Natural Resources Canada | Ressources naturelles Canada

GEOLOGICAL SURVEY OF CANADA
OPEN FILE 8818

Offshore sediments in the Lake Erie Basin, Ontario, Canada, and Michigan, Ohio, Pennsylvania, and New York, U.S.A.

C.F.M. Lewis and B.J. Todd

2021

Canada

GEOLOGICAL SURVEY OF CANADA
OPEN FILE 8818

Offshore sediments in the Lake Erie Basin, Ontario, Canada, and Michigan, Ohio, Pennsylvania, and New York, U.S.A.

C.F.M. Lewis and B.J. Todd

2021

Permanent link: https://doi.org/10.4095/328829

This publication is available for free download through GEOSCAN (https://geoscan.nrcan.gc.ca/).

Recommended citation

Lewis, C.F.M. and Todd B.J., 2021. Offshore sediments in the Lake Erie Basin, Ontario, Canada, and Michigan, Ohio, Pennsylvania, and New York, U.S.A.; Geological Survey of Canada, Open File 8818, 1 .zip file. https://doi.org/10.4095/328829

Publications in this series have not been edited; they are released as submitted by the author.

Table of Contents

List of Tables

List of Figures

List of Excel Files

Abstract

This Open File report contains Excel files and map figures with setting and background information for the location, description, interpretation, and some grain size and carbonate content data for sediment samples from Lake Erie, one of the Laurentian Great Lakes. The samples were obtained during the early 1960s and 1970s in surface grabs, cores and boreholes. Dive observations of lake bed conditions were obtained at some sample stations. Acoustic profiles collected at 14.25 kHz during the sampling and coring expeditions provided information on the stratigraphy of the offshore finer-grained sediment units, and the depth to glacial sediments. Selected echogram profiles are compared with cored sediment sequences and other profiles are combined with lower frequency seismic reflection traverses to provide cross-sections of interpreted bedrock surface and sediment configuration beneath Lake Erie.

Introduction

Offshore sediments in Lake Erie were sampled and profiled extensively, mainly in the early 1960s, using the research vessel CNAV *Porte Dauphine* programmed by the Great Lakes Institute of the University of Toronto. Here, descriptions with some analytical data and limited interpretation are provided in two Excel files for the surface grab samples, gravity and piston cores, and a few boreholes, some of which were acquired in the early 1970s. Numerous echo sounding profiles were obtained to contribute to the mapping of surface sediment distribution, and to determine the depth to the surface of older, firmer sediments, commonly glacial sediments deposited during the Port Bruce and Port Huron phases of the Erie lobe of the Laurentide Ice Sheet. Figures and text are included to illustrate background geological information for the Lake Erie basin, the distribution of sampled sites and sounding tracks, examples of sediment-acoustic reflection correlation, chronology, and compilations of surface sediment types, water level history and their geochemical effects, topography of the subsurface glacial sediment surface, and cross-sections of the Lake Erie basin.

Setting and background

Lake Erie is the most southern of the Great Lakes and is situated fourth and second last in the chain of Laurentian Great Lakes that drain to the Atlantic Ocean via the St. Lawrence River (Government of Canada and United States Environmental Protection Agency, 1995). Major inflow to the western end of the lake originates from Lake Huron to the north via Lake Saint Clair and Detroit River, and the lake overflows at its eastern end via the Niagara River to Lake Ontario (Fig. 1). Regional characteristics of Lake Erie and its basin are described by Sly (1976), Thomas *et al*. (1976), Herdendorf (1989, 2013), Bolsenga and Herdendorf (1993), Holcombe *et al*. (1997, 2003, 2005) and others. The three main basins of Lake Erie with their maximum water depths below a mean low water datum of 173.5 m above sea level (International Great Lakes datum 1985) are the Eastern Erie basin (63–64 m), the Central Erie basin (24–25 m), and Western Erie basin (10–11 m). Hydrographic survey

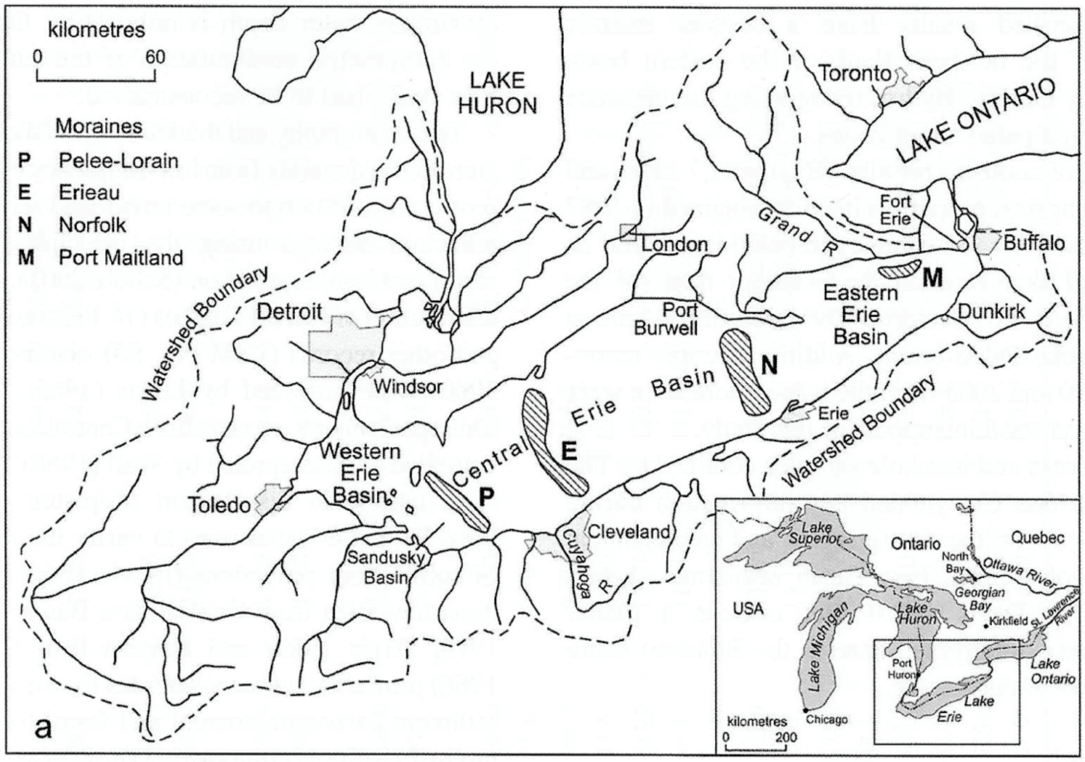

Figure 1. The watershed basin of Lake Erie, showing major offshore glacial moraines and inset map of the Great Lakes. From Lewis *et al*. (2012, fig. 1a).

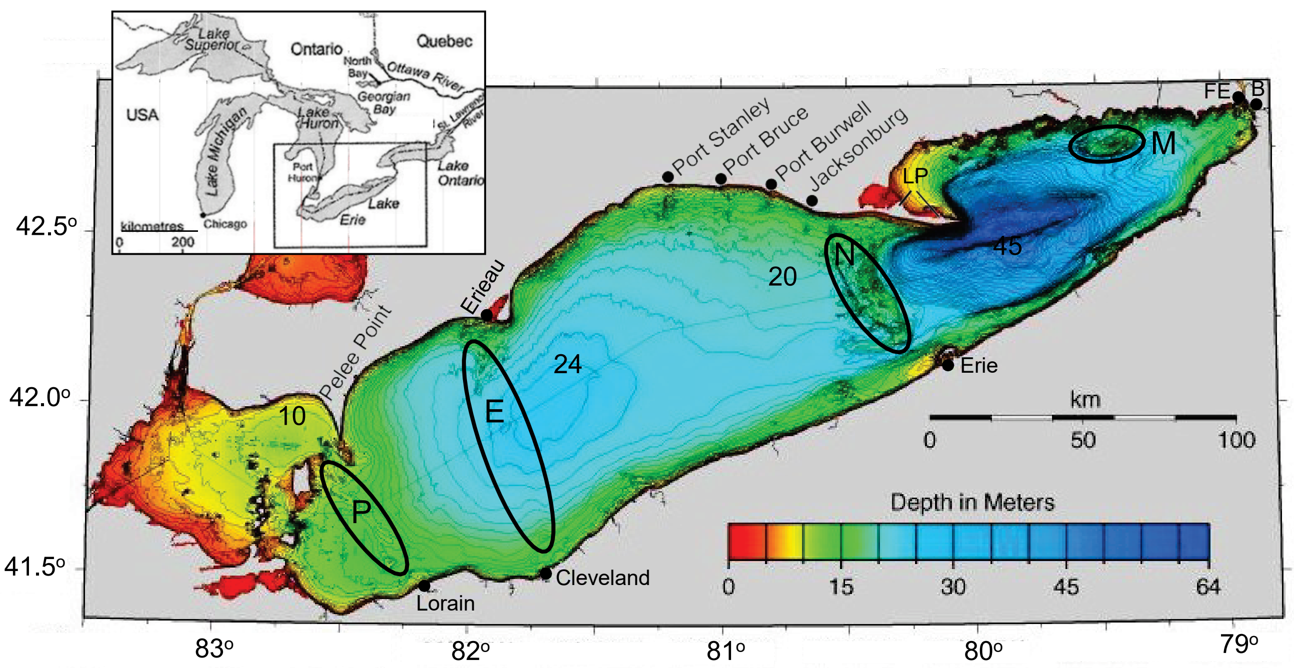

Figure 2. Bathymetry of Lake Erie, also showing major offshore moraines and inset map of the Great Lakes. Bathymetry illustrates water depth below low water datum of 173.5 m above sea level, from Lake Erie bathymetry by NOAA National Geophysical Data Center (1999). Inset map from Lewis *et al*. (2012, fig. 1a).

data have been compiled into a detailed map of bathymetry by the NOAA National Geophysical Center (1999) (Fig. 2).

The St. Lawrence Lowland physiographic region (Bostock, 2014; Barnett, 1992, fig. 21.23) includes all of the Lake Erie area, and the glacially eroded bedrock beneath the overlying sediments comprises gently dipping formations of Paleozoic sedimentary rocks. Except for the western basin, Lake Erie is underlain mainly by erodible Upper Devonian shales over less erodible Lower Devonian carbonate formations that dip gently southward into the Allegheny (Appalachian) Basin, with dips increasing eastward (Hough, 1958). The western Erie basin overlies the Findlay (southward) and Algonquin (northward) inter-basin arches which expose older Silurian limestone, dolomite, and shaley dolomite formations in parts of the shore zone and in the islands of the western basin (e.g., Pelee, Kelleys, Bass, Sister, and other small islands). These rocks dip gently southeastward into the Allegheny (Appalachian) Basin on the eastern side of the arches, and are flat-lying or gently tilted northwestward toward the Michigan Structural Basin on the western side of the arches (Hough, 1958; Sanford and Baer, 1983; Johnson *et al*., 1992).

History of glaciation and lake levels in the Lake Erie basin

The glacial history and history of glacial lakes in the Lake Erie basin since deglaciation of the Laurentide Ice Sheet (LIS) have been interpreted by Chapman and Putnam (1984), Barnett (1985, 1992) and Calkin and Feenstra (1985) (Fig. 3). Lake levels in the Erie basin from late glacial time to the present were evaluated and progressively interpreted over time by Hartley (1961a,b), Lewis *et al*. (1966), Lewis (1969), Coakley and Lewis (1985), Lewis *et al*. (2012), and Lewis (2016) (Fig. 4a). Following the maximum extent of the Laurentide Ice Sheet about 25.4 (21 ^{14}C) ka BP, the Lake Erie basin was deglaciated about 18.8 (15.5 ^{14}C) ka BP during the Erie phase to form glacial Lake Leverett. It was fully reglaciated by the Port Bruce readvance to the Ohio-Indiana border region (Fig. 3) (Calkin and Feenstra, 1985; Barnett, 1985, 1992). Glacial lakes Maumee, Arkona, and lower phases, including Lake Ypsilanti (Kunkle, 1963), then occupied parts of the Erie basin during the eastward oscillatory retreat of the Port Bruce ice lobe (Fig. 3), finally draining eastward across northern New York to the Hudson River and Atlantic Ocean. Glacial advances reached the eastern Erie basin in the subsequent early Mackinaw ~ 16.1 (13.4 ^{14}C) ka BP and Port Huron 15.5 (13.0 ^{14}C) ka BP phases (Fig. 3) (Barnett, 1979, 1985, 1992). The Port Huron advance blocked eastern drainage routes, raised meltwater levels to glacial Lake Whittlesey which drained westward across Michigan into the Lake Michigan basin and southward to the Gulf of Mexico. Glacial Lake Warren succeeded Lake Whittlesey, and lower lake phases again occupied the basin and drained eastward. Retreat of the Port Huron ice reduced lake levels to an unnamed lowstand until meltwater from the Lake Huron basin to the north overflowed into the Lake Erie basin (Fig. 4a). About 12.6–12.3 (10.6–10.4 ^{14}C) ka BP, this meltwater in the form of Main Lake Algonquin overflowed to Erie basin and passed large volumes of meltwater through it from outburst floods in northern glacial lakes (Tinkler *et al*., 1992; Lewis *et al*., 2012). The Algonquin overflow was subsequently diverted to the Ottawa River via outlets southeast of

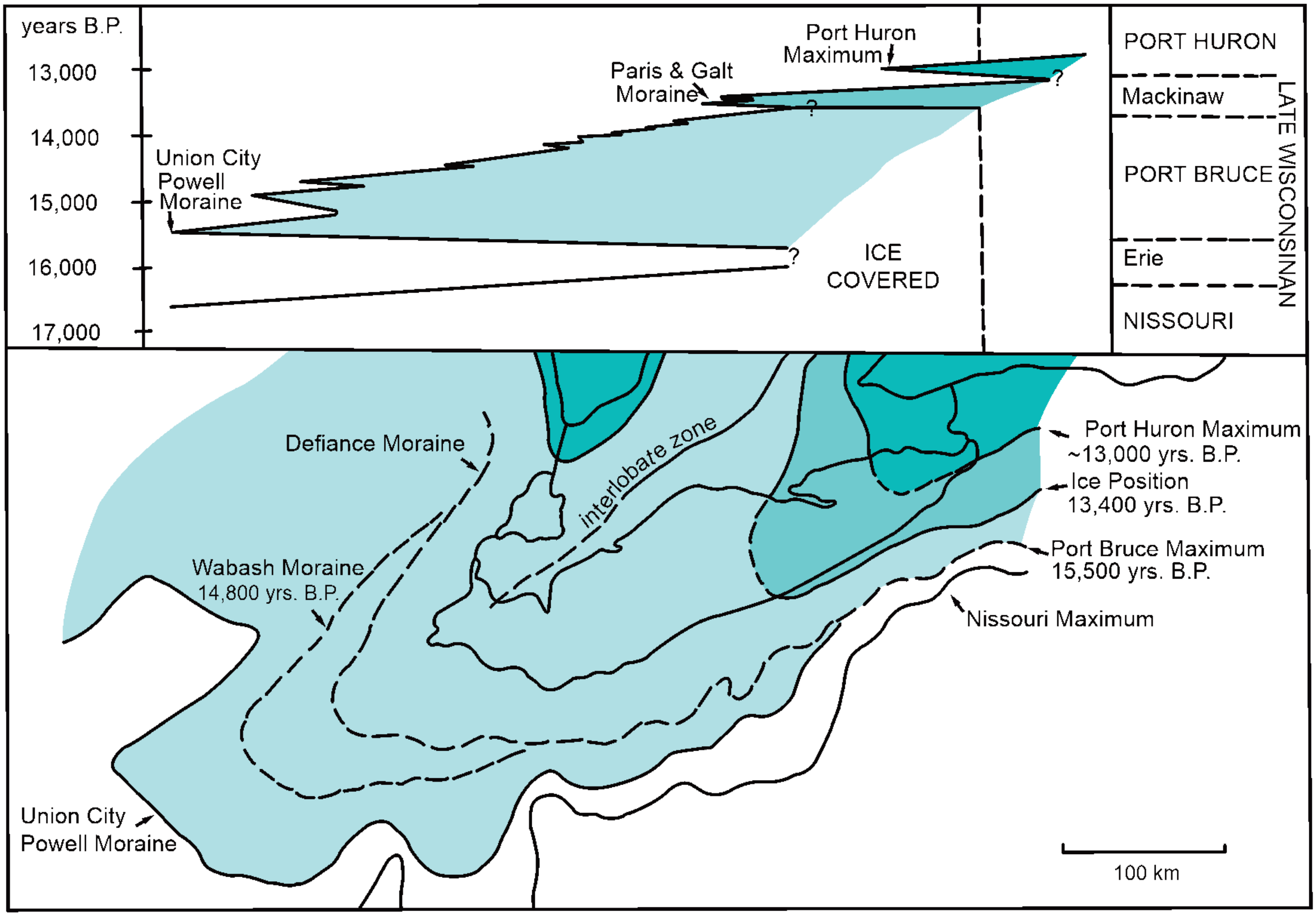

Figure 3. Time-distance diagram and map of glacial and moraine positions in the Lake Erie basin by Barnett (1985) and Barnett and Karrow (2018). From Barnett and Karrow (2018) and Lewis *et al.* (2021 submitted).

North Bay ON by ongoing ice retreat (Figs. 1 and 2, inset maps) (Karrow *et al*., 1975; Eschman and Karrow, 1985; Calkin and Feenstra, 1985; Barnett, 1992).

With diversion of Lake Algonquin, the inflow to Erie basin was greatly reduced, and combined with the onset of a period of dry climate (McCarthy and McAndrews, 2012), water levels in the Erie basin subsided to a multi-millennial lowstand. Lake Erie then was a hydrologically closed basin, too low to overflow its sills in the Niagara River (Fig. 4a) (Lewis *et al*., 2012; Lewis, 2016). As differential glacial isostatic uplift raised the North Bay outlet relative to the southern part of the Huron basin at Port Huron (Fig. 1 and inset map), Huron basin water (Nipissing transgression) again began overflowing southward into the Erie basin about 7.5 (6.5 ^{14}C) ka BP and raised the Erie lake level to overflow its Niagara River sills. Full discharge of Lake Nipissing to Lake Erie occurred about 4.5 ka BP (Thompson *et al*., 2011). Sandy sediments near the mouth of the Detroit River in the western basin are interpreted to have been deposited in a delta nourished by the Lake Nipissing overflow (Herdendorf and Bailey, 1989). These changes ended the closed basin conditions in Lake Erie (Fig. 4a) and established the present drainage configuration of the southern Great Lakes (Lewis *et al*., 2012; Lewis, 2016). Lake level subsided about 2–3 m approximately 3400 (3200 ^{14}C) years ago when control shifted, due to erosion, from the Niagara River Lyell–Johnson sill downstream of Niagara Falls to the present sill between Fort Erie ON and Buffalo NY.

Geochemical effects associated with lake level changes in the Erie basin

The water level history of the Lake Erie basin (Fig. 4a) is supported by variations in the mineral calcite ($CaCO_3$) component of its sediments (Fig. 4b), and in variations of the $\delta^{18}O$ isotopic composition of fossil mollusc shells and ostracod valves also from its sediments. Calcite contents ranging between 9% and 17.5% by weight at Long Point in the eastern Erie basin during the 16 to 13.5 cal ka period are consistent with abundant calcite contents in onshore glacial sediments in Ontario (Barnett, 1998). Long Point sediments at this time likely represent sediments eroded from shore exposures while the post Maumee and Whittlesey glacial lakes occupied the basin. A subsequent distinct decline in calcite content to values less than 5% correlates with introduction of glacial Lake Algonquin overflow from the Lake Huron basin in the centuries leading to 12.5 ka (Eschman and Karrow, 1985). These meltwaters, under-saturated with respect to $CaCO_3$, likely dissolved a portion of the calcite mineral grains during their sedimentation in the Erie basin and reduced the calcite content of the sediment deposits. As the Algonquin overflow switched to other outlets in Huron basin and bypassed the Erie basin in the centuries after 12.4 ka, the Erie sedimentary calcite contents returned to their previous values.

In the ensuing dry climate and with limited water supply, Lake Erie evaporated to lower relative levels as it became a hydrologically closed basin. The higher calcite contents at this time, that reached 19% in the eastern basin and 24% in the central basin, are attributed to warmer lake water in the closed basin in which dissolved calcite precipitated from the lake water and the precipitate (lacustrine whitings) settled to the sedimentary deposits. After about 6.5 ka, calcite contents began

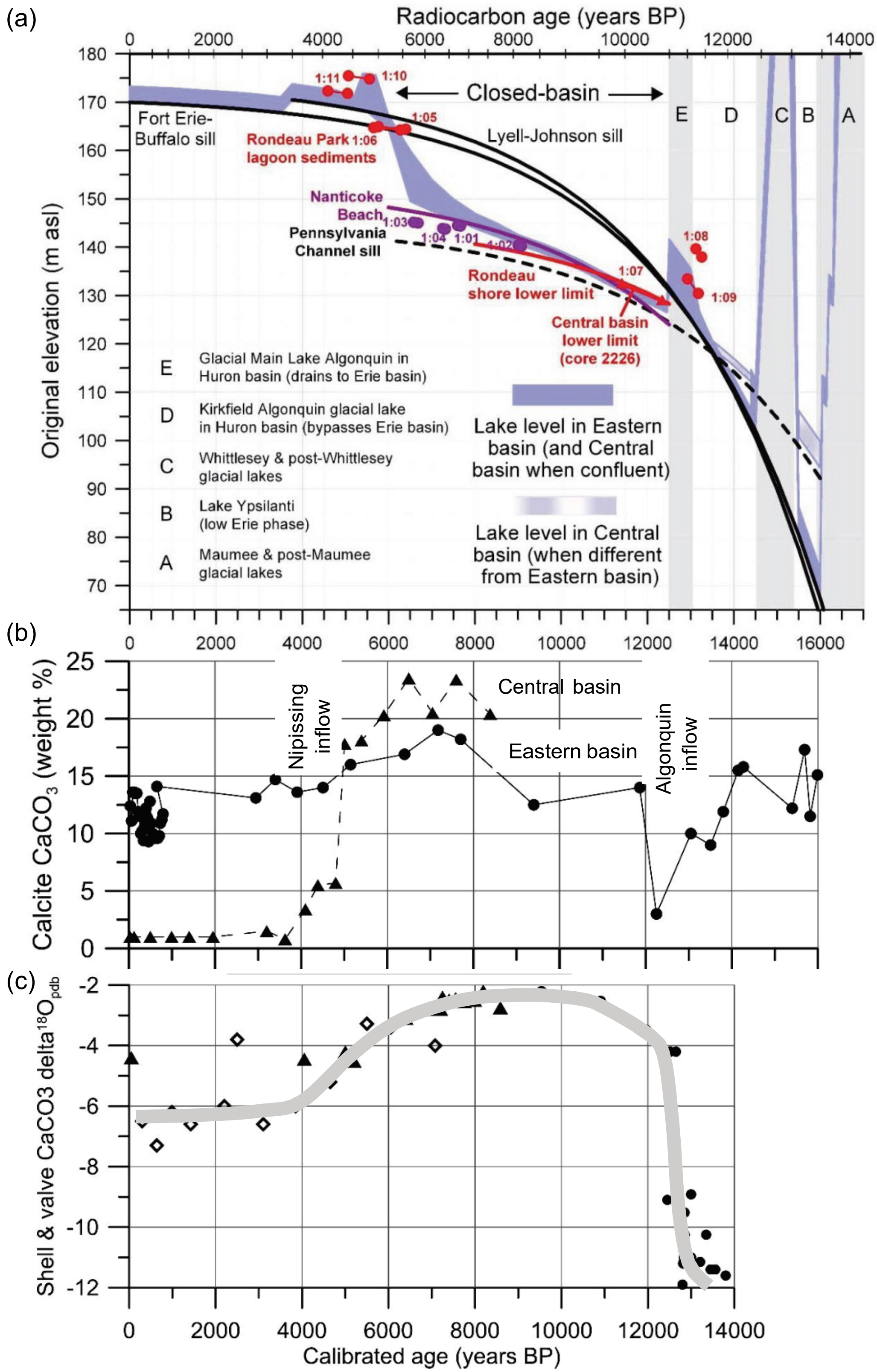

Figure 4. (a) Lake level history of the Erie basin. From Lewis (2016, fig. 10a), also Lewis *et al*. (2012, fig. 5). (b) Mineral calcite content variation in offshore sediments of the Erie basin. Eastern basin values are for the Long Point area from borehole LP1 and nearby piston core 2356p. Central basin values are from borehole 13194, 37 km southeast of Erieau ON. From Lewis *et al*. (2012, fig. 7). (c) Oxygen isotope contents in ostracod valves and mollusc shells from Erie basin sediments. Solid circle values from borehole LP1, solid triangle values from borehole 13194, and open diamond values from Tevesc *et al*. (2011) as illustrated in Lewis *et al*. (2012, fig. 7).

declining as the Nipissing transgression in Huron basin began overflowing from the southern Huron basin outlet to introduce under-saturated water to Lake Erie again. By 4.5 ka the Lake Nipissing (Huron basin) overflow of under-saturated water was being fully discharged to the Erie basin (Thompson *et al*., 2011), as at present, to reduce sedimentary calcite contents in the Central basin to nearly 0%. Calcite content remained in the 10% to 15% range in the Long Point area of the Eastern basin as these sediments were probably eroded from calcite-rich glacial sediments exposed in the northern shore bluffs of the Central basin. The eroded sediments were rapidly transported eastward by longshore drift in the higher lake level augmented by Nipissing inflow, and deposited in the Long Point area, thereby not allowing sufficient time for significant carbonate solution to occur.

An interpretation of a compilation of the oxygen isotope composition of mollusc shells and ostracod valves from Erie basin sediments (Fig. 4c), largely as a proxy for summer lake water temperatures, similarly reveals relationships with water level variations in the basin (Fig. 4a). Starting with negative values below -10‰ after 14 ka and continuing to 13 ka and later (Fig. 4c), the oxygen isotope values record the presence of cold glacial meltwater in the Erie basin. A sharp rise in isotopic composition to -4‰ is a response to the end of Algonquin overflow after 12.4 ka. A continued slow rise to nearly -2‰ between 9 ka and 8 ka reflects warmer lake water during the period of closed basin conditions. Isotopic values (and lake water temperature) declined gradually over the following 4 millennia as the Nipissing transgression in the Huron basin gradually increased the influx of cooler Huron basin water. By 4.5 ka, the overflow of Nipissing (Huron basin) lake water was fully established (Thompson *et al*., 2011), bringing the Erie basin oxygen isotopic composition down to about -6‰ to -7‰. Delta ^{18}O values remained at these levels signifying the continued full discharge of Lake Huron to Lake Erie, as at present.

Lake Erie sediment information

Most sediment samples and acoustic lake bed profiles were collected during lake-wide synoptic limnological sampling expeditions during the early 1960s of the research vessel CNAV *Porte Dauphine* programmed by the Great Lakes Institute of the University of Toronto. The sediment samples have been discarded and are not available. Occasional research cruises of CCGS *Limnos* with geological objectives during subsequent years provided additional sediment information from Lake Erie.

Sediment sample recovery

Surface sediment samples

About 289 samples of the sediment surface were acquired with a clam-shell type grab sampler of 2.5 litre capacity (Lewis, 1967) modelled after one designed by Franklin and Anderson (1961). They were described immediately on board the research vessel, and their distribution is included in Figure 5. Lake bed acoustic characteristics, surface sediment sample descriptions, and the upper parts

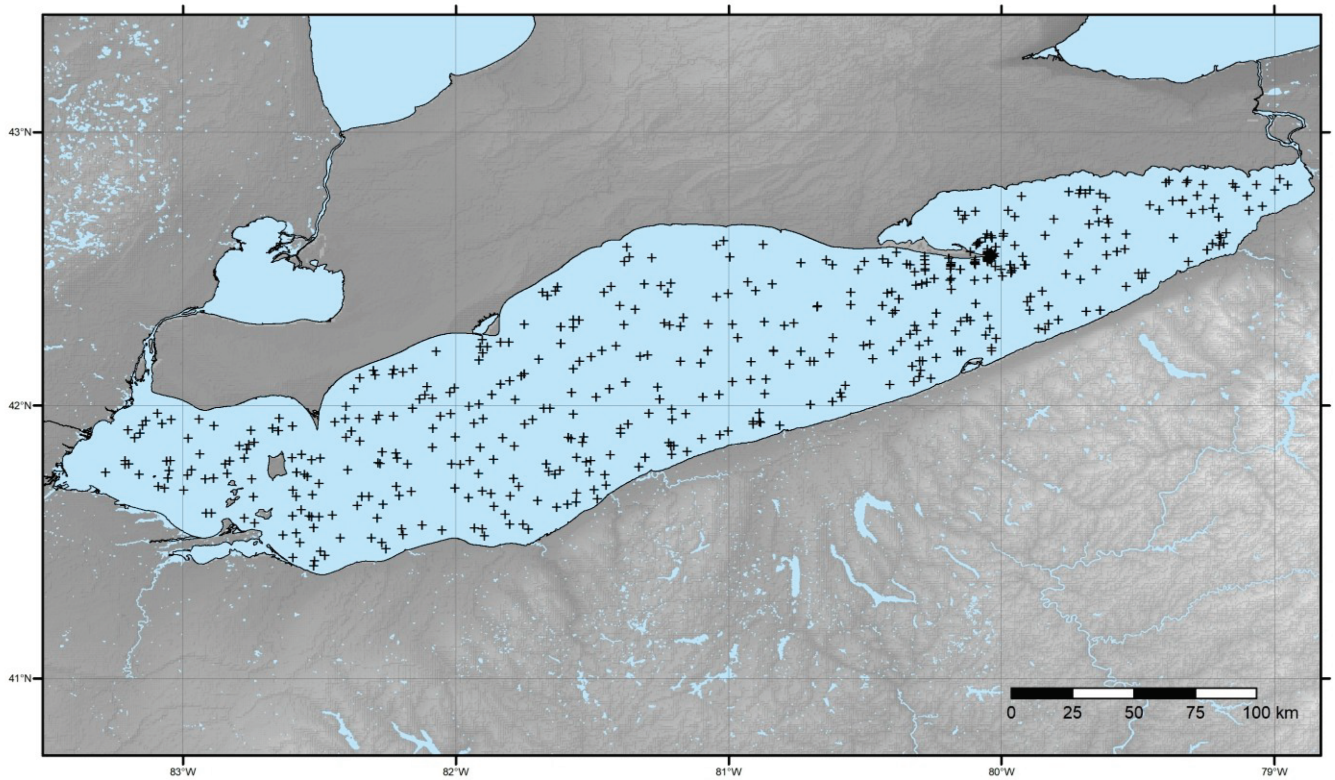

Figure 5. Lake Erie map of locations (+) of surface grab samples and cores that recovered post-early Holocene sediments.

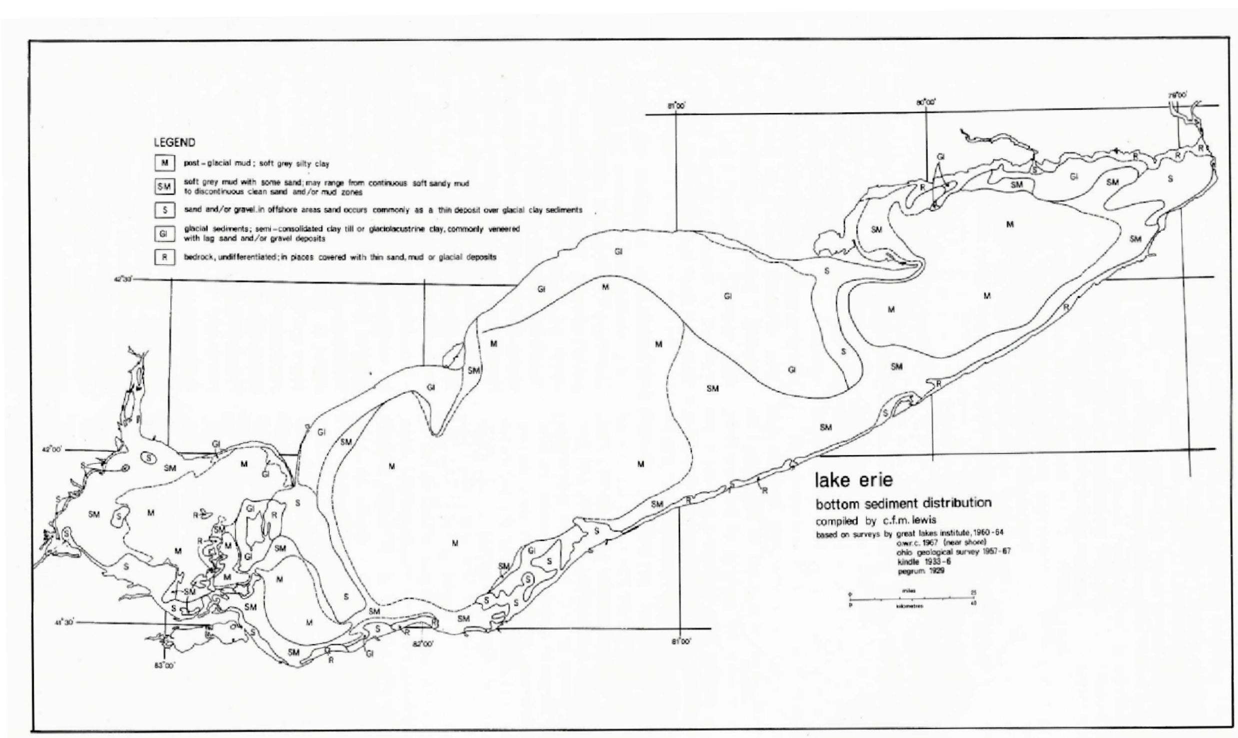

Figure 6. Lake Erie bottom sediment distribution. From Thomas *et al*. (1976, fig. 2).

of cores were used to identify and map the distribution of surface sediment types in Lake Erie. The surface sediment map is published as figure 2 in Thomas *et al*. (1976), and is shown here as Figure 6.

Sediment cores using gravity and piston corers.

A 3-m long gravity corer, weighted with steel plate fins, made of AX casing (inside diameter of 4.8 cm) with a ball check valve on top and sharpened cutter at bottom (Lewis, 1967) recovered sediment sequences up to 1–2 m long depending on sediment resistance to penetration. Sediment descriptions of cores 6–7 m long were recovered by a standard piston corer. This corer penetrated up to 10 m in soft lacustrine silt and clay, and is similar to instruments used for oceanographic sedimentary studies (Hvorslev and Stetson, 1946; Kullenberg, 1947). Sediment cores obtained with the gravity and piston corers are designated in the Excel files with a number and the letter 'g' or 'p', respectively. The sediments in the upper parts of many of these cores also provided information for the distribution map of surficial lake bed sediment types (Fig. 6).

Sediment penetration of the core barrels was measured and listed at most sites. In a consideration of about 335 cores, including both gravity and piston cores, apparent core shortening amounted to 35% to 40% with a standard deviation of 16% to 17%. Core shortening is thought to have been caused by sediment compression and/or by intervals of sediment bypassing during the coring process. At some coring sites, diver observations of the lake bottom were made using self-contained breathing apparatus (SCUBA) to learn that the surface of the eroded glacial deposits is characterized by a rippled sand and gravel lag (Lewis, 1967; Lewis *et al*., 2021, submitted). Additional cores, some used for interpretation of Lake Erie water level history, were obtained via CCGS *Limnos* in 1987, 1990 and 1993 (Cameron, 1991; Lewis *et al*., 2012).

Boreholes

A borehole at the tip of Long Point recovered spit sediments, underlying lacustrine and glacial sediments, and the limestone bedrock surface in February 1962. Some sections of this borehole are stored with the Geological Survey of Canada in Ottawa, ON. Sediments over bedrock were accessed in several geotechnical boreholes southeast of Erieau, ON, in 1972 during collaborative studies with Consumer Gas Co. of Toronto, ON (Lewis *et al*., 1973). Samples from these boreholes are not available. Sediment data is in the Excel files (File 2, sheet 3) and figures (Fig. 7).

Descriptions and data for the lake bed surface grab samples are provided in Excel file 1, and their locations are plotted in Figure 5 with plus signs. Core and borehole sediment descriptions and data are listed in Excel file 2, sheets 1, 2, and, 3. Sheet 1 lists results for 379 gravity and piston cores that penetrated only modern and post-early Holocene sediments; locations of these cores are shown also in Figure 5 with plus signs. Sheet 2 lists 209 gravity and piston cores that recovered early Holocene lowstand and/or late glacial sediments; their locations are shown in Figure 7 with red circles.

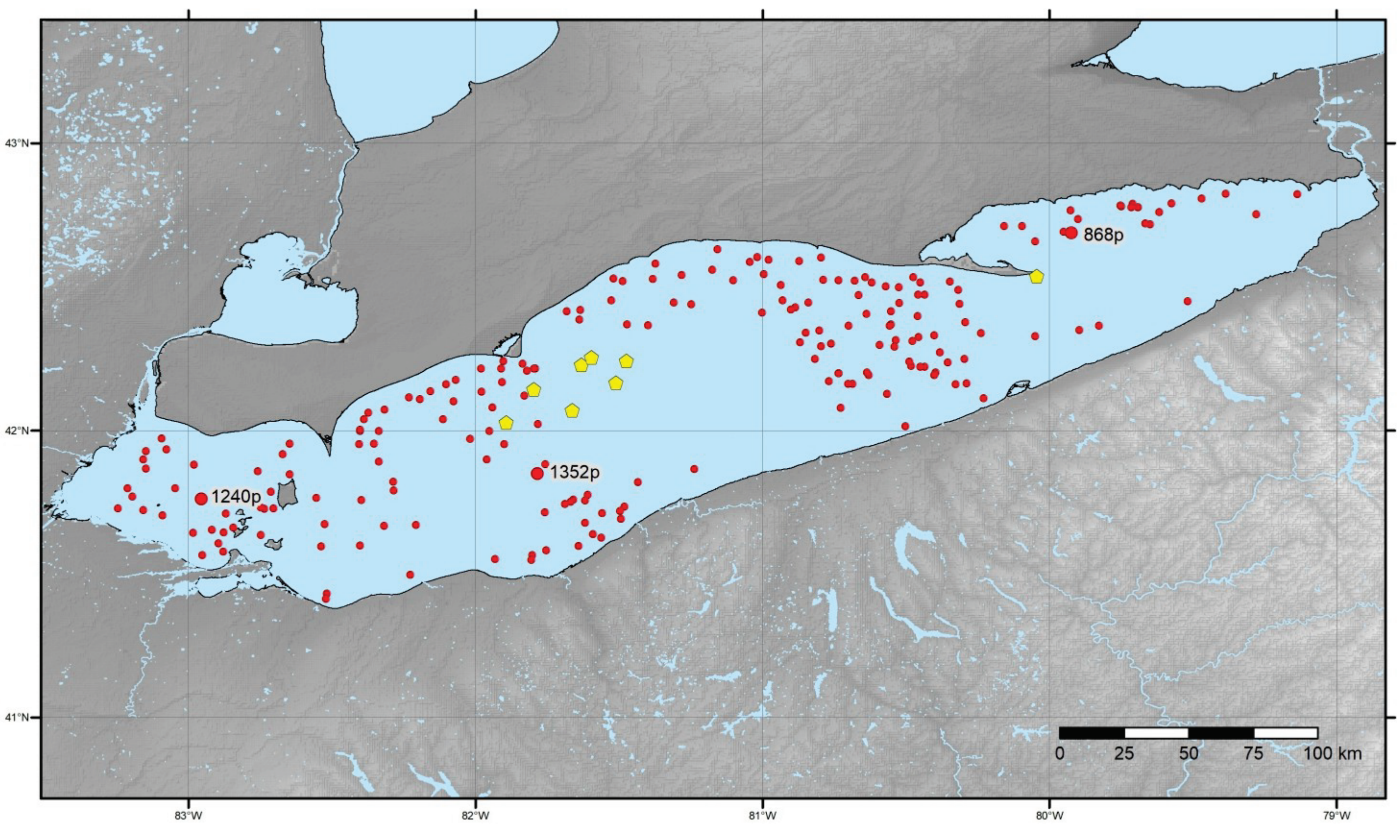

Figure 7. Lake Erie map of core (gravity and piston cores that recovered early Holocene and/or glacial sediments, ●) and borehole (⬠) locations.

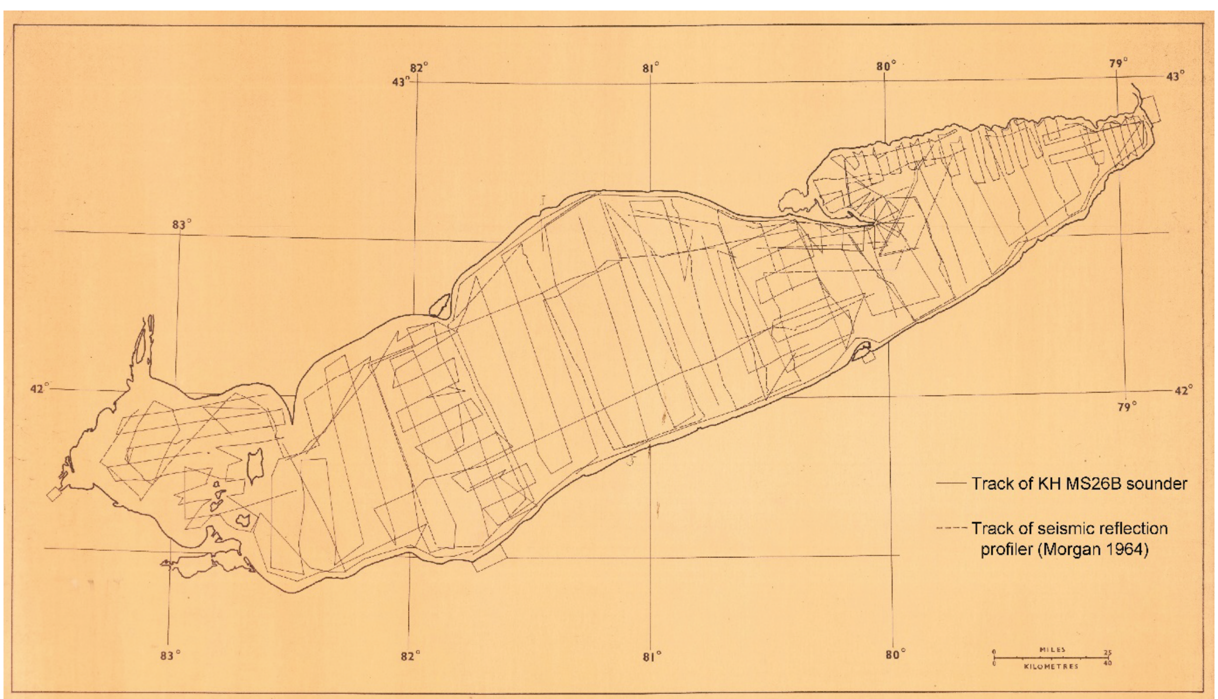

Figure 8. Lake Erie map of ship traverses while recording high resolution profiles of the lakebed using a Kelvin Hughes MS 26B echo sounder (solid lines), and a deeper penetrating seismic reflection system (Morgan, 1964; Morgan *et al.*, 2020) (dashed lines).

Sheet 3 describes sediments recovered in 8 boreholes, and their locations are also shown in Figure 7 with large five-sided yellow symbols.

Sediment stratigraphy from acoustic profiles

A Kelvin Hughes sounder (14.25 kHz) operated continuously to record the acoustic character and depth of surface and subsurface reflections for later correlation to sediment contacts observed in the cores (Fig. 8). Echograms collected along the transects shown in Figure 8 are archived at Geological Survey of Canada Atlantic. Boundaries of glacial sediment units were detected on the eroded surface of glacial deposits on the northern side of the central Erie basin and projected into shore bluff exposures. The glacial units werecorrelated to known onshore units and their distribution mapped offshore (Lewis *et al*., 2021 submitted). Examples of the correlation of echogram reflections with sediment sequences in three cores are shown in Figure 9. Example echograms showing the truncated tops of subsurface glacial sediment units beneath soft Holocene sediment in the eastern and central basins are shown in Figure 10. Contours of depth below mean lake level (~174 m above sea level) to the surface of glacial sediments, or possibly, in places, to the surface of early Holocene lowstand sediments are illustrated in Figure 11.

Chronology in the Lake Erie basin

Postglacial radiocarbon dates of mollusc shells in the Lake Erie basins are too old by 826±12 years because of carbonate hard water error (HWE), as found by dating modern shells of known age from the Lake Erie environment (Table 1 from Lewis *et al*., 2012, table S1b). The principal radiocarbon-dated constraints used for the interpretation of lake level history as shown in Figure 4 are reproduced in Table 2 from Lewis *et al*. (2012, table 1). Many additional dates in the Lake Erie basin concerning water level history are shown in relation to the interpreted history (Fig. 4) in the Supplementary Material of Lewis *et al*. (2012). The dates in Table 2 were recalibrated using the latest ^{14}C dataset (IntCal20) and calibration program (Calib 8.1) (Stuiver and Reimer, 1993; Reimer *et al*., 2020), and only minor insignificant changes from calibrations in 2012 with respect to the water level history were noted. Additional chronological data were obtained in one core using paleomagnetic secular variation (Lewis *et al*., 2012, supplementary material), and by correlating some offshore cores with radiocarbon-dated terrestrial sites using common horizons/zones in their pollen stratigraphy (Lewis *et al*., 1966, 2012 supplementary material, submitted; Cameron, 1991; Lewis and Anderson, 1992).

Other results

Selected sediment samples were analysed for their grain size distribution using sieves for the sand fraction and settling velocities measured by hydrometer for their silt and clay fraction (ASTM, 1964). Some samples were analysed for their calcite and dolomite weight percentages using the Chittick apparatus to measure their relative speed in evolving CO_2 gas in HCl (Dreimanis, 1962).

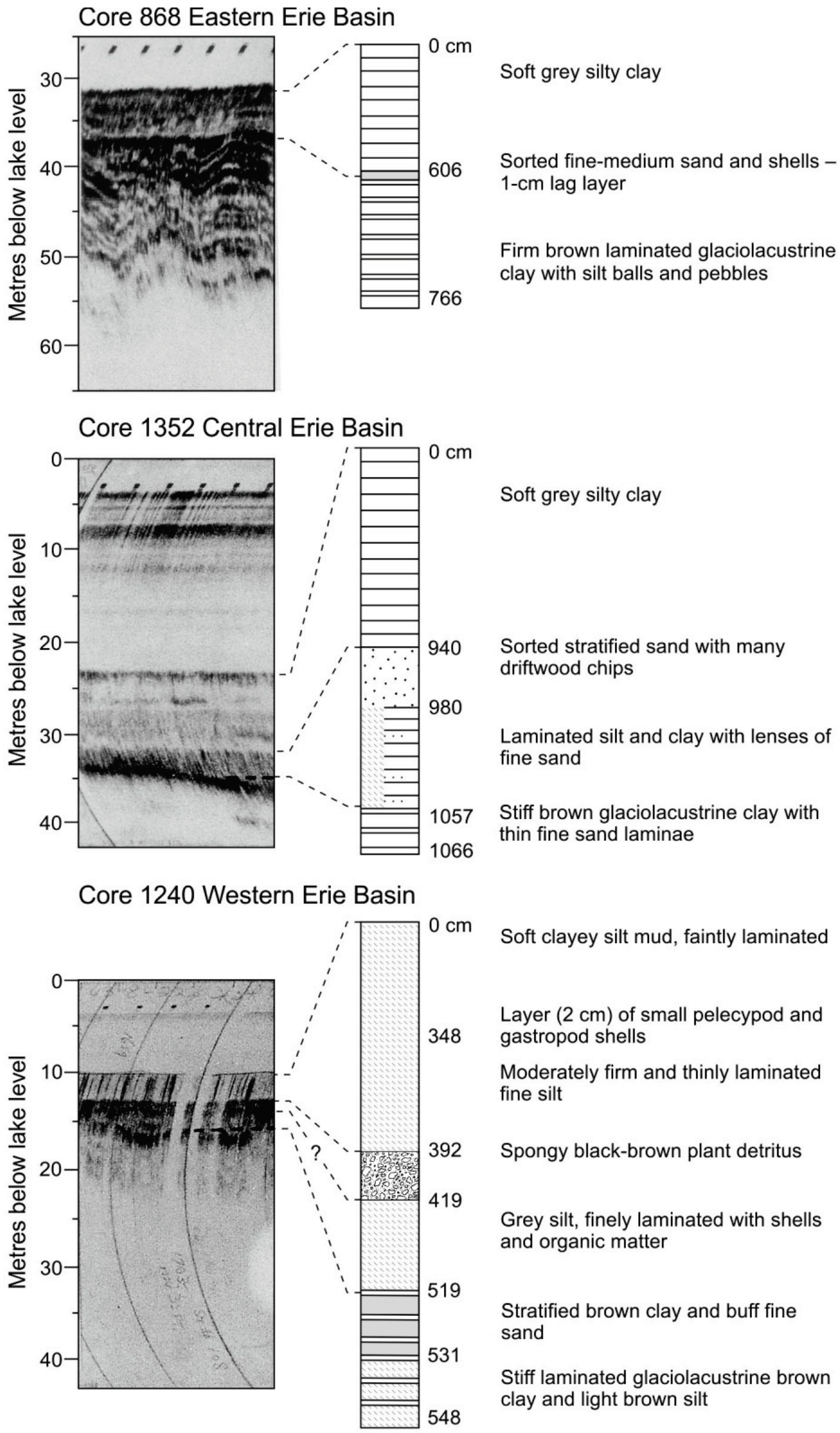

Figure 9. Diagrams showing correlations of Kelvin Hughes MS 26B acoustic surface and sub-bottom reflections (14.25 kHz) with contacts between sediment types in piston cores from the eastern, central, and western basins of Lake Erie. From Lewis *et al*. (2012, fig. S4).

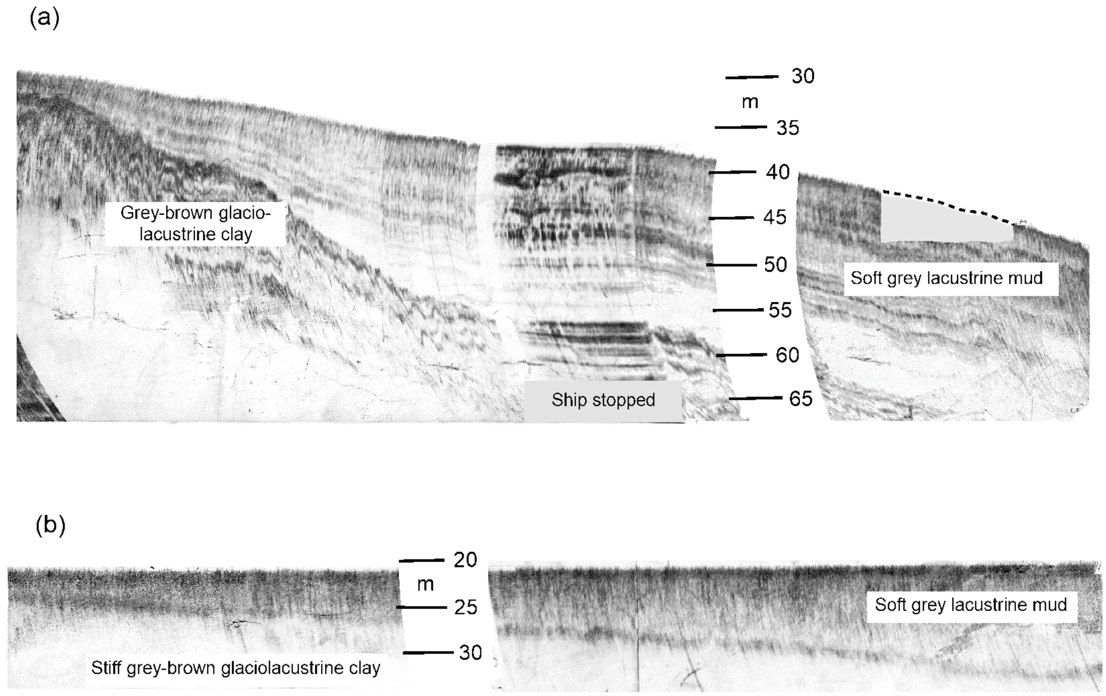

Figure 10. Example offshore Kelvin Hughes MS 26B sounder records showing reflections from the surfaces of soft silty clay mud (lake bed), and subsurface compact glacial sediments (or firm lowstand sediments in some places). (a) eastern basin, (b) central basin. Depth scale in metres below mean lake level (~ 174 m above sea level) assuming velocity of sound in water and sediment is ~1460 ms^{-1}.

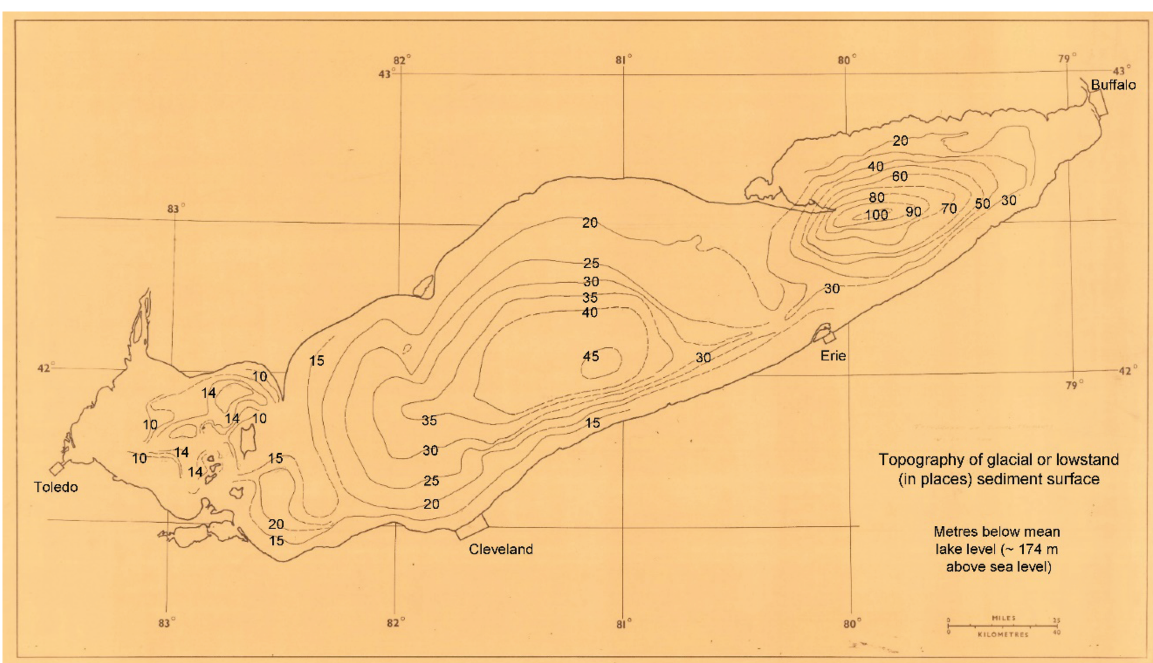

Figure 11. Lake Erie map showing the contoured surface of compact glacial sediments (or firm early Holocene lowstand sediments, in places) below mean lake level (~174 m above sea level). Depths in metres measured from Kelvin Hughes MS 26B 14.25 kHz sounding records assuming a sound velocity of ~1460 ms^{-1}. Contour interval = 5 m.

Ostracod specimen in the Long Point borehole were analysed for stable isotope composition (Lewis and Anderson, 1992), as were mollusc shells from a borehole near Erieau, ON (Fritz *et al*., 1975). Grain size distributions and carbonate contents are listed in the Excel files beside the sediment unit descriptions to which the analytical results apply. Pollen, isotope, chronological, and other data for the borehole sediments reside in publications by Lewis *et al*. (1966, 1973), Fritz *et al*. (1975), Lewis and Anderson (1992), and Lewis *et al*. (2012, submitted).

Interpretation

Most of the sediment descriptions in the Excel files contain a bracketed statement, e.g., (Holocene mud, or Hol mud), concerning the probable age and/or environment of deposition for the sediment units. Some are based on chronological analyses of in situ material. Most of the interpretations are based on the stratigraphic position of the units and/or interpretation of their physical characteristics, or inferred in terms of glacier positions or history of water levels as described in the foregoing 'Setting and background' section and its references in this report.

Glacial sediments

Most sediments attributed to a glacial origin were identified by their lack of organic remains, and their dense, compact, or hard consistency. Stratified glacial sediments with compact consistency were attributed to a glaciolacustrine origin whereas compact massive or unstratified glacial sediments containing a mixed assemblage of grain sizes were attributed to a glacial diamicton origin, mostly subglacial till, but some with a few indications of lamination may have originated as glacial debris flows or flow tills (Barnett and Karrow, 2018). The glacial sediments are interpreted as deposits of the Port Bruce, Mackinaw, or Port Huron phases of the Michigan Sub-episode (formerly Late Wisconsinan) or the glacial lakes associated with these advances, generally predating 13 (~11 ^{14}C) ka BP (Fig. 2) (Karrow *et al*., 2000). Some younger laminated glaciolacustrine-type sediment may have been deposited by overflow of glacial meltwater from Lake Algonquin in the Lake Huron basin about 12.5–12.4 (10.6–10.2 ^{14}C) ka BP.

Postglacial lowstand sediments

Lacustrine laminated sediment of firm consistency, some with scattered remains of organic material, and overlying a thin zone of sandy lag concentrate over glacial sediments, were interpreted as deposition during the postglacial lowstand of Lake Erie (Fig. 4a) (Lewis *et al*., 2012; Lewis, 2016). These sediments would have been deposited during the long multi-millennial lowstand during the early to mid-Holocene, about 12.4–7.0 (10.4–6.0 ^{14}C) ka BP between the Algonquin and Nipissing overflow events from the Lake Huron basin (Fig. 4a). Where analysed, the carbonate contents of these sediments commonly contain enhanced values of calcite over that of the underlying glacial sediments or overlying late Holocene sediments due to precipitation of that mineral (as lacustrine whitings) in the presumed warmer and calcite-saturated waters of the closed lowstand (Figs. 4b,c, Lewis *et al*., 2012, fig. 7).

Mid to late Holocene and present sediments

The youngest sediments in Lake Erie were deposited or formed during and after the Nipissing overflow beginning about 7.0 (6.0 ^{14}C) ka BP (Fig. 4). In deep offshore areas these sediments are generally soft muds consisting of silt- and clay-sized particles. Where analysed, the carbonate content of these sediments commonly exhibits reduced values of calcite due to enhanced solution in the lake water affected by the unsaturated overflow waters from Lake Huron. The higher water levels, facilitated by the Nipissing overflow, enabled sandy sediments eroded from shore bluffs of the north shore of the central basin to be carried by longshore drift eastward into the eastern basin to construct the Long Point spit. In relatively nearshore areas where glacial sediments are or were exposed, the youngest lake bed material consists of a rippled lag concentrate composed of sand and gravel (Lewis, 1967). All these younger sediments are labelled as of Holocene age in the sediment descriptions.

Cross-sections of eastern and central Lake Erie

Data defining bathymetry and configuration of sediment strata were combined with depths to bedrock to compile cross-sections of the offshore sediments over bedrock in the eastern and central basins of Lake Erie (Fig. 12). The former are based on acoustic echograms, sediment cores, and boreholes, and the latter were adopted from seismic reflection profiles (Morgan, 1964; Morgan *et al*., 2020). The seismic reflection profiles are not available. Sections indicate, in general, that glacial and postglacial unlithified sediments dominate the bedrock basin beneath Lake Erie. The sections show also the greater depths of water (63–64 m) and bedrock (to ~130 m) in the eastern basin (sections CD and EF) compared with the central basin (24–25 m water and ~80 m to bedrock in sections GH and IJ) of Figure 12.

Acknowledgements

The Great Lakes Institute at the University of Toronto is thanked for support and provision of ship time for research in Lake Erie. Geological guidance was provided by Drs. R.E. Deane (University of Toronto) and J. Terasmae (Geological Survey of Canada). Captain Hodge, officers, and crew of CNAV *Porte Dauphine* are appreciated for their dedicated assistance in collecting samples and sounding records from Lake Erie. The staff of the Great Lakes Institute are thanked for their many contributions to this research. Collaboration with The Consumers Gas Company, Toronto, is appreciated. The Long Point borehole was funded by the Geological Survey of Canada. Dr. T.W. Anderson (Geological Survey of Canada) kindly undertook many pollen analyses and correlations in support of sediment chronology. Drs. R.L. Thomas and J.P. Coakley and the staff of the Technical Operations Group at Canada Centre for Inland Waters are thanked for their assistance in obtaining and

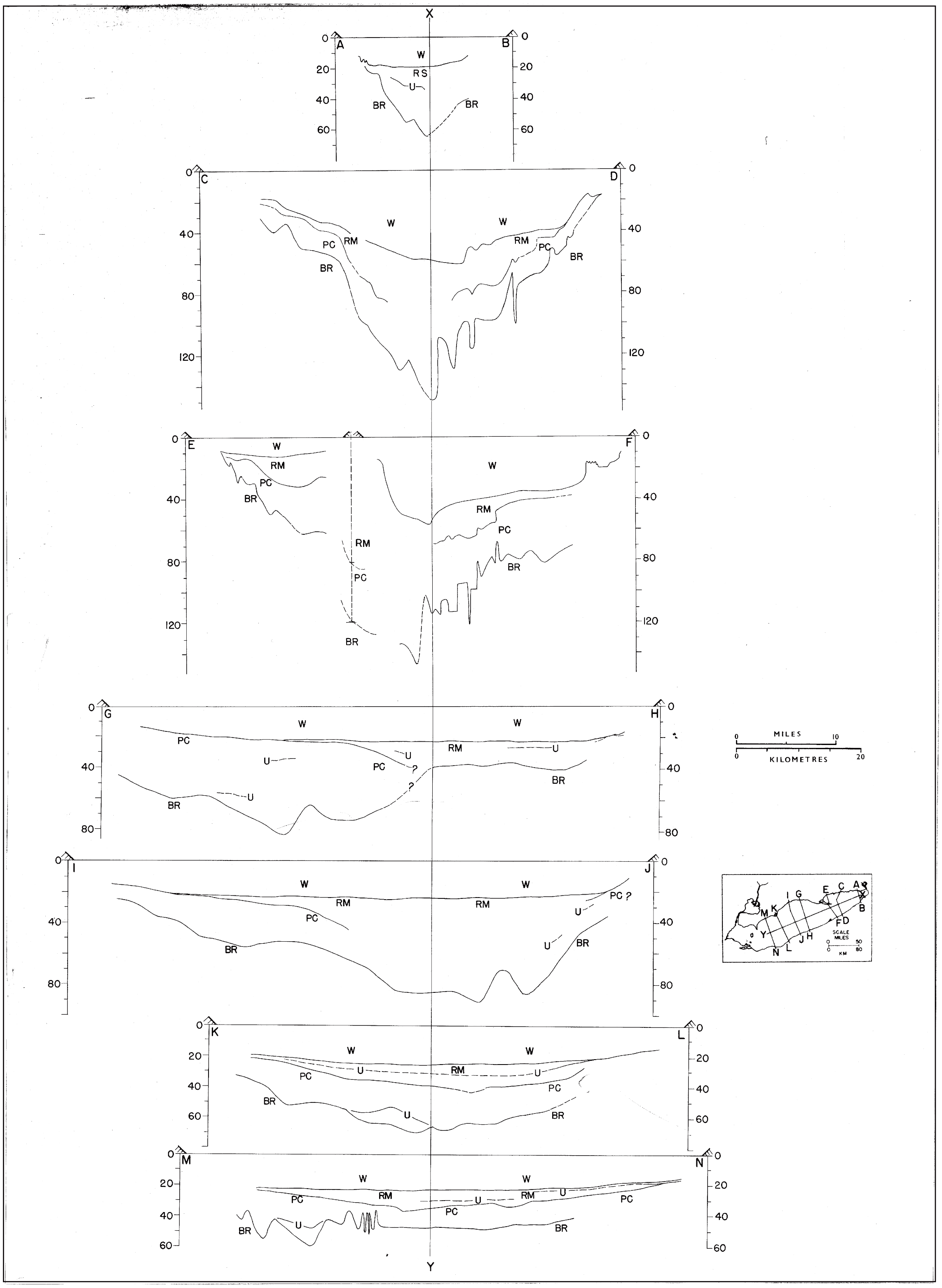

Figure 12. Cross-sections of the eastern and central basins of Lake Erie based on Kelvin Hughes MS 26B (14.25 kHz) records and seismic reflection profiles (Morgan, 1964; Morgan *et al.*, 2020). Borehole LP1 is shown in section EF. Depths in metres are below mean lake level of ~174 m above sea level. W = lake water, RM = Holocene muddy sediment, RS = Holocene sand, PC = Pleistocene glacial till and lacustrine sediment, U = reflection of unknown origin, BR = Paleozoic bedrock.

using ship time aboard CCGS Limnos in 1987, 1990 and 1993 in support of Lake Erie geological studies. We thank Walta-Anne Rainey (Geological Survey of Canada Atlantic) for preparation of the map figures of sample sites, and Gordon D.M. Cameron (Geological Survey of Canada Atlantic) for review and improvement of this report.

References

ASTM 1964. Quantitative determination of the distribution of particle sizes in soils. *In*: Book of ASTM Standards, Part 4, American Society for Testing and Materials, 1916 Race St., Philadelphia.

Barnett, P.J. 1979. Glacial Lake Whittlesey: the probable ice frontal position in the eastern end of the Erie basin. Canadian Journal of Earth Sciences, **16**: 568–574.

Barnett, P.J. 1985. Glacial retreat and lake levels, north central Lake Erie basin. *In*: P.F. Karrow and P.E. Calkin (eds.) Quaternary Evolution of the Great Lakes, 185–194, Geological Association of Canada Special Paper 30, St. John's NL.

Barnett, P.J. 1992. Quaternary Geology of Ontario. *In*: P.C. Thurston, H.R. Williams, R.H. Sutcliffe, and G.M. Stott, (eds.) Geology of Ontario, 1011–1088, Ontario Geological Survey, Special Volume 4, Part 2.

Barnett, P.J. 1998. Quaternary geology, Long Point–Port Burwell area. Ontario Geological Survey, Report 298, 143 p.

Barnett, P.J. and Karrow, P.F. 2018. Ice-marginal sedimentation and processes of diamicton deposition in large proglacial lakes, Lake Erie, Ontario, Canada. Canadian Journal of Earth Sciences, **55**: 846–862. dx.doi.org/10.1139/cjes-2017-0006

Bolsenga, S. J. and Herdendorf, C.E. 1993. Lake Erie and Lake St. Clair Handbook. Wayne State University Press, Detroit MI, 467 p.

Bostock, H.S. 2014. Geology, Physiographic Regions of Canada. Geological Survey of Canada Map1254A (2nd edition), scale 1: 5,000,000, doi 10.4095/293408

Calkin, P.E. and Feenstra, B.H. 1985. Evolution of the Erie-basin Great Lakes. *In:* P.F. Karrow, and P.E Calkin (eds.) Quaternary Evolution of the Great Lakes, 149–170, Geological Association of Canada Special Paper 30, St. John's NL.

Cameron, G.D.M. 1991. Seismostratigraphy of Late Quaternary sediments and lake level history, eastern Lake Erie. M.Sc. Thesis, Dalhousie University, Halifax, 157 pp.

Chapman, L.J. and Putnam, D. 1984. The Physiography of Southern Ontario. Ontario Geological Survey Special Volume 2, 270 p. Accompanied by Map P.2715 (coloured), scale 1:600,000.

Coakley, J.P. 1989. The origin and evolution of a complex cuspate foreland: Pointe-aux-Pins, Lake Erie, Ontario. Géographie physique et Quaternaire, **43**: 65–76.

Coakley, J.P. and Lewis, C.F.M. 1985. Postglacial lake levels in the Erie basin, pp. 195–212. *In:* P.F. Karrow, and P.E. Calkin (eds.) Quaternary Evolution of the Great Lakes, Geological Association of Canada Special Paper 30, St. John's NL.

Dreimanis, A. 1962 Quantitative gasometric determinations of calcite and dolomite by using Chittick apparatus. Journal of Sedimentary Petrology, **32**: 520–529.

Eschman, D.F. and Karrow, P.F. 1985. Huron basin glacial lakes: a review. *In*: P.F. Karrow and P.E. Calkin (eds.) Quaternary Evolution of the Great Lakes, 79–93. Geological Association of Canada Special Paper 30, St. John's NL.

Finkelstein, S.A. and Davis, A.M. 2006. Paleoenvironmental records of water level and climatic changes from the middle to late Holocene at a Lake Erie coastal wetland, Ontario, Canada. Quaternary Research, **65**: 33–43.

Franklin, D.R. and Anderson, D.V. 1961. A bottom sediment sampler. Limnology and Oceanography, **6**: 233–234.

Fritz, P., Anderson, T.W., and Lewis, C.F.M. 1975. Late-Quaternary climatic trends and history of Lake Erie from stable isotopes. Science, **190**: 267–269.

Government of Canada and United States Environmental Protection Agency. 1995. The Great Lakes, an environmental atlas and resource book, 3rd edition. http:\\www.epa.gov/greatlakes/atlas/index.html.

Hartley, R.P. 1961a. Bottom deposits in Ohio waters of central Lake Erie. Ohio Division of Shore Erosion, Department of Natural Resources, Technical Report No. 6, 14 p.

Hartley, R.P. 1961b. Bottom sediments in the island area of Lake Erie. Ohio Division of Shore Erosion, Department of Natural Resources, Technical Report No. 9, 22 p.

Herdendorf, C.E. 1989. Paleogeography and Geomorphology of Lake Erie. *In*: Lake Erie Estuarine Systems: Issues, Resources, Status, and Management, NOAA Estuary-of- the-Month Seminar Series no. 14, p. 35–70.

Herdendorf, C.E. 2013. Research overview: Holocene development of Lake Erie. Ohio Journal of Science, **112** (2)**:** 24–36

Herdendorf, C.E. and Bailey, M.L. 1989. Evidence for an early delta of the Detroit River in western Lake Erie. Ohio Journal of Science, **89**:16–22.

Holcombe, T.L., Warren, J.S., Taylor, L.A., Reid, D.F., and Herdendorf, C.E. 1997. Lakefloor geomorphology of western Lake Erie. Journal of Great Lakes Research, **23**: 190–201.

Holcombe, T.L. Taylor, L.A., Reid, D.F., Warren, J.S., Vincent, P.A., and Herdendorf, C.E. 2003. Revised Lake Erie postglacial lake level history based on new detailed bathymetry. Journal of Great Lakes Research, **29**: 681–704.

Holcombe, T.L., Taylor, L.A., Warren, J.S., Vincent, P.A., Reid, D.F., and Herdendorf, C.E. 2005. Lake-floor geomorphology of Lake Erie. World Data Center A for Marine Geology and Geophysics Research Pub RP-3, 26 pp.

Hough, J.L. 1958. Geology of the Great Lakes. University of Illinois Press, Urbana. 313 p.

Hvorslev, M.J. and Stetson, H.C. 1946. Free-fall coring tube, a new type of gravity bottom sampler. Geological Survey of America Bulletin, **57**: 935–949.

Johnson, M.D., Armstrong, D.K., Sanford, B.V., Telford, P.G., and Rutka, M.A. 1992. Paleozoic and Mesozoic Geology of Ontario, 907–1008. *In*: P.C. Thurston, H.R. Williams, R.H. Sutcliffe, and G.M. Stott (eds.) Geology of Ontario, Special Volume 4, Part 2, Ontario Geological Survey, Sudbury ON.

Karrow, P.F., Anderson, T.W., Clarke, A.H., DeLorme, L.D., and Sreenivasa, M.R. 1975. Stratigraphy, paleontology, and age of Lake Algonquin sediments in southwestern Ontario, Canada. Quaternary Research, **5**: 49–87.

Karrow, P.F., Dreimanis, A., and Barnett, P.J. 2000. A proposed diachronic revision of Late Quaternary time-stratigraphic classification in the eastern and northern Great Lakes area. Quaternary Research, **54**: 1–12. doi:10.1006/qres.2000.2144,

Kullenberg, B. 1947. The piston core sampler. Svenska *Hydrografisk-Biologiska Kommissionens skrifter*. Tredje, Serien: Hydrografi, Band 1, Hafte 2, 1–46.

Kunkle, G.R. 1963. Lake Ypsilanti: a probable late Pleistocene low-lake stage in the Erie basin. Journal of Geology, **71**: 72–75.

Lewis, C.F.M. 1967. Sedimentation studies of unconsolidated deposits in the Lake Erie basin. Ph.D. thesis, University of Toronto, Toronto ON. 132 p.

Lewis, C.F.M. 1969. Late Quaternary history of lake levels in the Huron and Erie basins. Proceedings of 12th Conference of Great Lakes Research, International Association of Great Lakes Research, pp. 250–270.

Lewis, C.F.M. 2016. Understanding the Holocene closed-basin phases (lowstands) of the Laurentian Great Lakes and their significance. Geoscience Canada, **43**: 179–197. http://www.dx.doi.org/10.12789/geocanj.2016.43.102

Lewis, C.F.M., Anderson, T.W., and Berti, A.A. 1966. Geological and palynological studies of Early Lake Erie deposits. Publication No. 15, Great Lakes Research Division, The University of Michigan, Ann Arbor MI.

Lewis, C.F.M. and Anderson, T.W. 1992. Stable isotope (O and C) and pollen trends in eastern Lake Erie, evidence for a locally induced climatic reversal of Younger Dryas age in the Great Lakes basin. Climate Dynamics, **6**: 241–250.

Lewis, C.F.M., Wootten, A.E., and Davis, J.B. 1973. Stratigraphic and engineering studies of unconsolidated sediments in central Lake Erie, near Erieau, Ontario. Report of Activities, Geological Survey of Canada Paper 73–1 Part A, pp 205–210.

Lewis, C.F.M., Cameron, G.D.M., Anderson, T.W., Heil Jr., C.W., and Gareau, P.L. 2012, Lake levels in the Erie Basin of the Laurentian Great Lakes: Journal of Paleolimnology, **47**: 493–511. http://dx.doi.org/10.1007/s10933-012- 9578-5.

Lewis, C.F.M., Cameron, G.D.M., Barnett, P.J., and Anderson, T.W. submitted 2021. Offshore-onshore correlation of glacial sedimentary units in the central basin of Lake Erie, Ontario. Canadian Journal of Earth Sciences.

McCarthy, F. and McAndrews, J. 2012. Early Holocene drought in the Laurentian Great Lakes basin caused hydrologic closure of Georgian Bay. Journal of Paleolimnology, **47**: 411–428.

Moore, T., Rea, D.K., and Godsey, H. 1998. Regional variation in modern radiocarbon ages and the hard-water effects in Lakes Michigan and Huron. Journal of Paleolimnology, **20**: 347–351. https://doi.org/10.1023/A:1007920723163.

Morgan, N. A. 1964. Geophysical studies in Lake Erie by shallow seismic methods. Ph.D. thesis, University of Toronto. Toronto ON.

Morgan, N.A., Todd, B.J. and Lewis, C.F.M. 2020. Interpreted seismic reflection profiles, sediment thickness and bedrock topography in Lake Erie, Ontario, Canada and Michigan, Ohio, Pennsylvania and New York, U.S.A. Geological Survey of Canada Open File 8733, 25 p.

NOAA National Geophysical Data Center. 1999. Bathymetry of Lake Erie and Lake Saint Clair. United States NOAA National Centers for Environmental Information. https://doi.org/10.7289/V5KS6PHK. Accessed [5 May 2021], also ngdc.noaa.gov/mgg/greatlakes/lakeerie_cdrom/html/e_images.htm, and click images/le.jpg.

Pengelly, J.W., Tinkler, K.J., Parkins, W.G., and McCarthy, F.M.G. 1997. 12 600 years of lake level changes, changing sills, ephemeral lakes and Niagara Gorge erosion in the Niagara Peninsula and Eastern Lake Erie basin. Journal of Paleolimnology, **17**: 377–402.

Reimer, P.J. *et al*. 2009. INTCal09 and MAR09 radiocarbon calibration datasets. Radiocarbon, **51**:1111–1150

Reimer, P., Austin, W.E., Bard, E., Bayliss, A., Blackwell, P.G., Bronk, R. *et al*. 2020. The IntCal20 Northern Hemisphere radiocarbon age calibration curve (0–55 cal kBP). Radiocarbon, **62**: 725–757. doi: 10.1017/RDC.2020.41.

Sanford, B.V. and Baer, A.J. 1983. Geological map of Southern Ontario. Geological Survey of Canada, Ottawa, Map 1335A, scale 1: 1,000,000.

Sly, P.G., 1976. Lake Erie and its basin. Journal of the Fisheries Research Board of Canada, **33** (3):355–370.

Stuiver, M. and Quay, P.D. 1981. Atmospheric ^{14}C changes resulting from fossil fuel CO_2 release and cosmic ray flux variability. Earth and Planetary Science Letters, **53**: 349–362.

Stuiver, M. and Reimer, P.J. 1993. Extended ^{14}C data base and revised CALIB 3.0 ^{14}C age calibration program. Radiocarbon, **35**: 215–230.

Terasmae, J. 1970. Report on stratigraphic drilling in Point Pelee National Park, Ontario. Contract report 68–200, National and Historic Parks Branch, Canada Department of Indian and Northern Affairs, 6 p.

Tevesc, M.J.S., Smith, J.E., Coakley, J.C., and Risk, M.J. 1997. Stable carbon and oxygen isotope records from Lake Erie sediment cores: mollusk aragonite 4600 BP–200 BP. Journal of Great Lakes Research, **23**: 307–316.

Thomas, R.L., Jaquet, J.-M., Kemp, A.L.W., and Lewis C.F.M. 1976. Surficial sediments of Lake Erie. Journal of the Fisheries Research Board of Canada, **33**: 385–403.

Thompson, T.A., Lepper, K., Endres, A.L., Johnston, J.W., Baedke, S.J., Argyilan, E.P., Booth, R.K., and Wilcox, D.A. 2011. Mid Holocene lake level and shoreline behavior during the Nipissing phase of the upper Great Lakes at Alpena, Michigan, USA. Journal of Great Lakes Research, **37**: 567–576.

Tinkler, K.J., Pengelly, J.W., Parkins, W.G., and Terasmae, J. 1992. Evidence for high water levels in the Erie basin during the Younger Dryas chronozone. Journal of Paleolimnology, **7**: 215–234.

Table 1. Dates used to obtain HWE (hard water error) in Lake Erie basin (from Supplementary Material in Lewis *et al*. 2012, table S1b)

Location	Lat N Long W	Lab No Age BP	Species, date collected	True pre1950 age, yr	Mean $\Delta^{14}C$[1]	Inert CO_2 correction[2], yr	HWE correction[3], yr	CMNML No[4]
1 Shore E of Port Colborne ON	42º53' 79º14'	OS48332 815±30	*Ligumia nastuta*, 1935	15	-17.7	144	656±30	CMNML 022459
2 Port Dover ON	42º47' 80º12'	OS48331 1470±25	*Leptodea fragilis*, 1890	60	-5.85	47	1363±25	CMNML 002453
3 4 mi W of Marble-head OH	41º33' 82º49'	OS48333 890±30	*Fusconia flava*, 1950	0	-23.2	189	701±30	CMNML 014866
4 Port Dover ON	42º47' 80º12'	UCI74204 1020±15	*Leptodea fragilis*, (muscle attached) 1890	60	-5.85	47	913±15	CMNML 002453

Mean pooled HWE correction from mollusc shell dates 1, 3 and 4[5] = 826±12

[1] From Stuiver and Quay (1981 table 1); average value for year of collection and previous 3 years
[2] Correction = $-8033\ln(1+\Delta^{14}C/1000)$ (Moore et al. 1998)
[3] HWE = column 3 – column 5 – column 7 (Moore et al. 1998)
[4] CMNML = Canadian Museum of Nature catalogue number
[5] Shell in entry 2 is thought to have been dead at time of collection so its date was rejected

Table 2. Principal ^{14}C dates used to interpret water level history of Lake Erie (from Lewis *et al*. 2012, table 1).

No. & Site Name	Lat N Long W Depth m	Laboratory No/Conventional date	Material dated, stratigraphy	Elevation/ Reference uplift m	Cal age[1] BP	Original Elevation m asl	References
1. Nanticoke Paleo-beach	42° 43.20′ 79° 58.40′ 21	OS48336 7,610 ± 50	Shell in sorted sand, 96–105 cm core depth	151.3 29.1	7670 7600 *7430* *7330*	144.2 144.3	Core 90Limnos-002P or 90-01-003-264P
2. Nanticoke Paleo-beach	42° 43.20′ 79° 58.40 21	OS48334 8,930 ± 40	Shell in sorted sand, 146–153 cm core depth	150.8 29.1	9090 9000 *9120* *8990*	139.8 140.1	ditto
3. Nanticoke Paleo-beach	42° 43.20′ 79° 58.40′ 21	OS48335 6,650 ± 40	Shell in sorted sand, 215 cm core depth	150.1 29.1	6680 6560 *6740* *6500*	144.9 145.0	ditto
4. Nanticoke Paleo-beach	42° 43.20′ 79° 58.40′ 21	OS48337 7,180 ± 35	Shell in sorted sand, 228–233 cm core depth	150.0 29.1	7320 7250 *7320* *7180*	143.6 143.7	ditto
5. Rondeau Park borehole	42° 18.90′ 81° 50.90′	WAT378 5,330 ± 250	Paleo lagoon organics under 9.6 m beach sand	167.2 17.4	6400 5760 *6390* *5760*	164.4 164.9	A.J. Cooper pers comm (1983), Coakley (1989)
6. Rondeau Park borehole	42° 18.90′ 81° 50.90′	WAT379 5,180 ± 280	Paleo lagoon organics under 9.9 m beach sand	166.9 17.4	6270 5660 *6240* *5650*	164.2 164.7	ditto
7. Core 2,226	41° 45.30′ 81° 55.00′ 23.5	GSC330 10,200 ± 180	Driftwood at top of silty clay and sand laminae	143.7 16.1	12,370 11,410 *12,440* *11,410*	128.2 131.9	Lewis *et al.* (1966), Lewis (1969)
8. Crown Site	43° 00.0′ 79° 23.90′	TO3356 12,130 ± 80	*Pisidium* shells in clay at 0.4 m depth	183.9 38.6	13,270 13,120 *13,290* *13,120*	136.1 138.0	Tinkler et al. (1992), Pengelly *et al.* (1997)
9. Humber-stone Bog	42° 54.10′ 79° 11.20′	BGS1382 11,150 ± 175	Peat over clay and sand 1.8 m below surface	175.2 38.1	13,230 12,850 *13,220* *12,840*	128.5 133.2	Tinkler *et al.* (1992)
10. Blueberry Pond	42° 55.20′ 79° 31.00′	BGS1826 4,620 ± 100	Basal peat over sand	179 35.1	5570 5070 *5480* *5060*	174.7 175.4	Pengelly *et al.* (1997)
11 Gates Creek a	42° 49.60′ 79° 51.90′	BGS1634 4,280 ± 150	Wood in base of mud over sand	175 est'd 31.6	5050 4580 *5050* *4580*	171.7 172.3	ditto

12. Nanticoke Paleo-beach	42° 43.20′ 79° 58.40′ 21	UCI89049 6,345 ± 20	Shell in sorted sand, 267–269 cm core depth	149.6 29.1	6310 6290 *6380* *6290*	145.0 145.0	Core 90Limnos-002P or 90-01-003-264P
13. Nanticoke Paleo-beach	42° 43.20′ 79° 58.40′ 21	UCI89050 11,500 ± 30	Shell in sorted sand, 300.5–301.5 cm core depth	149.3 29.1	12,640 12,570 *12,720* *12,690*	119.3 119.9	ditto
14. Bates Marsh	42° 20.00′ 81° 50.80′	SNU02-023 4,220 ± 60	Basal peat under 5 m water	176.2 17.4	4850 4640 *4850* *4640*	174.5 174.7	Finkelstein and Davis (2006)
15. Gates Creek b	42° 49.60′ 79° 51.90′	BGS1666 3,420 ± 100	Wood from level of declining aquatic pollen	174 est'd 31.6	3830 3570 *3830* *3560*	172.0 172.2	Pengelly *et al.* (1997)
16. Red Head Pond, Pelee Pt.	41° 57.20′ 82° 30.40′ 3.5	I-3992 3,520 ± 100	Basal gyttja	169.8 15.9	3960 3650 *3960* *3640*	168.7 168.9	Terasmae (1970)
17. Big Pond, Pelee Pt.	41° 58.00′ 82° 31.10′	I-3993 3,310 ± 100	Basal gyttja	169.8 15.9	3680 3410 *3690* *3410*	168.8 169.0	ditto

No. number, Lat latitude, Long longitude, Elevation above sea level in m, Cal calibrated or calendar
1. Shell dates have been corrected for hard water error (HWE) by subtracting 826 years from their conventional age (column 3) before calibration. All calibrated with a 10-year moving average using the Calib6.0.1 program with limits in upright font (Stuiver and Reimer, 1993) and INTCAL09 dataset (Reimer *et al*., 2009). Entries below in italic font are 1σ limits from the Calib8.1.0 program using the INTCAL20 dataset (Reimer *et al*., 2020). One sigma (σ) age limits rounded to nearest 10 years.
2. Core 90-01-003-264P, renamed 90Limnos-002P at Geological Survey of Canada Atlantic.