93-36

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Reconstruction of Post-Iroquois Shoreline Evolution in Western Lake Ontario: Procedure and Preliminary Results

By:
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RECONSTRUCTION OF POST-IROQUOIS SHORELINE EVOLUTION IN WESTERN LAKE ONTARIO: PROCEDURE AND PRELIMINARY RESULTS

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Coakley and Karrow: Reconstruction of post-Iroquois shoreline evolution in western Lake Ontario

Abstract

When Lake Iroquois drained between 11.7 - 11.4 ka BP, lake level in the Ontario basin fell from a high of more than 40 m above present lake level to a minimum close to the then-existing sea level, which was approximately 40 m below present sea level. Since that time, lake level has been rising at an exponentially-decreasing rate in the western portion of the basin as a result of postglacial and neotectonic uplift of the outlet near Kingston, at the eastern end. The published lake level history has been combined with other less well-known parameters (the post-Iroquois regional topography, erosion / deposition rates, and distribution of resistive shore materials) to reconstruct the evolution of the western Lake Ontario shoreline. Borehole, long piston-core, and other subsurface data sources, primarily from the western portion of the lake near Hamilton Harbour, provide most of the physical constraints. Time-references were provided by radiocarbon dates on shallow-water organics in the subsurface sediments. A computer program was designed to calculate and contour the changing elevations of the rebounding post-Iroquois topographic surface, allowing the time-dependent water plane elevation to be superimposed. Semi-quantitative allowance was made for differential erosion and deposition along the advancing shoreline. The reconstruction provides a perspective on past and future shoreline evolution in the basin and possibly on the location of potentially commercial offshore deposits of aggregate.

Reconstruction of post-Iroquois shoreline evolution in western Lake Ontario

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Introduction

The most downstream of the Great Lakes, Lake Ontario, covers an area of 19 000 km ^{2}. Its level varies seasonally and cyclically over longer periods, but is at present approximately 75 m above sea level (a.s.l.). The 1000-km-long shoreline of Lake Ontario (Fig. 1) is constantly evolving under the combined influence of changes in water level, erosion of the unconsolidated glacial sediments making up much of the shoreline, and redeposition as spits and bars (Boulden 1975). Underlying these relatively short-term processes, however, is an ongoing postglacial evolutionary trend that over the past 11 000 years has completely changed the hydrological regime of the basin. This trend is related to the lacustrine transgression caused by lake level rise as the basin outlet undergoes postglacial isostatic and neotectonic uplift.

In order to unravel the evolutionary history of Lake Ontario, careful investigations into its sediment record are necessary. Furthermore, diagnostic physiographic features, often obscured by weathering and burial under younger sediments, must be identified and interpreted. The aim of this paper is to utilize the considerable data base on postglacial geology and bottom sediment deposits of the basin to reconstruct and verify the progression of shoreline positions in the western end of the Lake Ontario basin (hereafter referred to as the western basin). The western basin offers the simpler evolutionary situation as the eastern basin contains the St. Lawrence River outlet, and is divided by prominent sills into several sub-basins (Fig. 2). The changes brought about by rising lake levels are therefore not as straightforward nor as dramatic there as those at the western end of the basin opposite the rising outlet. A secondary aim is to demonstrate the results of a computer program designed to compensate for time-dependent isostatic rebound in reconstructing the elevation of the surface onto which the lake was being impounded, and to indicate the shoreline position corresponding to the lake level curve. A reconstruction such as this serves to put modern processes in a long-term context and provides valuable insights into future shore-related trends in the lake.

Previous work

Most of the work conducted to date on the postglacial record of the area has focused on Lake Iroquois sediment deposits exposed on land (e.g., Karrow 1987). Because of the Holocene lacustrine transgression, most of the post-Iroquois sediments are submerged below the lake and are accessible only by long piston-cores in depositional basins or land-based boreholes through transgressive depositional features such as the Burlington Bar (Fig. 1). Lewis and McNeely (1967) and Lewis (1969) provided the initial sub-surface investigations of surficial and subsurface sediments in the Ontario basin, using a combination of coring and seismic profiling. These sub-bottom investigations were carried further by Thomas et al. (1972) and Sly and Prior (1984).

Physiographic background

Lake Iroquois

Lake Iroquois (Fig. 3) came into existence more than 12 000 years (12.0 ka) before present (BP) when the Laurentide ice sheet retreated away from the Niagara escarpment (Karrow et al. 1961; Karrow 1981; Fullerton 1980; Muller and Prest, 1985). Its outflow was eastward through an outlet in the southeast portion of the basin near Rome, New York, reaching the Atlantic via the Mohawk / Hudson River system. Projection of the levels of the raised Iroquois beaches in the Ontario basin shows that the zero isobase or hinge-line, the imaginary line south of which the shoreline is unwarped, lies to the south of the basin. Hough (1958) placed it "a few miles southwest of Buffalo, New York". The highest unwarped elevation of Lake Iroquois (projected to the hinge-line) was estimated by Hough (1958) at 330 feet (100 m) a.s.l., or 25 m above present lake level (a.p.l.). The highest Lake Iroquois shoreline in the western part of the lake Ontario basin is about 35 m a.p.l. (Karrow et al. 1961; and Anderson and Lewis 1985). The difference between this and the hinge-line elevation was explained by Karrow et al. (1961) as evidence of differential uplift of about 10 m in the Hamilton area.

Evidence of the former existence of Lake Iroquois is common in the western basin and includes raised wave-cut cliff shorelines and spit / bar features (shown by the dashed line on Fig. 4A), exposed nearshore ramps, and considerable thicknesses of offshore glaciolacustrine clay below the modern sediment cover (Fig. 2; Thomas et al. 1972; 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 traverses a narrow ridge composed of cross-bedded, gravelly bar deposits.

Post-Iroquois events

When glacial ice retreat opened the lower St. Lawrence valley outlet approximately 11.7 ka BP (Pair and Rodriguez 1993; Anderson and Lewis 1985), Lake Iroquois drained to lower levels (Fig. 3). Lake levels in the basin fell in stages, and at around 11.4 ka BP had reached their minimum at more than 100 m below present lake level (b.p.l.). Although the precise dates of these events are still debated, the figure of 11.4 ka BP will be used in this paper as the reference time for initiation of post-Iroquois rebound and lake level rise. 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. No supporting evidence in the form of marine fossils, however, has been found to date anywhere in the basin.

Evidence of a low-level Early Lake Ontario phase in the western basin is sparse and somewhat controversial, the most convincing being the apparently extensive, linear deposits of coarse-grained, stratified sediments sampled in piston cores below modern muds at 72 - 103 m b.p.l. (Lewis and NcNeely 1967; 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. The deposits were pollen-dated by Anderson and Lewis 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.

This situation contrasts with that in the eastern basin where radiocarbon dates correlating to Early Lake Ontario (11.3 and 11.9 ka BP) were obtained approximately 40 m higher in elevation on thin, peaty layers above glaciolacustrine sediments (Young and Sirkin, 1994). These new data raise questions about the minimum level that can only be answered later after a more thorough review of their stratigraphic interpretation.

Because of postglacial rebound at the eastern (outlet) end, the basin was tilted, and waters rose in the western basin from the minimum stage to present levels. The presence of the above bar feature, and the absence of any others upslope, suggest to us that levels initially remained fairly stable for some time before rising steadily in concert with uplift of the outlet. The definitive analysis of postglacial lake level history, based on 33 dated elevations from all over the lake, is presented in Anderson and Lewis (1985), and is discussed later. Lake levels continue to rise even at present, albeit at a reduced rate - around 20 cm.century^{-1} (Kite 1972).

Seismic records of glacial clay reflectors below the modern muds all show angular unconformities and truncation consistent with the erosion of an undetermined thickness of unconsolidated Lake Iroquois sediments during the lacustrine transgression (Sly and Prior 1984). The continuing lacustrine transgression is evident in the steady present-day rates of shore erosion along the southern non-bedrock shores (close to 1 m.a^{-1} (Boulden 1975)), and in the drowned mouths of local streams (e.g., Sixteen-Mile Creek, Bronte Creek). Incidentally, these drowned creek-mouths, and sheltered areas such as Hamilton Harbour, represent the only shallow-water areas where sediment columns dating back several thousands of years are preserved (Flint et al. 1988; McCarthy and McAndrews 1988).

Data base and procedure for reconstruction

The data base used in the reconstruction of the shoreline evolution of western Lake Ontario was compiled from the literature, from recent borehole and core data from Hamilton Harbour, and from seismic and acoustic profiles offshore in the lake.

Borehole and core data

Figures 4A and B show the location of the boreholes and cores making up the stratigraphic data base. The borehole data are restricted to on-land locations, and thus are confined to features such as the Burlington Bar, that presumably have transgressed over older lacustrine deposits in a similar manner to the sandy forelands in Lake Erie (Coakley 1992). However, because the deeper boreholes on the Bar were for engineering purposes, they contain only rudimentary sediment descriptions and few useful geological data. The exception is borehole PFK2 (Fig. 4B; Karrow 1987, p.53), where wood encountered at about 25 m b.p.l. was dated at 5.2 ka BP (Table 1). Geologically useful boreholes were obtained from Grenadier Pond (McCarthy and McAndrews 1988) and Sixteen-Mile Creek (Flint et al. 1988), labelled MM and FDF respectively (Fig. 4A. These boreholes provided radiocarbon dates (Table 1) on shallow-water organics that appear in the lake level curve (Anderson and Lewis 1985).

Core data, though limited to sediments soft enough for penetration and retrieval, allow access to less disturbed sediment columns below tens of metres of water. More than six long piston cores have been taken in Hamilton Harbour (Fig. 4B) by the authors and others. These cores are almost all characterized by a sandy or gravelly basal unit (constituting the refusal layer), overlain by an organic-rich layer of variable thickness which yielded radiocarbon dates (Table 1). The topmost unit is a uniform mud layer. This sequence is illustrated in cores HH26 and HH33 (Fig. 5).

Based on the maximum age of the organics found in the Hamilton Harbour cores (7 to 8 ka BP), it is assumed that the wide-spread, uniform textured sand below the organics was deposited by Lake Iroquois or subsequent high-level phases. If this is the case, then there must have been a considerable period (more than 3 ka) of non-deposition or erosion in the area, probably associated with subaerial exposure. The basal sand layer could also have been reworked to some degree as it was inundated later on. The overlying organic layer in HH26 is characterized by well-preserved organic debris and leaves, predominantly of white birch and other upland species (J.S. Pringle, Hamilton Royal Botanical Gardens, pers. commun. 1993). Ostracode and pollen studies on the basal organic-rich section of this core are still in progress, but the overall impression is that of an upland fluvial system with marshy overbank borders, where water depths were probably less than 2 m (L.D. Delorme, National Water Research Institute, pers. commun. 1993). The much thicker silty clay unit at the top was clearly laid down in deeper water than the organic unit, most likely in water depths not much different than at present. Further studies are in progress on the core data, but the sediment sequence clearly indicates a trend from shallow to deep water in the Harbour over the past 7000 years.

Postglacial lake level curve

Another important component of the data base used here is the postglacial lake level curve for Lake Ontario (Fig. 6) modified after Anderson and Lewis (1985). When the new Hamilton Harbour dates are plotted in figure 6, they are in good agreement with the curve, except for the older points. At an elevation of approximately 47 m a.s.l., these tend to lie above the Anderson and Lewis curve. This divergence supports the interpretation put forward earlier that before 7 ka BP, a fluvial marsh situated at a higher elevation than the main lake occupied the Hamilton Harbour area. Although other curves have been published for the Ontario basin (Karrow et al. 1961; Flint et al. 1988; Sly and Prior 1984; McCarthy and McAndrews 1988; Young and Sirkin, 1994) the Anderson and Lewis curve is the most comprehensive, and so will be used in this paper.

Reconstruction of the Iroquois paleo-surface

Before attempting to reconstruct the shoreline evolution, the original configuration of the Lake Iroquois bottom exposed as the lake was lowered to minimum levels must be defined. To do this, the present surface must be adjusted semi-quantitatively for material eroded from and deposited on the paleo-surface during the intervening time. This information is not known and must be inferred from other indicators.

Topographic and subsurface indicators

The most useful indicators of such changes are found in examination of transverse and longitudinal cross-sections (see figure 4 for location) constructed from the 1:400 000 combined bathymetric / topographic map of Lake Ontario (Canadian Hydrographic Service no. 881). These sections, considerably exaggerated for enhancement of changes in relief, are shown in figures 7 to 9.

Offshore subsurface data, providing information on post-Iroquois (modern) sediment thickness and degree of erosion of the Lake Iroquois deposits, were obtained primarily from Thomas et al. (1972) for the entire basin and Sly and Prior (1984) for the Niagara area. Significant areas of gas-impregnated sediments in Hamilton Harbour hampered collection of acoustic or seismic data there, but the number of boreholes and piston cores from the area (Fig. 4) allowed an adequate interpretation of the local Iroquois surface below the Harbour (Fig. 9).

Because of the scarcity of cores and seismic data penetrating the full modern sediment record offshore, use is made here of proxy sedimentation-rate data in order to estimate the thickness of sediments overlying the Iroquois paleo-surface. For instance, using figure 2, taking an average dry-weight sedimentation rate of 114 $g.m^{-2}. a^{-1}$ for the Niagara (western) basin, and assuming a porosity of 88% (Hamilton Harbour silty clay) yielded a corresponding volumetric sedimentation rate of 0.04 $cm.a^{-1}$, or 4.6 m over 11.4 ka. Maximum rates (up to 620 $g.m^{-2}. a^{-1}$) occur near the extreme west end, for a volumetric rate of approximately 0.18 $cm.a^{-1}$, or about 20 m over 11.4 ka. These thicknesses are in good agreement with sparse seismic data (C.F.M.

Lewis, Geological Survey of Canada, pers. commun. 1993).

Paleo-surface data base

The position of the Iroquois paleo-surface was deduced by careful examination of the cross-sections and allowing for erosion and deposition, (Fig. 7 to 9). In using the above indicators, several reasonable assumptions must be made:

- The surface between the still-prominent Iroquois bluff and the present lakeshore, now subaerially exposed, represents the Lake Iroquois nearshore slope, and was once linked smoothly to the offshore Iroquois paleo-surface preserved below the modern sediments.

- Apart from human construction and minor mass-wasting processes, such as solifluction, the well-vegetated subaerial part of this surface has not changed significantly since draining of Lake Iroquois.

- Below a water depth of 100 m or so, close to the minimum post-Iroquois lake level in the Ontario basin, the original position of the Iroquois surface has been preserved by a cover of post-Iroquois (modern) sediments.

The reconstructed Iroquois paleo-surface was obtained by adjusting the cross-section profiles for erosion / deposition, as indicated by the smoothed dashed sections of the profiles. The adjusted profiles were then digitized manually to compile a data-base of elevations at the intersections of a square 10 km grid superimposed over the study area (Fig. 10). Note that the grid is arranged so that it is orthogonal to N20°E, the commonly reported direction of maximum uplift of the Iroquois water plane (Wilkinson 1959; Anderson and Lewis 1985).. The abscissa of the grid was placed along a line passing just south of Buffalo (Fig. 10), the approximate position of the Lake Iroquois hinge-line (Hough 1958). A similar approach was used by Coakley (1985, 1992) in a reconstruction of Lake Erie postglacial shoreline evolution.

The array of three-dimensional values (X, Y: the distances east and north of an arbitrary point of origin on the zero isobase west of Hamilton; and Z: the elevation above sea level of the inferred Iroquois surface) represents the present-day configuration of the surface, after more than 11 ka of postglacial isostatic rebound.

Removal of the effect of rebound on the Iroquois topographic surface

The objective of the next exercise was to depress the present surface to its position at 11.4 ka BP, soon after the time Lake Iroquois drained, and to return it, in regular time-steps, to its present position. This compensates for the upwarping of the respective water planes and returns them to their original horizontal position. The adjusted Lake Iroquois topographic surface was defined by the array of elevations described above. The process of this rebound followed basically an exponential decay model, with uplift rates initially rapid, then declining with time. The model used for the adjustment was presented originally in Andrews (1968) and recently in Anderson and Lewis (1985):

$$U_t = U_{tot} * e^{-k(T - t)}$$

where: U_t is the uplift remaining at time (t), expressed in thousands of years, ka;

U_{tot} is the total uplift since the reference time (T), i.e 11.4 ka BP ;

k is the relaxation coefficient, representing the time required for the total uplift to be reduced to 1/e (e = 2.71) of its original value. The value used here, 0.404, was developed in Anderson and Lewis (1985).

U_{tot}, the total uplift since time 11.4 ka BP, varied with distance from the zero isobase from 10 m near Hamilton to 35 m at the north limit of the study area (Fig. 10). These values were taken from Anderson and Lewis (1985, Fig. 8). Intermediate values for U_{tot} at the grid intersections were interpolated linearly (the curvature of the water-plane in this area is low enough to be negligible).

A computer program was especially designed to carry out the iterative calculations of the exponential equation to obtain U_t at each grid point and also to produce a contoured plot of the rebounding surface at specified time intervals. In arriving at the elevation of the appropriate time-dependent water-line, and thus the shoreline position, we made use of the postglacial lake level curve (Fig. 6).

Shoreline reconstruction

Early Lake Ontario

Figure 11 shows the reconstructed shoreline position for western Lake Ontario at ca. 11.4 ka BP, at around the time of Early Lake Ontario. The elevation contours of the reconstructed (depressed) Iroquois paleo-surface produced by the computer program are also shown, together with the location of piston cores that contained subsurface "beach" indicators. The elevation for the Early Lake Ontario level was taken from the depth of this material in Lewis and Anderson Core 11, the deepest of the three, i.e. approximately 100 m b.p.l., which, after adjustment for rebound in the intervening period, resulted in an elevation of 115 m b.p.l.. To obtain the reconstructed Early Lake Ontario shoreline position at 11.4 ka, a line was traced along the 115 m contour of the depressed Iroquois surface.

If it is assumed that the TI sill served as the main control sill for lake levels at that time, then its calculated elevation should be close to that of the reconstructed shoreline. Using the plotted paleo-waterplanes in Anderson and

Lewis (1985; Fig.8), and an assumed present elevation of the sill of 10 m b.p.l., we calculate that the sill would have been about 125 m b.p.l. This is admittedly a rough check, given the sparse data base, but the agreement with our figure is reason for confidence in the reconstruction process.

The reconstructed shoreline is seen to have been located up to 20 km offshore from the present shoreline position. What is now Hamilton Harbour was, at the time, some 25 km inland, and approximately 100 m above the contemporary lake level. It was apparently located in what appears to have been an upland valley area, carrying drainage from the Niagara escarpment along the Dundas Valley. It is reasonable to postulate that large streams now entering the lake were initiated or reactivated at that time by the sharp drop in base level in the basin. For that reason, they are shown projecting lakeward from their present positions (Fig. 11).

This reconstructed shoreline fits well with other interpretable indicators such as notches on recent seismic profiles of both sides of the lake at approximately 100 to 110 m b.p.l. (C.F.M. Lewis, Atlantic Geoscience Centre, pers. commun. 1993). The presence of such indicators is evidence that the low-level phase was in existence for some time, i.e. long enough to create significant shore features (wave-cut bluffs and beach deposits).

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 12B and C. It is evident that the shoreline position moved landward on all sides, especially on the south side, under the effects of differential tilting (north side rebounding more rapidly than the south). The rate of transgression of the shoreline must have been close to uniform and fairly rapid as no definite notch, beach deposit, or other shoreline indicator is evident on the cross-sections or in seismic profiles, so it is difficult to verify the reconstructed positions shown in figures 12B and C. Vague shoreline notches can be interpreted slightly above the Early Lake Ontario level, but they are undated. The "Grimsby - Oakville Bar" shows no westward extension in the subsurface. It is therefore reasonable to conclude that there was a fairly rapid rise in levels after the postulated stability of Early Lake Ontario. Such a rapid deepening and burial of the "beach" deposits could be linked to the initial transfer of lake level control from the Duck-Galoo sill to the Thousand Island (TI) sill further downstream. Subsequent rise in levels would probably be at a reduced rate as TI sill rebound slowed with time.

This period probably was accompanied by the development of substantial sandy accretionary features at suitable sites along the shoreline. Accelerated erosion of the unlithified Lake Iroquois and Scarborough Formation (just east of Toronto) sand deposits would have released large quantities of sand for beach and spit development (Fig. 12B, C, D, and E). It is reasonable that a baymouth bar / spit feature, comparable to the present Burlington Bar (Fig. 4B) would have been established at the western end of the lake as shown. This would be compatible with the expected large contributions of sand from inflowing streams (Niagara, Don, Humber, and Credit Rivers, and the many smaller creeks entering the north shore) and shore erosion.

Hamilton Harbour paleogeography

The earliest radiocarbon date from Hamilton Harbour (approximately 7 ka BP) is interpreted as marking the initiation of Hamilton Harbour as a separate lacustrine sub-basin. The thick organic deposits near the base of cores HH26 and HH33 (Fig. 5) indicate that at the time, the Harbour was occupied by a substantial, but shallow body of water in which organic matter was being deposited in quantity (Fig. 13A). The elevation of these deposits (approximately 15 m above the contemporary lake level offshore) indicates that the depositional site was still in an upland area, possibly in the floodplain of the stream draining the Dundas Valley. The site of the present Harbour was likely characterized by a perched drainage basin behind a topographic barrier. Indeed, the glacial-sediment topographic high extending below and lakeward of the present Burlington Bar (A-B; Fig. 9) suggests a transverse feature, possibly a relict moraine across the western lake basin. The stream associated with this area likely drained into the western end of the lake offshore through a gap in the above barrier. The areas bordering the Harbour were apparently occupied by shallow-water marsh, as is indicated by the 4 - 5 ka BP ages on organics from cores HH26 and PFK 1 and 2. The extent of the submerged area at this time cannot be determined precisely but was presumably much greater (Fig. 13 B) than earlier. In the absence of evidence to date, no attempt was made to assess the extent of the so-called Nipissing "Flood", purported to have occurred around this time (Anderson and Lewis 1985; McCarthy et al. 1994; and Edwards et al. 1994).

The time when rising waters in the Ontario basin achieved confluence with the marshy waters of the Hamilton Harbour predecessor is difficult to determine precisely on the basis of the data presently available. According to recent research by Yang (1994) using diatom profiles in core HH26 (Fig. 5), confluence with the lake was clearly established some time between 5.8 and 2.7 ka BP. However, periodic appearances of open-lake species date as far back as 6.8 ka BP, indicating that storms or fluctuating lake levels were able to affect the Harbour area before that time.

An additional indication of the time of Lake Ontario incursion into Hamilton Harbour is also provided by the entry of osctracode species such as Darwinula stevensoni and Limnocythere verrucosa in core HH26 (Delorme, 1994) . This section of the core was dated at between 5.88 ka BP to 4.73 ka BP.

The transition from isolated basin to connected arm of the lake is also indicated in the sediment texture changes noted in widely-spaced sediment cores from the Harbour. These show that above the organics-rich layer (i.e. younger than 4.3 ka BP), sediment type changes rather abruptly to a fine silty clay. Such a consistent event indicates a significant paleoenvironmental change, e.g., an abrupt change in sediment supplies or a rapid deepening of the water body together with sheltering from wave action.

Conclusions

In reconstructing the position of the changing interface between a topographic surface rebounding in a non-linear fashion, and the rising lake level, the result can only be termed hypothetical and schematic. There are so many poorly-known variables and processes (e.g., is the rebound process best simulated as an exponential or some other type of model?) that a precise reconstruction of past shorelines is not realistic. However, the procedure is useful in illustrating with reasonable accuracy the evolutionary changes in the landscape in the western part of the Ontario Basin over the past 11.4 ka.

The computer program proved useful in returning the present surface to its immediately post-Iroquois position, adjusting for the exponential isostatic rebound which has since occurred. In addition to providing further insight into long-term shoreline trends in western Lake Ontario, the reconstruction could prove valuable in pointing to the location of commercial aggregate deposits below the lake. Such deposits are usually associated with well-sorted coarse sediments of beach or fluvial origin. Nevertheless, more subsurface data of high quality are necessary in order to calibrate the above model and thus to provide a greater degree of confidence in the reconstructed shoreline positions.

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FIGURE CAPTIONS

Figure 1: Location map of western Lake Ontario, Laurentian Great Lakes.

2: Gravimetric sedimentation rates obtained from Ambrosia-controlled piston cores (from Thomas et al. 1972). A gravimetric sedimentation rate of 100 $g.m^{-2}.a^{-1}$ is equivalent to 0.035 $cm.a^{-1}$ volumetric, assuming 88% porosity. Multiplying by 11.4 ka provides a supplementary estimate of postglacial sediment thickness.

3: Lake Iroquois and post-Iroquois phases in the Lake Ontario basin from Prest (1970). Note the changing outlet locations.

4: A. Locations of piston cores, boreholes, and cross-sections in the western basin of Lake Ontario.

B. Location of piston cores, boreholes, and cross-sections in the Hamilton Harbour area.

5: Sediment units observed in piston cores from Hamilton Harbour. Location of cores is given in figure 4B. Note slight difference in vertical scale.

6: Lake level curve for the Lake Ontario basin reproduced from Anderson and Lewis (1985), with elevation / radiocarbon dates from western Lake Ontario superimposed (open squares); solid dots represent data from Hamilton Harbour cores.

7,8: Transverse cross-sections through western basin of Lake Ontario, showing physiography and bottom sediments. Cross-section locations are shown in figure 4A. Vertical exaggeration: X235. The dashed line indicates adjustments for erosion.

9 (Top) Cross-section through western basin of Lake Ontario (location on figure 4A). Note lack of sediment cover over the Whitby-Olcott sill (Fig. 2). Vertical exaggeration: X235.

(Bottom) Cross-section through Hamilton Harbour, showing the interpreted Iroquois surface based on borehole and piston core data. The transect follows the trend of the buried valley (Karrow 1987) connecting the Dundas Valley to Lake Ontario. Some cores located off the transect and show Iroquois surface at a higher (AL3, 4) or lower (PFK 1,2, and 3) elevation. Vert. exaggeration: X100.

10: Western Lake Ontario and eastern Lake Erie showing the 10 km square grid used in reconstructing the original Iroquois surface. Note the position of the main Lake Iroquois isobase outside the Ontario basin, and the changing direction of maximum tilting for proglacial lake shorelines in both basins.

11: Reconstruction of the Early Lake Ontario shoreline. Contours reconstructed by the computer programme and an elevation reference (-139 m) are shown for comparison with subsequent phases shown in figure 12. Solid dots indicate the position of Anderson and Lewis' (1985) dated piston cores. Present shoreline is shown by the dashed line.

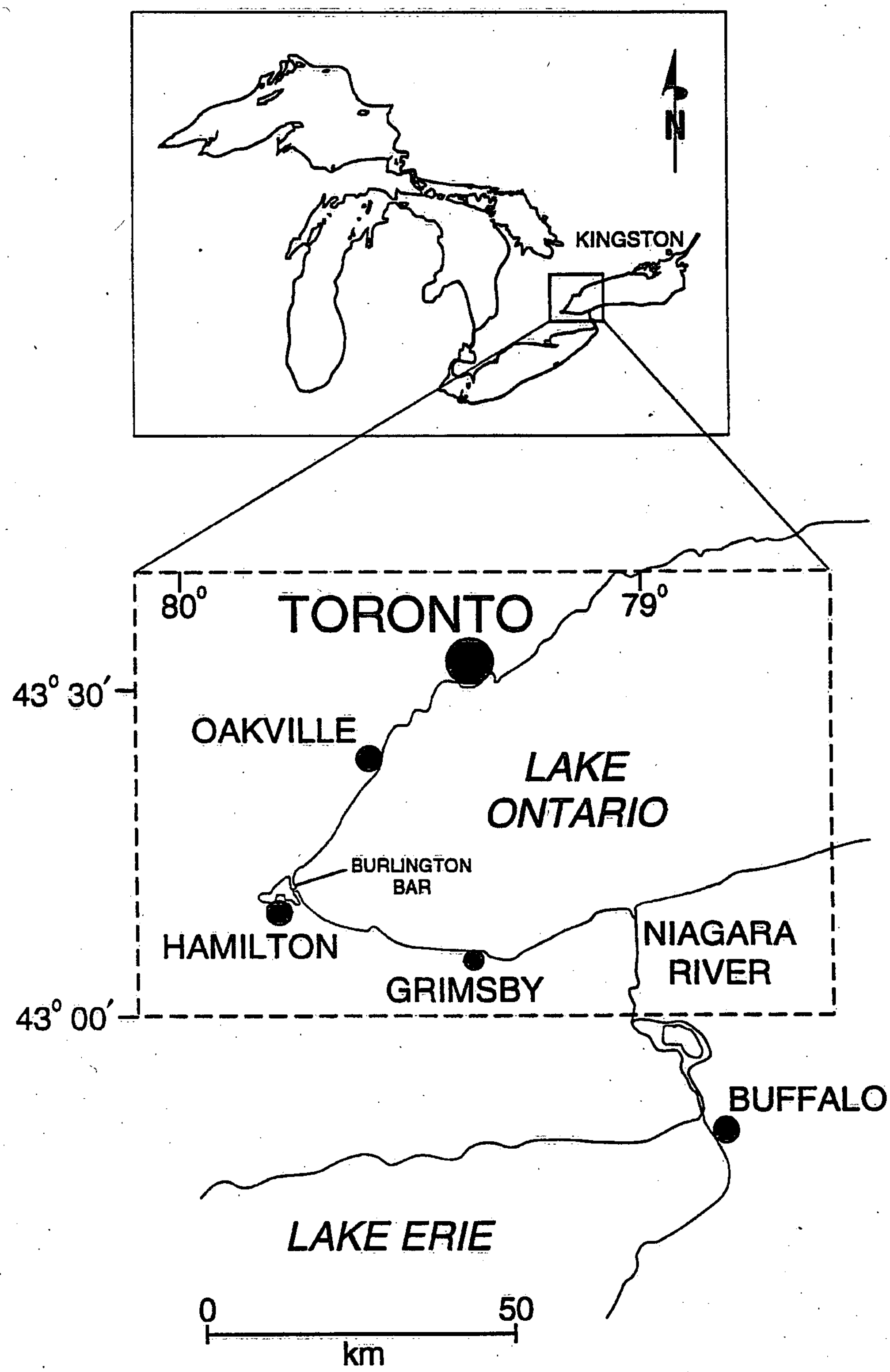
12: Reconstruction of the shoreline evolution in western Lake Ontario from ca. 9 ka BP to present. Solid dots indicate the position of Anderson and Lewis' (1985) dated piston cores. Interpreted accretionary features shown, including the hypothesized foreland near Toronto, are based on trends of the raised Iroquois shoreline and on the presence of deep-water coarse sediments offshore.

13: Paleogeography of the Hamilton Harbour area at approximately 7 (A) and 5 ka BP (B) based on extent and elevation of dated sub-bottom organic deposits. Bracketed values in the headings are inferred water level elevations in the sub-basin taken from figure 6.

Table 1: Radiocarbon dates and elevations (IGLD (1985) Lake Ontario) from shore-zone sites in western Lake Ontario. Dated-sample locations are given in figure 4. Asterisks denote AMS dating technique used.

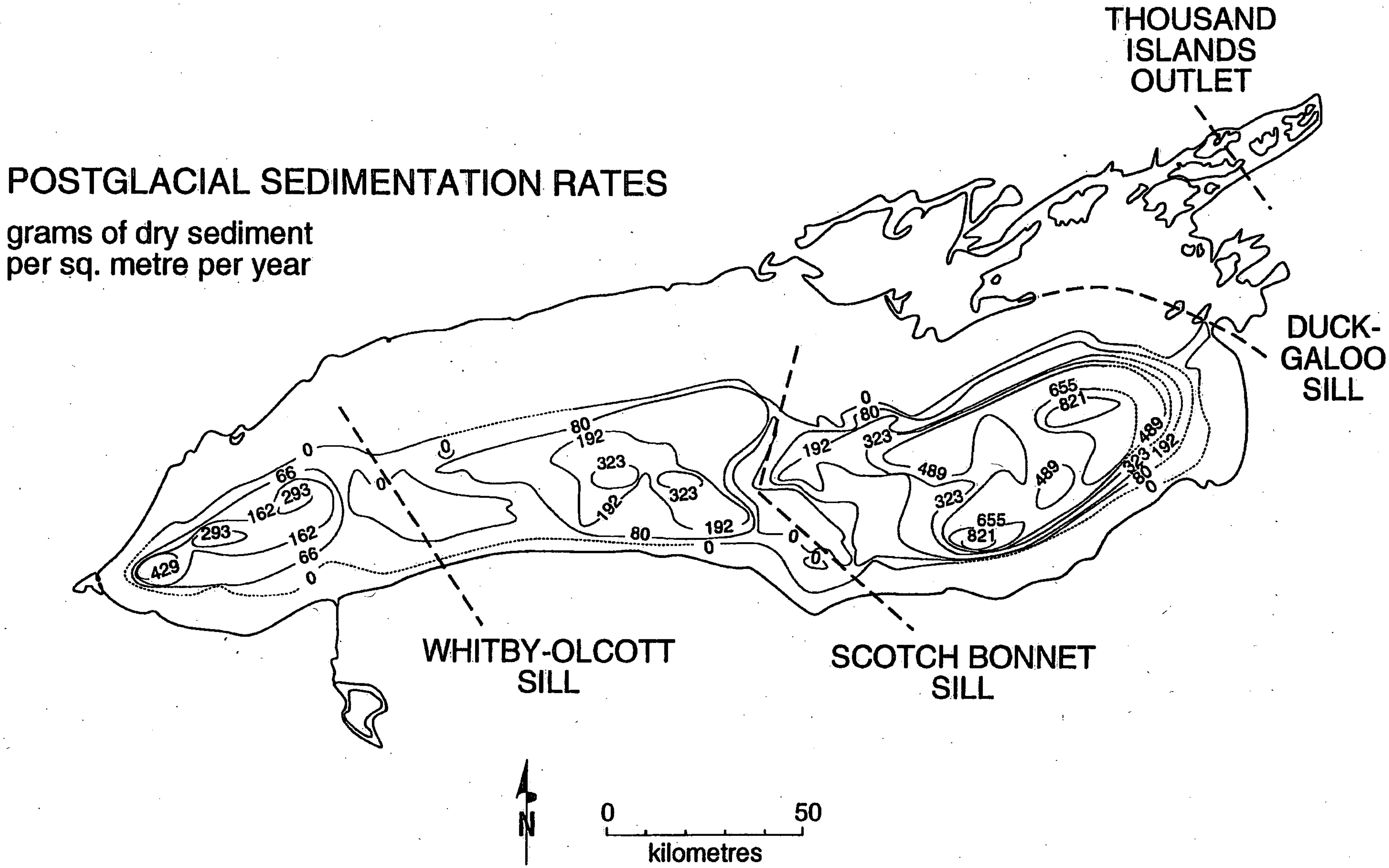
TABLE 1. Radiocarbon dates and elevations (IGLD (1985) Lake Ontario: 74.2) from shore-zone sites in western Lake Ontario. Dated-sample locations are given in figure 4. Asterisks denote AMS dating technique.

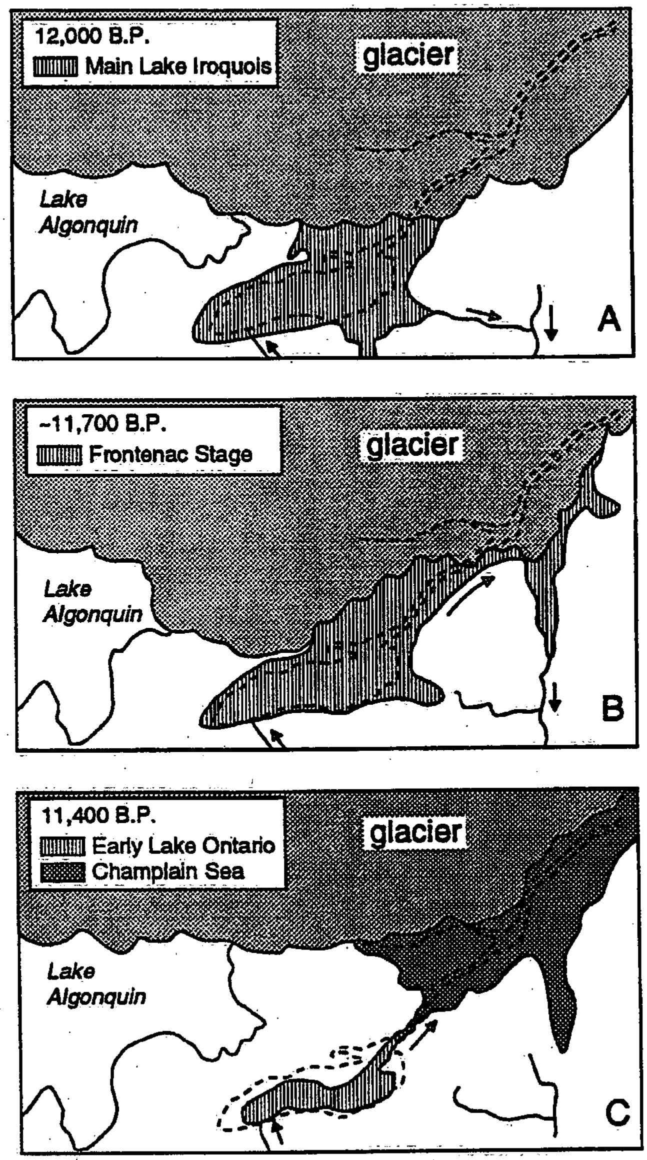
Sample Ident.	Elevation IGLD (m)	Age (yrs. BP)	Error (+/-)	Lab. No.	Comments
HH26-P2-3c	47.47	6830	70	TO 3572*	Powdery wood fragment
HH26-P2-5c	47.04	7970	120	WAT 2589	Coarse sand, shells, organic bits
HH26-P2-8c	46.77	7510	100	WAT 2581	Woody gyttja (?)
HH26-P2-9c	46.74	7440	100	WAT 2583	Woody gyttja (?)
HH33-P1-2c	56.49	4340	90	WAT 2647	Well-preserved leaves, mostly white birch
HH33-P1-6c	53.80	5720	60	TO 3881	Wood fragments from gyttja
HH33-P2-1c	71.85	1330	60	TO 3571*	Small, well-preserved twig
HH33-P2-2c	57.04	4960	120	WAT 2590	Black fibrous gyttja with silty sand
HH33-P2-5c	56.6	4540	90	WAT 2588	Layer containing wood, twigs, leaves
HH33-P2-8c	56.14	4740	130	WAT 2592	Gyttja with fine sand
AL-2	56.7	5140	200	GSC 2164	Plant detritus below silty clay
AL-3	56.7	5260	90	GSC 2147	Woody gyttja over sand
FDF-12	66.5	3225	110	BGS 680	Organics in sand
FDF-51	67.8	2780	100	BGS 694	Gyttja
FDF-84-3	72.8	970	100	BGS 1125	Gyttja
MM-0	62.2	4230	60	WAT 1332	Marl
MM-0	62.2	4094	60	TO-160	Twig
MM-0	68.6	2370	60	WAT 1591	Silty mud
MM-2	68.8	2930	80	WAT 1328	Marl
MM-1	67.9	2980	60	WAT 1330	Marl
MM-2	72.3	1270	50	TO 163	Pine needles
MM-2	73	1070	100	TO 162	Pine needles
MM-3	71.6	1970	100	WAT 1334	Marl
PFK-1	55.4	4400	50	WAT 343	Wood
PFK-2	50	5240	140	Y 614A	Wood in silt / sand
PFK-3	67.5	2820	160	Y 613A	Wood in silt / sand
PRESENT	75.09	0			

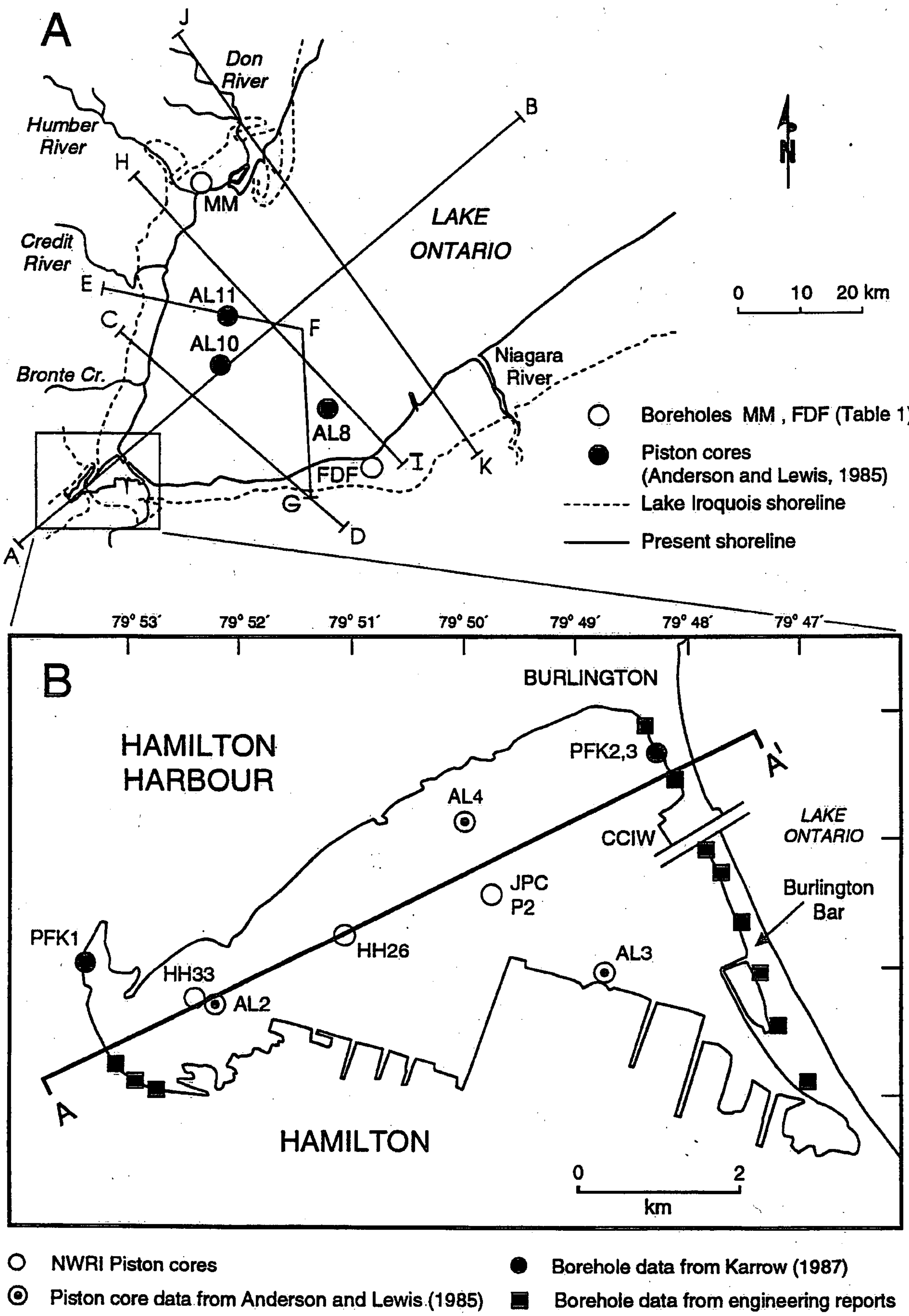


N
KINGSTON
80°
79°
TORONTO
43° 30′
OAKVILLE
LAKE
ONTARIO
BURLINGTON
BAR
HAMILTON
GRIMSBY
NIAGARA
RIVER
43° 00′
BUFFALO
LAKE ERIE
0
50
km

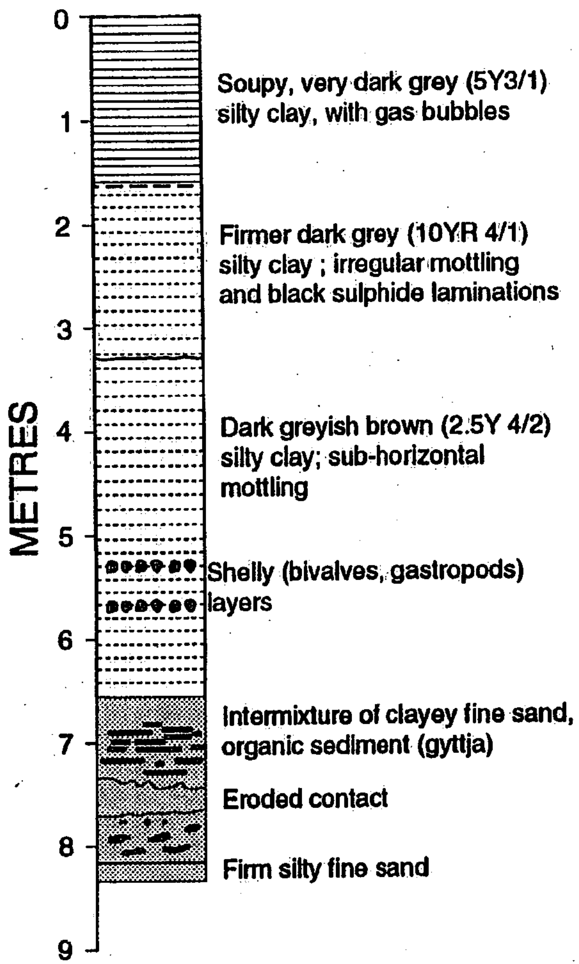
LAKE ONTARIO



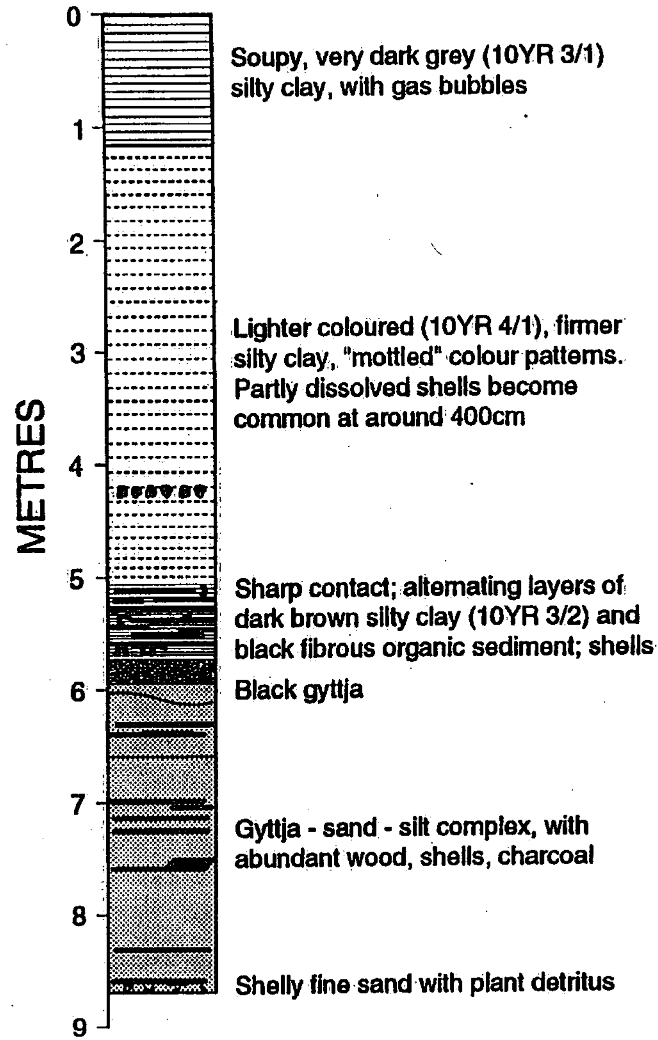

12,000 B.P.
Main Lake Iroquois
glacier
Lake
Algonquin
A
~11,700 B.P.
Frontenac Stage
glacier
Lake
Algonquin
B
11,400 B.P.
Early Lake Ontario
Champlain Sea
glacier
Lake
Algonquin
C

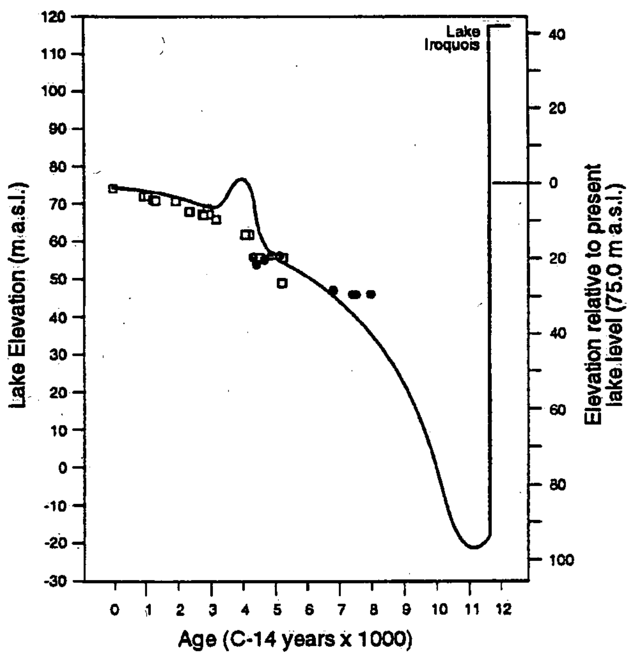

A
J
Don
River
Humber
River
B
H
MM
LAKE
ONTARIO
Credit
River
E
AL11
F
C
AL10
Bronte Cr.
Niagara
River
AL8
FDF
I
K
G
D
A
0 10 20 km
N
Boreholes MM, FDF (Table 1)
Piston cores
(Anderson and Lewis, 1985)
Lake Iroquois shoreline
Present shoreline
B
79° 53′
79° 52′
79° 51′
79° 50′
79° 49′
79° 48′
79° 47′
43° 19′
43° 18′
43° 17′
43° 16′
BURLINGTON
HAMILTON
HARBOUR
PFK2,3
A′
AL4
CCIW
LAKE
ONTARIO
JPC
P2
Burlington
Bar
PFK1
HH26
AL3
HH33
AL2
A
HAMILTON
0 2
km
NWRI Piston cores
Piston core data from Anderson and Lewis (1985)
Borehole data from Karrow (1987)
Borehole data from engineering reports

CORE HH26
(Water depth: 21m)

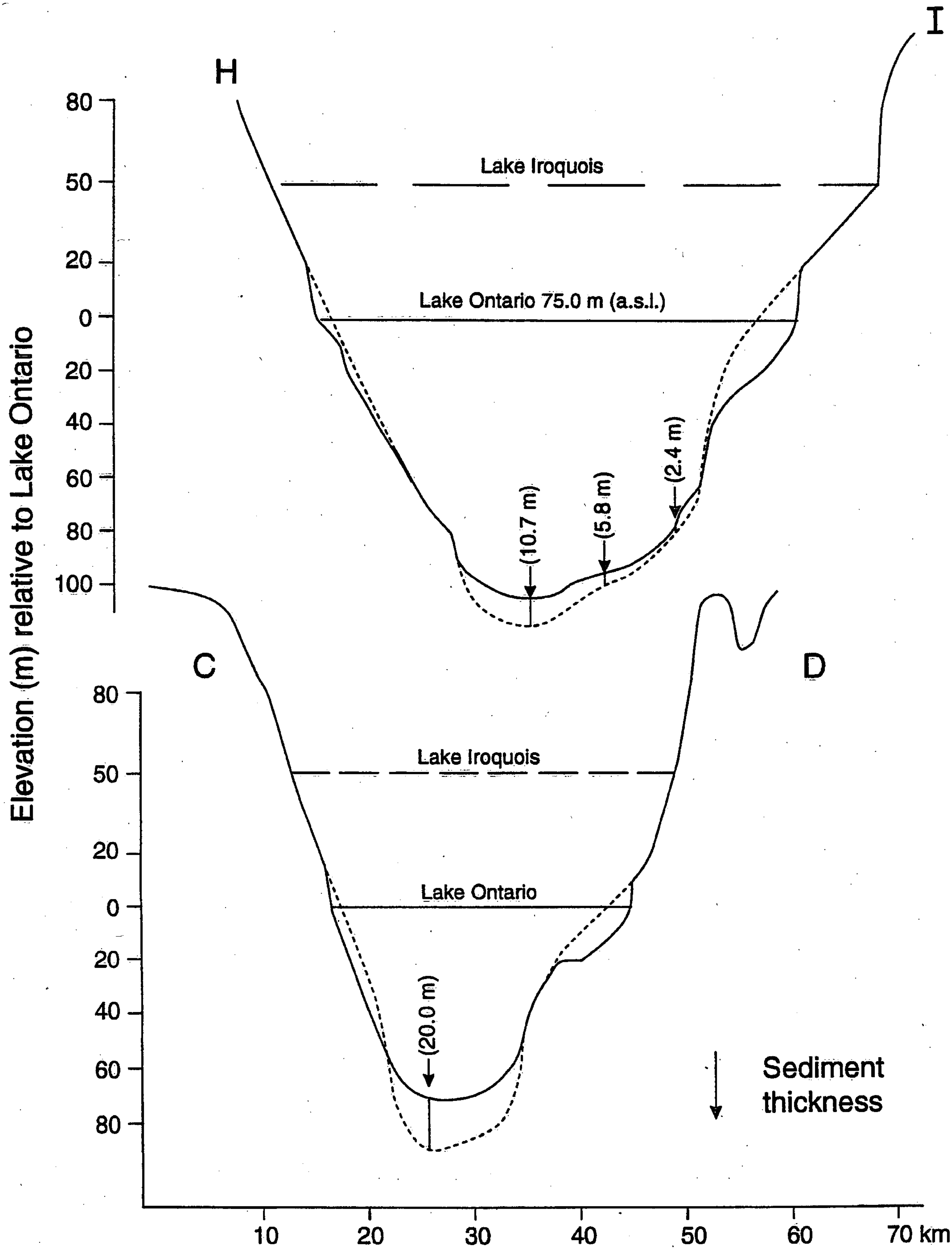


CORE HH33
(Water depth: 12.7m)

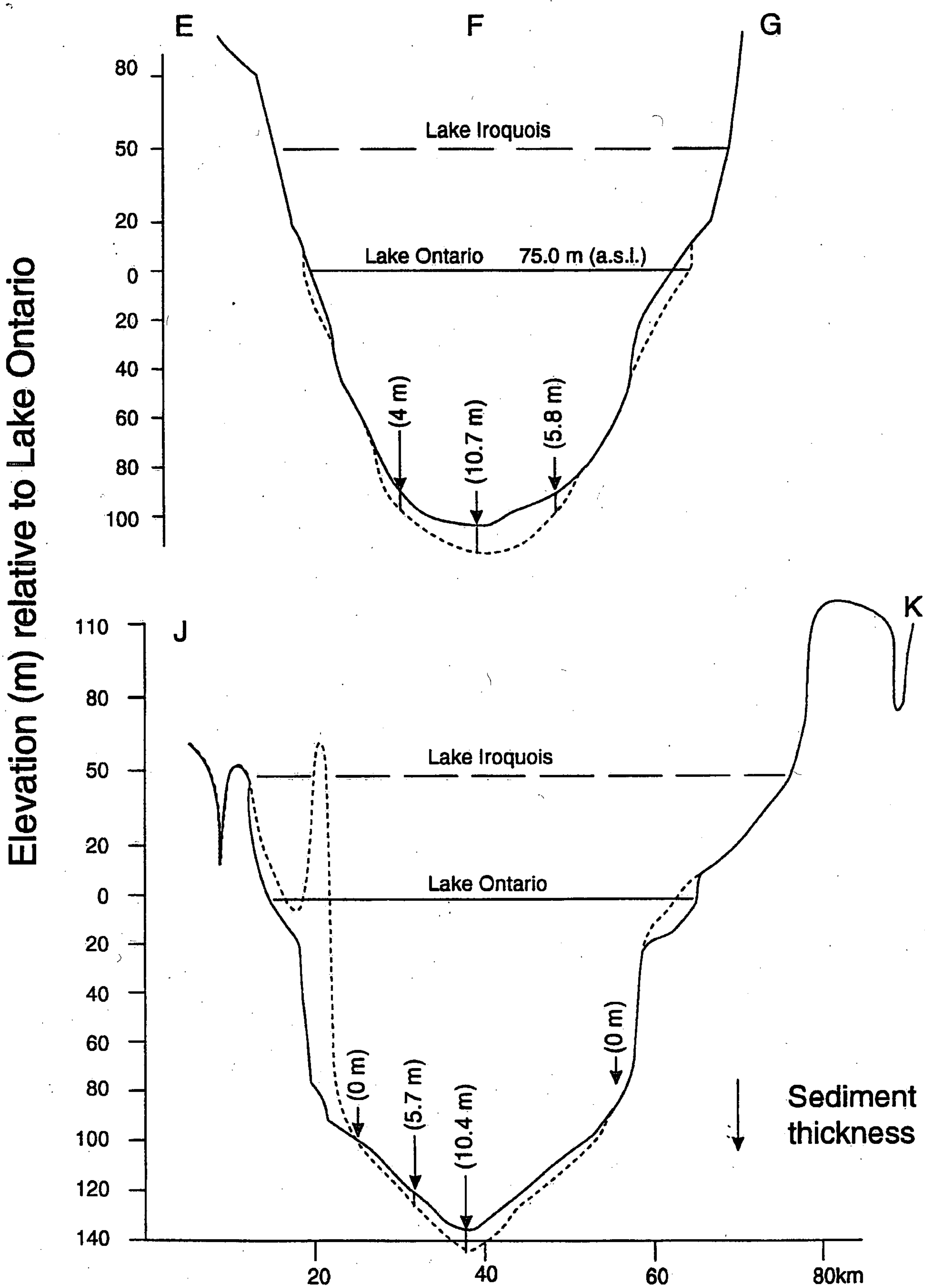




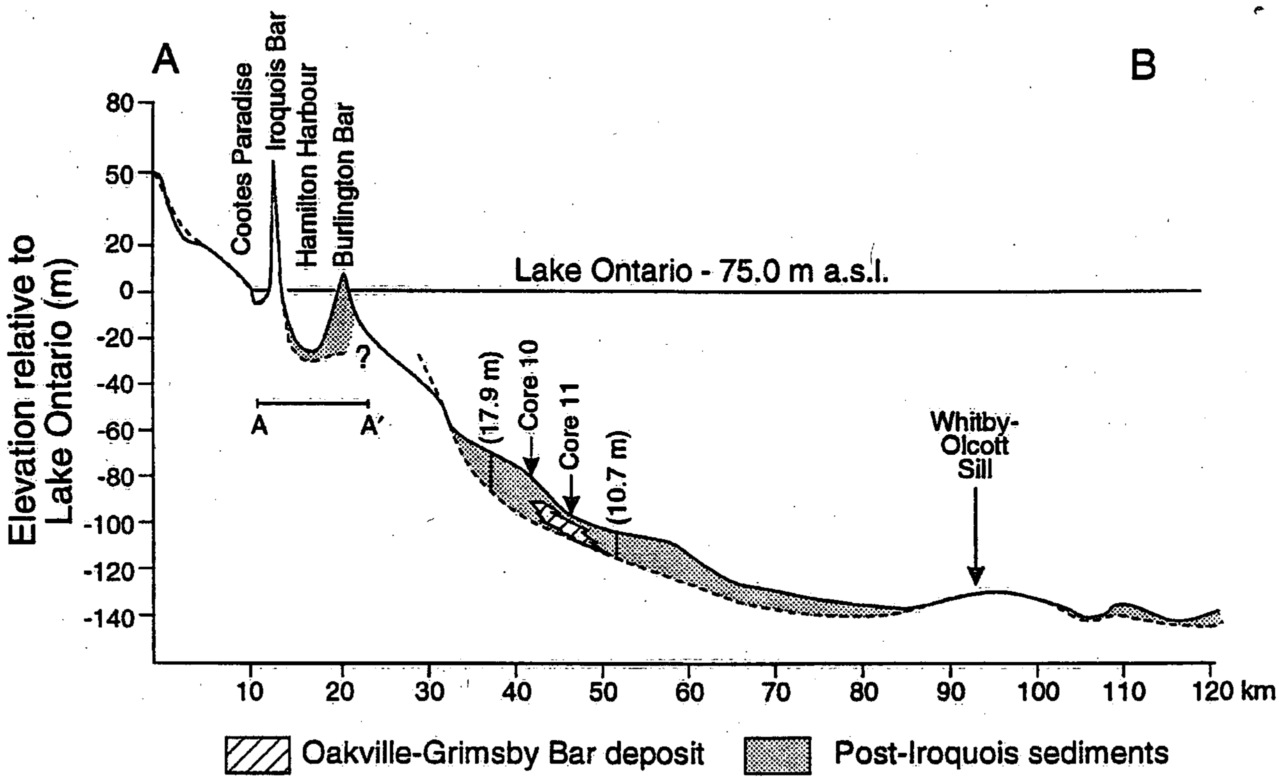
Lake Iroquois
Lake Elevation (m.a.s.l.)
Elevation relative to present lake level (75.0 m a.s.l.)
Age (C-14 years x 1000)

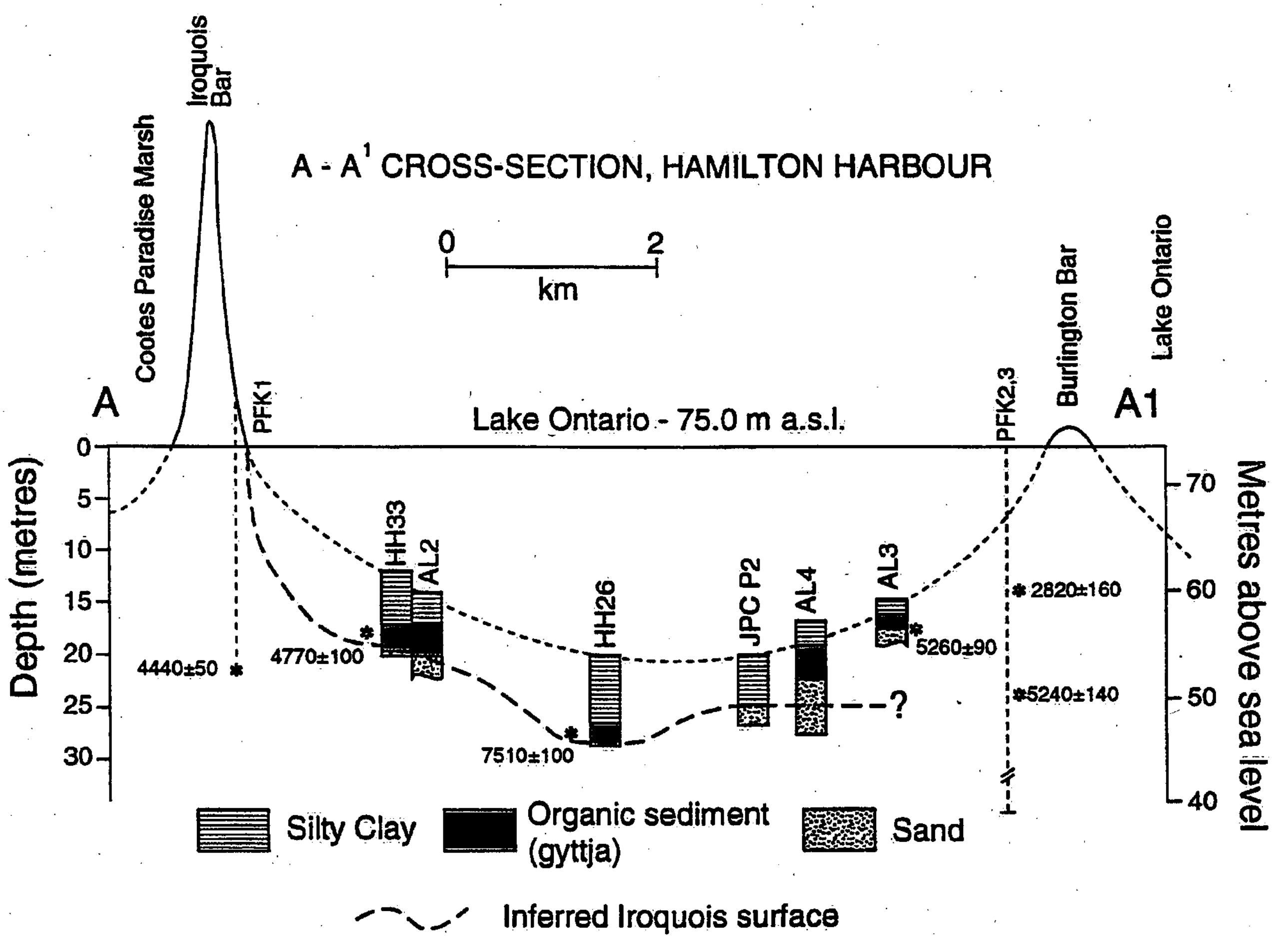


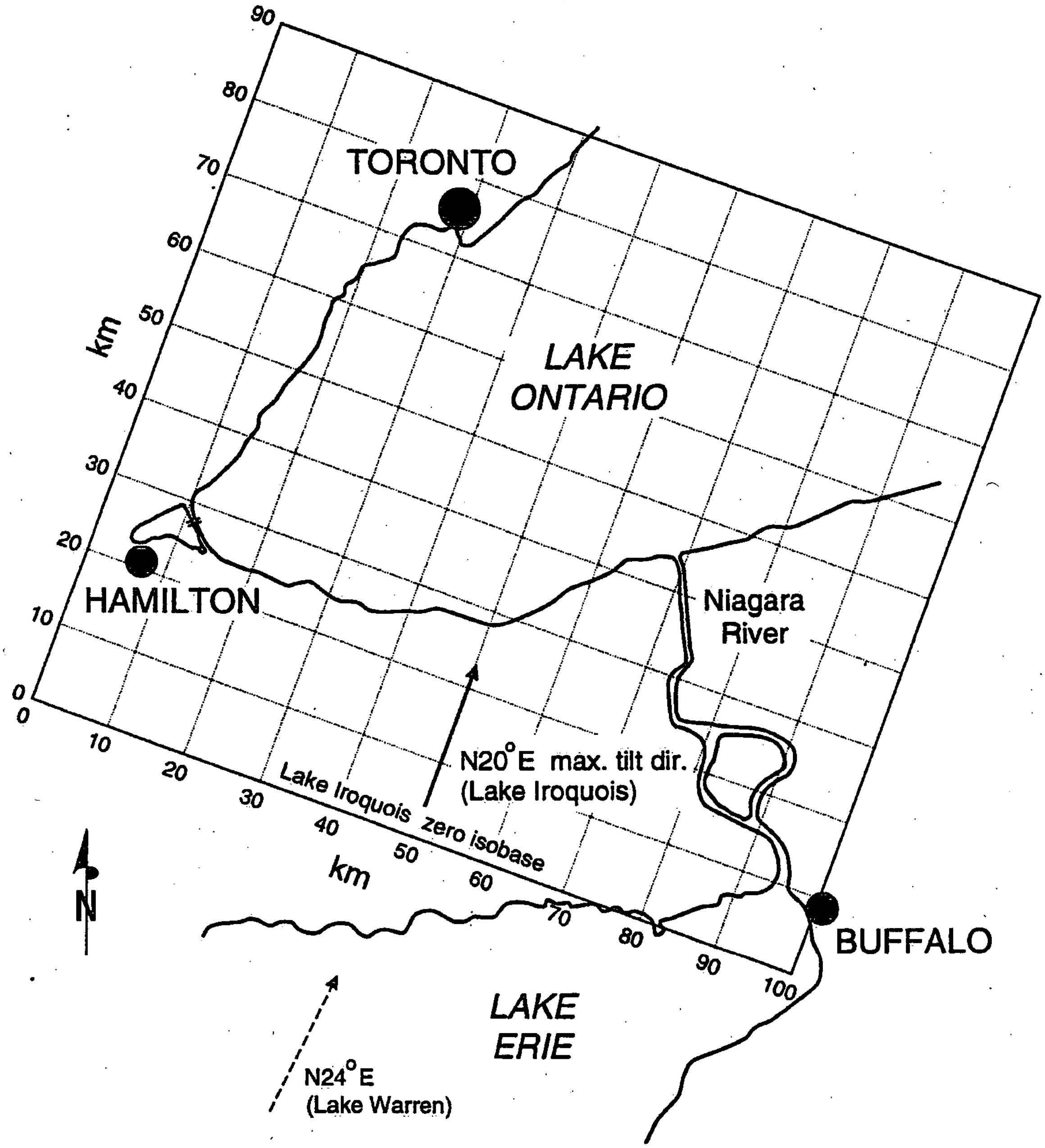
H
I
80
50
20
0
20
40
60
80
100
Lake Iroquois
Lake Ontario 75.0 m (a.s.l.)
(10.7 m)
(5.8 m)
(2.4 m)
Elevation (m) relative to Lake Ontario
C
D
80
50
20
0
20
40
60
80
Lake Iroquois
Lake Ontario
(20.0 m)
Sediment thickness
10
20
30
40
50
60
70 km



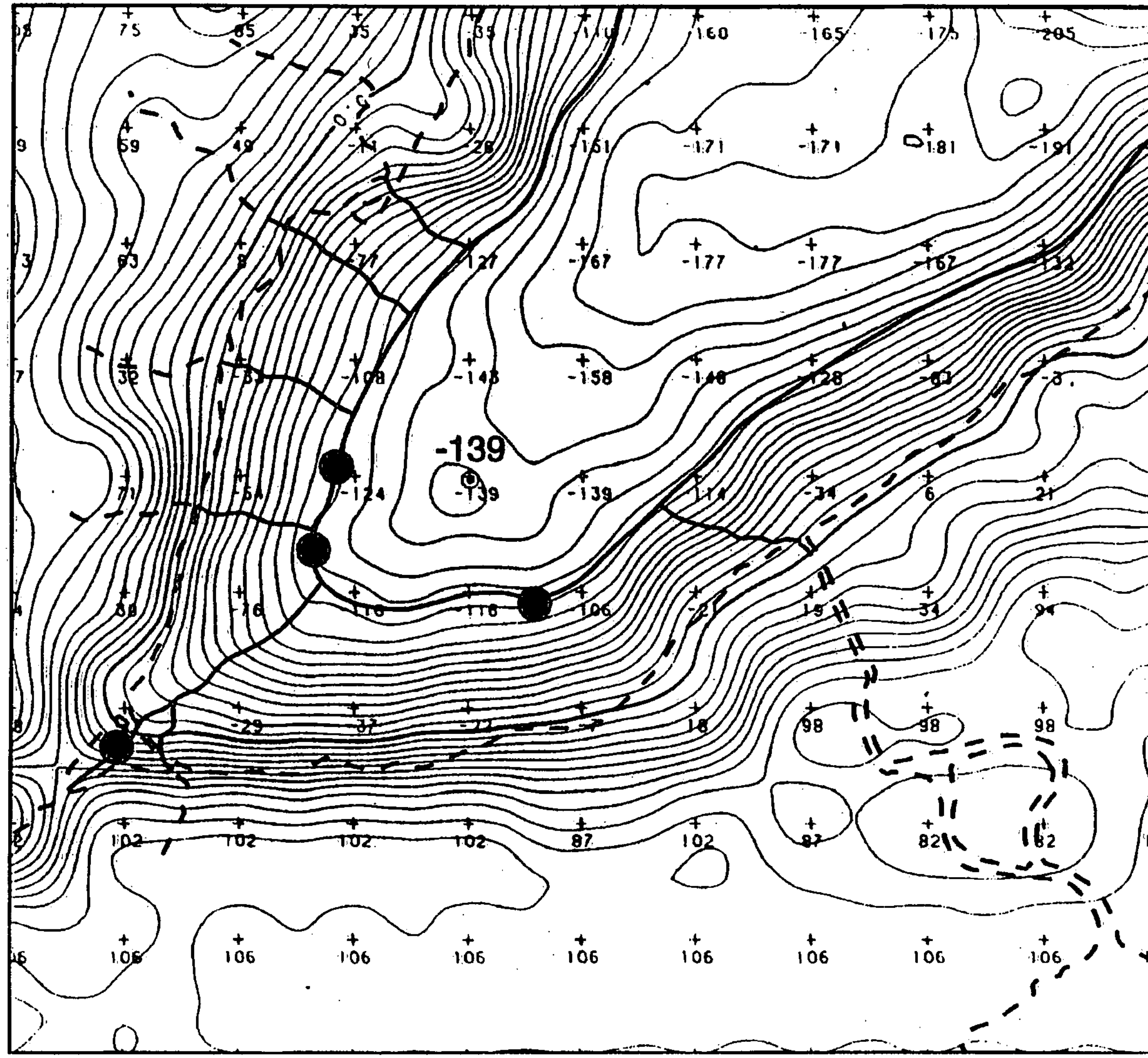
Elevation (m) relative to Lake Ontario
E
F
G
80
50
20
0
20
40
60
80
100
Lake Iroquois
Lake Ontario 75.0 m (a.s.l.)
(4 m)
(10.7 m)
(5.8 m)
J
K
110
80
50
20
0
20
40
60
80
100
120
140
Lake Iroquois
Lake Ontario
(0 m)
(5.7 m)
(10.4 m)
(0 m)
Sediment thickness
20
40
60
80km


A
B
Cootes Paradise
Iroquois Bar
Hamilton Harbour
Burlington Bar
Lake Ontario - 75.0 m a.s.l.
Elevation relative to Lake Ontario (m)
80
50
20
0
-20
-40
-60
-80
-100
-120
-140
?
A
A'
(17.9 m)
Core 10
Core 11
(10.7 m)
Whitby-Olcott Sill
10
20
30
40
50
60
70
80
90
100
110
120 km
Oakville-Grimsby Bar deposit
Post-Iroquois sediments

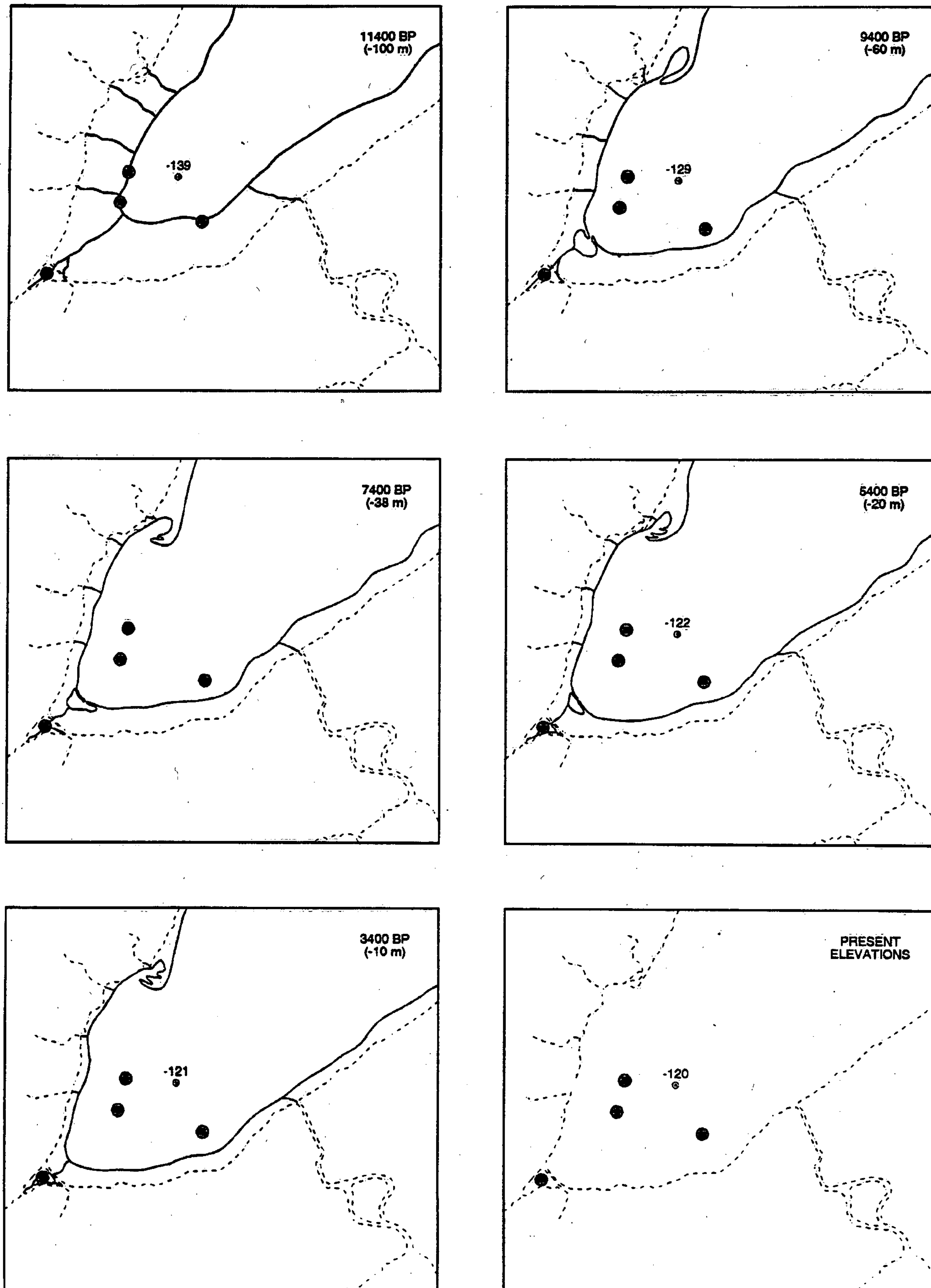

Iroquois Bar
Cootes Paradise Marsh
A - A1 CROSS-SECTION, HAMILTON HARBOUR
0
2
km
Burlington Bar
Lake Ontario
A
PFK1
Lake Ontario - 75.0 m a.s.l.
PFK2,3
A1
Depth (metres)
0
5
10
15
20
25
30
HH33
AL2
HH26
JPC P2
AL4
AL3
4440±50
4770±100
7510±100
5260±90
2820±160
5240±140
?
Metres above sea level
70
60
50
40
Silty Clay
Organic sediment (gyttja)
Sand
Inferred Iroquois surface

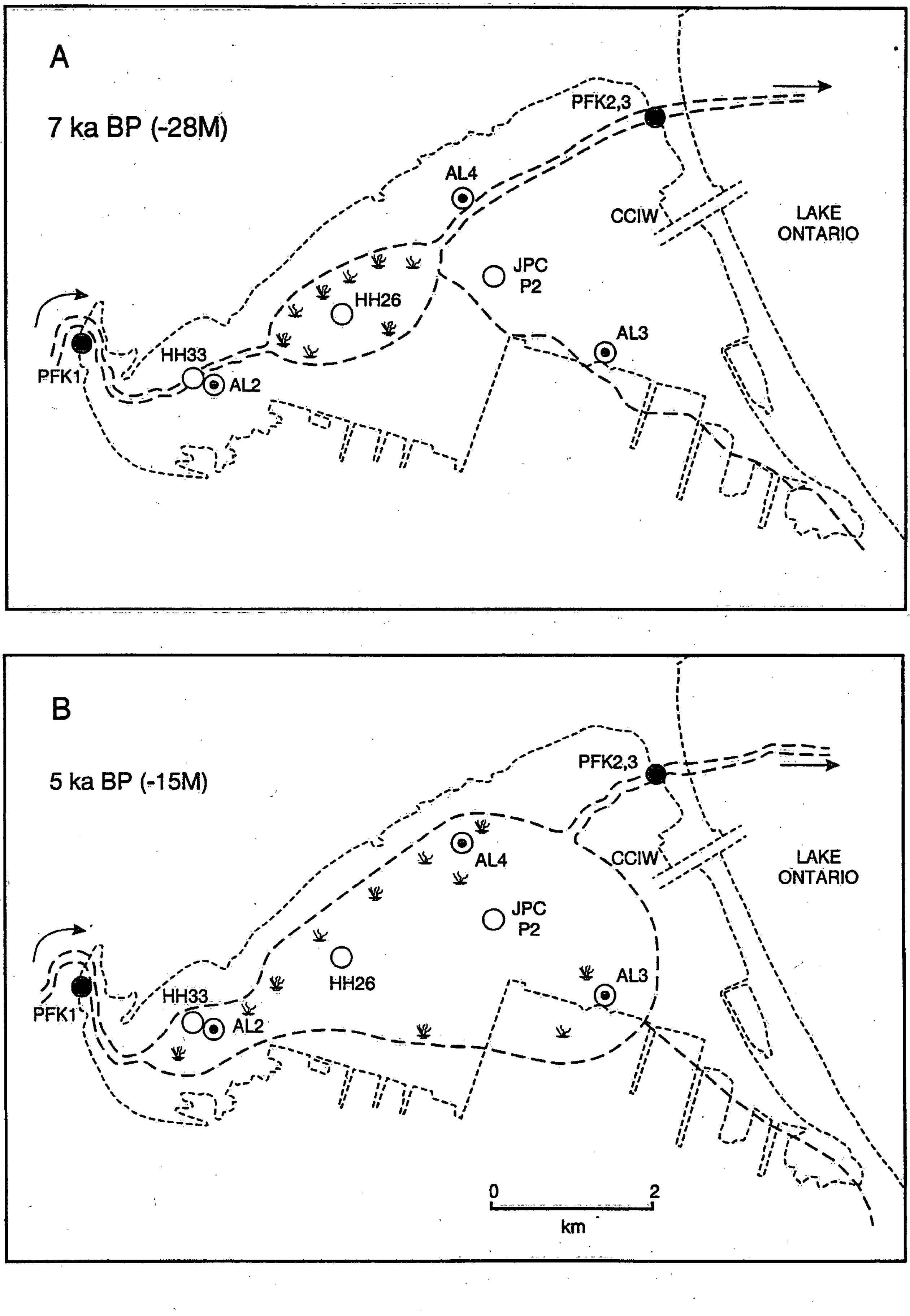


TORONTO
LAKE
ONTARIO
km
HAMILTON
Niagara
River
N20°E max. tilt dir.
(Lake Iroquois)
Lake Iroquois zero isobase
km
BUFFALO
LAKE
ERIE
N24°E
(Lake Warren)
N



11


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


A
7 ka BP (-28M)
PFK2,3
AL4
CCIW
LAKE
ONTARIO
JPC
P2
HH26
AL3
HH33
AL2
PFK1
B
5 ka BP (-15M)
PFK2,3
AL4
CCIW
LAKE
ONTARIO
JPC
P2
HH26
AL3
HH33
AL2
PFK1
0
2
km

Environment Canada Environnement Canada

Canada

Canada Centre for Inland Waters
P.O. Box 5050
867 Lakeshore Road
Burlington, Ontario
L7R 4A6 Canada

National Hydrology Research Centre
11 Innovation Boulevard
Saskatoon, Saskatchewan
S7N 3H5 Canada

St. Lawrence Centre
105 McGill Street
Montreal, Quebec
H2Y 2E7 Canada

Place Vincent Massey
351 St. Joseph Boulevard
Gatineau, Quebec
K1A 0H3 Canada

Centre canadien des eaux intérieures
Case postale 5050
867, chemin Lakeshore
Burlington (Ontario)
L7R 4A6 Canada

Centre national de recherche en hydrologie
11, boul. Innovation
Saskatoon (Saskatchewan)
S7N 3H5 Canada

Centre Saint-Laurent
105, rue McGill
Montréal (Québec)
H2Y 2E7 Canada

Place Vincent-Massey
351 boul. St-Joseph
Gatineau (Québec)
K1A 0H3 Canada