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SEDIMENTARY ENVIRONMENT OF LAKE ONTARIO: GEOLOGIC SETTING, SEDIMENT PROCESSES, AND ENVIRONMENTAL HAZARDS

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Sedimentary Environment of Lake Ontario: Geologic Setting, Sediment Processes, and Environmental Hazards

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MANAGEMENT PERSPECTIVE

This review paper was prepared as a background statement on the geology of Lake Ontario and on the issues that surround its postglacial history and sediments. Its aim is to identify, and contribute to the reduction of, deleterious human impacts on the health of ecosystem. The major issues raised are related to the management of the lake ecosystem, including the geological hazards present in its shore zones (LaMP).

Geological processes played a major role in the creation of Lake Ontario. The most recent phase dates from about 11 400 years before present (BP) when retreat of the last continental glacier opened the St. Lawrence valley outlet and drained the high-level proglacial lake then occupying the Ontario basin to sea level. Since then, continuing postglacial isostatic rebound of the basin outlet caused lake levels to rise in the western end about 100 m (estimated present rate is 20 $cm.century^{-1}$). Postglacial silty clay deposition, 2-8 m thick, occurs in the deeper areas of the four offshore basins: Mississauga, Niagara, Rochester, and Kingston, with thicker accumulations bordering the western and southern margins of the basins. Sediment inputs from the upper Lakes and the Niagara River contribute the most to the levels of toxic contaminants entering the lake The Niagara River, the largest tributary, brings in an estimated at 5×10^6 tonnes per year. Shore erosion supplies an estimated $3\ 10^6$ tonnes of relatively clean sediment. Priority contaminant levels in sediments remain high, but many have fallen considerably since the 1970s, e.g. mercury, PCB, and Mirex. Atmospheric deposition and direct municipal and industrial discharges comprise the other important sources of contaminants within the lake watershed. Other important environmental issues discussed are seismic risks to urbanized shore-zone areas, shore erosion, and habitat change brought about by zebra mussel colonization.

SOMMAIRE À L'INTENTION DE LA DIRECTION

Cet article de synthèse a été préparé pour faire un bilan de la géologie du lac Ontario et des questions concernant ses sédiments et son histoire postglaciaires. Il a pour but de déterminer les effets anthropiques nocifs pour la santé de l'écosystème et de contribuer à les réduire. Les principales questions soulevées se rapportent à la gestion de l'écosystème lacustre, y compris les risques géologiques dans ses zones riveraines.

Les processus géologiques ont joué un rôle important dans la création du lac Ontario. La phase la plus récente date d'environ 11 400 ans avant le présent (BP), moment où, en se retirant, le dernier glacier continental a ouvert la décharge de la vallée du Saint-Laurent et a fait baisser au niveau de la mer les eaux du lac proglaciaire de niveau élevé qui occupait alors le bassin ontarien. Depuis, le relèvement isostatique postglaciaire continu de la décharge du bassin a fait monter de 100 m environ le niveau du lac à l'extrémité ouest (le taux de relèvement est présentement estimé à 20 cm par siècle). On trouve des sédiments postglaciaires limono-argileux d'une épaisseur de 2-8 m dans les zones profondes des quatre bassins éloignés des rives, Mississauga, Niagara, Rochester et Kingston, avec des accumulations plus épaisses sur les bordures ouest et sud des bassins. Les sédiments provenant des lacs Supérieur et Huron et de la rivière Niagara constituent la principale source des contaminants toxiques qui pénètrent dans le lac Ontario. On estime que la rivière Niagara, qui est son affluent le plus important, y déverse 5×10^6 tonnes de sédiments par année et que l'érosion littorale produit 3×10^6 tonnes de sédiments relativement propres par année. Les niveaux de contaminants prioritaires dans les sédiments restent élevés même si on note dans plusieurs cas d'importantes baisses depuis les années 70, par exemple pour le mercure, les PCB et le mirex. Les retombées atmosphériques et les décharges municipales et industrielles directes constituent les autres sources importantes de contaminants dans le bassin hydrographique du lac. Les autres questions environnementales importantes discutées sont les risques sismiques des zones riveraines urbainisées, l'érosion littorale et les changements dans les habitats résultant de la colonisation par la moule zébrée.

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Abstract

Lake Ontario, the most downstream of the Laurentian Great Lakes, covers a surface area of approximately 19 000 km^2 (300 km long by 60 km wide). The basin is asymmetric with a steeper southern margin reflecting the regional southward dip of erodible shale bedrock underlying Ordovician erosion-resistant limestone. The basin is traditionally thought to have resulted mostly from glacial erosion and scour along a pre-existing stream valley system, but erosion by subglacial meltwater floods has been recently suggested. The present lake dates back to the time when glacial retreat opened the St. Lawrence valley and drained the high-level proglacial Lake Iroquois to sea level about 11 400 years before present (BP). The post-Iroquois low phase is known as Early Lake Ontario. Because of continuing postglacial isostatic rebound, the valley outlet soon rose above sea level, raising lake levels in the western end about 100 m at an exponentially declining rate (estimated present rate is 20 $cm.century^{-1}$). Low-level shore positions lie buried beneath postglacial sediment deposits and are inferred from evidence in seismic profiles, cores, and boreholes. Postglacial silty clay deposition, 2-8 m thick, is confined to deeper areas of the four offshore basins: Mississauga, Niagara, Rochester, and Kingston, with thicker accumulations bordering the western and southern margins of the basins. Sediment inputs via the Niagara River, the largest tributary, are estimated at 5×10^6 tonnes per year. Shore erosion supplies an estimated three million tonnes. Levels of hazardous contaminants coming into the lake from the upper Lakes and the Niagara River remain high, but some toxic metals, PCB and Mirex, have fallen considerably since the 1970s. Atmospheric deposition, upstream lakes, and municipal and industrial discharges continue to be important sources of contaminants within the lake watershed. Other important geoscience or sediment-related issues are seismic risks to an increasingly urbanized shore-zone, shore erosion, and the effects of habitat change brought about by zebra mussel colonization of the benthic environment in Lake Ontario.

RÉSUMÉ

Le lac Ontario, le plus en aval des Grands Lacs laurentiens, couvre une surface d'environ 19 000 km^2 (sa longueur est de 300 km et sa largeur de 60 km). Le bassin est asymétrique, avec une bordure sud abrupte résultant de l'inclinaison vers le sud de sa fondation schisteuse érodable qui se trouve sous une roche calcaire ordovicienne résistant à l'érosion. On admet généralement que le bassin a surtout été créé par l'érosion et l'affouillement glaciaires le long de la vallée d'un réseau fluvial préexistant, mais on a récemment proposé comme origine l'érosion par des inondations d'eau de fonte sous-glaciaire. Le lac actuel remonte à la période, environ 11 400 ans avant le présent (BP), où le recul glaciaire a ouvert la vallée du Saint-Laurent et fait baisser au niveau de la mer les eaux du lac Iroquois, lac proglaciaire qui avait alors un niveau élevé. La phase post-Iroquois de niveau bas est appelée lac Ontario inférieur. En raison de la persistance du relèvement isostatique postglaciaire, la décharge de la vallée a rapidement dépassé le niveau de la mer, ce qui a fait monter le niveau à l'extrémité ouest du lac d'environ 100 m à un taux de décroissance exponentiel (présentement estimé à 20 cm par siècle). Les parties basses de la rive sont enfouies sous des sédiments postglaciaires et se manifestent dans les profils sismiques, les carottes et les trous de forage. On trouve des sédiments postglaciaires limono-argileux d'une épaisseur de 2-8 m dans les zones profondes des quatre bassins éloignés des rives, Mississauga, Niagara, Rochester et Kingston, avec des accumulations plus épaisses sur les bordures ouest et sud des bassins. On estime que la rivière Niagara, qui est son affluent le plus important, déverse dans le lac Ontario 5×10^6 tonnes de sédiments par année, et que l'érosion littorale en produit 3×10^6 tonnes par année. Les niveaux de contaminants prioritaires provenant des lacs Supérieur et Huron et de la rivière Niagara restent élevés même si on note dans plusieurs cas d'importantes baisses depuis les années 70, par exemple le mercure, les PCB et le mirex. Les retombées atmosphériques, l'apport des lacs d'amont et les décharges municipales et industrielles restent des sources importantes de contaminants dans le bassin hydrographique du lac. Les autres questions importantes discutées, qui touchent aux géosciences ou aux sédiments, sont les risques sismiques dans les zones riveraines de plus en plus urbanisées, l'érosion littorale et les changements dans les habitats résultant de la colonisation du milieu benthique du lac Ontario par la moule zébrée.

Introduction

Lake Ontario is the fifth in a chain of five Great Lakes that drain via the St. Lawrence River to the Atlantic Ocean. It has long been an important transportation route for shipping in the economy of its basin, first for native traders, European exploration and trade, and military supply, then for support of the agricultural economy and related industries that developed with settlement after the early 1800s. In the same century, canals were constructed to link shipping with upstream Lake Erie (Welland Canal), downstream in the St. Lawrence River and through New York State via Oswego River and the Erie Canal. After the 1940s, the basin rapidly urbanized and industrialized (Chapman and Putnam 1984), and in 1990-91 was home to approximately 8.2 million people in Canada and the United States (Anonymous 1995), with the densest population centred around Toronto, Hamilton, and Rochester (Fig. 1).

Now part of an international seaway, Lake Ontario is frequently traversed by both lake freighters and ocean-going vessels. The lake supports commercial fisheries, as well as sport fishing and aquatic recreation. It is also a source of water for drinking, cooling, and manufacturing, a sink for waste and sewage, as well as a habitat for wildlife. These multiple and sometimes conflicting uses have stressed the lacustrine environment and left an anthropogenic imprint. In this review paper we describe the physical setting and geological evolution of the lake, building on previous studies. Then we focus on the geoscience aspects of the environmental quality of the lake, and stability of its basin and infrastructure; specifically sediment contamination, habitat mapping, shore erosion and seismic hazard.

Physical and geological setting

Lake Ontario, with a volume of 1640 km^3, occupies an elongated basin 306 km in an east-west direction and 84 km wide at its maximum breadth. It covers an area of about 19 000 km^2 of New York State and the Province of Ontario, spanning the international boundary between the United States and Canada (Anonymous 1995).

Drainage basin

The drainage basin of the lake occupies 82 990 km^2 (Anonymous 1995) of terrain that ranges in elevation from lake level (74 m asl) to over 500 m above sea level (asl), and in bathymetry down to 244 m below present lake level (bpl) (Fig. 1). The northern and eastern parts of the basin drain crystalline rocks of the Precambrian Shield, an area that discharges to eastern Lake Ontario (Fig. 2). The remainder of the basin is underlain by unmetamorphosed Paleozoic marine (mostly) sedimentary rocks in strata that thicken and dip gently southward into the Appalachian sedimentary basin. Strata also tend to thin over broad structural arches northeast and northwest of the lake (Fig. 2). The bedrock surface has been extensively eroded during at least 200 million years of post-Paleozoic exposure. The eroded edges of the depositional strata mostly outcrop in an east-west pattern with younger rocks to the south. The outcrop pattern swings northwest in the western part of the basin, reflecting uplift on the Algonquin Arch (Fig. 2).

The bedrock surface developed relief in the order of 10s to 100s m in response to differing rates at which different rock lithologies eroded during exposure in the post-Paleozoic period (Table 1). Prominent north-facing (northeast-facing in the western part of the basin) cuestas are maintained by resistant dolostones and limestones — the Niagara Escarpment (Lockport in New York) by Early and Late Silurian dolostones of the Lockport and Guelph Formations, and the Onondaga Escarpment further south by Middle Devonian limestone of the Onondaga Formation (Figs. 2 and 3). Lowlands such as the Lake Ontario basin formed in weaker rock types. The bedrock profile (Fig. 2) illustrates the close relationship of Lake Ontario basin with eroded strata of the relatively weak Late Ordovician shales (unit 3 in Fig. 2 and Table 1).

The bedrock surface is mostly covered with unlithified sediments deposited during and following Quaternary glaciations, mostly the result of the last glaciation, by the Laurentide Ice Sheet, which reached its maximum extent about 18 ka (Fig. 3) (Barnett 1992). Bedrock is generally exposed only in stream and river valleys, on escarpments, and over wider expanses of Paleozoic rocks in the northeastern sector of the basin and on the Precambrian Shield. The thickest glacial drift is usually found in moraines (Fig. 3). Some achieve sufficient elevation to form drainage divides, such as the Oak Ridges moraine northwest of the lake, and the Valley Heads moraine south of the lake.

Table 1. Legend for bedrock geology map, Figure 2

Geological Age[1]		Rock Group[1]	Dominant Lithologies[1]	Sequence/Cycle[1] Number	Age Ma
PALEOZOIC					
9	Mississippian[2]	Pocono Gp[2]	Sandstone[2]	9	<358
8	Middle and Late Devonian[2]	Hamilton-Conewango Gps[2]	Shale, limestone, sandstone[2]	8	358-380
7	Early-Middle Devonian	Onondaga/Oriskany Fms	Limestone, sandstone	7	380-401
6	Late Silurian	Salina/Bertie Fms	Shale, dolostone	6	401-417
5	Early-Late Silurian	Clinton Gp. & Lockport/Guelph Fms	Dolostone, limestone, shale	5	417-432
4	Early Silurian	Cataract Gp.	Sandstone, shale	4	432-438
3	Late Ordovician	Blue Mountain/Georgian Bay/Queenston Fms	Shale, sandstone	3	438-450
2	Middle-Late Ordovician	Simcoe/Basal/Ottawa Gps	Limestone	2	450-478
1	Cambrian-Early Ordovician	Potsdam/Beekmantown Gps	Sandstone	1	478-570
PRECAMBRIAN - Proterozoic					
0	Mesoproterozoic	Grenville Province[3]	Gneiss, metasediments, plutonic igneous rocks[3]		990-1240 (Meta-morphism)[3]

[1] Johnson et al., 1992 and Sanford, 1993 except where noted otherwise. [2] Rogers et al., 1990. [3] Easton, 1992.

Lake basin

The basin is thought to have resulted mostly from glacial scour of a pre-existing river valley and fluvial drainage system — Laurentian River of Spencer (1891) (Hough 1958) (Chapman and Putnam 1984). More recently, Shaw and Gilbert (1991) have suggested subglacial scour by high velocity turbulent meltwater flows as an effective erosion process. This is a useful concept for understanding a widespread unconformity associated with an isolated drumlin field beneath lacustrine sediments in the deepest (eastern) part of the lake (Mayer et al. 1994; Lewis et al. 1997b). However, the idea of subglacial erosion by meltwater flows is controversial and is resisted by some (Muller and Pair 1992; Eyles and Boyce 1999).

The lake basin has been divided into four major sub-basins (Fig. 4A) by Thomas et. al. (1972a,b); a fifth sub-basin, Genesee Basin, in the northwestern quadrant of the Rochester basin has recently been identified (Virden et al. 1999, in press). The average depth of the whole lake is 86 m (Anonymous 1995). The maximum depths of the sub-basins as shown on the most recent bathymetric map (Virden et al. 1999, in press) are 140 m (Niagara), 192 m (Mississauga), 178 m (Genesee), 244 m (Rochester), and 56 m (Kingston). The lake basin is asymmetric with a steeper southern margin. The gently sloping northern margin reflects the southward dip of underlying Ordovician limestone and shale bedrock (Fig. 2). The Niagara River, entering western Lake Ontario from the south and carrying discharge from Lake Erie and the upper Great Lakes, is the major inflow at 173 $km^3.y^{-1}$ (200 000 $ft^3.s^{-1}$ or approximately 6000 $m^3.s^{-1}$). The outflow (209 $km^3 . a^{-1}$) is from the northeastern end of the basin into the St. Lawrence River. The residence time for water in the basin is about 7-8 years.

Late Glacial and Postglacial History of Lake Ontario

Lake Ontario basin was deglaciated around 12 000 yr BP when the Laurentide Ice retreated north of the Niagara Escarpment, allowing waters to pond between the ice-front and the height of land to the south. These proglacial lakes, beginning with Lake Iroquois (Fig. 3), overflowed and stabilized at the elevation of outlets to the east, the highest being over the basin rim near Rome, New York (Fig. 5) (Karrow et al. 1961; Karrow 1981; Fullerton 1980; Muller and Prest 1985). The various phases in the basin beginning with Lake Iroquois are summarized below.

Lake Iroquois

Lake Iroquois (Figs. 3,5) lasted several hundred years, with its drainage eastward through the Mohawk / Hudson River system to the Atlantic Ocean. The highest Lake Iroquois shoreline in the western part of the lake Ontario basin is about 35 m above present level (Coleman 1937; Karrow et al. 1961).

Evidence of the former existence of Lake Iroquois is common in the western basin and includes raised wave-cut cliffs and spit / bar features, exposed nearshore ramps, and considerable thicknesses of offshore glaciolacustrine clay below the modern sediment cover (Thomas et al.

1972a,b; Sly and Prior 1984). One prominent example of raised Lake Iroquois shore deposits is found at the western end of Hamilton Harbour where the main highway and railroad access to the city of Hamilton traverses a narrow ridge composed of cross-bedded gravel, a barrier bar of the former lake.

When glacial ice retreat opened the lower St. Lawrence valley outlet approximately 11.7 ka BP (Pair and Rodrigues 1993; Anderson and Lewis 1985), Lake Iroquois drained to lower levels (Fig. 5). Lake levels in the basin fell in stages, and about 11.4 ka BP had reached their minimum at more than 100 m below present lake level in the western basin. Because this elevation was close to the sea-level at the time, Fairchild (1907) and Pair et al. (1988) proposed that the marine influence of the adjacent Champlain Sea, then occupying the St. Lawrence valley, had extended into the Ontario basin, a phase Fairchild named "Gilbert Gulf", in honour of G.K. Gilbert. The only marine evidence in the basin is sediment amino acids in a core from Rochester basin, some of which show possible marine origin (Schroeder and Bada 1978). Anderson and Lewis (1985) have suggested the Champlain Sea in the St. Lawrence Valley was confluent with Early Lake Ontario and Pair et al. (1988) explain that stable marine conditions were prevented from being established in Lake Ontario owing to the predominance of freshwater outflow from the Ontario basin and the low salinities that existed in the western Champlain Sea at the time.

Evidence of a low-level Gilbert Gulf and Early Lake Ontario phase in the western basin is sparse and somewhat controversial. The most convincing indication is the apparently extensive, linear deposits of coarse-grained, stratified sediments sampled below the modern muds at 72 - 103 m below present lake level (bpl.) (Lewis and NcNeely 1967; Lewis and Sly 1971; Anderson and Lewis 1985). Anderson and Lewis (1985) postulate a shallow-water environment of deposition (shoreface or bar) and termed the feature, the Oakville-Grimsby Bar. They pollen-dated the deposits at 10 to 11.4 ka BP. The relative prominence of the feature and the range of pollen-age estimates make it likely that the Bar was formed at, or close to, the minimum level, confluent with the Champlain Sea. Observations in echograms of erosion surfaces and inferred ice-wedge casts at lower elevations (Sly and Prior 1984) imply subaqueous mechanisms for sediment disturbance, or closed basin conditions and lowered lake levels following isostatic emergence of the outlet sill and isolation of the basin from the Champlain Sea.

Early Lake Ontario shoreline: Figure 7A shows the reconstructed shoreline for Early Lake Ontario at ca. 11.4 ka BP with topographic contours of elevation below present mean lake level (bpl). The shoreline is located at the piston cores that contained subsurface "beach" indicators from the Grimsby-Oakville Bar of Anderson and Lewis (1985). The elevation for the Early Lake Ontario level was taken from the adjusted depth of this material and traced throughout the region at -115 m bpl. This reconstructed shoreline fits well with other interpretable indicators such as sub-bottom notches and terraces on seismic profiles and in multibeam sonar images (Lewis et al. *in press*) at approximately 100 to 110 m bpl. Also, the reconstructed shoreline is within reasonable agreement with the adjusted elevation of the presumed outlet controls (<125 m bpl) on Early Lake Ontario levels (Coakley and Karrow, 1994).

The reconstructed shoreline is seen to have been located up to 20 km offshore from the present shoreline position. Downcutting by inflowing streams was likely reactivated by the sharp drop in base level in the basin.

Intermediate phases: 9.4 and 7.4 ka BP: From the above minimum level, waters in the basin rose steadily in concert with the outlet sill. The reconstructed shoreline positions at 9.4 and 7.4 ka BP are shown in Figures 7B and 7C. These imply that the shoreline position moved landward on all sides at a uniform and fairly rapid rate, especially on the south side.

This period probably was accompanied by the development of substantial sandy accretionary features at suitable sites along the shoreline. Erosion of the Pleistocene Don and Scarborough Formations (just east of Toronto) (Karrow 1967) would have released large quantities of sand for beach and spit development (Figs. 7B, C, D, and E). It is reasonable that a westward-migrating baymouth bar / spit feature, comparable to the present Burlington Bar (Fig. 7B) would have been maintained at the western end of the lake as shown. This sandy material from shore erosion was likely augmented by inputs of sand from inflowing streams (Niagara, Don, Humber, and Credit Rivers, and many smaller creeks).

The continued landward advance of the lake beginning at the time of Early Lake Ontario is expressed in persistent long-term shore recession especially along the southern shores where bedrock is not exposed, and in the drowned mouths of local streams. These drowned stream-mouths, and sheltered areas such as Hamilton, Toronto, and Kingston Harbours, represent the few shallow-water areas where a sedimentary record of the last 3 to 4 thousand years is preserved (Coakley and Karrow, 1994; Flint et al. 1988; McCarthy and McAndrews 1988; Dalrymple and Carey, 1990).

Sediment deposits in Lake Ontario

Sediment stratigraphy

The stratigraphy of the Quaternary sediment fill in the lake basin has been investigated by acoustic/seismic profiling and gravity/piston coring: by Lewis and McNeely (1967) for approximately the upper metre; by Lewis and Sly (1971) for the Toronto area; by Sly and Prior (1984) and Sly (1984) for the Niagara and Kingston areas, respectively, by Anderson and Lewis (1975) and Hutchinson et al. (1993) for central and eastern areas; and Lewis et al. (1995) and Pippert et al. (1996) for the western area. A seismic profile (Fig. 8) illustrates the sediment fill in a cross-section of the bedrock basin north of Niagara River mouth. The total Quaternary fill reaches 30 m in places along the axis of the basin, and locally as much as 50 m. As synthesis of the stratigraphy and depositional history is in progress, a preliminary outline is provided below based on available information from the foregoing and recent field investigations:

A dense, stony, sandy silt to silty sand diamicton (till) lies discontinuously on bedrock. This deposit contains Precambrian and Paleozoic bedrock clasts, and is locally up to 30 m thick. In a few buried valleys, it unconformably overlies older Quaternary sediments. The deposit is interpreted as a subglacial basal till which resembles, and is probably correlative with, Newmarket Till known onshore north of Toronto beneath the Oak Ridges Moraine (Fig. 3) as a deposit of the Laurentide Ice Sheet at the last glacial maximum 18-20 ka (Gwyn and DiLabio 1973; Barnett et al. 1991; 1998).

The offshore basal diamicton surface is eroded. In places, it is drumlinized, as in the deep Rochester Basin below 160 m water depth (Lewis et al. 1997b); in many other places it is completely missing due to erosion, and overlying sediments rest directly on bedrock.

A complex sub- and proglacial sequence of flow tills?, prograded sediments, turbidites, and laminated glaciolacustrine (e.g. Lake Iroquois) sediments overlie the basal diamicton in the western part of the lake. In the eastern part, the sequence is simpler, and in many places

Sediment sources

The principal coarse sediment sources are the drainage basin, shore and shallow lakebed. Sediment being deposited in Lake Ontario basin can be subdivided into two main sources: sediments from shore erosion, and sediments borne on inflowing tributary streams.

Shore zone erosion

The exposed shoreline of Lake Ontario consists of erodible materials, such as glacial sediment bluffs (62.7%) and sandy shore / marsh (20%), and non-erodible, e.g. bedrock (10%), and land-fill / shore-protected (7%). These shorelines are composed mostly of unconsolidated glacial sediments (except for the bedrock shores in the extreme northeast) averaging around 35% fines (silt + clay). The erodible shoreline reaches are retreating at medium-term (over the period 1953-1973) rates ranging from 3.8 $m.a^{-1}$ in the Niagara area, to less than 0.5 elsewhere (Boulden 1975), although minor sections of the shoreline show accretion over the same period. On the U.S. side, the figures are comparable and show the glacial sediments comprising the shoreline eroding at medium-term (13 years) rates of up to 3.7 $m.a^{-1}$, but averaging around 0.5 $m.a^{-1}$ (Brennan and Calkin, 1984).

In considering the impact of contaminant loading on a lake ecosystem, it is useful to compare the volumetric input of relatively "clean" fine sediment, derived from erosion of glacial sediments, to that coming in from tributaries which allow ample opportunity for contaminant uptake by the sediment. The most comprehensive study of sediment loading into Lake Ontario from shore erosion sources was carried out by the International Joint Commission (IJC) Reference Group on Great Lakes Pollution from Land Drainage Activities (PLUARG) (Monteith and Sonzogni, 1976; Thomas and Haras, 1978); their results are presented in Table 2. The figure shown for the roughly 550 km of mainland shoreline on the Canadian side of the lake (3.1×10^6 tonnes) was derived from the 1.7×10^6 m^3 given in Boulden (1975) based on medium-term erosion rates, and assuming a dry density of 1.8 tonnes. m^3 for these sandy silt materials. The inputs from the 480 km-American side are presented in Monteith and Sonzogni (1976, Table 18) and total 0.61×10^6 m^3, or 1.1×10^6 tonnes. Combining these figures yields a total annual sediment input of 2.3×10^6 m^3, or 4.2×10^6 tonnes per year. If undetermined, but significant erosion of the nearshore slope is added, the above figure could be increased by up to 25%, to around 5.25 x 10^6 tonnes. Given their average composition of approximately 35% fines (silt + clay), Lake Ontario shoreline materials could annually supply about 1.8 million tonnes of fine-grained material to the offshore depositional areas of the lake. This figure is significantly less than the 2.77 x 10^6 tonnes of fine-grained material calculated by Kemp and Harper (1976). However, because of the quality of the shore erosion and grain-size data from both sides, and the need to interpolate or estimate rates of erosion between stations, the true value most likely lies between 1.5 and 3 million tonnes of fine-grained material per year. Much of the total sediment delivered by shore erosion (sand-sized or larger) tends to remain within the nearshore zone. These inputs are summarized in Table 2 below.

Table 2. Sediment inputs to Lake Ontario

Sediment Inputs from	Canadian side (x 10^6 tonnes.y $^{-1}$)	U.S. side (10^6 tonnes.y $^{-1}$)	Basin total (10^6 tonnes.y $^{-1}$)
Shore erosion	3.1 [1]	1.1 [2]	4.21 (total); 2.77 [3] (fines)
Niagara River	-	-	4.6 [3] (fines)
Other tributaries	0.2 [4]	0.4 [5]	0.6; 1.08 [3] (fines)
Other sources (atmospheric, etc.)			0.73 [3]
TOTAL INPUT	3.3	1.5	4.8 - 9. 14 [3]
OUTFLOW			3.44 [3]

[1] Boulden, 1975; Thomas and Haras (1978)

[2] Monteith and Sonzogni (1976); Brennan and Calkin (1984)

[3] Kemp and Harper (1976)

[4] Inland Waters / Lands Directorate (1990); [5] Mildner (1974)

Sediment inputs via tributary streams

Detailed information on sediment yield from 52 individual watersheds on the Canadian side (excluding the Niagara River) were presented in Ongley (1973). These data assisted Kemp and Harper (1976) in calculating the sediment inputs actually arriving into Lake Ontario from tributaries (Table 2). Their figure for total annual input of fine-grained sediment (suspended load) from these tributaries is 5.64 x 10^6 tonnes. The largest contributor is the Niagara River, whose 6 obtained average rates of 435, 260, 550, and 530 $g.m^{-2}.a^{-1}$ for the Niagara, Mississauga, Rochester, and Kingston basins, respectively, based on assumption of constant sedimentation rates above the *Ambrosia* and *Castanea* pollen horizons (time-lines for 1835 and 1930, respectively) in cores from these basins. These mass sedimentation rates correspond to linear rates of approximately 0.5 to 1 $mm.a^{-1}$. Robbins et al. (1978) used excess isotopic dating techniques (^{210}Pb and ^{137}Cs) on sediment profiles to calculate sedimentation rates of 0.78 $g.cm^{-2}.a^{-1}$ for a site in the western basin and 0.057 $g.cm^{-2}.a^{-1}$ for one in the Kingston basin. These correspond to linear rates in the top 10 cm of approximately 0.34 and 0.28 $cm.a^{-1}$, respectively. The rates obtained were confirmed based on ^{210}Pb by Farmer (1978), who calculated average linear rates of 0.11, 0.08, and 0.09 $cm.a^{-1}$ for the Niagara and Rochester basins, respectively.

Environmental Issues and Hazards

In addition to the threat of toxic contaminants accumulating in the bottom sediments, other environmental issues with a geoscience component that are of concern for managers of Lake Ontario include habitat change, shore recession, and seismic hazard.

Contaminants in Lake Ontario sediments

There has always been a direct connection between sediments and toxic contaminants, largely because many tend to partition with the fine sediment particulate phase and to be concentrated in sediment sinks. While this transfer to the lake bottom assists in the eventual burial and isolation of these contaminants from the biosphere, it is detrimental to benthic communities living on or in the sediment. For this reason, monitoring levels of targeted contaminants in sediment profiles offers useful information on spatial and temporal (historical) trends in contaminant dynamics. The sediments of Lake Ontario carry evidence of historically increased lake eutrophication (biological production and sedimentation of organic matter and calcite) and industrial waste accumulation (Schelske et al. 1988; Schelske 1991; Schelske and Hodell 1991). This trend started in the early to mid 1800s with European settlement, deforestation and widespread practice of mixed farming, horticulture and animal husbandry. Since the 1940s, the Lake Ontario watershed has become the industrial hub of Canada and western New York state, and now supports a population of about 8.2 million (Anonymous 1995). Intense industrialization of the watershed and of the Niagara River valley, in particular, has resulted in increased levels in the modern sediments of industrial emission contaminants, such as PAH, PCB, DDT, Mirex, Dieldrin, Dioxin and metals such as Hg, Pb, Cu, Zn, Cd, Be and V. Among these are several that have been designated as priority pollutants by the IJC (LAMP, 1998). With a few exceptions discussed below (mercury and arsenic), however, trace metal and organic contaminant concentrations measured in the sediments remain below standard environmental guidelines. This is probably due to remediation initiatives, the large diluting effect of the lake, and the concurrent input and deposition of clean sediments derived from shore erosion (see section above).

Trace metals. Thomas (1972) was the first to examine the distribution of contaminants of concern such as mercury (Hg) in Lake Ontario sediments. Based on core profiles, Kemp and Thomas (1976) estimated that Hg contamination commenced after 1906 and peaked around 1943 (Fig. 9A). On examination of distribution plumes of high concentration values for Hg (Fig. 10), Thomas (1983) concluded that the main source was the Niagara River. The concentration pattern for Hg showed a northern trend with a subsequent curvature toward the west. This pattern is compatible with the mean far-field circulation plume for the Niagara River water mass (Murthy, 1996).

Mudroch (1983) studied the vertical distribution of Hg and five other important trace metals (Pb, Zn, Cu, Cr, Ni) in cores from the western basin of the lake. All the metals showed a significant decline over the past 20 years to levels below standard guidelines (Fig. 9B). Spatial distributions also confirmed the Niagara River as the prime source. Nriagu et al. (1981, Table 5) documented the content of seven trace metals in sediment samples (top 1 cm) from several basins in Lake Ontario. More recently, Strachan and Eisenreich (1990) estimated total Pb loadings to Lake Ontario at 240-570 tonnes.a^{-1}.

The most recent and comprehensive report on metals in sediments in Lake Ontario was published by the New York State Department of Environmental Conservation (Swart et al. 1996) Vertical sediment sample profiles from cores from six depositional sites covering all four basins were analyzed for selected trace metals and organics and were dated using ^{137}Cs. The report found that surface concentration values varied according to location, with highest values found in stations near the Black and Oswego Rivers, where most of the metals, especially mercury (Hg) exceeded the Ontario Ministry of Environment and Energy (OMEE) guidelines (Persaud et al., 1993). In almost all the trace metal and organic compound profiles examined, there was a significant decrease in concentration from maximum values 10 to 20 cm below the surface, indicating considerable improvement in sediment quality over the past decades.

Although the Niagara River is the largest source for metals to Lake Ontario, with estimated input of 110 $tonnes.a^{-1}$ of lead (Pb) (Strachan and Eisenreich, 1990), Nriagu et al. (1983) confirmed another significant input, ranging from 12 tonnes per year for Pb, to 395 tonnes for Zn, to 14,000 tonnes for Fe, from Hamilton Harbour. Comparable values for other major streams such as the Humber and Don Rivers are not available. Atmospheric loadings for trace metals are estimated in Eisenreich and Strachan (1992); they estimate Pb loading at 48 $tonnes.a^{-1}$.

Mirex. Concentrations in Lake Ontario sediment of Mirex, a persistent organic compound used as a pesticide and fire retardant, were found to be low, i.e.. usually less than 30 $ng.g^{-1}$ (Holdrinet et al. ,1978). On the basis of samples collected in 1968, they identified a major distribution pattern that extended from the Niagara River mouth along the south shore to the eastern end of the Rochester Basin (Fig. 10). A secondary pattern was associated with the Oswego River. In a later publication, Thomas (1983) interpreted the distribution plumes of high concentration values for Mirex and PCB in the lake as evidence that the main source for Mirex (like that for Hg and PCB) was the industrialized zone located in the central reaches of the Niagara River. The distribution pattern for these contaminants tended to follow and accumulate in the higher sedimentation southern side of the basins, following the mean far-field circulation plume for the Niagara River water mass (Murthy, 1996).

Loadings of PCB and PAH to Lake Ontario. The two most monitored organic compounds in lakes are PCB and PAH. These persistent carcinogenic compounds are derived from combustion and from industrial activities and are brought into the lake by different routes:

- Point sources (tributaries, spills, and direct industrial discharges)
- Atmosphere

Point sources: PCB and PAHs are associated with smokestack emissions from industrial and municipal activity, or from runoff from municipal surfaces onto which these are deposited. Being virtually insoluble in water, they rapidly become adsorbed onto sediment particles and are eventually are deposited in downstream lakes and tributaries. These discharge points and an estimate of the loadings involved are shown in Figure 11. In addition to other published estimates, this figure contains the latest and most comprehensive view of point source loadings for PCB and other priority pollutants, namely those from the report of the Lake-wide Management Plan for Lake Ontario (LAMP, 1998, Table 3-4). As in the case of metals and other organic compounds, the Niagara River is the most important source tributary, with large contributions also associated with sites in New York (Black River, Oswego River) and the Hamilton - Toronto area. These sources account for approximately 29% of the PCB inputs and 79% of the PAH inputs. Strachan and Eisenreich (1990) estimated that approximately 12% of the PCB total inputs came from tributaries. Anthropogenic organic components, such as combustion residues including PAHs probably associated with ships and shipping practice in part, have been detected recently in western Lake Ontario sediments by petrological (Mukhopadhyay et al. 1997), geochemical (Kruge et al. 1998), and multibeam sonar backscatter studies (Mayer et al. 1994; Lewis et al. 1999) studies.

Atmosphere: Because contamination from industrial sources are now being effectively controlled, the atmosphere is now the main source of toxic organic pollutants to the Great Lakes (Hillery et al. 1998). The data shown in Figure 11 are compiled from earlier published data and summarizes existing data on quantitative inputs of PCB and PAH to Lake Ontario. PCB. Both these compounds are produced by combustion and industrial smokestack emissions and are carried long distances. The large surface area of the lake enhances the wet and dry deposition and transfer of these compounds to the bottom sediment. However, loadings for PCB has declined dramatically since 1970, when controls on its use were initiated (Lake Ontario LAMP, 1998). In fact, in reporting on measurements made by the Integrated Atmospheric Depositional Network, Hillery et al. (1998) concluded that in all the five Great Lakes, the net atmospheric deposition was practically nil, and may even be negative, as degassing (gas transfer out of the lake) of volatiles may now be the dominant transfer process in the water column.

Outflows and sedimentation: Of the 490 tonnes.a^{-1} of PCB entering Lake Ontario (Strachan and Eisenreich, 1990), about 80% ends up in bottom sediments, while 20% exits via the St. Lawrence River. The decline in PCB and Mirex inputs documented above are readily apparent in the sediment profiles described by Durham and Oliver (1983), where both appear at a small fraction of their former concentrations (Fig. 12).

Groundwater: Porewaters from sediment cores have shown evidence of groundwater input to the lakebottom (Bowins et al. 1992; Frape et al. 1992). Studies are in progress to evaluate this evidence and the possibility of contaminant transport into the lake by groundwater (Pers. communication, R. Drimmie, University of Waterloo).

Shore recession

As mentioned earlier, shore erosion is an ongoing process in Lake Ontario dating back to Early Lake Ontario. The average rates given earlier are long term rates and do not accurately reflect short-term rates that may be much higher. These high rates usually coincide with periods of high lake levels combined with storms and can result in rapid recession of the shore that is a real threat to shoreline properties. Boulden (1975) found short-term rates of up to 10.65 $m.a^{-1}$ in the Niagara peninsula area and 2.0 $m.a^{-1}$ in the Scarborough Bluffs area of the lake just east of Toronto. Such rates have caused the destruction, or necessitated the relocation, of buildings close to the shore. Given that climate affects both lake levels and storminess, there is a real need to evaluate the likelihood of increased shore damage due to future climate change.

Neotectonics and seismicity in the Lake Ontario basin

Although Lake Ontario is located within the North America craton, remote from continental margins where earthquakes are most active, the North American plate is under regional NE-SW compressive stress (Adams, 1987) and earthquakes do occur, but at a relatively low rate and magnitude (Mohajer 1993). The largest recorded earthquake occurred in 1929 at Attica NY, south of the lake, and was of magnitude 5.2. An earthquake of similar magnitude, 5.4, was detected south of Lake Erie in Ohio and felt throughout the western Lake Ontario region on September 25, 1998.

Traditionally, seismic hazard assessments for building codes and the design of sensitive infrastructure have assumed earthquakes are distributed randomly within large regions distinguished by the cumulative record of historically-recorded earthquake magnitude and frequency. With the interpretation of faults and zones of weakness in Proterozoic (Grenville) crustal rocks beneath the Paleozoic and Quaternary cover, based in part on gravity and magnetic lineaments, the possibility of reactivation of ancient faults has been raised (Wallach, 1990, Wallach and Mohajer, 1990; Wallach et al., 1998; Marilakos, 1998). This, added to the discovery of Quaternary faulting (age between 50 and 13 ka) in eastern Toronto (Mohajer et al., 1992), further raised the possibility that seismicity might not be randomly distributed, but might be preferentially located on previous faults or zones of structural weakness with the result that seismic hazard could be higher in the vicinity of these zones than formerly thought. With the growth of population and infrastructure around the western end of the lake, the uncertainty of the seismic hazard has been of increasing concern.

With two nuclear power stations located on the north shore near the intersection of the Niagara-Pickering and Georgian Bay Linear Zones (Fig. 13), a new assessment of seismic hazard has been initiated by the Atomic Control Board of Canada (Geomatrix, 1997), and geoscience research accelerated to better understand the possibility of neotectonic fault reactivation and non-random seismicity. Deep seismic reflection profiles have imaged the earth's crust and shown the presence of discontinuities dipping gently eastward beneath the lake basin (Forsyth et al. 1994a,b). The surface projections of some of these boundaries (faults) in Precambrian terrane are shown in Figure 13.

The lake sediments and underlying late Quaternary strata provide an unrivalled opportunity to search for evidence of paleo-seismicity or fault reactivation, with the goal of extending the record of previously monitored large earthquakes from a century or less to over the past 10 000 years or so. This would provide a sounder basis for the prediction of future large earthquakes. Sonar and high-resolution seismic reflection surveys have been conducted in parts of the lake. Bedrock faults have been identified (Sanford, 1995), and neotectonic features have been suggested (Thomas et al., 1989a,b;1993). One set of features, pop-ups on an exposed bedrock surface south of Toronto, has been validated (Armstrong et al., 1998) as buckling under regional compressive stress, similar to pop-ups found onshore in eastern North America (White and Russell, 1982; Wallach et al., 1993). Other features, first interpreted as of neotectonic origin, have proved to be problematic as alternate mechanisms have been suggested for their formation. For example, in western Lake Ontario, some narrow (about 10 m) linear zones of intense acoustic backscatter, like those initially postulated to reflect faulting, were found to contain debris from shipping (Cameron and Lewis, 1994). Also, broad diffuse lineaments of backscatter in multibeam sonar images were found to lie on lines joining ports on opposite sides of the lake, rather than in alignment with tectonic lineaments. When sampled they contained elevated concentrations of combustion products, and so were interpreted as the cumulated record of steamship ash disposal (Mayer et al., 1994; Lewis et al., in press). In eastern Lake Ontario, south-southwest-trending ridges have been alternately interpreted as Holocene faults (Thomas et al., 1993; McQuest Marine Sciences Ltd., 1995), or as subglacial landforms (Hutchinson et al., 1993; Lewis et al., 1998). Further delineation and resolution of neotectonic and paleoseismic features are topics of ongoing research and debate.

Habitat change

The ecosystem of Lake Ontario is undergoing major changes which impact to a greater or lesser degree the quality of its bottom sediments. Suitable spawning areas for fish species (usually sandy gravel) are being impacted by development of estuarine and nearshore areas. The most important change of all, however, is associated with the entry into the benthic ecosystem of exotic species such as the zebra and quagga mussels (combined here under the term, Dreissenids). These benthic organisms were introduced inadvertently to Lake Ontario (Griffiths et al. 1991) in the late 1980s. Now they occupy significant areas of the lake bottom to depths of more than 85 m. Total Dresssenid biomass increased from less than 1 kg to 145 kg per 10 minute trawl between 1992 and 1995 (Mills et al. 1999). Likewise, Dermott and co-workers at the Great Lakes Laboratory of Fisheries and Aquatic Sciences (GLLFAS) note a dramatic increase in the abundances of Dreissenids between 1990 and 1995, especially in the southern nearshore zone of the lake (Dermott and Munawar, 1999). Spot samples taken from the south shore east of the Niagara River showed numbers of Dreissenids rising from 57 per m^2 to over 21 000 per m^2.

The main impact of this change has been felt in shoreline installations that depend on extracting large quantities of water for cooling purposes or for drinking. Encrusting filter-feeders such as Dreissenids cause considerable damages to these facilities by narrowing, and eventually blocking, the cooling water intakes on the lake bottom. In the case of municipal drinking water intakes, there have been reports of episodes of bad tastes and odours associated with Dreissena colonization. While the total populations in Lake Ontario are still far below those noted in the shallower Lake Erie (Leach 1993), Dreissenids might here as well be playing an important role in contaminant and nutrient transfer from the water column to the bottom sediments.

Summary

The Lake Ontario basin owes its origin to erosion processes, especially those associated with repeated Quaternary glaciations, which excavated relatively weak Late Ordovician shales in a Paleozoic marine sedimentary sequence. Since the retreat of the last glacier around 12.0 ka B.P., modern sediments have accumulated in the deeper offshore areas of the basin while erosion in the nearshore and shoreline areas has resulted in long-term refinement of the shape of the lake as the basin differentially uptilted about 100 m to the northeast as a result of glacial rebound. Erosion rates vary considerably depending on location and reference period but are generally higher on the southern side of the lake. Rates reach 3.8 $m.a^{-1}$ in the Niagara area and up to 3.7 $m.a^{-1}$ on the U.S. side, supplying an estimated 4.2×10^6 tonnes of sediment, or more than 2.8 million tonnes of fine-grained material to the offshore depositional areas of the lake per year. Tributaries, including the Niagara River, deliver approximately 6 to 9×10^6 $tonnes.a^{-1}$. Sediment contamination in Lake Ontario is generally confined to localized areas of concern usually in the vicinity of industrial centres such as the Niagara River and the larger urban centres. Tributary streams draining these areas supply the bulk of the stream-delivered priority toxic contaminants to the lake. With few exceptions (Mirex), atmospheric inputs supply most of the organic contaminants observed in the sediments. Sediment quality is improving with time, however, and in almost all the profiles examined, there was a significant upward decrease in concentrations of trace metals and organic compounds from maximum values 10 - 20 cm below the surface. In the case of PCBs, net atmospheric deposition is now practically nil, and may even be negative, as degassing of volatiles predominates in the water column. A potentially complicating factor in contaminant dynamics in the sediments is the spread of Dreissenid mussels over significant parts of the lake.

Another important geological hazard potentially observed through the sediments is pre-historic and modern seismic activity. Although Lake Ontario is far removed from oceanic margins where serious earthquake activity is expected, infrequent earthquakes with magnitudes up to 5.4 do occur in the area. The possibility that seismicity might not be randomly distributed, but might be preferentially located on bedrock zones of structural weakness, some of which traverse population centres and sensitive infrastructure around the western end of the lake, has been of increasing concern. This is especially true for the two nuclear power stations located on the north shore near the intersection of the Niagara-Pickering and Georgian Bay Linear Zones. With its basin population of more than 8 million, studies of hazards associated with the geology and sediment regime of Lake Ontario will continue to provide valuable information for public decision-makers and stakeholders.

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Figure captions for SOLO manuscript

Figure 1	Colour-shaded relief map of the Lake Ontario drainage basin, showing major topographic features and important place names. The map is based on United States Geological Survey 30 arc-second topographic data and bathymetric data of US National Oceanic and Atmospheric Administration and Canadian Hydrographic Service (CHS) as compiled for CHS Map 880-A. Hypsometric and bathymetric tints refer to colour representation of elevation and depth divisions, respectively.
Figure 2	Bedrock geology of the Lake Ontario basin. See Table 1 for further information. Compiled from information in Goddard (1965); Easton (1992); Johnson et al. (1992); Ontario Geological Survey (1992a,b); Rogers et al. (1990); Sanford (1993, 1995).
Figure 3	Selected features of glacial geology and physiography of the Lake Ontario basin. Modified after Muller and Prest (1985, Fig.1); Dyke and Prest (1987); Barnett et al. (1991); Coleman (1937); and Pair and Rodrigues (1993).
Figure 4	Sedimentological attributes of the Lake Ontario basin after Thomas et al. (1972a,b). A) Outline of sub-basins, sills and inshore zone. B) Distribution of major bottom sediment types. C) Mass sedimentation rates of offshore mud.
Figure 5	Paleogeographic sketch maps of ice retreat and lake phases in the Lake Ontario basin, 12 000 BP to 11 400 BP. Adapted from Prest (1970) and Coakley and Karrow (1994).
Figure 6	Generalized water level history relative to land around the western part of Lake Ontario, adapted from Anderson and Lewis (1985).
Figure 7	Maps showing reconstructed evolution of the shoreline in the western part of Lake Ontario basin from the Early Lake Ontario phase at 11 4300 BP to the present. Adapted from Coakley and Karrow (1994).
Figure 8	Sleeve gun seismic profile across Lake Ontario looking west from east of Toronto to Niagara River area showing representative sequence (top to bottom) of Holocene muds, glaciolacustrine clays, and diamict glacial sediments over the bedrock surface. From Lewis et al. (1997a).
Figure 9	Profiles in surficial sediments of toxic heavy metals. A) Selected metals in sediments from eastern Lake Ontario, from Kemp and Thomas (1976). B) Profiles of mercury in sediments of western Lake Ontario, from Mudroch (1983).
Figure 10	Distribution of selected organic contaminants in Lake Ontario (adapted from Thomas (1983)). Top: Mirex Middle: Mercury Bottom: Total PCB.

Figure 11 Total calculated loadings of PCBs and PAHs into Lake Ontario from tributary stream (includes industrial and municipal inputs) and atmospheric sources, compiled from the recent literature. Figures are in kilograms per year.

Figure 12 History of sediment PCB and Mirex concentrations showing decline in loadings since 1960. Adapted from Durham and Oliver (1983).

Figure 13 Tectonic lineaments from Wallach et al. (1998) and as compiled by Mohajer (1993). Precambrian faults from Easton (1992) and Forsyth (1994a). Thomas et al. (1993) have also proposed lineaments paralleling the long axis of the lake as an extension of the St. Lawrence rift zone. Earthquakes as compiled by Mohajer (1993). A current seismicity map based on monitoring by a high resolution seismometer network, operated since 1991 by University of Western Ontario and Ontario Hydro, can be viewed at www.gp.uwo.ca/docs/eqmap.html.

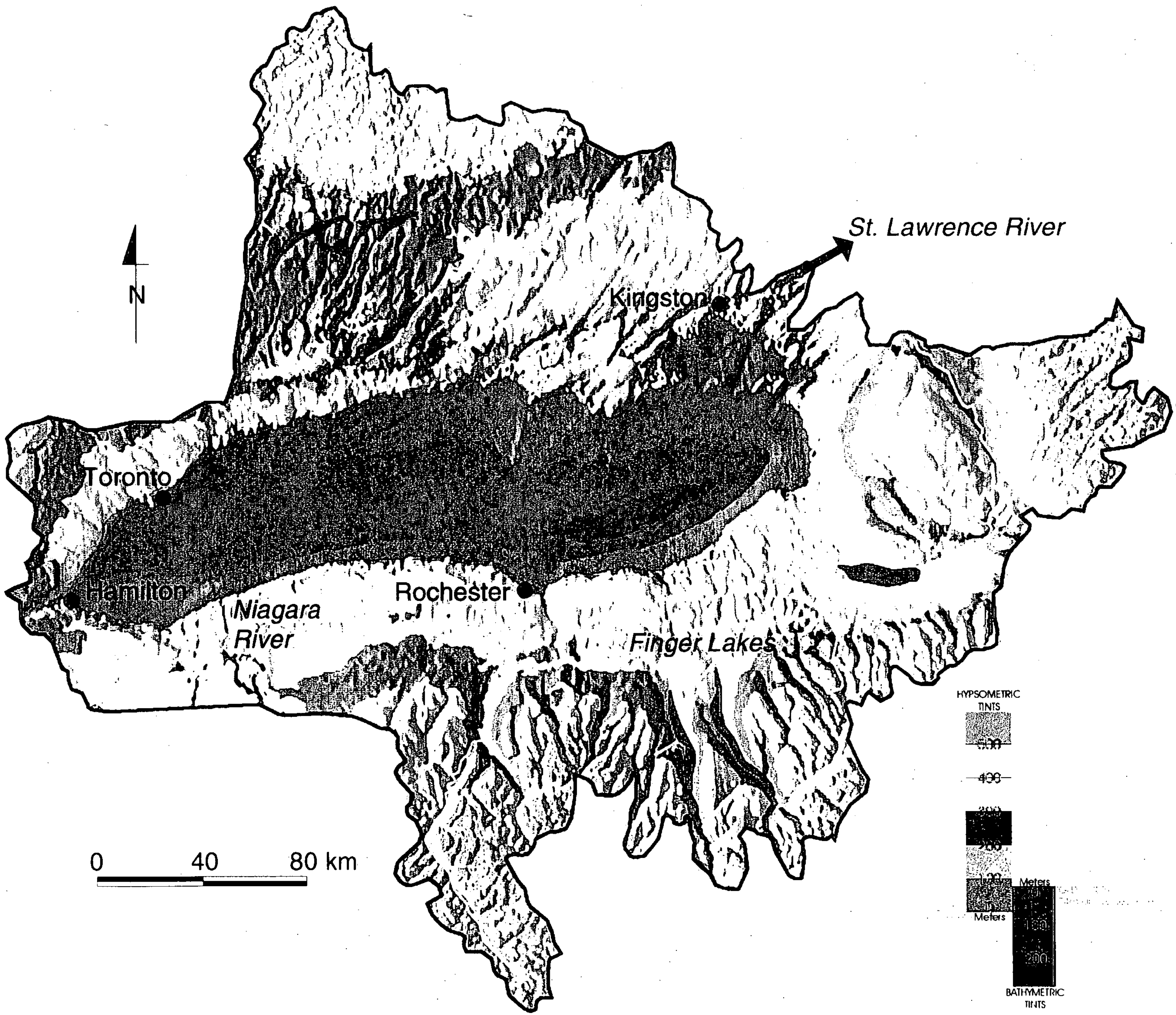
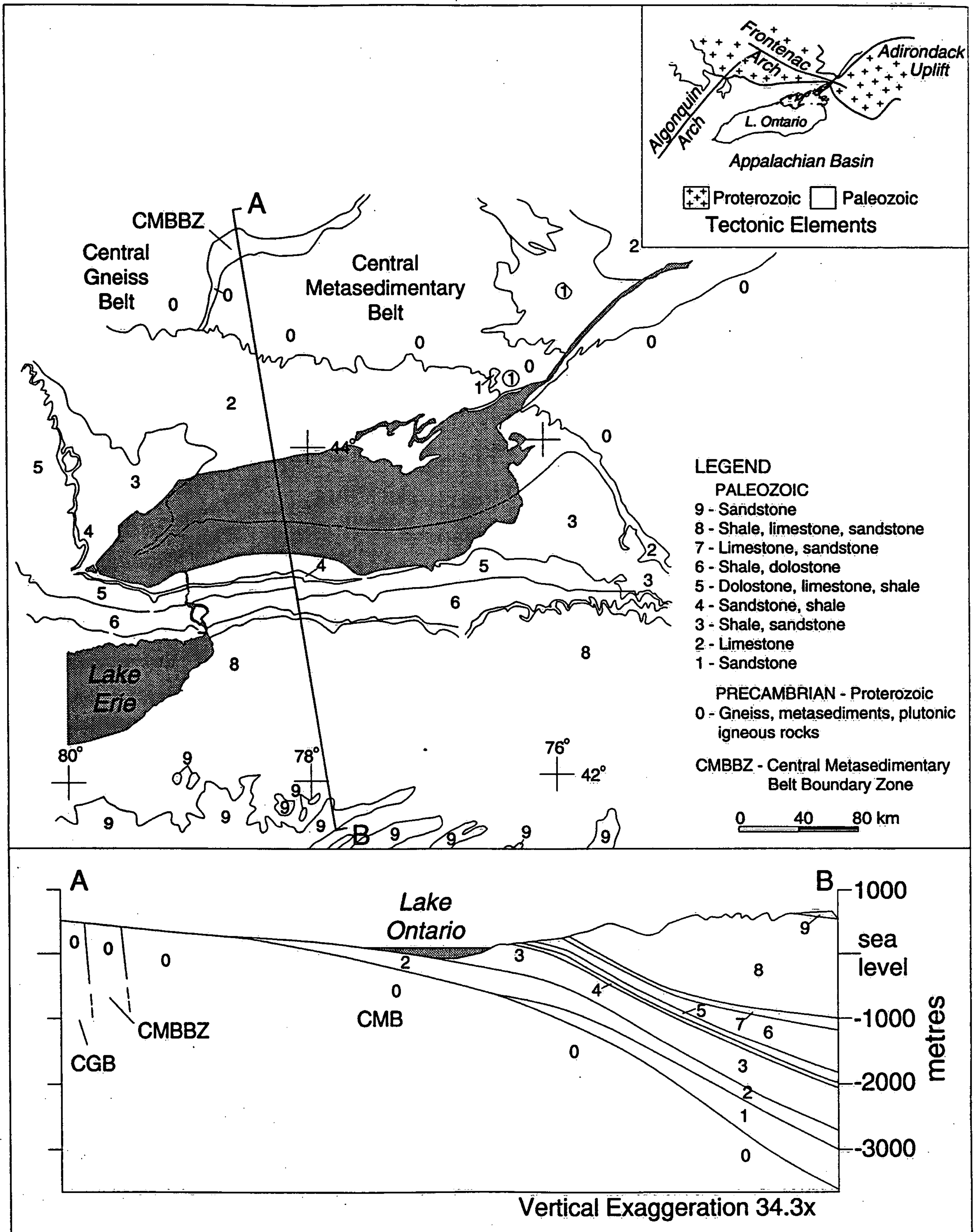

St. Lawrence River
N
Kingston
Toronto
Hamilton
Niagara River
Rochester
Finger Lakes
0
40
80 km
HYPSOMETRIC TINTS
500
400
Meters
Meters
100
200
BATHYMETRIC TINTS

Fig. 1

Fig 2



Frontenac Arch
Adirondack Uplift
Algonquin Arch
L. Ontario
Appalachian Basin
Proterozoic
Paleozoic
Tectonic Elements
A
CMBBZ
Central Gneiss Belt
Central Metasedimentary Belt
44°
Lake Erie
80°
78°
76°
42°
B
LEGEND
PALEOZOIC
9 - Sandstone
8 - Shale, limestone, sandstone
7 - Limestone, sandstone
6 - Shale, dolostone
5 - Dolostone, limestone, shale
4 - Sandstone, shale
3 - Shale, sandstone
2 - Limestone
1 - Sandstone
PRECAMBRIAN - Proterozoic
0 - Gneiss, metasediments, plutonic igneous rocks
CMBBZ - Central Metasedimentary Belt Boundary Zone
0 40 80 km
A
B
Lake Ontario
1000
sea level
-1000
-2000
-3000
metres
CMBBZ
CGB
CMB
Vertical Exaggeration 34.3x

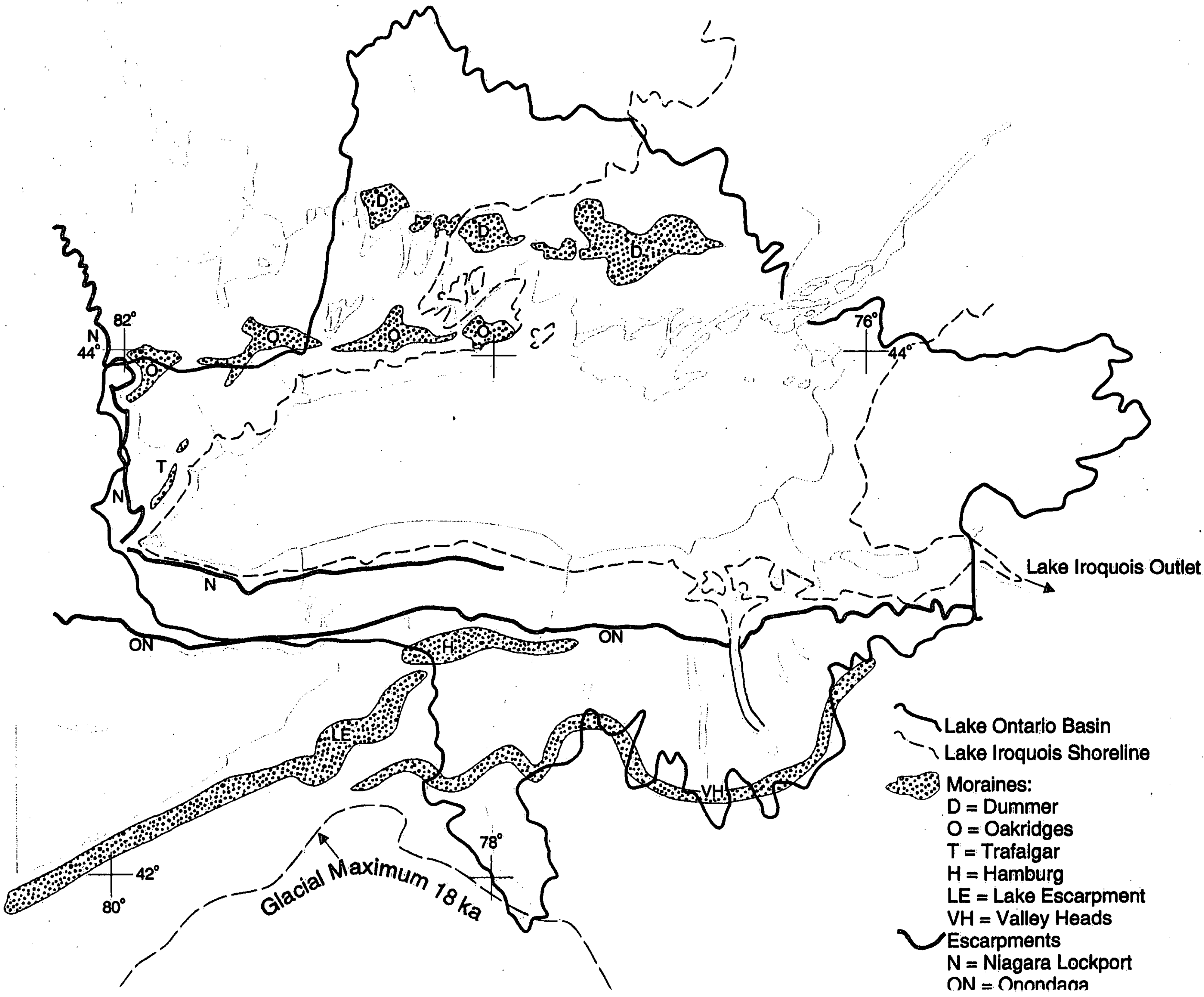

Lake Iroquois Outlet
82°
N
44°
76°
44°
D
D
D
O
O
O
O
O
T
N
N
ON
ON
H
LE
VH
78°
42°
80°
Glacial Maximum 18 ka
Lake Ontario Basin
Lake Iroquois Shoreline
Moraines:
D = Dummer
O = Oakridges
T = Trafalgar
H = Hamburg
LE = Lake Escarpment
VH = Valley Heads
Escarpments
N = Niagara Lockport
ON = Onondaga

Fig. 3

Fig. 4

LAKE ONTARIO

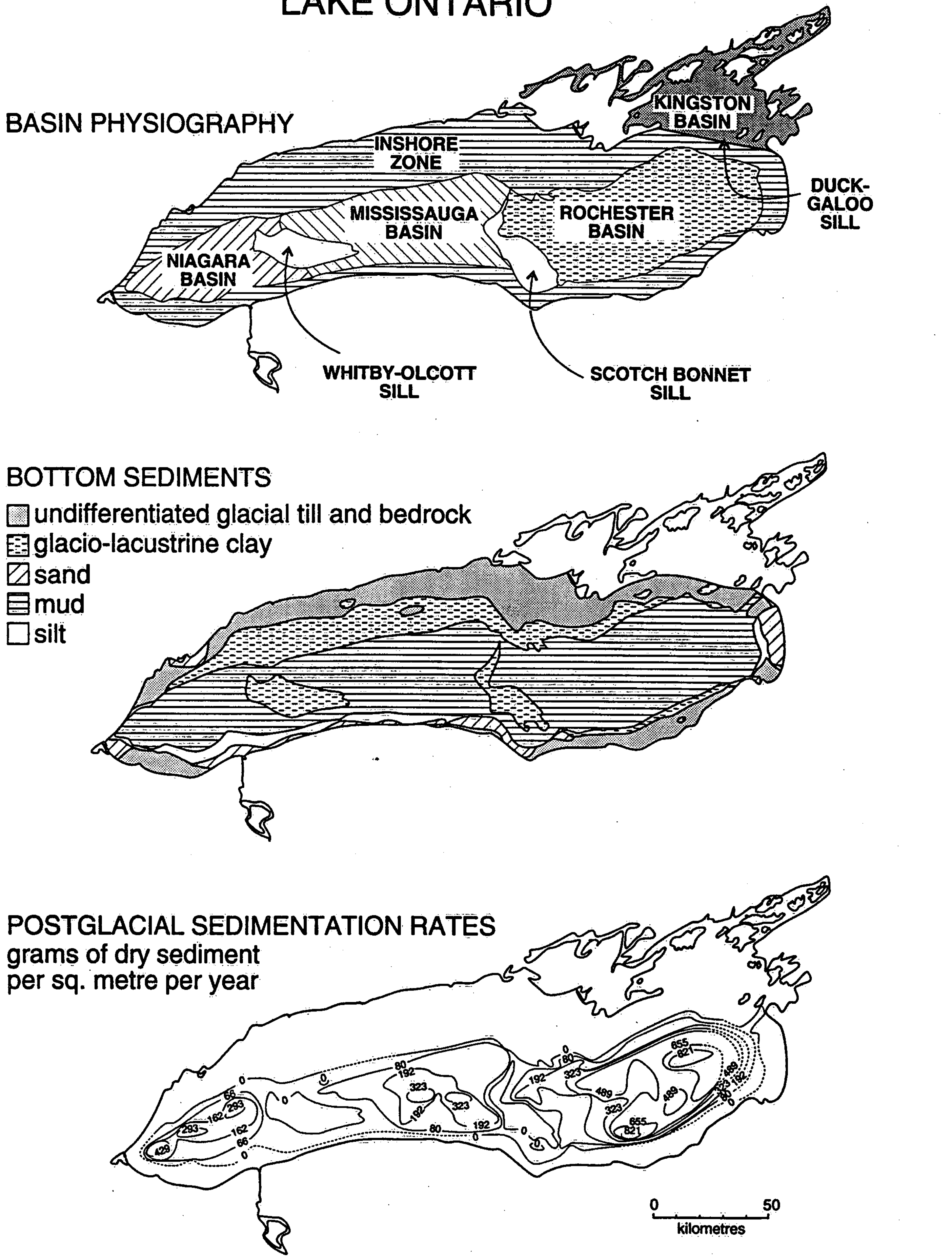
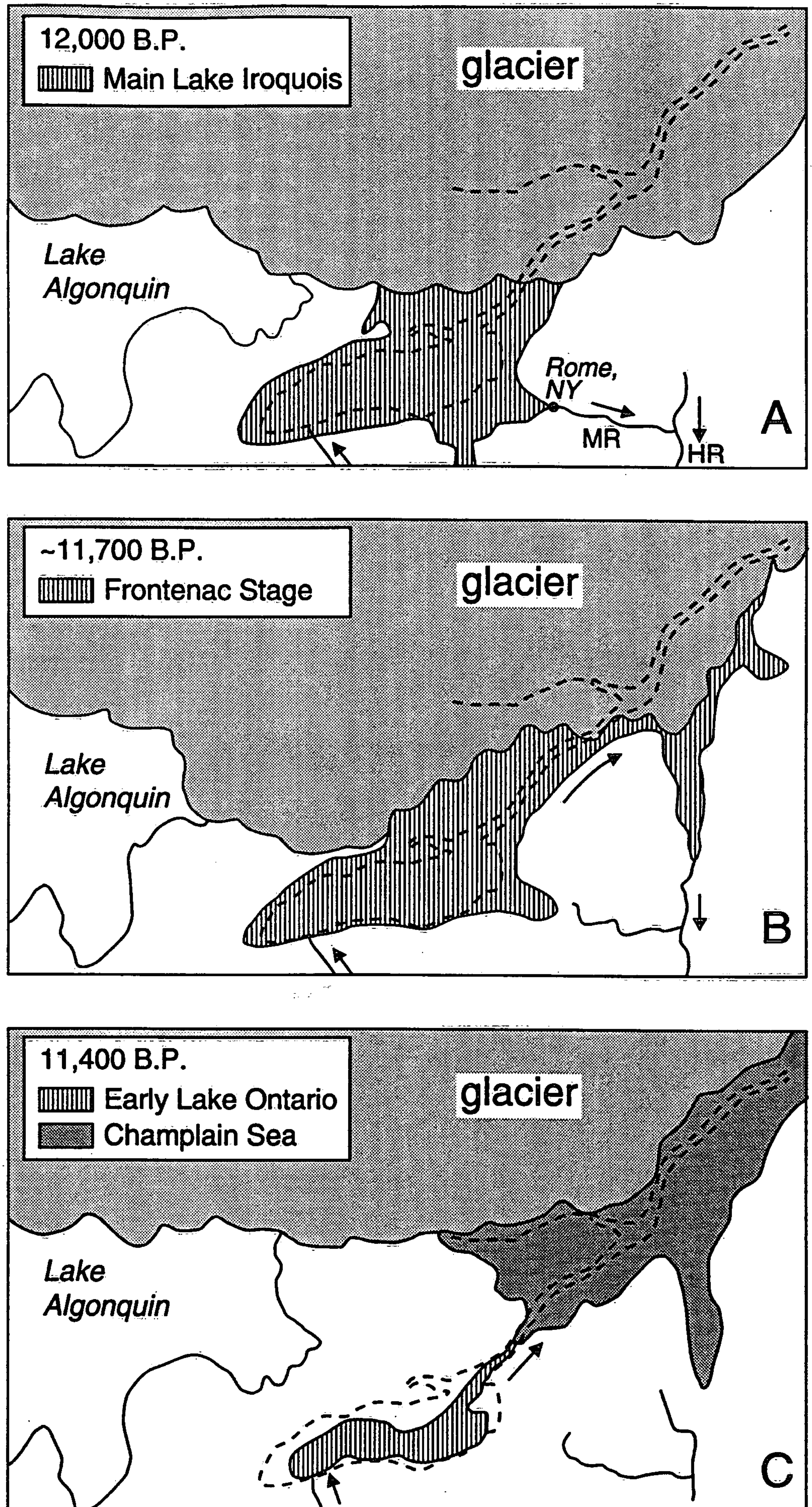
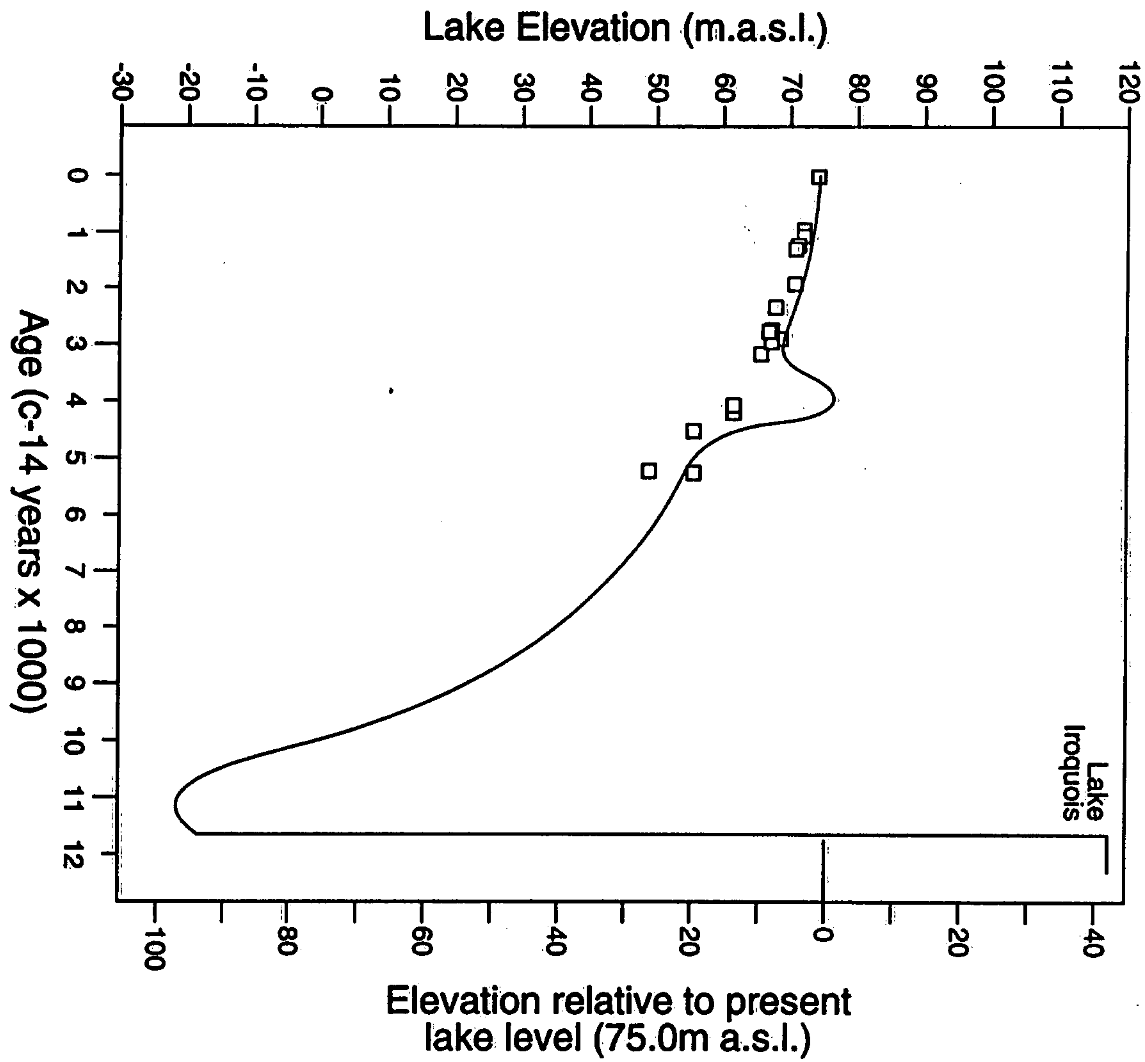
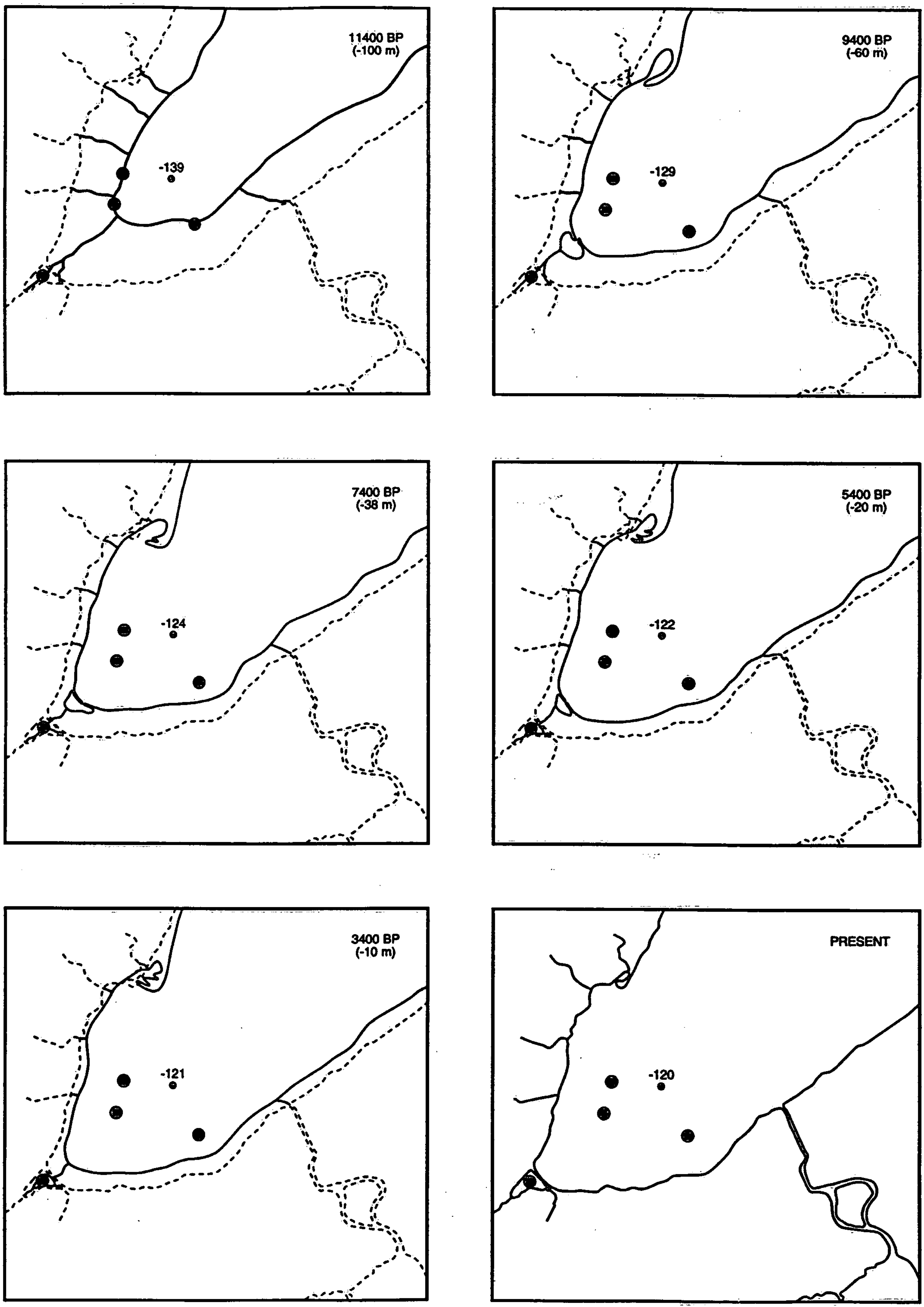


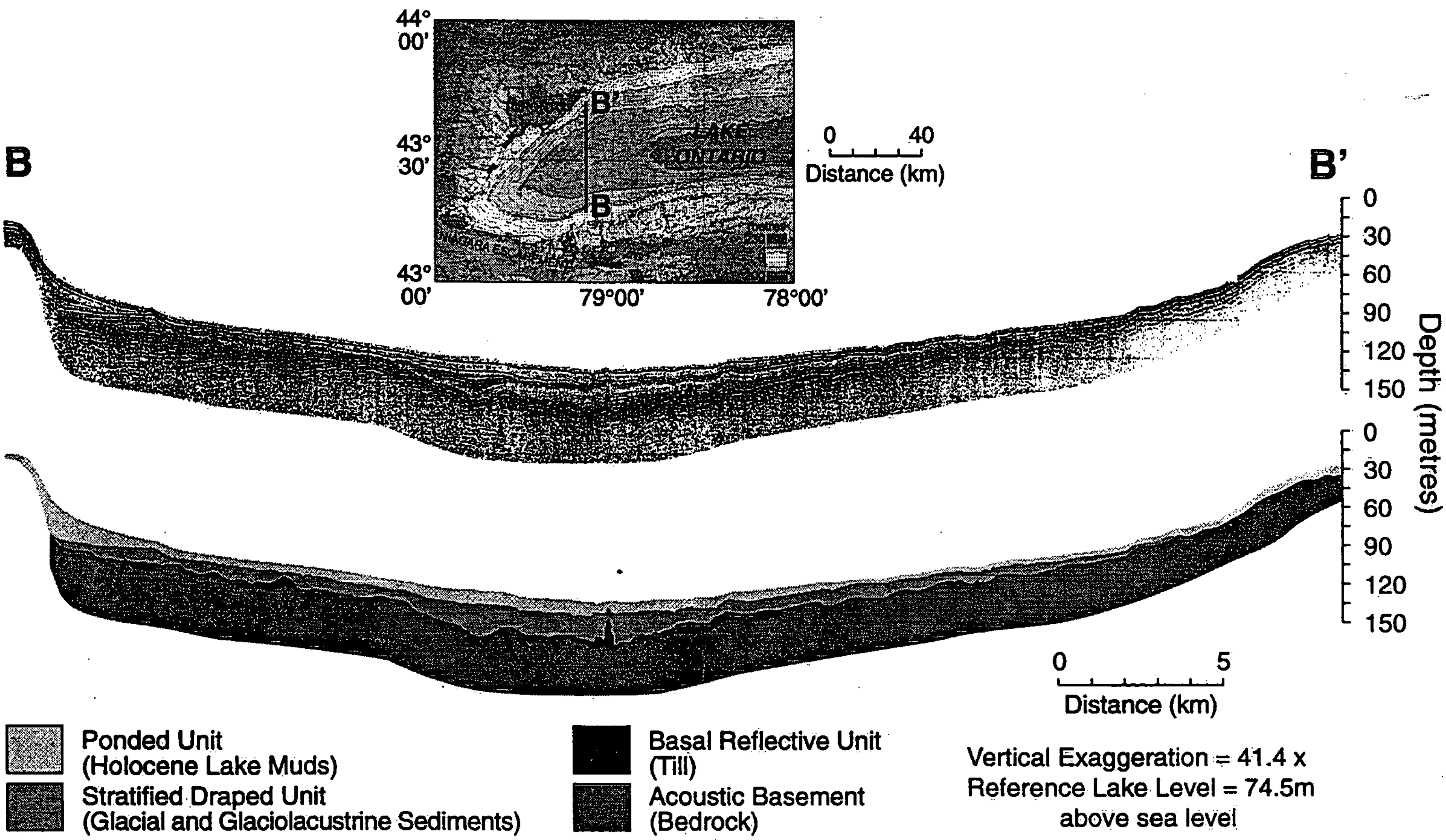
Fig 5


12,000 B.P.
Main Lake Iroquois
glacier
Lake Algonquin
Rome, NY
MR
HR
A
~11,700 B.P.
Frontenac Stage
glacier
Lake Algonquin
B
11,400 B.P.
Early Lake Ontario
Champlain Sea
glacier
Lake Algonquin
C

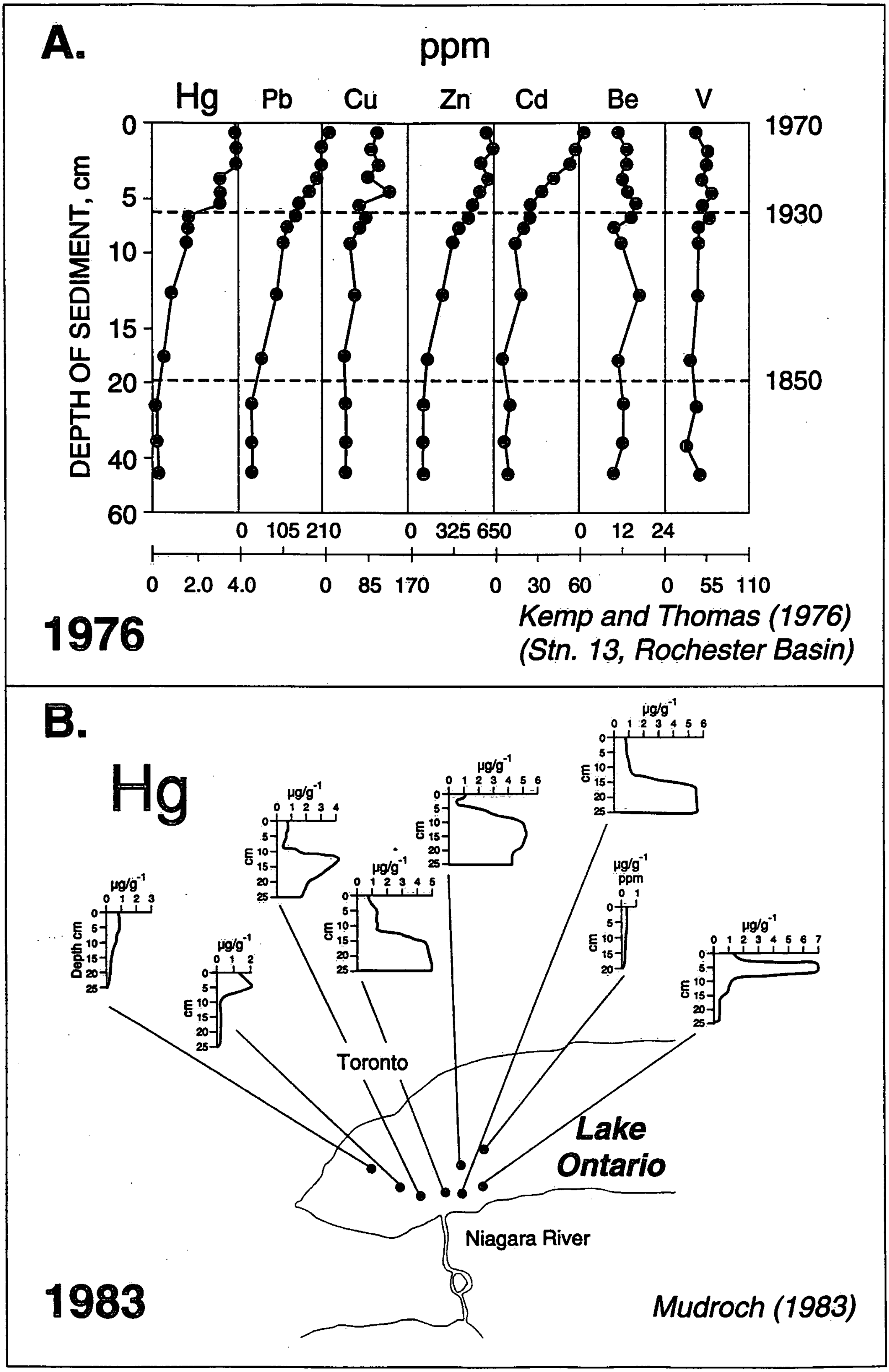


Lake Elevation (m.a.s.l.)
Age (c-14 years x 1000)
Lake Iroquois
Elevation relative to present lake level (75.0m a.s.l.)

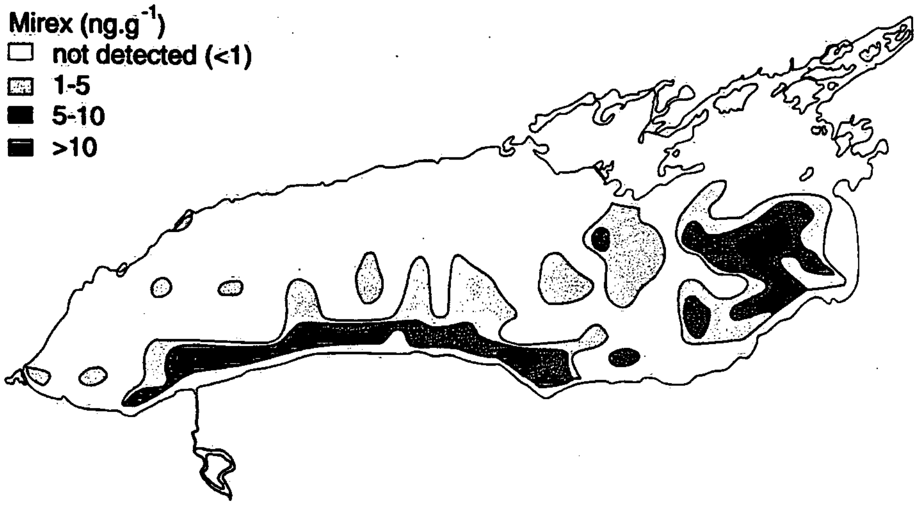

11400 BP
(-100 m)
-139
9400 BP
(-60 m)
-129
7400 BP
(-38 m)
-124
5400 BP
(-20 m)
-122
3400 BP
(-10 m)
-121
PRESENT
-120

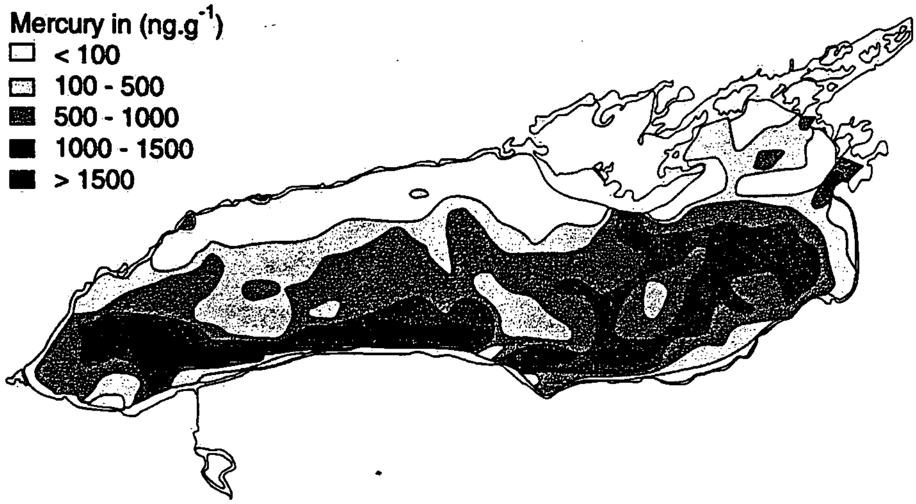


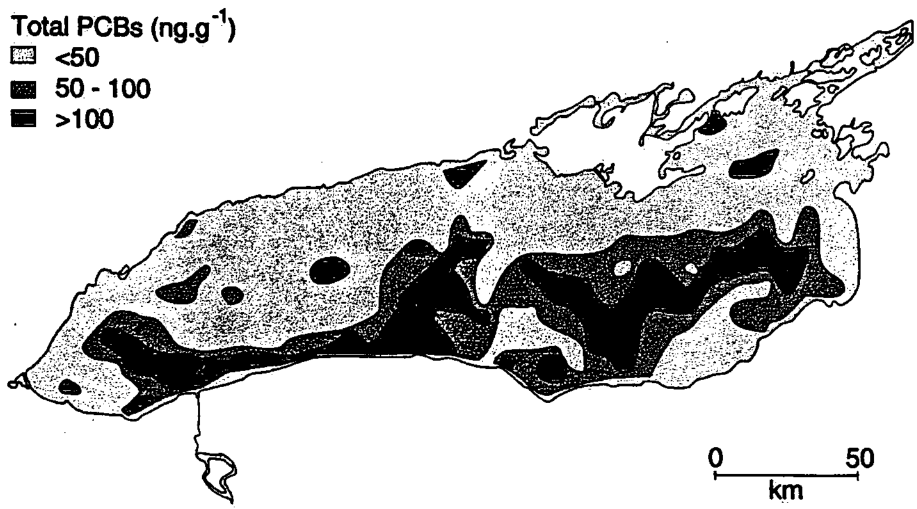
ml179010.fh8



A.
ppm
Hg
Pb
Cu
Zn
Cd
Be
V
DEPTH OF SEDIMENT, cm
0
5
10
15
20
40
60
1970
1930
1850
0 105 210
0 325 650
0 12 24
0 2.0 4.0
0 85 170
0 30 60
0 55 110
1976
Kemp and Thomas (1976)
(Stn. 13, Rochester Basin)
B.
Hg
µg/g-1
ppm
Depth cm
cm
Toronto
Lake Ontario
Niagara River
1983
Mudroch (1983)


Mirex (ng.g^{-1})
not detected (<1)
1-5
5-10
>10


Mercury in (ng.g^{-1})
< 100
100 - 500
500 - 1000
1000 - 1500
> 1500


Total PCBs (ng.g^{-1})
<50
50 - 100
>100
0
50
km

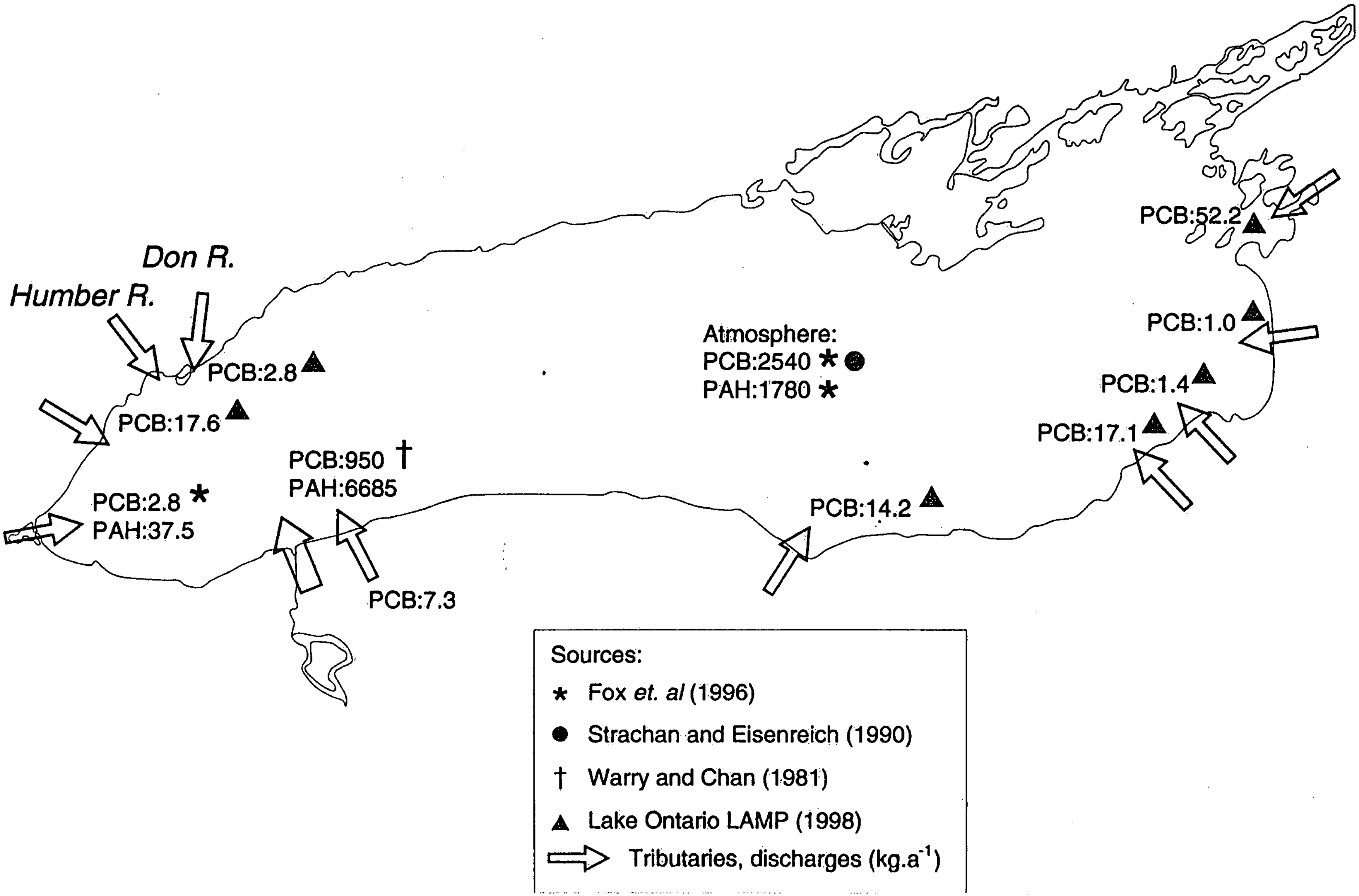
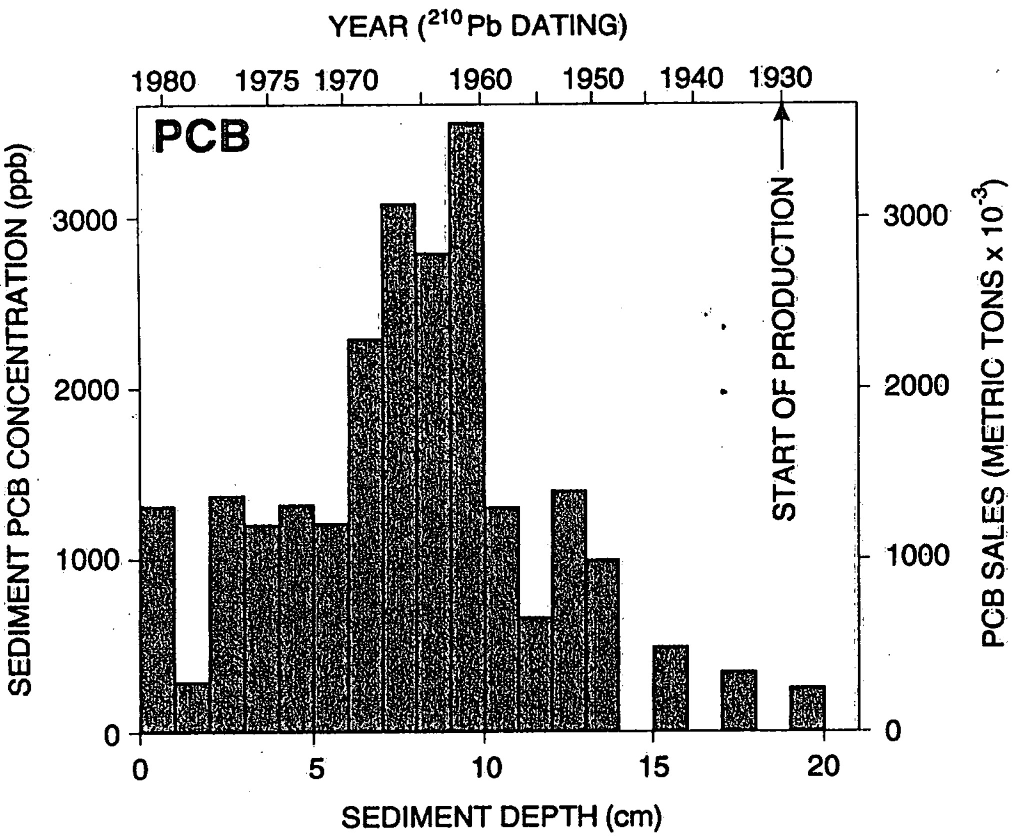
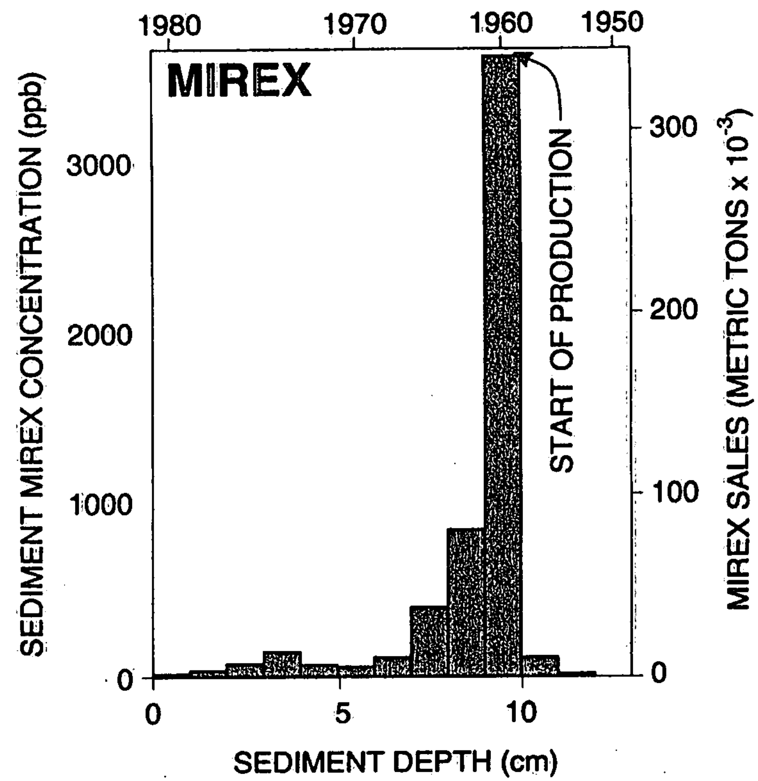

Don R.
Humber R.
PCB:2.8
PCB:17.6
PCB:2.8
PAH:37.5
PCB:950
PAH:6685
PCB:7.3
Atmosphere:
PCB:2540
PAH:1780
PCB:14.2
PCB:52.2
PCB:1.0
PCB:1.4
PCB:17.1
Sources:
Fox et. al (1996)
Strachan and Eisenreich (1990)
Warry and Chan (1981)
Lake Ontario LAMP (1998)
Tributaries, discharges (kg.a-1)

Fig. 11

Fig. #





Durham and Oliver (1983)

Fig. 12

Fig 12

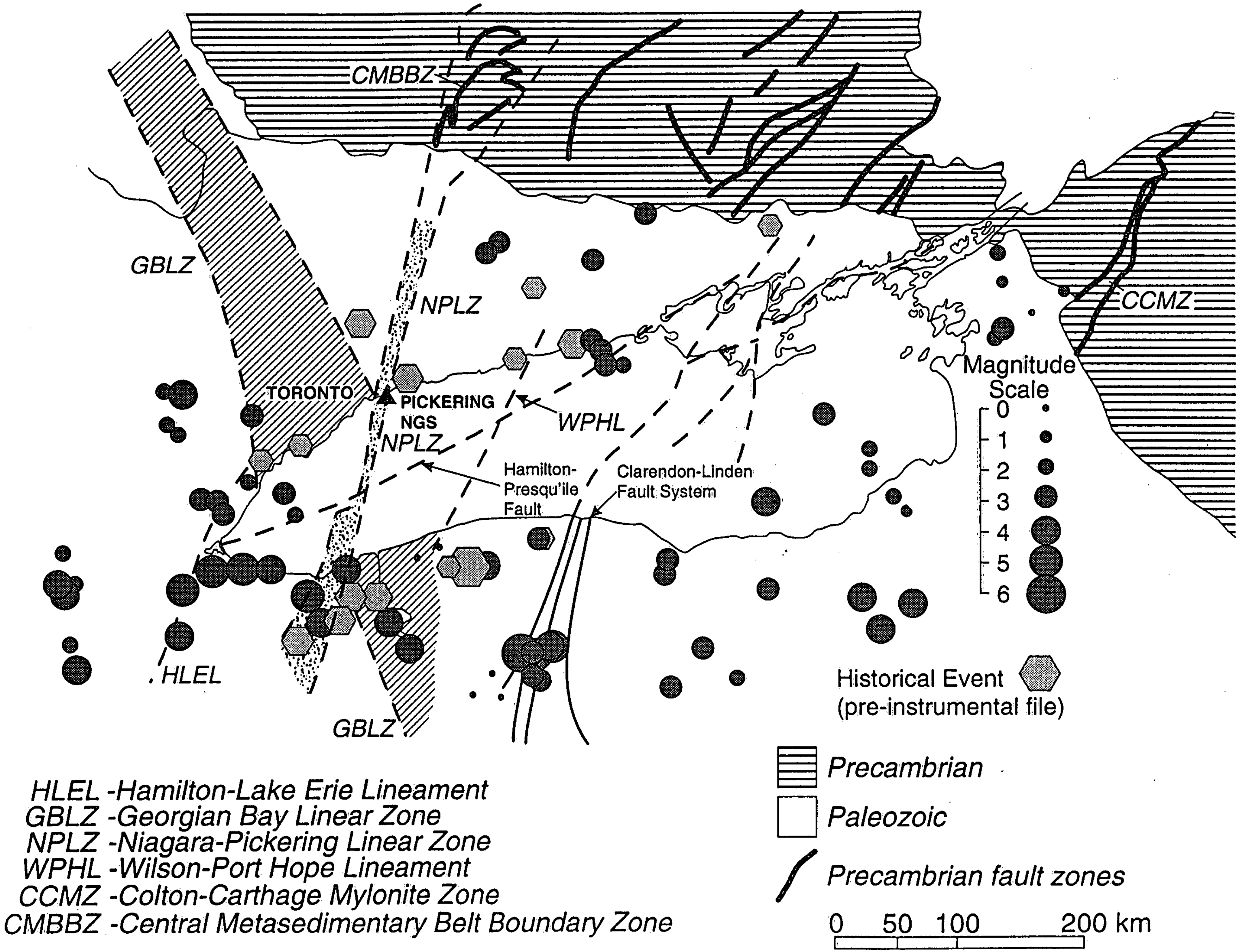

CMBBZ
GBLZ
NPLZ
CCMZ
Magnitude Scale
0
1
2
3
4
5
6
TORONTO
PICKERING NGS
NPLZ
WPHL
Hamilton-Presqu'ile Fault
Clarendon-Linden Fault System
HLEL
GBLZ
Historical Event (pre-instrumental file)
Precambrian
Paleozoic
Precambrian fault zones
0 50 100 200 km
HLEL -Hamilton-Lake Erie Lineament
GBLZ -Georgian Bay Linear Zone
NPLZ -Niagara-Pickering Linear Zone
WPHL -Wilson-Port Hope Lineament
CCMZ -Colton-Carthage Mylonite Zone
CMBBZ -Central Metasedimentary Belt Boundary Zone

Fig. 13

Fig 13

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