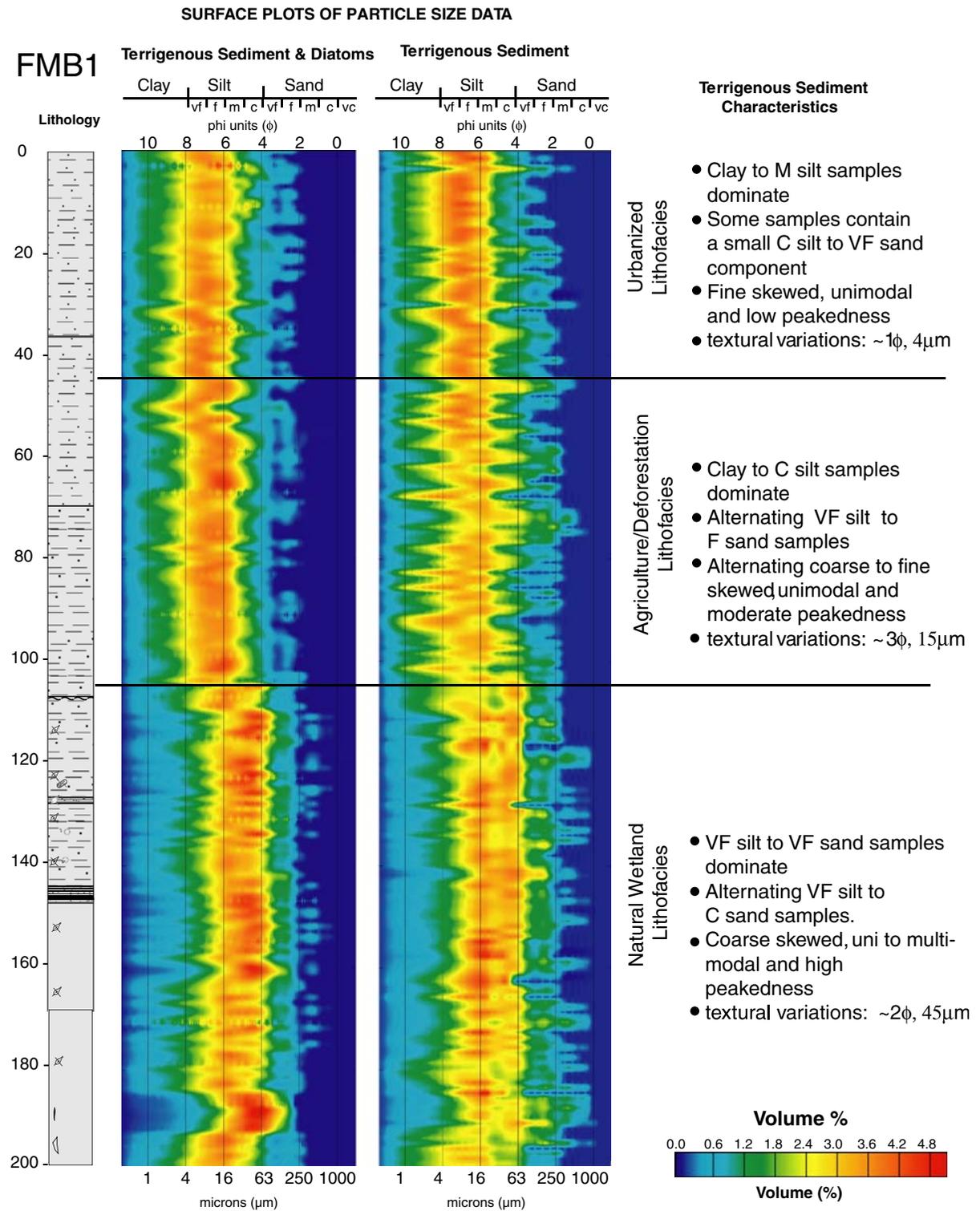
Fig. 7 PSD surface plot of FMB1 and summary lithofacies characteristics. The contour interval is 0.6% volume

influence of localized sediment sources. The mean and standard deviations in FMB2 shifted to lower values within the AD lithofacies but the mode did not shift to the same extent as in FMB1 (Tables 1, 2). The transition between AD and NW in FMB2 is also made more complex by the presence of an intervening unit of silt interbedded with fine to medium sands (ALD lithofacies; Fig. 6).

Urbanized lithofacies

An additional Urbanized (U) lithofacies was identified in FMB1 (0–40 cm), which was not present in FMB2. The base of the U lithofacies was recognized in the terrigeneous sediments by a decrease in the average mode from 12.7 μm to 9.8 μm when compared to the underlying AD lithofacies. Similarly for the terrigenous + diatoms fraction, the mean decreased from 30.8 μm to 21.2 μm and the mode from 13.5 μm to 9.44 μm. The differences in the modal and mean values of the U and AD lithofacies were statistically different at 95% level of confidence using a two-tailed z-test. The U lithofacies showed less inter-sample variability than the underlying units and was dominated by very fine to fine silt (6–8ϕ, 4–16 μm) with variations of approximately 1ϕ or 4 μm (Fig. 7). The U lithofacies also showed dominantly uni-modal and fine-skewed sample distributions, in contrast with the more multi-modal and coarse-skewed characteristics of the underlying AD lithofacies.

The ^{210}Pb dates indicate the onset of the U lithofacies was 1,978 ± 5, which is synchronous with a phase of rapid urban expansion in the watershed (Fig. 3). The sedimentation rate has increased dramatically during this period from 1 cm/year to more than 2 cm/year (Fig. 4). The U lithofacies also corresponded with high thecamoebian abundance (Fig. 5) and the eutrophication indicator *Cucurbitella tricuspis*, but magnetic susceptibility remained unchanged from the AD lithofacies.

Discussion and conclusions

The natural wetland ecosystem

The high-resolution particle size data from Frenchman's Bay (Figs. 5, 6) provide important insights into the pre-settlement conditions in the lagoon and their alteration by subsequent land use changes during European settlement. During the unaltered phase, a pristine wetland ecosystem existed, with a narrow beach barrier restricting open-lake transfer with Lake Ontario (Eyles and Chow-Fraser 2003; Clark 2004). The natural wetland sedimentation was characterized by deposition of a more coarsely textured lithofacies (NW) consisting of organic-rich silt alternating with fine sand interbeds. The ^{210}Pb dates and glass sherd fragments indicate that the lithofacies was deposited prior to the main phase of European settlement, sometime between 1669 and 1850 ± 56.

The lack of a thecamoebian biofacies dominated by the eutrophication indicator *Cucurbitella tricuspus* suggests that eutrophication was minimal in the NW lithofacies and that natural processes were operating in the lagoon. Furthermore, this suggests that any impacts on the wetlands from early settlement (i.e., pre-1840s) were minimal. The low magnetic susceptibility of the lithofacies derives from the high organic and carbonate content of the sediment (LOI > 50%; $CaCO_3$ > 15%; Fig. 5) and lower abundance of magnetite-bearing clastic sediment (ca. < 40%). The abundant plant matter and presence of $CaCO_3$ (marls) are indicative of a lagoon with abundant submergent and emergent aquatic vegetation, including carbonate-secreting species (e.g., *Myriophyllum*) that require clear water, oligotrophic conditions. The low clastic sediment content of the NW lithofacies may also reflect the effective baffling and trapping of terrigenous sediments by fringing marsh vegetation (Chow-Fraser et al. 1998). The terrigenous sediments would have been derived from the natural processes of hill-slope erosion and down cutting of streams into fine-grained lacustrine deposits (Lake Iroquois Clay deposit; Fig. 2).

The alternation of silt and sand interbeds within the NW lithofacies records the episodic input of coarser sediments into the lagoon, most likely as a result of flood discharge events or overwash of sands from Lake Ontario during large storm surges (Clark 2004). However, our particle size sampling and geochronology were not sufficiently detailed to determine if these variations were either in seasonal or annual sedimentation patterns, as our 1 cm samples may

have encompassed sub-annual to multi-year sediment accumulations. The particle size oscillations no doubt represent seasonal (i.e., spring snowmelt) as well as episodic inputs of sediments (large storms) into the lagoon. Prior to European settlement and construction of the navigation channel (Fig. 1), the beach barrier completely restricted the lagoon from Lake Ontario. This suggests the NW lithofacies is dominantly terrigenous sediment delivered to the lagoon by streams with minor inputs from Lake Ontario via overwash and aeolian sediment transport.

Agriculture and deforestation

The main phase of European settlement (post-1840s) in Frenchman's Bay is recorded by a dramatic shift (at ~106 cm in FMB1 and ~50 cm in FMB2) in all three proxies that are presented in this paper: sediment texture, thecamoebian abundance, and magnetic susceptibility (Figs. 5, 6). The increase in thecamobean abundance at this boundary, and in particular the presence of *Cucurbitella tricuspis*, indicates a dramatic decline in water quality and eutrophication of the lagoon (Reinhardt et al. 2005). The eutrophication can be linked to erosion of nutrient-rich soils and the introduction of animal and human waste effluents to the lagoon following land clearance and the growth of agriculture and rural settlements (Reinhardt et al. 2005). During later stages of urbanization of the watershed (post-1960s), the integration of natural streams with the municipal sewage system greatly exacerbated the eutrophication problem (Eyles and Chow-Fraser 2003).

The sharp increase in the magnetization of the sediments and the abrupt shift in sediment texture (AD lithofacies; Figs. 5–7) provide evidence for the dramatic land disturbance that accompanied European settlement in southern Ontario (e.g., Wenninger and McAndrews 1989). Both parameters show a significant increase in the terrigenous sediment delivery to the lagoon and a corresponding decrease in the production of organic matter (Figs. 5, 6). We interpret the shift in these proxies as evidence for a dramatic increase in erosion rates signalling the onset of wholesale clear-cutting of indigenous forests, which began in the 1840s. According to Skibicki (1991), by 1851

more than 50% of the Township of Pickering had been cleared and 90% by the early 1940s, leaving large tracts of land susceptible to erosion. The magnetic susceptibility curve provides a direct record of these erosion impacts, recording the influx of magnetic minerals (principally titano-magnetites) derived from erosion of the basin soils and their transport to the lagoon by streams and as wind-blown dust (Clark 2004).

The shift in sediment texture to *finer* particle sizes in lithofacies AD (Figs. 5, 6) would at first seem counter-intuitive, as deforestation is generally associated with increased overland flow, greater peak discharges and greater flow competence, leading to enhanced transport of *coarser* particle sizes. We, however, note that the surficial geology in Frenchman's Bay is dominated by fine-grained lacustrine deposits (Lake Iroquois deposits; Fig. 2) and that enhanced fluvial and hill-slope erosion would result in an increased yield of silt- and clay-sized sediments. This was confirmed by field observations of the four stream channels entering the lagoon; the stream beds were incised in places 1–3 m into the Lake Iroquois silts and clays and there was ubiquitous mass wasting of channel sides. Three bulk samples of Lake Iroquois sediments obtained from the stream sections had a mean (21.0 μm), mode (7.5 μm) and standard deviation (26.2 μm) which was similar to the lagoon AD and U lithofacies (mean = 18.2 μm, mode = 8.4 μm, and standard deviation = 27.6 μm). The similarity in particle size and the basin surficial geology suggest that the Lake Iroquois deposits are the most likely source of the lagoon sediment in the post-settlement period (AD, U lithofacies). Some silt- and clay-sized sediment was no doubt derived by erosion of other surficial units exposed within the watershed (i.e., Halton Till, Iroquois beach deposits) but these were likely less significant, as they occupy a much smaller percentage of the total watershed area and are composed dominantly of coarser-grained materials (Fig. 2).

Sediment exchange with Lake Ontario was also made possible in 1843 with the construction of navigation channel at south end of the lagoon (Fig. 1). Under normal flow conditions, this would entail the direct outflow of water from the lagoon and the by-passing of fine suspended silt

and clay into Lake Ontario (Eyles and Chow-Fraser 2003). During large storm surge events however, the flow can be reversed, allowing water and sediment from the open lake to flow into the lagoon. Such storm surge events could explain the episodic inter-lamination of silts with fine sand in lithofacies AD. The ALD lithofacies may also represent overwash processes or may be related to the construction and operation of a shipping dock and wharf in the vicinity of FMB2 that was active until the early 1900s (McKay 1961). The rapid sediment accumulation rates in the lagoon and the silt-rich character of the AD lithofacies suggests that by-passing and export of sediment was greatly outweighed by the influx of sediment from the catchment.

The re-suspension and redistribution of sediment in Frenchman's Bay by waves, currents and boating activities are also likely to have been significant, given the shallow water depths in the lagoon (Fig. 1). Steamship traffic in the lagoon began in the mid-1800s and later in the early 20th-century marinas and wharves were established at the south end of the bay for recreational boating (Fig. 1). Because of the shallow water depths, steamship and power boating activities were restricted to several narrow maintained navigation channel within the bay. Sediment disturbance by prop wash could have been important within the channels and may have contributed to resuspension and focussing of fine-grained sediments into the deepest part of the lagoon. Sediment scour and reworking does not seem to have been a factor in areas of the lagoon outside of the navigation channel, as all of the environmental parameters studied (particle size, magnetics, thecamoebeans, ^{210}Pb) show down-core trends that can be correlated between coring locations (Clark 2004; Reinhardt et al. 2005). In the presence of significant scour (i.e., by wind-drive currents or props), the lagoon bottom sediments would be homogenized to some depth and coherent down-core trends would not be expected. The continuity of the lagoon sediment record may also reflect the cohesive nature of the bottom silts and clays and the growth of algal films in the eutrophic lagoon, which would act to bind the sediment and further limit lagoon-bed erosion (Chow-Fraser 1998).

Urbanization

The urbanization of the watershed began in mid-1950, and by the early 1970s more than half of the watershed was in urban cover (Skibicki 1991). The shift to finer particle sizes (very fine silt and clay) in the 1970s (U lithofacies; Figs. 5, 7) reflects the increasing contributions of fine silt- and clay-sized particles washed from urban surfaces (Wolman and Shick 1967; Booth and Jackson 1997; Owens et al. 2005) as the urban area expanded and large portions of the natural drainage network were integrated with the municipal sewer system (Eyles and Chow-Fraser 2003). Studies have shown that solids from sewage treatment plants and road dust are among the most important sources of fine suspended sediment, contributing up to 40% of the total sediment flux in urbanized streams (Carter et al. 2003; Robertson et al. 2003). Such engineered storm sewer systems also have a high hydraulic efficiency and tend to move large quantities of fine-grained suspended sediments, even during low flow stages. As a consequence, sediments discharged and deposited from urbanized streams and storm sewers are typically enriched in finer particle sizes when compared to natural river systems (Booth and Jackson 1997; Owens et al. 2005).

A further factor that could explain the enrichment in clay and fine silt in the U lithofacies is the flocculation of fine suspended sediments in the lagoon by chemical and microbial processes. 'Flocs' are aggregates of fine suspended sediments formed in freshwater by bacterial binding and by adsorption of dissolved ions derived from road de-icing chemicals and the erosion of urban surfaces (Rao et al. 1991; Droppo and Ongley 1994; Droppo et al. 2002). Chemical flocculation of clays is likely to be of importance in Frenchman's Bay, particularly during winter thaw events and the spring freshet, when the lagoon receives large volumes of road salt contaminated runoff from Highway 401 (Eyles and Chow-Fraser 2003). High levels of chlorides have also been measured in the groundwater around the periphery of the marsh, indicating that the subsurface transfer of dissolved ions to the lagoon is also significant, and also presents a longer term problem for the lagoon water quality (e.g., Howard et al. 1993). Microbial

flocculation may further contribute to fine suspended sediment accumulation, especially during summer months when increased water temperatures and nutrient loadings lead to seasonal eutrophication of the lagoon (Warren and Zimmermann 1994; Droppo et al. 2002).

A further consequence of the expansion of impervious urban cover in the basin over the past 50 years (currently > 80%) has been the drastic alteration of the stream discharge characteristics, resulting in higher peak discharges and the increased occurrence of flash flooding during spring melt and summer storm events (Eyles and Chow-Fraser 2003). These events are responsible for significant incision and erosion of stream banks and deliver large quantities of fine sediment to the present-day lagoon (i.e., U lithofacies). Monitoring of suspended sediment concentrations in Krosno Creek in 2002 (Eyles and Chow-Fraser 2003) for example showed that during one summer storm event more than 3 tonnes of suspended sediments were discharged into the lagoon over a single 4-h monitoring period. This includes a large volume of sediment that is held in storage and flushed out during peak discharges but also much 'new' sediment eroded from stream banks and beds. Our results show that after ~170 years after initial European settlement that erosion and excessive sediment accumulation in the lagoon is still a major problem. The trends actually appear to be accelerating with the expansion of the urban area and show no signs of a declining sediment yield, which has been observed in other 'mature' urbanized systems following the peak in development activity (e.g., Wolman and Schick 1967; Owens et al. 2005).

Wetland health

The degradation of the wetlands from European settlement through to current urbanization have been significant (Eyles and Chow-Fraser 2003); including a loss of emergent and submergent aquatic vegetation, increasing fragmentation of the wetland, and loss or impairment of fish and wildlife habitats. Many of these impacts can be related to the dramatic increase in the delivery of fine suspended sediment and an increase the turbidity of the lagoon following European settlement. Studies of modern wetlands have shown that diversity of submergent macrophytes drops dramatically with increasing water turbidity, as they require clear water for optimal growth (Chow-Fraser et al. 1998; Lougheed et al. 1998). The emergent marsh vegetation would also have been impacted by higher silt and clay contents of bottom substrates, which are less suitable substrates for macrophyte growth. The loss of emergents in turn would have lead to increased turbidity in the lagoon, as they play an important role in trapping and attenuating fine suspended sediments in marshes (Deiter 1990). The reduction in plant fragments and organic matter within the post-settlement layers (AD and U lithofacies) attest to these impacts on the marsh vegetation. During initial land clearance, the eutrophication of the lagoon would have further exacerbated the loss of macrophytes, as a result of algal colonization of bottom substrates and further reductions in the water clarity (Chow-Fraser 1998). These impacts were intensified by the introduction of chemical fertilizers and discharge of agricultural and sewages effluents to lagoon during later urbanization (Eyles and Chow-Fraser 2003). The future restoration of wetland habitats in Frenchman's Bay represents a significant challenge and is clearly dependent upon remedial measures that will limit suspended sediment inputs and reduce nutrient loadings into the lagoon.

References

Ball H, Jalava J, King T, Maynard L, Potter B, T Pulfer (2003) The Ontario Great Lakes Coastal Wetland Atlas: a summary of information (1983–1997). Environment Canada: Ontario Ministry of Natural Resources

Baptista Neto JA, Smith BJ, McAllistera JJ (1999) Sedimentological evidence of human impact on a near-shore environment: Jurujuba Sound, Rio de Janeiro State, Brazil. Appl Geogr 19:153–177

Beckwith PR, Ellis JB, Revitt DM, Oldfield F (1986) Heavy metal and magnetic relationships for urban source sediments. Phys Earth Planet In 42:67–75

Beierle BD, Lamoureux SF, Cockburn JMH, Spooner I (2002) A new method for visualizing sediment particle size distribution. J Paleolimnol 27:279–283

Bird BW, Kirby ME (2006) An alpine lacustrine record of early Holocene North American monsoon dynamics from Dry Lake, Southern California (USA). J Paleolimnol 35:179–192

Blais JM, Kalff J, Cornett RJ, Evans RD (1995) Evaluation of 210Pb dating in lake sediments using stable Pb, Ambrosia pollen and 137Cs. J Paleolimnol 13:169–178

Boar RR, Harper, DM (2002) Magnetic susceptibilities of lake sediment and soils on the shoreline of Lake Naivasha, Kenya. Hydrobiologia 488:81–88

Booth DB, Jackson CR (1997) Urbanization of aquatic systems-degradation thresholds, stormwater detention, and the limits of mitigation. Am J Water Resour Assoc 22:1–17

Carter J, Owens PN, Walling DE, Leeks GJL (2003) Fingerprinting suspended sediment sources in a large urban river system. Sci Total Environ 314:513–534

Chow-Fraser P (1998) A conceptual ecological model to aid restoration of Cootes Paradise Marsh, a degraded coastal wetland of Lake Ontario, Canada. Wetla Ecol Managem 6:43–57

Chow-Fraser P, Lougheed V, Le Thiec V, Crosbie B, Simser L, Lord J (1998) Long-term response of the biotic community to fluctuating water levels and changes in water quality in Cootes Paradise Marsh, a degraded coastal wetland of Lake Ontario. Wetla Ecol Managem 6:19–42

Cisternas M, Araneda A, Marti'nez P, Pe'rez S (2001) Effects of historical land use on sediment yield from a lacustrine watershed in central Chile. Earth Surf Proc Land 26:63–76

Clark C (2004) Sediment magnetic record of post-colonial environmental change in Frenchman's Bay, Lake Ontario. MSc Thesis, McMaster University, Canada

Conely DJ, Schelske CL (2001) Biogenic silica. In: Smol JP, Birks HJP, Last WM (eds) Tracking environmental change using lake sediments, vol 3, Kluwer Academic Publishers, Dordrecht, Netherlands, pp 281–293

Dieffenbacjer-Krall AC, Nurse AM (2005) Late glacial and Holocene record of lake levels of Mathews pond and Whitehead Lake, Northern Maine, USA. J Paleolimnol 34:283–309

Dieter CD (1990) The importance of emergent vegetation in reducing sediment resuspension in wetlands. J Freshw Ecol 5:467–473

Droppo IG, Irvine KN, Jaskot C (2002) Flocculation of cohesive sediments in the urban continuum: implications for stormwater management. Environ Technol 23:27–41

Droppo IG, Ongley ED (1994) Flocculation of suspended sediment in rivers of southeastern Canada. Water Res 28:1799–1809

Eyles N, Chow-Fraser P (2003) Remediation of an urban-impacted watershed and lagoon: Frenchman's Bay, city of Pickering. Ontario Innovation Trust and the City of Pickering Final Report

Eyles N, Doughty M, Boyce JI, Meriano M, Chow-Fraser P (2003) Geophysical and sedimentological assessment of urban impacts in a Lake Ontario watershed and lagoon: Frenchman's Bay, Pickering, Ontario. Geosci Can 30:115–128

Howard KWF, Boyce JI, Livingstone SJ, Salvatori SL (1993) Road salt impacts on ground-water quality—the worst is still to come! GSA Today 3:319–321

Lougheed VL, Crosbie B, Chow-Fraser P (1998) Predictions on the effect of carp (Cyprinus carpio) exclusion on water quality, zooplankton and submergent macrophytes in a Great Lakes wetland. Can J Fish Aquat Sci 55:1189–1198

McCarthy F, McAndrews JH (1988) Late Holocene water levels in Lake Ontario 4320–2000 years BP: evidence from the Grenadier Pond, Toronto, Canada. J Paleolimnol 1:99–114

McDonald MA, Healey JR, Stevens, PA (2002) The effects of secondary forest clearance and subsequent land-use one erosion losses and soil properties in the Blue Mountains of Jamaica. Agr Ecosyst Environ 92:1–19

McKay A (1961) The Pickering Story: on the occasion of the one hundred and fiftieth anniversary of the township of Pickering. The Township of Pickering Historical Society, Pickering, Canada

Murray MR (2002) Is laser particle determination possible for carbonate-rich lake sediments? J Paleolimnol 27:173–183

Nakamura F, Kameyama S, Mizugaki S (2004) Rapid shrinkage of Kushiro Mire, the largest mire in Japan, due to increased sedimentation associated with land-use development in the catchment. Catena 55:213–229

Nelson EJ, Booth DB (2002) Sediment sources in an urbanizing, mixed land-use watershed. J Hydrol 264:51–68

Oldfield F, Appleby PG (1984) Empirical testing of 210Pb-dating models for lake sediments. In: Haworth EY, Lund JWG (eds) Lake sediments in environmental history. Leicester University Press: 93–124

Owens PN, Batalla RJ, Collins AJ, Gomez B, Hicks DM, Horowitz AJ, Kondolf GM, Marden M, Page MJ, Peacock DH (2005) Fine-grained sediment in river systems: environmental significance and management issues. River Res Applic 21:693–717

Patterson RT, Dalby A, Kumar A, Henderson LA, Boudrea R (2002) Arcellaceans (thecamoebians) as indicators of land use change: settlement history of the Swan Lake area, Ontario as a case study. J Paleolimnol 28:297–316

Patterson RT, Kumar A (2002) A review of current testate rhizopod research in Canada. Palaeogeog Palaeoclim Palaeoecol 180:225–251

Petrovsky E, Ellwood B (1999) Magnetic monitoring of air-, land- and water-pollution. In: Maher BA, Thompson R (eds) Quaternary climates, environments, and magnetism. Press Syndicate of the University of Cambridge, Cambridge, pp 219–322

Petrovsky EA, Kapicka A, Jordanova N, Knab M, Hoffman V (2000) Low-field magnetic susceptibility: a proxy method of estimating increased pollution of different environmental systems. Environ Geol 39:312–318

Punning J, Koff T, Kadastik E, Mikomäg A (2005) Holocene lake level fluctuations recorded in the sediment

composition of Lake Juusa, southeastern Estonia. J Paleolimnol 34:377–390

Rao SS, Droppo IG, Taylor CM, Burnison BK (1991) Freshwater bacterial aggregate development: effect of dissolved organic matter. Water Poll Res J Can 26:163–171

Reinhardt EG, Little M, Donato S, Findlay D, Krueger A, Clark C, Boyce J (2005) Arcellacean (thecamoebian) evidence of land-use change and eutrophication in Frenchman's Bay, Pickering, Ontario. Environ Geol 47:729–739

Robertson DJ, Taylor KG, Hoon SR (2003) Geochemical and mineral magnetic characterization of urban sediment particulates, Manchester, UK. Appl Geochem 18:269–282

Sambridge M, Braun J, McQueen H, (1995) Geophysical parametrization and interpolation of irregular data using natural neighbors. Geophys J Int 122:837–857

Skibicki AJ (1991) Frenchman's Bay Resource: cultural and institutional aspects. Urbanization, conservation, and sustainable development: the case of French-

man's Bay, Toronto, Ontario. Heritage Resources Centre, University of Waterloo, Waterloo, pp 69–102

Smith JA, Hodgson DA, Bentley MJ, Verleyen E, Leng MJ, Roberts SJ (2006) Limnology of two Antarctic epishelf lakes and their potential to record periods of ice shelf loss. J Paleolimnol 35:373–394

Warren LA, Zimmermann AP (1994) Suspended particulate grain size dynamics and their implications for trace metal sorption in the Don River. Aquat Sci: 348–362

Warwick WF (1980) Palaeolimnology of the Bay of Quinte, Lake Ontario: 2800 years of cultural influence. Department of Fisheries and Oceans, Ottawa. Bulletin 206, 117 p

Wenninger JM, McAndrews J (1989) Late Holocene aggradation in the lower Humber River valley, Toronto, Ontario: Can J Earth Sci 26:1842–1849

Wolman MG, Schick A (1967) Effects of construction on fluvial sediment, urban and suburban areas of Maryland. Wat Resour Res 3:451–464