

## Revised Lake Erie Postglacial Lake Level History Based on New Detailed Bathymetry

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**ABSTRACT.** *Holocene lake level history and paleogeography of Lake Erie are re-interpreted with the aid of new bathymetry, existing water budget data, and published information. Morphology and elevation of present and former shoreline features (sand ridges, forelands, spits, bars, and fans) record the water level at which they were formed. Of eighteen such features observed in Lake Erie, six occur nearshore and were formed at or near present lake level, and twelve features apparently formed at lower lake levels. It seems likely that lake level fell below the level of the outlet sill during the 9–6 ka climate optimum, when warmer and drier conditions prevailed. During such times lake level likely rose and fell as controlled by the water budget, within a window of constraint imposed by increases and decreases in evaporation, which would have varied directly with lake surface area. Near Buffalo, possible shoreline features occurring 3–6 km offshore at depths of 9–12 m could have formed at lower lake levels. Annual water volumes in each term of the water budget, (runoff, precipitation, and evaporation) are large relative to the volumetric capacity of Lake Erie itself. Such events as introduction of even a modest amount of upper Great Lakes water, or the onset of cooler and less dry climate conditions, could cause significant, rapid, lake level rise. Schematic reconstructions illustrate changing paleogeography and a Holocene lake level history which has varied with: blocking/ unblocking of outlet sills; erosion of outlet sills; distance from outlet sills; differential isostatic rebound; upper Great Lakes drainage flowing into or bypassing the lake; and climate-driven water budget of the Lake Erie drainage basin.*

**INDEX WORDS:** *Bathymetry, Holocene, Lake Erie, lake floor features, lake level, lake surface area, lake water volume, paleogeography, water budget.*

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## INTRODUCTION

Lake Erie, shallowest and southernmost of the Great Lakes, has had the longest and in some respects the most complex postglacial lake history of any of the Great Lakes. Relatively modest rises or falls in lake level caused major changes in the paleogeography of the lake basin. Holocene changes in lake level at a given location were controlled by a combination of the following factors: amount of isostatic rebound, distance from the outlet sill, level of the outlet sill, lowering/ erosion of the outlet sill, volume of water passing through the lake, lake surface area, and paleoclimate. New evidence pertaining to lake levels comes from recently compiled, detailed bathymetry (National Geophysical Data Center 1998) which reveals lake-floor features indicative of former, but now inundated, shorelines. Previous work has addressed the history of postglacial lake levels in broad outline. Now, with the new evidence provided by the detailed bathymetry, it is appropriate to consider again the Holocene lake-level history of Lake Erie.

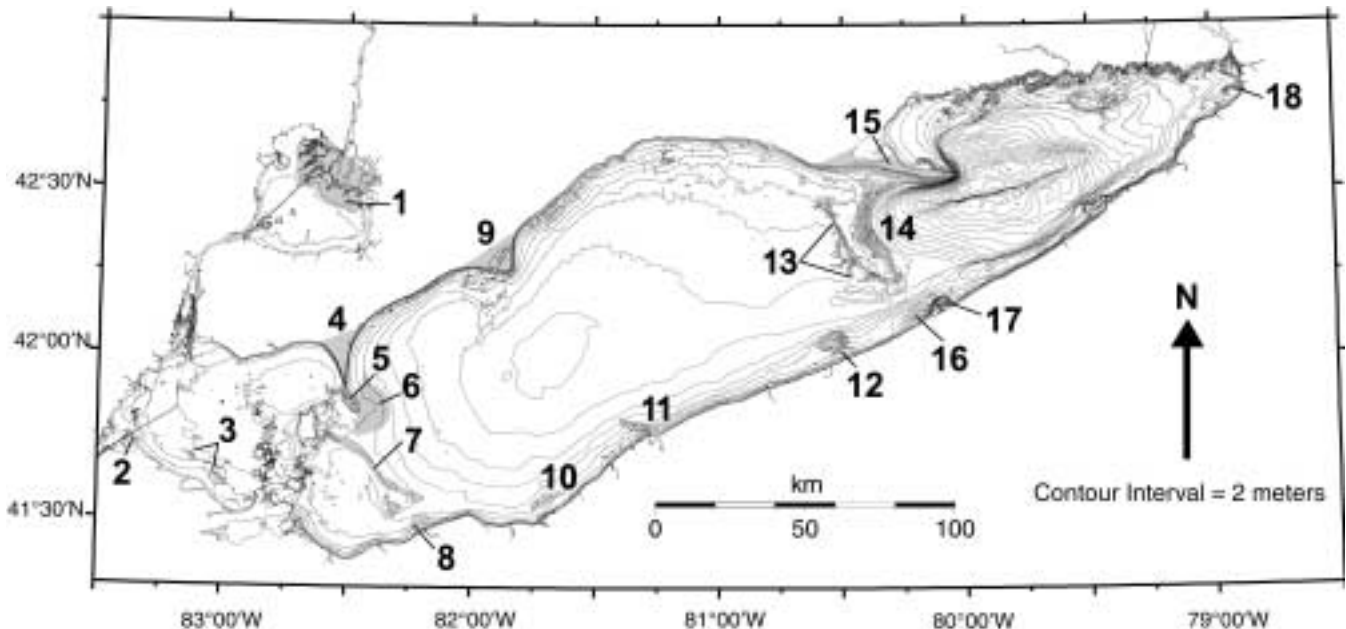
In this paper we identify and briefly describe lake floor features which are indicative of present and former lake levels. Computations of lake surface area and water volume are presented, which are more precise than previous computations relying on less detailed shorelines and bathymetry. Aspects of the present lake water budget are examined, with implications for water budgets during an early Holocene low water phase. Aspects of control of lake level by the water budget during times of lowered lake levels are discussed. Finally, a model for the Holocene lake level history of Lake Erie is presented and discussed.

Coakley and Lewis (1985) assembled information from: 50 radiocarbon dates on samples recovered from the lake floor; shoreline elevations of deglacial Lakes Whittlesey, Warren, Algonquin, and others; lake floor geomorphology documenting now drowned shorelines and channels; and miscellaneous other information; and they reconstructed a Holocene history of Lake Erie water levels. Calkin and Feenstra (1985), from a variety of evidence (elevation and tilt of former strandlines, level of downcutting of river channels, ice advances and retreats, chronology of high-standing proglacial lakes), and Barnett (1985), from studies of the geomorphology of southern Ontario, reconstructed lakes and lake levels within the Lake Erie basin during the past 14,000 years. Earlier reconstructions of lake level history were accomplished by

Lewis (1969), and Sly and Lewis (1972). Pengelly *et al.* (1997) modeled the history of high-water lake levels of the past 12,500 years based on field information gathered from the Niagara region.

Reconstructions vary as to details and water levels. Some salient features of the models: 1) high lake level stages of proglacial lakes and Lake Algonquin followed by very low lake levels in early Holocene time, 2) isostatic rebound and concomitant gradual rise in lake levels in the early Holocene, 3) stable or slowly rising lake levels in Middle Lake Erie time, 4) rise in lake levels accompanying the Nipissing Rise to slightly higher than at present, and 5) lowering of lake levels to just below present level following the Nipissing Rise event. Calkin and Feenstra (1985) cited evidence for Lake Ypsilanti, a Lake Erie lowstand (low-standing stream gravels near Ann Arbor and Ypsilanti; Kunkle, 1963; depth to channels cutting till beneath the central basin of Lake Erie; Wall, 1968) prior to Lake Whittlesey time during the Mackinaw Interstade. The reconstructions recognize that lake level has been controlled since deglaciation by isostatically rebounding outlet sills of the Niagara River; and that the Nipissing rise accompanied a shift in upper Great Lakes drainage from the North Bay outlet to the Port Huron outlet. Pengelly and associates (1997) cited evidence for a post-Nipissing lowering of lake level 3,600–2,900 ya due to erosion of a former sill in the Niagara River referred to as the Lyell-Johnson Sill.

The Nipissing Rise is generally associated with diversion of upper Great Lakes outflow from the North Bay outlet to the Port Huron outlet in mid-Holocene time. Lewis (1969) and Pengelly *et al.* (1997) discuss evidence for this event and the times of its occurrence and cite the work of previous investigators. Two rising water events are recognized by these and other investigators, Nipissing I, which peaked between 5,500 and 5,000 ya, and Nipissing II, which peaked between 4,500 and 3,800 ya. There was a significant period (6,000 to 4,000 ya) when outflow of upper Great Lakes water was shared between three outlets—Chicago, North Bay, and Port Huron—in varying amounts, before final transfer of a majority of upper Great Lakes water to the Port Huron outlet. Recently, evidence from carbon and oxygen isotope ratios from molluscs and ostracods, contained in Lake Erie sediment cores, suggested a single and permanent water-change event (Nipissing II?) occurring about 3,600–4,600 ya (Kempthorne *et al.* 2000).



**FIG. 1.** Lake Erie and Lake St. Clair bathymetric features indicative of present and former lake levels. Numbered features, including bars, spits, banks, sand ridges, forelands, and fans, are discussed in the text.

#### LAKE FLOOR FEATURES INDICATIVE OF PRESENT AND FORMER LAKE LEVELS

Sand ridges, forelands, spits, bars, and fans are Holocene depositional features which formed in the shore zone and record lake level at the time of their formation. Therefore their occurrence at elevations other than present records the levels of former shorelines. Pre-existing topographic features such as moraines and drumlins, which date from the last period of glaciation, if later eroded in the shore zone, may also record lake level.

Of the eighteen such features recording present or former shorelines identified in Lake Erie and Lake St. Clair, based on the detailed bathymetry, six are sites of sediment deposition at present lake level. The remaining twelve features are interpreted as having formed beneath the modern lake surface during the Holocene at lower lake levels, and later abandoned. Two of these features are thought to have formed at lower lake levels, but alternative interpretations are possible, as noted.

Each of the eighteen features thought to record present and former shorelines are numbered 1–18 and are shown in Figure 1. These features are also listed below in the same numerical order. Accompanying notes briefly describe each feature, summarize its historical interpretation, and give a rough estimate of the lake level at which it was formed.

For a more detailed description of each feature, refer to the detailed bathymetric map (National Geophysical Data Center 1998). For a more detailed discussion of the geomorphology of western Lake Erie features, refer to Holcombe *et al.* 1997.

**St. Clair Delta.** The dominant feature of Lake St. Clair, this platform of deltaic deposits and multiple distributary channels is bounded by foreset slopes extending downward from platform depths of less than 1 m to more than 3 m depth. The delta is areally large but the lake basin is only 5–6 m deep. Delta sediments prograde, but aggrade only minimally. A smaller delta of the Clinton River, which extends into Lake St. Clair from the northwest shore, partially coalesces with the St. Clair Delta and is included with this feature. Lake St. Clair is too small to be significantly affected by differential isostatic rebound, therefore the lake has remained near its present level since opening of the Port Huron outlet about 4,000–5,000 ya. A similar large delta did not form off the Detroit River. Lake level at 4,000 ya in Lake Erie was several meters lower than at present in the larger, slightly deeper western basin of Lake Erie.

**2) Maumee Spits.** An outer spit extends northward and northwestward from the south shore of Maumee Bay, and an inner spit extends southeastward from the north shore of Maumee Bay. These

features formed during late Holocene time in 2–3 m of water and are thought to be adjusted to present lake level. The spits are formed of sand and gravel deposits, and the intervening areas contain silt and clay muds (Hartley 1960). The Maumee Spits seem to have formed at a rapid rate. Lake history here is short (about 2,000 years) and water depth is shallow.

**3) Reefs Area Spits.** Drowned spits extend to the NW and SE away from the bedrock reefs in the western basin of Lake Erie. These features lie at a depth of 4 to 7 m. The relict spits and the area surrounding the bedrock reefs are underlain by sand and gravel at present (Herdendorf and Braidech 1972), in contrast to deeper mud-filled areas of the western basin. Bathymetry shows that the reefs area in the western basin was formerly an eroding headland and site of net longshore divergence at water depths of 4 to 7 m (Holcombe *et al.* 1997). Judging from the water level history discussed below, these features formed around 2,000–3,400 ya, before being inundated and abandoned.

**4) Point Pelee Spit.** Point Pelee is a symmetrical horn-shaped spit which extends southward into Lake Erie from the Ontario shore and is adjusted to present lake level. Point Pelee Spit is formed of sand brought in from both the west and east by longshore drift. The spit formed in post-Nipissing time (0–4,000 ya) on a morainic foundation (Coakley 1978), at a site of longshore convergence activated when the western basin of Lake Erie was flooded by rising water. Bathymetry and shoreline erosion patterns demonstrate that the Point Pelee spit retreated northward as water level rose.

**5) Point Pelee Ridge.** Point Pelee Ridge is about 6–7 km long, 3–4 km wide, extends southward from Point Pelee, is capped by complex small-scale topography, and lies at a depth of about 5 m. Point Pelee Ridge is interpreted as a former extension of Point Pelee Spit, abandoned as a shoreline feature perhaps about 2,000 ya when rising water level exceeded a few meters lower than present. The feature was apparently part of a longer larger spit along which sand from the Ontario shore was swept southward and deposited.

**6) Point Pelee Fan.** Extending to the east of the Point Pelee Ridge is a small fan which crests at 11–12 m below present lake level, is recognizable downslope to a depth of 18 m, and extends southwestward as far as the Pelee-Lorain Ridge. This feature seems likely to have formed when lake levels were 11–12 m below present lake level, earlier than Point Pelee Ridge, and probably during the events of the Nipissing Rise around 4,000–5,400

ya. Morphology of the Point Pelee Fan suggests a point-source of sediment influx, possibly a river draining the western basin, although a more recent origin, with Point Pelee Ridge as a source of sediments, is not ruled out.

**7) Pelee-Lorain Ridge.** The Pelee-Lorain Ridge rises 1–3 m above the surrounding lake floor and extends 35 km southeastward from Pelee Island almost to the Ohio shore. It lies at a crestal depth of 10–12 m and separates the Sandusky basin from the central basin of Lake Erie. Its crest is broad and hummocky in the southeast, where relief increases to about 2 m, and a NW-SE valley separates the ridge into two segments. It was determined that the southeastern part of the ridge (Hartley 1960) is capped with sand and gravel deposits overlying a foundation of till deposits. Commercial quantities of sand accumulated at the southeastern extremity of the ridge (Hartley 1961). This feature is interpreted as a drowned spit, possibly sited over a low morainic ridge, which formed by southeastward longshore movement of sand from the former shoreline located southeast of Pelee Island and 11–12 m below present lake level. The Pelee-Lorain Ridge would have been an actively forming feature in early Nipissing time (4,000–5,400 ya) when lake levels were 11–12 m lower than at present, and the Sandusky basin was very shallow and separated from the central basin by the Pelee-Lorain Ridge, which formed a peninsula.

**8) Lorain Bank.** A submerged delta-like feature lies opposite the Pelee-Lorain Ridge at 10–12 m water depth off the mouth of the Black River. Mapping (Fuller and Foster 1998) and sediment sampling (Hartley 1961) revealed the presence of glacial till, capped by sand over part of its extent. The sand cover continues upslope to the shore and for 5 to 10 km along the shore in either direction (Pincus 1960). This feature is interpreted as a site of active formation contemporaneous with the Pelee-Lorain Ridge and the Point Pelee Fan. Its origin is uncertain; it may be an old, submerged delta of the Black River, possibly situated on a morainic foundation, or it may owe its formation in part to longshore convergence opposite the terminus of the Pelee-Lorain Ridge.

**9) Pointe Aux Pins.** Pointe aux Pins has the shape and morphology of a cusped foreland. It has been interpreted as a sediment constructional feature formed in a zone of net longshore convergence (Carter *et al.* 1987, Coakley 1992). A succession of beach ridges extends southward parallel to the eastern face of this foreland, and these same beach

ridges intersect with the southwest face of the feature (see Carter *et al.* 1987, p. 156). Patterns of beach ridges suggest erosion on its SW face and incremental addition of successive beach ridges to its SE face (Carter *et al.* 1987). Pointe aux Pins likely formed in post-Nipissing time, is active today, and is adjusted to present lake level. Pointe aux Pins may have initially formed opposite the moraines of Erieau Ridge, located just inland from the point, and slowly migrated northeastward along the shore.

**10) Cleveland Ridge.** Two approximately  $4 \times 8$  km terraces, one at about 15 m depth and one at about 17 m depth, occur on the Cleveland Ridge about 5 km and 10 km from the south shore, respectively. The Cleveland Ridge itself has been interpreted as morainic in origin (Sly and Lewis 1972), and sand and mud deposits, together with some glacial drift, have been mapped in the area (Thomas *et al.* 1976, Fuller and Foster 1998). Location of the terraces associates them with the Cuyahoga River, and their depth clearly points to their formation in pre-Nipissing time. A deltaic origin is suggested.

**11) Fairport Ridge.** A small ( $3 \times 6$  km) terrace at 12–15 m depth and about 5 km from shore coincides with the Fairport Ridge, a NW-SE ridge which extends from near shore out to a depth of 18 m about 10 km from shore. Postglacial sands and muds, and glacial sediments, have been mapped in the area (Thomas *et al.* 1976, Fuller and Foster 1998). This terrace of deltaic aspect lies offshore of the Grand River, and its depth associates it with pre-Nipissing, mid-Holocene time.

**12) Conneaut Bank.** Conneaut Bank is a delta-shaped feature about  $10 \text{ km} \times 15 \text{ km}$  in size, slightly elongated in the longshore direction. Most of its terrace-top resides at a depth of 13–15 m. The feature is capped by small ridges of 1–2 m relief which are linear in approximately the E-W direction, diagonal to the shore. The top of the bank seems to follow a NW-SE broader ridge which is asymmetrical, being steeper toward the northeast. Surficial deposits of sand and/or gravel have been mapped on the top of the Bank (Hartley 1961). Conneaut Bank is interpreted as a delta which formed in middle Holocene, pre-Nipissing time. It is larger than other features of its kind along the south shore of Lake Erie. On the other hand, there are no large rivers entering the lake at this point. This leads to speculation that: 1) early in the Holocene Conneaut Creek, or another nearby stream, may have drained a larger area; 2) sediments on Conneaut Bank could have been augmented by sands transported from the Ontario shore

via Clear Creek and Long Point Ridges; and 3) Conneaut Bank may have been an active delta for a longer period of time than the terraces farther west, because of greater stability of lake levels in this area in the early and middle Holocene (see lake level model and paleogeography discussed below).

**13) Clear Creek Ridge.** Clear Creek Ridge extends for a distance of about 50 km, from the north shore across the lake in a southeastward direction as far as the northern edge of the channel leading from the central to the eastern basin of Lake Erie. First discovered during preparation of new bathymetry (National Geophysical Data Center 1998), Clear Creek Ridge is a narrow linear ridge segmented into longitudinal hills in its northern half. Farther south the morphology of the ridge is broader, more continuous, and more complex, with numerous subsidiary ridges. The ridge has a fairly uniform crestral depth in the range of 16 m, and it lies 5–15 km west of the Long Point-Erie Ridge. Clear Creek Ridge, Long Point, and the Long Point-Erie Ridge are located near prolific sources of easily eroded sand on the Ontario shore (Barnett 1998, Rukavina and Zeman 1987). Clear Creek Ridge probably developed as a spit or bar in the early Holocene (pre-Nipissing time), when water first flooded the central basin. Large quantities of sand were swept southward, creating a peninsula, forming complex topography, and contributing to the sand deposits which occur along the southern reaches of the ridge.

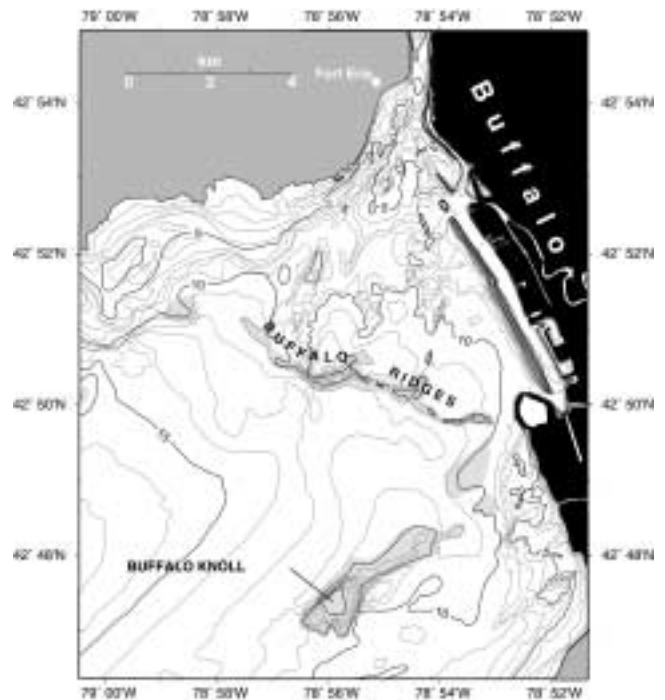
**14) Long Point-Erie Ridge.** Long Point-Erie Ridge, a broad (14–22 km) arcuate ridge of 5–10 m overall relief, extends across Lake Erie from Long Point to the banks of the 5 km wide, 23 m deep channel connecting the eastern basin with the central basin, and it forms the boundary between the two basins. Morphology of this ridge is broader, more complex, less linear, more segmented, and shallower than the Clear Creek Ridge. The ridge is interpreted as a previously existing end moraine which developed about 13,400 ya (Barnett 1998), and which has been referred to as the Norfolk Moraine (Sly and Lewis 1972, Calkin and Feenstra 1985). The ridge formed a peninsula for a lengthy period of time in the early and middle Holocene, when lake water rose into the area, and as a peninsula, it became the site of longshore movement of sands from the Ontario shore southward across the lake floor. The ridge probably continued as an active site for longshore sand movement after sand transport ceased on the slightly deeper Clear Creek Ridge. Crestal depth of this feature is consistently

about 14 m, which was probably its depth prior to being flooded by the Nipissing Rise.

**15) Long Point Spit.** Long Point Spit is actively building and its crestal elevation is adjusted to present lake level. This very large spit extends about 35 km east-southeastward from the Ontario shore out into the eastern Lake Erie basin. It exhibits complex depositional forms including a succession of en-echelon beach ridges diagonal to the main trend of the spit, and smaller, partially submerged small spits extending outward from the north side of the spit. Steep slopes and 55 m of relief, highest lakefloor relief in Lake Erie, separate the spit from the floor of the eastern basin of Lake Erie. It is a 5,000 ya-to-present feature (Coakley 1992) that apparently began to form after flooding associated with the Nipissing Rise inundated the Long Point–Erie Ridge. After flooding, the Long Point–Erie Ridge no longer formed a peninsula which impeded water circulation. Patterns of lake water circulation and longshore drift were apparently altered such that sands from the sand-rich Ontario shore which would have been formerly carried southward along the Clear Creek and Long Point–Erie Ridges were now employed in building and lengthening Long Point Spit.

**16) Presque Isle Bank.** This bank is 5 × 10 km in areal extent. It joins Presque Isle Spit and extends westward from it. Its crestal depth of 8 m is likely an index of water level at the time it was active. Atop this bank is a 1–2 m relief arc-shaped bar which resembles in size, shape, and orientation the main recurved portion of the Presque Isle Spit. Its position suggests eastward shift of the zone of longshore convergence to Presque Isle Spit, from its former position about 7–8 km to the west. Such an eastward shift in the convergence zone of net longshore drift may have been gradual, but more likely it was episodic. This feature likely mirrored the early development of Long Point Spit, only to be later abandoned when the nodal point of longshore convergence shifted eastward as Long Point Spit lengthened. This would place the period of its active development during the Nipissing Rise about 5,000 to 3,500 ya.

**17) Presque Isle Spit.** This feature is presently active and is adjusted to present water level. In morphology Presque Isle has the form of a recurved spit or hook, and has been described as a sand spit. It consists of an offshore bar which follows the arcuate outer shore of the spit facing the lake, and a succession of en-echelon sand ridges, which project shoreward from the main spit. From the pattern of sand



**FIG. 1a.** Bathymetry of the eastern end of Lake Erie showing the Buffalo Ridges and Buffalo Knoll. The two features are highlighted in gray. Contour interval 1 m.

ridges, it is apparent that the spit is eroding from the west and incrementally adding new sand ridges at its eastern extremity (Bolsenga and Herdendorf 1993). The spit is presently migrating eastward, apparently in response to a strong northeastward component of longshore drift (Carter *et al.* 1987).

**18) Buffalo Ridges.** In the northeastern corner of Lake Erie just off Buffalo, features resembling offshore bars and spits occur at depths of 10–12 m (Fig. 1a). The features were first outlined in detail in the new bathymetry (National Geophysical Data Center 1998) and given the name Buffalo Ridges. The ridges connect the offshore ends of three ridges extending southwestward from the Niagara River outlet at Fort Erie, and they form a barrier across the valleys between the headlands formed by the ridges. A similar bar or spit, also at 10–12 m depth, is on trend with the Buffalo Knoll, and extends northeastward away from the knoll. Six shallow basins behind the ridges resemble embayments. The Buffalo Ridges are interpreted as bay bars, extending away from eroded headlands and coalescing, which formed in pre-Nipissing time (5,000–9,000 ya) when water level fell below the level of the outlet sill. Two other possible interpretations are noted.

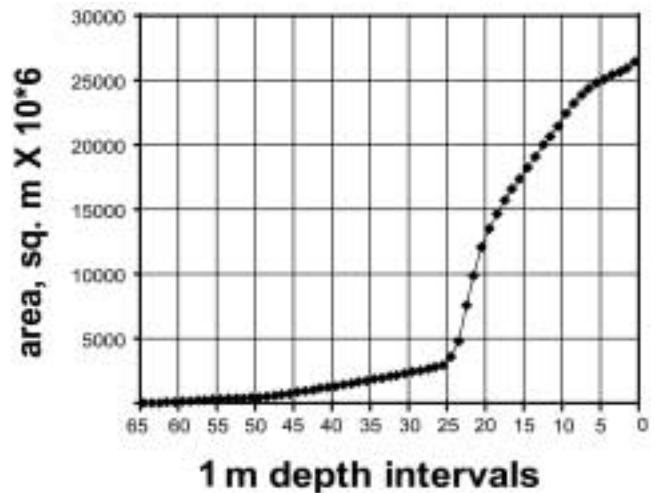
One, the feature could be an end moraine, and the small enclosed shallow basins on the shore side of the feature could be kettles. An inferred connection between the Crystal Beach Moraine in Ontario and the Alden Moraine in New York State (through the southern edge of Buffalo) extends through the area (Calkin and Feenstra 1985). Two, the feature could have formed during repeated bottom scouring and redeposition associated with heavy storms, whose effects at depth may be magnified at the eastern extremity of the lake.

#### LAKE AREA AND LAKE VOLUME AS A FUNCTION OF WATER LEVEL

Rate of increase in lake surface area and lake water volume as a function of rising lake level is simulated by hypsographic curves and cumulative lake water volume curves. These simulations are derived from the overall shape of the Lake Erie basin as it exists today, and they do not take into account 1) amount of infilling by sediments, and 2) amount of differential isostatic rebound, which has occurred in the Holocene. Nevertheless, the hypsometric and water volume computations are instructive in helping to explain Holocene lake level history as a function of overall shape of the lake basin, water budget, and paleogeography.

Surface area of Lake Erie was computed by cumulating the surface areas enclosed by each adjacent pair of 1 m contours projected to the zero datum, beginning with the 63–64 m interval, and ending with the 0–1 m interval. The results of this computation are shown as a cumulative hypsographic curve in Figure 2. The hypsographic curve simulates starting with an empty lake basin and filling it with 1-meter increments of water until the water level reaches the present lake level. In this manner the increase in lake surface area which would be achieved by each 1-meter increase in lake level is measured. The surface area at 0 m, 26,427,000,000 m<sup>2</sup>, or 26,427 km<sup>2</sup>, is the computed surface area of present Lake Erie.

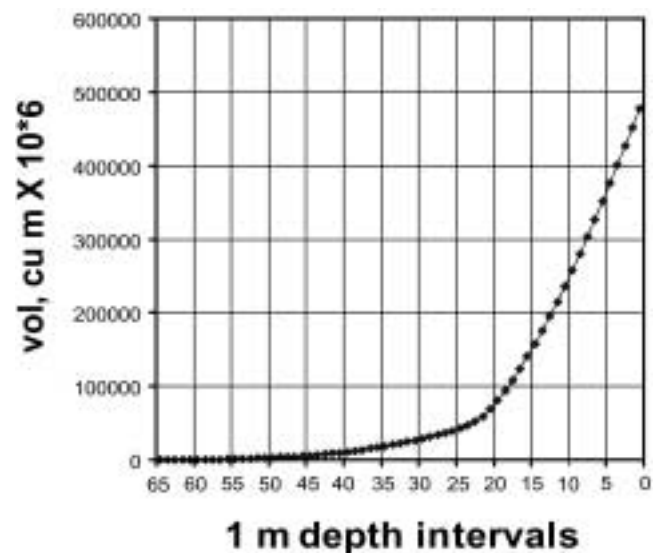
From the 64 m to 24 m depth levels, surface area does not increase at a high rate. At these levels water is confined to the relatively small eastern basin. At the breakpoint observed at 24–23 m depth, surface area increases dramatically with each 1-meter rise in lake level. This accelerated increase in surface area results from the simulated flooding of the large central basin of Lake Erie. Shallower than the 20–19 m interval, the rate of increase in



**FIG. 2.** Surface Area of Lake Erie as a function of lake level. Depicted are the surface areas enclosed by each successive pair of 1-m bathymetric contours, starting with 63–64 m, 62–63 m, 61–62 m, and continuing to 0–1 m depth; and cumulated from 64 m to 0 m.

lake surface area is less dramatic, but the rate of increase still exceeds that of the 64–24 m interval.

Lake volume as a function of lake level was likewise simulated by cumulating successive volumes of 1-meter layers of water stacked one upon the other, beginning with the 63–64 m layer and contin-



**FIG. 3.** Water Volume in Lake Erie as a function of lake level. Depicted are water volumes of successive stacked 1-meter-thick layers of lake water, cumulated from 63–64 m depth to 1–0 m depth.

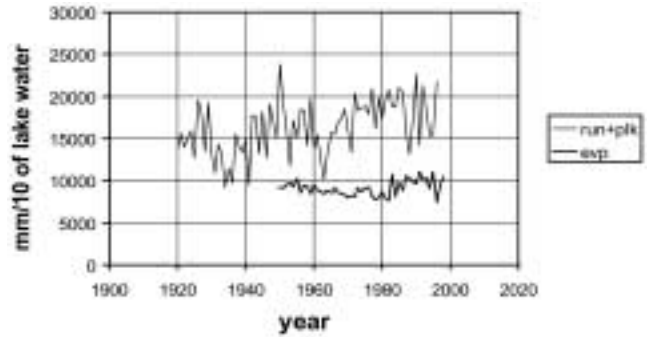
uing upward to the present lake surface (Fig. 3). Volume of each 1-meter layer is adjusted for bottom slope along its edges. The cumulative total is the computed water volume of present Lake Erie, 478,074,000,000 m<sup>3</sup>, or 478.074 km<sup>3</sup>. Increase in water volume accelerates at 25–20 m as does surface area, and for the same reasons. Unlike lake surface area, the incremental increase in cumulative water volume continues to accelerate as water level rises from 15 m to 0 m.

### LAKE WATER BUDGET

Quantitative measurements and estimates of the present water budget are of profound importance to understanding the water-level history of Lake Erie in the Holocene. Present-day water budget measurements and estimates for Lake Erie appear in spreadsheet form on the NOAA Great Lakes Environmental Research Laboratory website: <http://www.glerl.noaa.gov/data/arc/hydro/mnth-hydro.html>

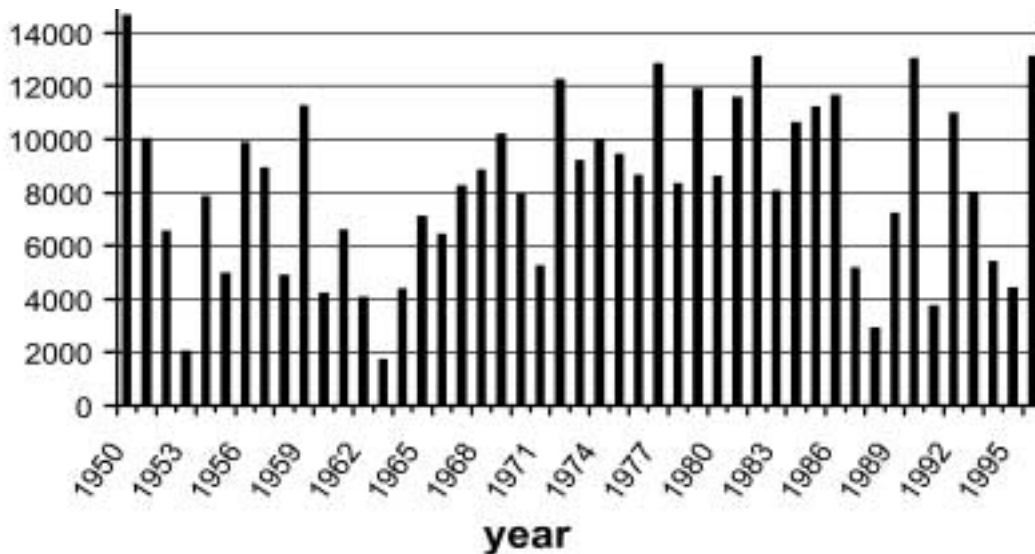
Highlights of the present Lake Erie water budget have been presented and discussed (Quinn and Guerra 1986).

Annual totals of runoff and over-lake precipitation (run+plk) from 1920–1996 are compared with annual total of evaporation (evp) from 1950–1998, as shown in Figure 4. These annual totals are from the Lake Erie drainage basin exclusive of Detroit River inflow. Evaporation exceeded the lowest historic (run+plk) during nine of the past 48 years. If



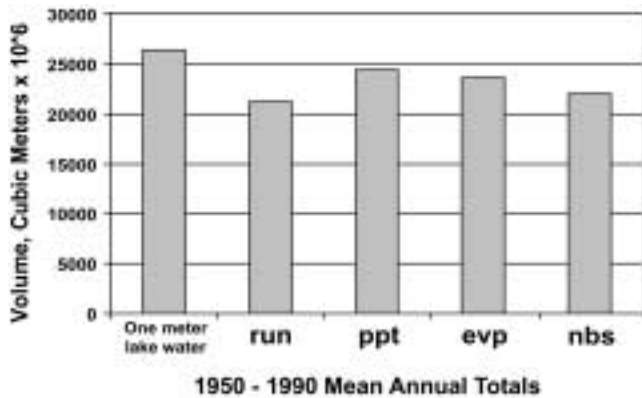
**FIG. 4.** Annual totals of Lake Erie drainage basin runoff + lake surface precipitation (run+plk), 1920–1996, compared with lake surface evaporation (evp), 1950–1998. Values are expressed in tenths of mm of lake water at present lake levels. Thin line is run+plk, heavy line is evp. Runoff from the Detroit River is not included in these annual totals.

historically high evaporation should occur in the same year as historically low precipitation, the condition would exist today for Lake Erie water level to fall below the outlet sill, if Detroit River runoff were not included in the water budget. The annual total of net basin supply (nbs=run+plk-evp) from 1950–1996, has remained positive though highly variable, as shown in Figure 5. It is apparent from Figure 5 that net basin supply could go negative



**FIG. 5.** Lake Erie annual total net basin supply (nbs = run+plk-evp) 1950–1996. Values are expressed in tenths of mm of lake water at present lake levels. Detroit River runoff is not included in these annual totals of nbs.





**FIG. 6.** Volume of 1 m of surface lake water, compared with 1950–1990 mean annual totals: runoff, over-lake precipitation, evaporation, and net basin supply. Values are expressed in millions of cubic meters. Detroit River runoff is not included in the annual totals. The volume of 1 m of lake water is computed for present lake level at the Lake Erie low water datum.

even today during an extraordinarily hot, dry, windy year, again assuming no Detroit River flow.

The 1950–1990 means of annual total water volume of runoff, over-lake precipitation, evaporation, and net basin supply, for the Lake Erie drainage basin exclusive of Detroit River inflow, shown in Figure 6, are all about the same magnitude. There is considerable variability from year to year, but even without Detroit River water being included, present net basin supply contributes enough water most years to raise water level of Lake Erie by almost 1 m in a year, enough to completely fill the lake basin in less than 20 years. Net basin supply is especially variable from year to year. Annual variations in runoff and/or precipitation and/or evaporation over the lake basin combine to have a large effect on the variability of net basin supply. Mean annual runoff carried by the Detroit River for 1940–1979 was about  $170,000 \times 10^6$  cubic meters (Quinn and Guerra 1986), or about  $8 \times$  runoff originating from within the Lake Erie drainage basin.

Considering the main features of today's Lake Erie water budget, as outlined above and illustrated in Figures 4–6, the following observations relate to the understanding of Holocene lake levels:

- 1) The amount of runoff entering present Lake Erie from the upper Great Lakes is almost an order of magnitude greater than that entering Lake Erie from the local drainage basin.

- 2) An amount of water equal to the entire present water capacity of the lake is supplied by the Detroit River in about 2 years.
- 3) An amount of water equal to the entire present water capacity of the lake is supplied by the local net basin supply in about 20 years.
- 4) The uppermost 10 m of Lake Erie water could be supplied by the Detroit River in little over a year, or by the local drainage basin in less than 10 years.
- 5) Lake surface evaporation is a significantly large term which during today's driest years would be large enough to equal over-lake precipitation plus drainage basin runoff, if the water contribution from the upper Great Lakes is not included.
- 6) Lake surface evaporation is directly proportional to lake surface area for a given climatic condition.
- 7) Lake Erie evaporation may have exceeded drainage basin runoff plus over-lake precipitation for long periods of time during the middle Holocene prior to the Nipissing Rise. During the middle Holocene (about 9–6 ka), climate models and paleoclimate data (pollen, lake levels) reveal warmer temperatures and greater aridity, compared to present, in the continental interior of North America (Webb *et al.* 1993). Summer insolation in the northern hemisphere exceeded that of today by 4 to 7 % (Kutzbach and Webb 1993).
- 8) Lake level rises resulting from greater humidity and lower temperatures, or from significant amounts of water entering Lake Erie from the upper Great Lakes, should appear as relatively rapidly occurring events in the Holocene record.

#### **DID LAKE ERIE BECOME A CLOSED LAKE BASIN IN EARLY AND MIDDLE HOLOCENE?**

The likelihood that Lake Erie resided within a closed lake basin in the early Holocene and possibly middle Holocene was recognized by Lewis (1999), who cited deeply-buried shoreline morphology and an unconformity in the eastern basin of Lake Erie as evidence. Lewis (1999) also computed sustainable lake-areas for Lake Erie, using the Bengtsson and Malm (1997) model and estimates of early Holocene paleoclimate, and found that the computed sustainable areas were less than projected

open-water lake areas for the early Holocene (9,500–7,000 ya).

Bengtsson and Malm (1997) discussed water budget within closed lakes, and the (run+plk-evp) conditions necessary for closure, and they presented equations for computing sustainable lake area in a closed lake if drainage basin area, drainage basin runoff, over-lake precipitation, and evaporation are known or estimated.

Another large lake in the continental interior of North America that probably existed within a closed basin during early and middle Holocene is Lake Winnipeg. Lewis *et al.* (2001) found evidence for closed lake basins and desiccation in seismic reflection data and cores obtained from this lake. From drainage basin areas and climate estimates they derived a sustainable lake-area model for the north and south basins of Lake Winnipeg. Their model (Lewis *et al.* 2001) projects a closed lake basin at approximately 8,300–5,300 ya.

Our exercise in reconstructing lake level history and paleogeography of Lake Erie, based on new bathymetry which reveals details of former shoreline features now submerged in Lake Erie, also leads us to seriously consider that Lake Erie was a closed lake basin in the early and middle Holocene.

For the early and middle Holocene we propose the following scenario for consideration. At first the central basin was the site of a small isolated lake separated from the lake in eastern Lake Erie by the sill in the Pennsylvania Channel (Pennsylvania Sill); later, as isostatic rebound progressed, rising water flooded the Pennsylvania Sill and formed a single lake. As the central basin was flooded, surface area of the lake increased. A very large increase in lake surface area was accomplished with only a few meters rise in lake level, as illustrated in Figure 2. Increase in the surface area of the lake proportionately increased evaporation (evp) relative to precipitation (plk) plus runoff (run). Increased evaporation as well as reduced precipitation during the 9,000–6,000 ya climate optimum (Webb *et al.* 1993) favored reduction of lake level below the level of the Lake Erie outlet sill. It seems likely that Lake Erie remained a closed lake basin for an extended period of time.

During the early and middle Holocene (10,300–5,400 ya), except for pulses of upper Great Lakes water (such as the Mattawan high-water event at about 8,500 ya), water supply for Lake Erie was limited to the Lake Erie drainage basin. Lake level was controlled by the Lyell-Johnson Sill,

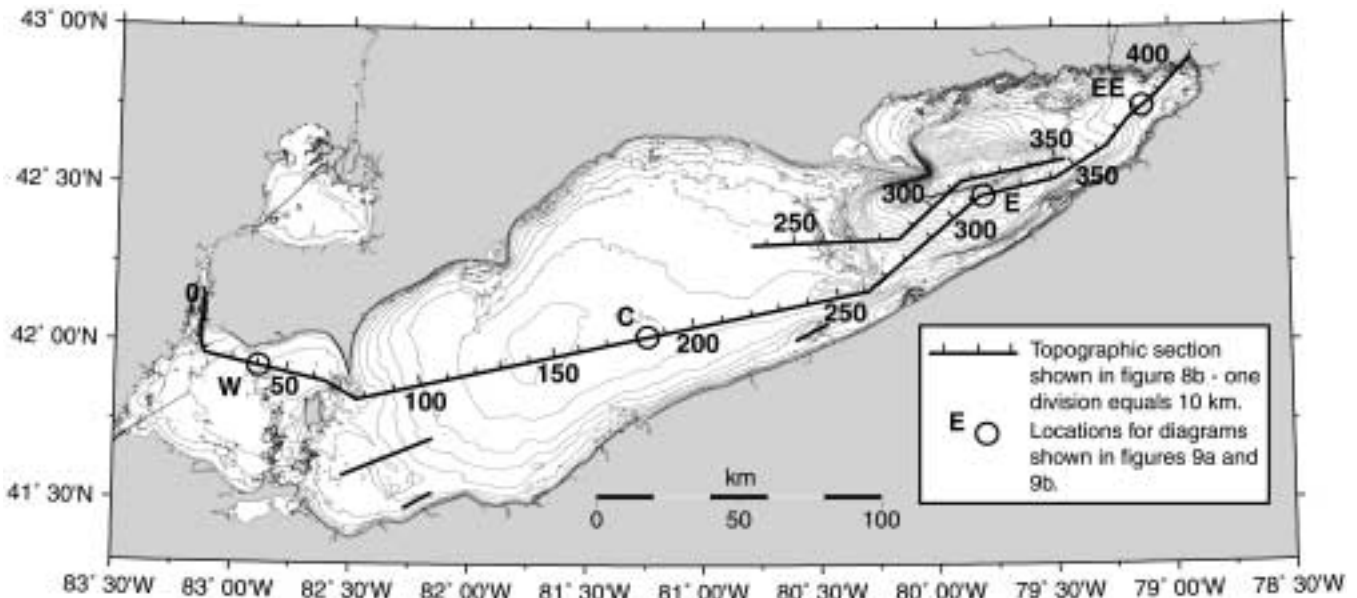
which was at a higher elevation than the Fort Erie Sill (Tinkler *et al.* 1994).

During the lengthy period Lake Erie is projected to be within a closed basin, water level undoubtedly fluctuated, but remained below (12–18 m?) today's level. Lake floor topographic features in the vicinity of the Long Point-Erie Ridge (Fig. 1) require water levels in this range for their formation. A number of radiocarbon dates show a long period of lake levels about 15 m lower than at present (Coakley and Lewis 1985). Control of water level by the water budget in a closed low-water basin, is compatible with a smooth decay in isostatic rebound as favored by isostatic rebound models of the Great Lakes region (Clark *et al.* 1994), and does not require a start-stop model. Throughout this period, the western basin probably remained mostly as dry land but with separate small marshes and lakes in several small basins (Coakley and Lewis 1985).

In the closed-lake scenario for Lake Erie, water level and lake area were held between upper and lower limits, in equilibrium with the water budget (run+plk-evp). Rising water level would have increased lake surface area and correspondingly increased the evaporation term, whereas runoff + over-lake precipitation would have remained constant. Water level would have been prevented from rising above the level at which the water budget (run+plk-evp) became negative. Lowering water level would have reduced lake surface area and correspondingly reduced the evaporation term, preventing water level from falling below the level at which the water budget becomes positive.

If the Buffalo Ridges (Fig. 1a) are in fact drowned shoreline features, this would constitute evidence that lake level did indeed fall below the level of the outlet sill. Morphologically the features resemble bay bars enclosing valleys between the NE-SW ridges which extend away from the area of the outlet sill. The bar complex is continuous across the ridges, which appear to be truncated. This suggests that the lake shore remained at about this level for a sufficient length of time to erode and straighten the headlands, but as recounted earlier, other interpretations are possible. The geomorphology of the Buffalo Ridges is one of the intriguing questions of Lake Erie geology remaining to be answered.

Twelve of the eighteen depositional features described in this paper are interpreted as having formed in the shore zone at lower lake levels. Once their period of active formation ceased, it seems unlikely that these features could long survive in a



**FIG. 7.** Longitudinal Lake Erie section lines shown in Figures 8a and 8b, and sites of postulated lake level histories illustrated in Figure 9. Distance along section lines is shown in kilometers. Sites of postulated lake level histories are labeled W, C, E, and EE. Geographic locations are W ( $41^{\circ} 54'N$ ,  $82^{\circ} 45'W$ ), C ( $42^{\circ} 02'N$ ,  $81^{\circ} 06'W$ ), E ( $42^{\circ} 33'N$ ,  $79^{\circ} 43'W$ ), and EE ( $42^{\circ} 48'N$ ,  $79^{\circ} 00'W$ ).

high-energy shore zone characterized by slowly rising water levels under the control of differential isostatic rebound. Rapid rise in lake level was needed to rapidly inundate these features before they could be reduced by shore zone erosion. This strengthens the argument in favor of lake levels about 10 m below the level of the outlet sill for considerable periods of time, followed by rapid rises in lake level in response to alterations in the water budget which favor such rise.

It has been commonly assumed that the Nipissing Rise in Lake Erie is associated with diversion of upper Great Lakes outflow from the North Bay and Chicago outlets to the Port Huron outlet. However, if water level fell below the level of the outlet sill in early Holocene time, a climate-driven return of water level to the level of the outlet sill could have been a significant rising water event. On the other hand, if water level remained at the level of the outlet sill through the mid-Holocene, then the introduction of upper Great Lakes water would be expected to raise water level by only an estimated 3 to 3.5 m (estimate based on today's elevation difference between the Lake Erie low water datum and the sill level at Fort Erie).

Figure 7 is an index map which shows the location of sections shown in Figures 8a and 8b, and

sites of lake level history simulations shown in Figure 9. Figure 8a illustrates inferred synchronous lake levels for three conditions which may have existed before and during the Nipissing Rise: 1) water budget negative, lake level 10 m below the level of the (Lyell-Johnson) outlet sill; 2) water budget weakly positive, no upper Great Lakes water, lake level adjusted to the level of the outlet sill; and 3) water budget strongly positive, includes upper Great Lakes water, lake level adjusted to the level of the outlet sill. In Figure 8a, the solid green line is a longitudinal end-to-end topographic profile of Lake Erie along the section line shown in Figure 7. Profiles of nearby topographic features are projected onto the plane of this section, including the Buffalo Ridges, eastern Lake Erie basin, Long Point-Erie Ridge, Clear Creek Ridge, Conneaut Bank, Pelee-Lorain Ridge, and Lorain Bank. The solid orange line approximates the buried interface between postglacial Holocene deposits above and glacial/ glacio-lacustrine deposits below, as previously mapped by Lewis (Lewis *et al.* 1966, Sly and Lewis 1972). Amount of sedimentation vs. time in the Holocene was interpolated linearly between the buried interface, interpreted to represent lake level at the beginning of Holocene, and the present lake floor. The interpolated sedimentation vs. time was used 1) to

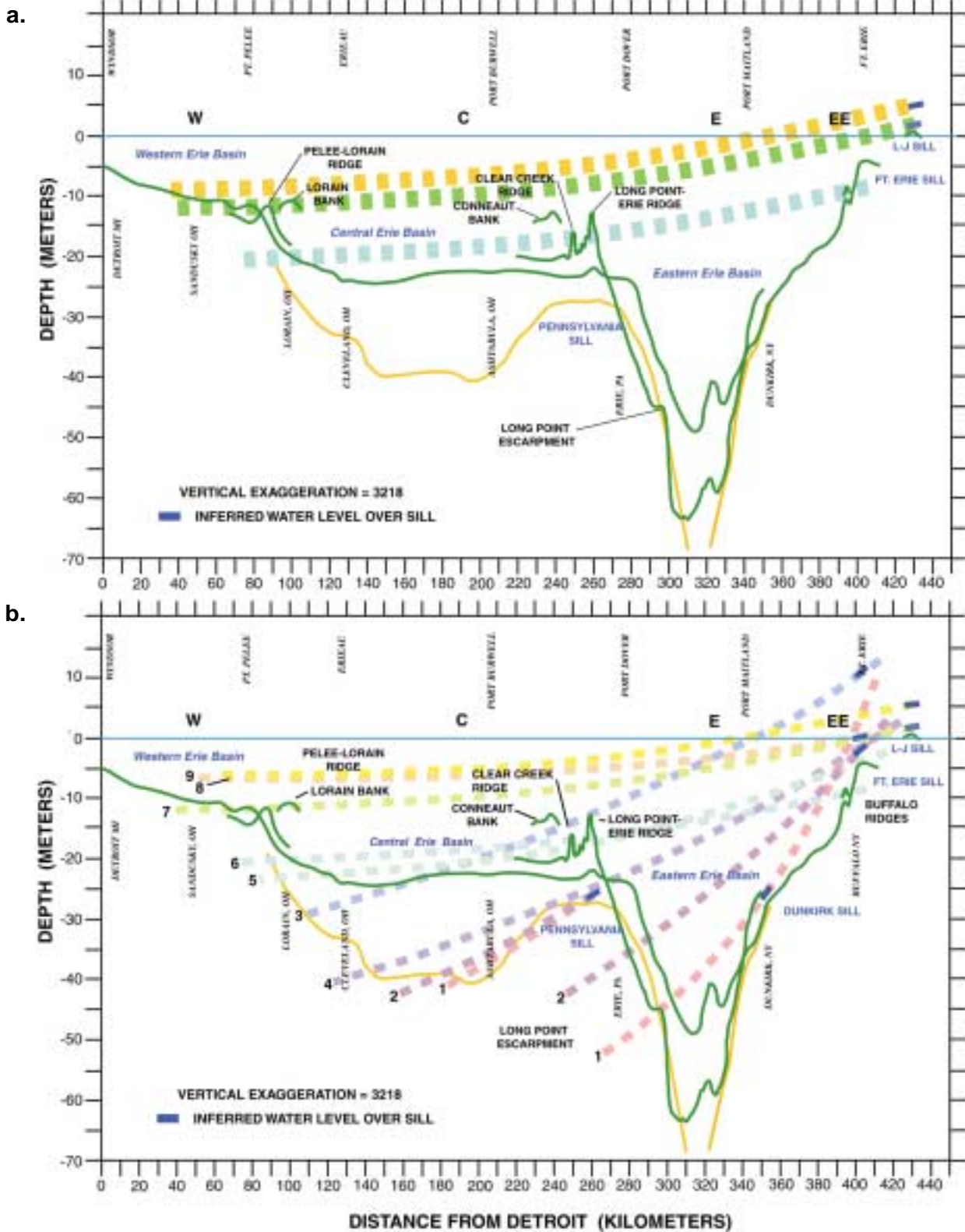


FIG. 8. a. Water planes for three possible lake levels in mid-Holocene time. Refer to text for additional explanation. b. Schematic model of lake levels at successive times during the Holocene. Refer to text for additional explanation.

estimate local depth as a function of time in Figure 9, and 2) to refine estimates of paleogeography shown in Figure 10. The three dashed lines show inferred water planes simulating three different lake levels at about Nipissing time. The blue dashed line shows inferred water plane for a pre-Nipissing lake, which has fallen 10 m below the level of the outlet sill. The green dashed line shows inferred water plane adjusted to the level of the outlet sill, but with the water supply limited to that coming from the Lake Erie drainage basin. The orange dashed line shows inferred water plane adjusted to the level of the outlet sill, but with the water supply including water from the upper Great Lakes.

In Figure 8b, the postulated former water levels (labeled 1 through 9) are sketched on a longitudinal topographic section through the deep axis of Lake Erie, to approximately agree with topographic features which are thought to be a record of the previous levels of shorelines. Positioning of each level also takes into account isostatic rebound models (Clark *et al.* 1994); the present position of the Lake Whittlesey and other shorelines as shown in Coakley and Lewis (1985); and lake level histories outlined in Barnett (1985), Calkin and Feenstra (1985), Pengelly *et al.* (1997), and Lewis (1969). Lake level 1, two lakes, one in the central Lake Erie basin and one in the eastern Lake Erie basin, were controlled by the Pennsylvania Sill and the Dunkirk Sill respectively. They are assumed to have about the same west-to-east elevation gain as the Lake Whittlesey shoreline, but are at a low elevation associating them with the Ypsilanti lowstand (Kunkle 1963), and are therefore assigned a time of 13,400 ya. Lake level 2, two lakes, are adjusted to the Pennsylvania Sill and the Fort Erie Sill, and are assigned an age of around 12,000 ya. Lake level 3, now a single lake, coincides with the highstand of Main Lake Algonquin and is assigned an age of 10,400 ya. Lake level 4 coincides with the beginning of the pre-Nipissing lowstand, before water occupied a significant area of the central Lake Erie basin, and before the shift to the Lyell-Johnson Sill; it is assigned an age of 10,300 ya. Lake level 5 illustrates a time about midway into the pre-Nipissing lowstand, after the central basin was flooded, and after lake level had fallen below the sill and consequently was controlled by the water budget; it is assigned an age of 7,500 ya. Lake level 6, adjusted to lakefloor features which occur all around the lake, and influenced by the Clark *et al.* (1994) and Larsen (1985) pre-Nipissing isostatic rebound models for Lake Michigan, is believed to represent

the period before the Nipissing Rise, and is assigned an age of 5,400 ya. Lake level 7 represents an early Nipissing Rise event prior to the main introduction of upper Great Lakes water, but after water level has risen to the level of the Lyell-Johnson outlet sill. It is assigned an age of 5,300 ya. Lake level 8 represents the Nipissing Rise, after introduction of upper Great Lakes water but before significant erosion of the Lyell-Johnson Sill. It is assigned an age of 3,600 ya. Lake level 9 represents a lower lake level resulting from erosion of the Lyell-Johnson Sill, and return of control of lake level to the Fort Erie Sill. It is assigned an age of 3,000 ya.

The locations for the sites depicted in Figure 9 are shown in Figure 7, and are labeled W (western Lake Erie) and C (central Lake Erie) (Fig. 9a), as well as E (eastern Lake Erie), and EE (near the outlet sill) (Fig. 9b). For Figure 9, low lake levels are inferred from location and depth of diagnostic bathymetric features, from the Clarke *et al.* (1994) isostatic rebound model, and from previous reconstructions of lake level history (Lewis 1969, Sly and Lewis 1972, Barnett 1985, Coakley and Lewis 1985). High lake levels and sill evolution are adapted from Pengelly *et al.* (1997) and Barnett (1998). Highstands in chronological order are 1) the series of short-lived glacial Lakes Maumee and Arkona (levels for each lake not shown), pre-13,600 ya; 2) the series of short-lived glacial Lakes Whittlesey, Warren, Wayne, Grassmere, and Lundy (levels for each lake not shown), 13,000–12,500 ya; 3) early Lake Algonquin, 12,000–11,600 ya; main Lake Algonquin, 11,000–10,400 ya; 4) main Mattawan, 8,500 ya; and 5) Nipissing, 5,400–3,600 ya. Lowstands in chronological order are 1) Ypsilanti low, 13,600–13,000 ya; 2) unnamed low, 12,500–12,000 ya; 3) Kirkfield low, 11,600–11,000 ya; and 4) pre-Nipissing Lake Erie 10,400–5,400 ya. Beginning with the Ypsilanti lowstand, lake level was controlled by the Dunkirk Sill, but by the time of the Kirkfield lowstand, lake level was controlled by the Fort Erie Sill. At about the time lake level fell following the main Algonquin highstand, the rising Lyell-Johnson Sill began to control lake level. With further isostatic rebound and lake level rise during 10,400–5,400 ya, lake water occupied a large area of the central basin, and lake level fell below the sill, controlled instead by the water budget during this period, when climate was warmer and drier than at present (Webb *et al.* 1993). This regime continued, with one or two pulses of high

a.

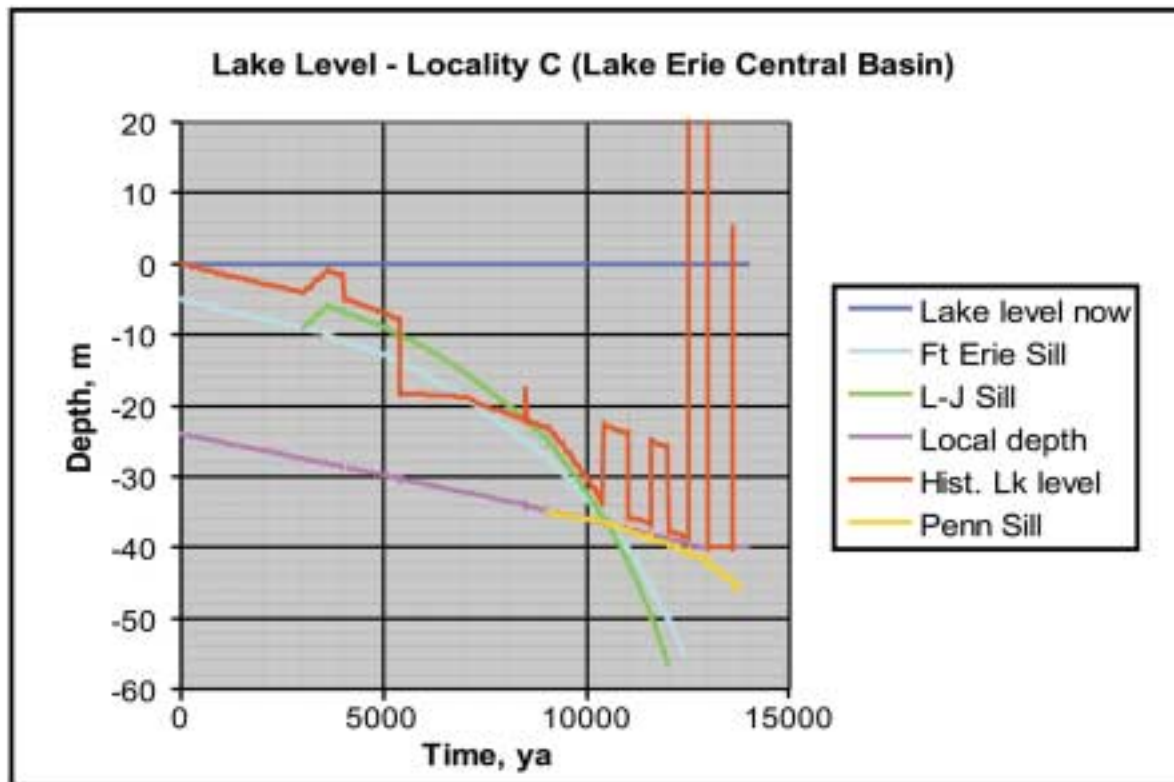
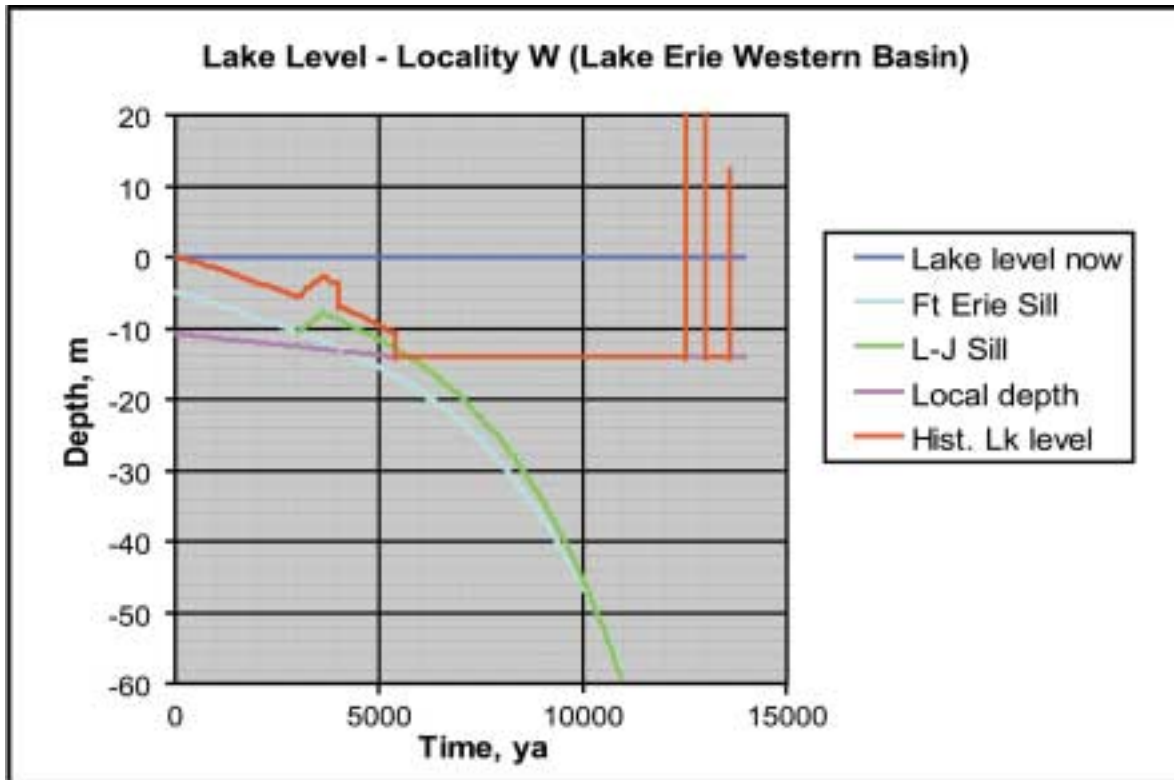
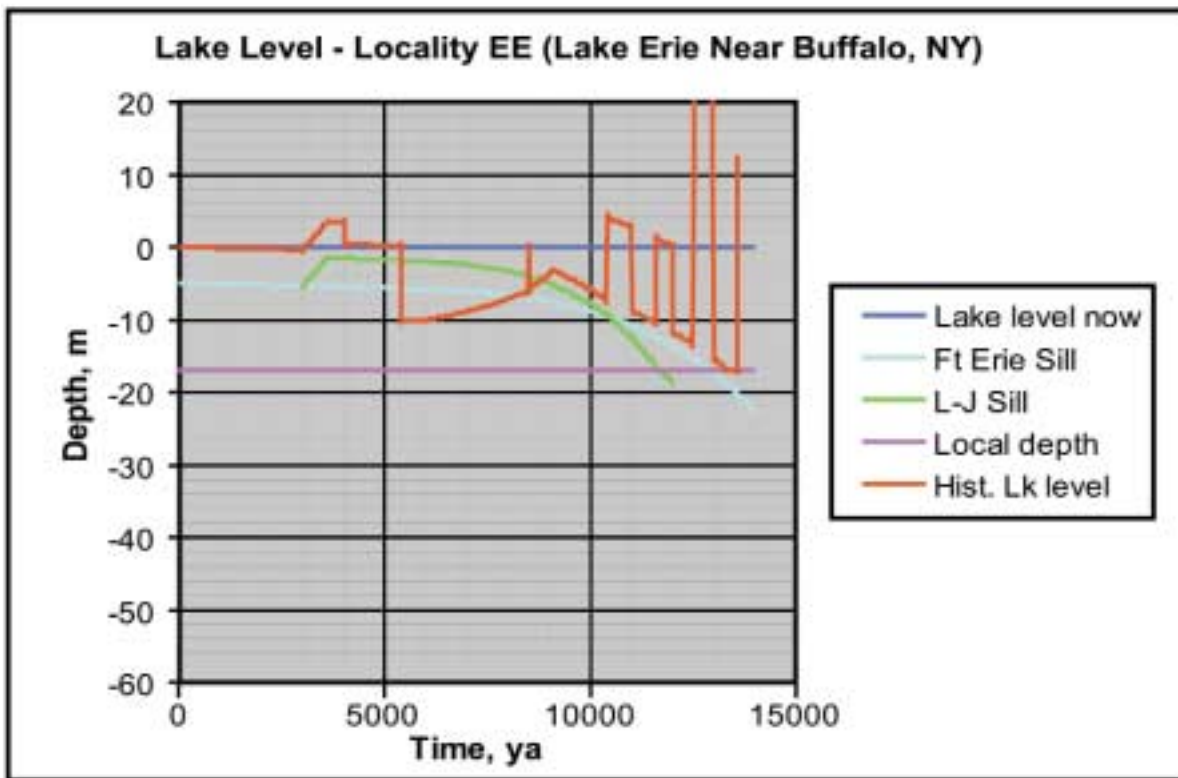
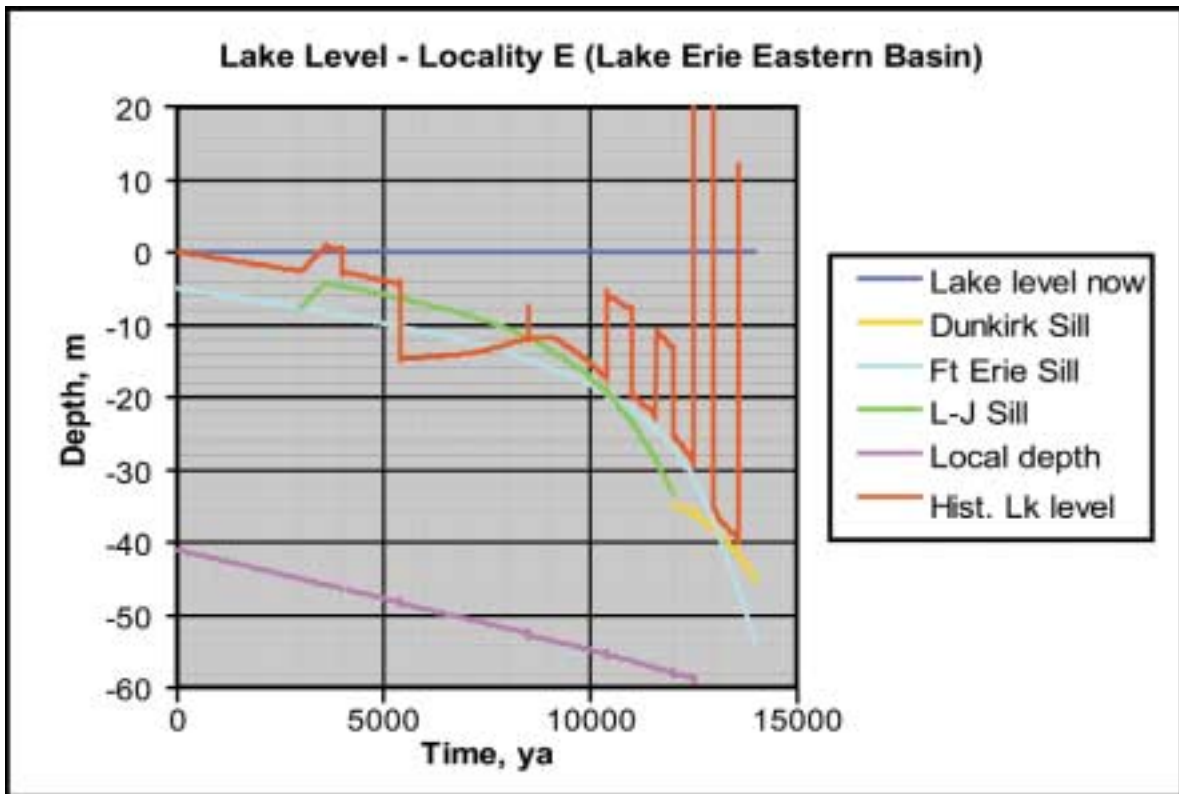
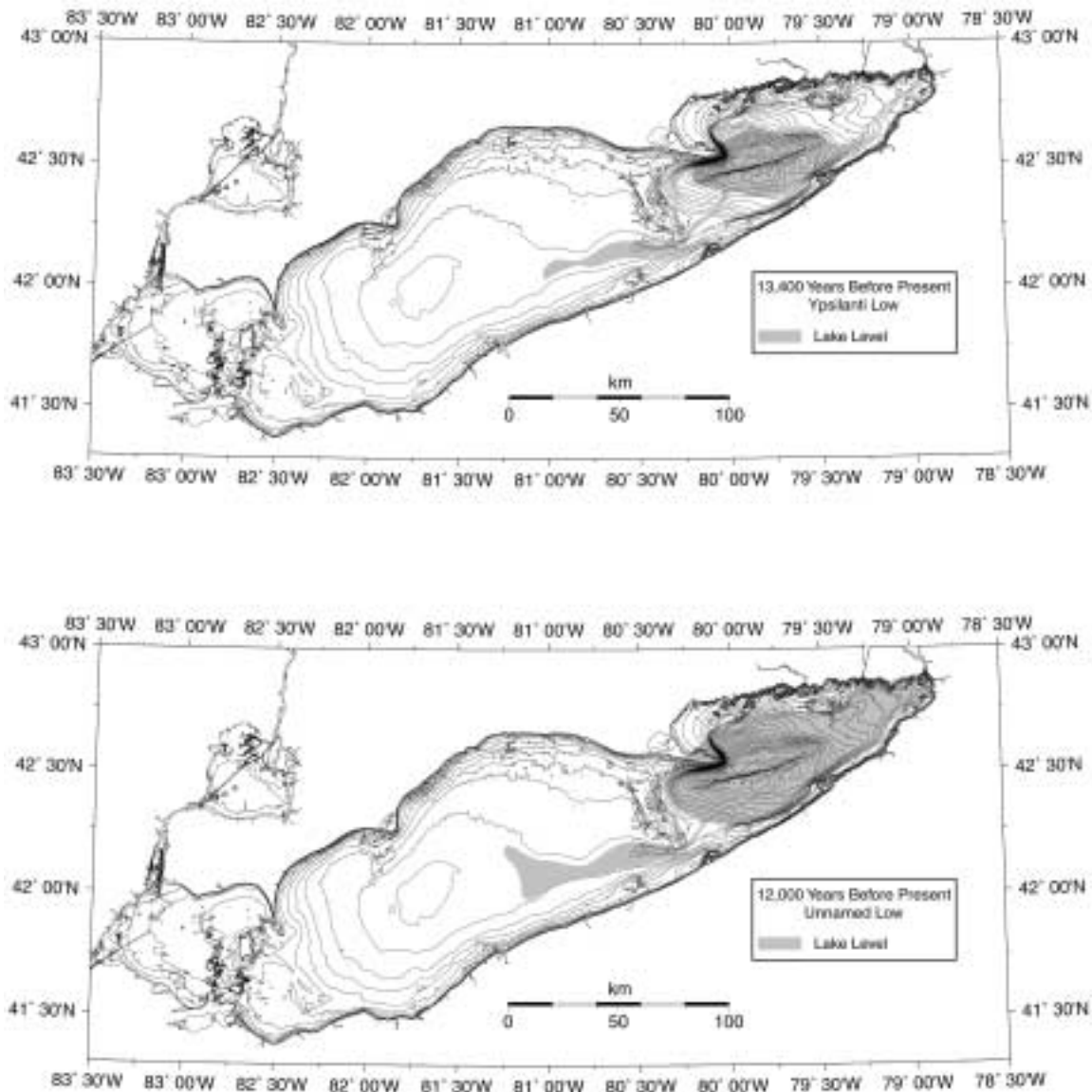


FIG. 9. Schematic model of Holocene lake level history at four locations: in the western, central, and eastern Lake Erie basins; and near the outlet sill in the eastern end of the lake. The locations for the sites depicted in Figure 9 are shown in Figure 7, and are labeled W (western Lake Erie) and C (central Lake Erie) (Fig. 9a), as well as E (eastern Lake Erie), and EE (near the outlet sill) (Fig. 9b). Refer to text for additional explanation.

b.





**FIG. 10.** *Postulated paleogeography of Lake Erie at nine selected times which are representative of the entire postglacial period from 13,600 ya to present. Refer to text for additional explanation. Figure 10 continued on next four pages.*

water over the Port Huron Sill (Mattawa high-stands), until changing climate and/or introduction of upper Great Lakes water initiated the Nipissing Rise, which returned water level to the level of the Lyell-Johnson Sill. Water level was elevated again by return of large-scale upper Great Lakes drainage about 4,000 ya. Water level then began to fall, as the Lyell-Johnson Sill was eroded, lowering water level onto the Fort Erie Sill, which controlled lake level from then until present.

Lake-level changes are represented as rapidly occurring events.

### RECONSTRUCTION OF HOLOCENE LAKE LEVEL HISTORY

Locations and depths of bathymetric features in Lake Erie which are indicators of present and historic lake levels (Fig. 1), together with relevant area (Fig. 2), volume (Fig. 3), and water budget data (Figs. 4–6), further constrain the postglacial lake



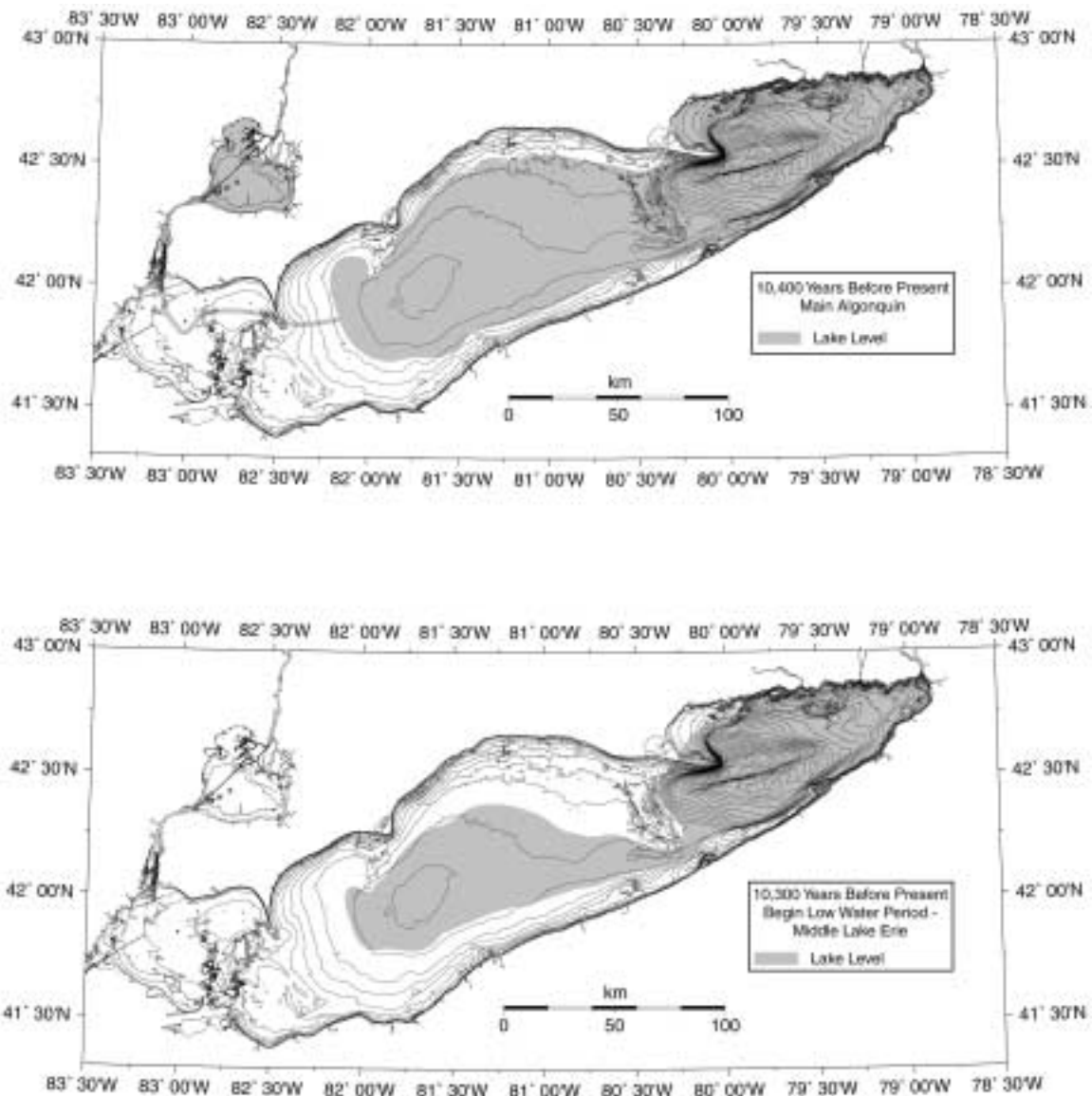


FIG. 10. Continued.

level history of Lake Erie. These additional data make reconstruction of Holocene lake levels a useful exercise, when previous reconstructions and existing lake level information are also taken into consideration. Toward this end we have developed a schematic model. This model, though elaborate, leaves questions unanswered, contains elements of speculation, and is undoubtedly simplified in comparison to the actual unfolding of events. Even so, we believe that it is a reasonable model which contributes to further understanding of Lake Erie's Holocene geology and lake level history.

The model incorporates the following features:

1. During earliest postglacial time (13,600–12,000 ya), lake level oscillated between very low levels, when the Niagara outlet was open but isostatically depressed, and very high levels, when the Niagara outlet was blocked by ice and outflow was toward the west.
2. Lake level rose and fell rapidly in response to blocking, unblocking, or erosion of the outlet sill; whether upper Great Lakes water passed through Lake Erie or bypassed it; and changes in the water budget. Large water budget terms, compared to the volume of 1 m of surface lake water (Fig. 6), support this statement.

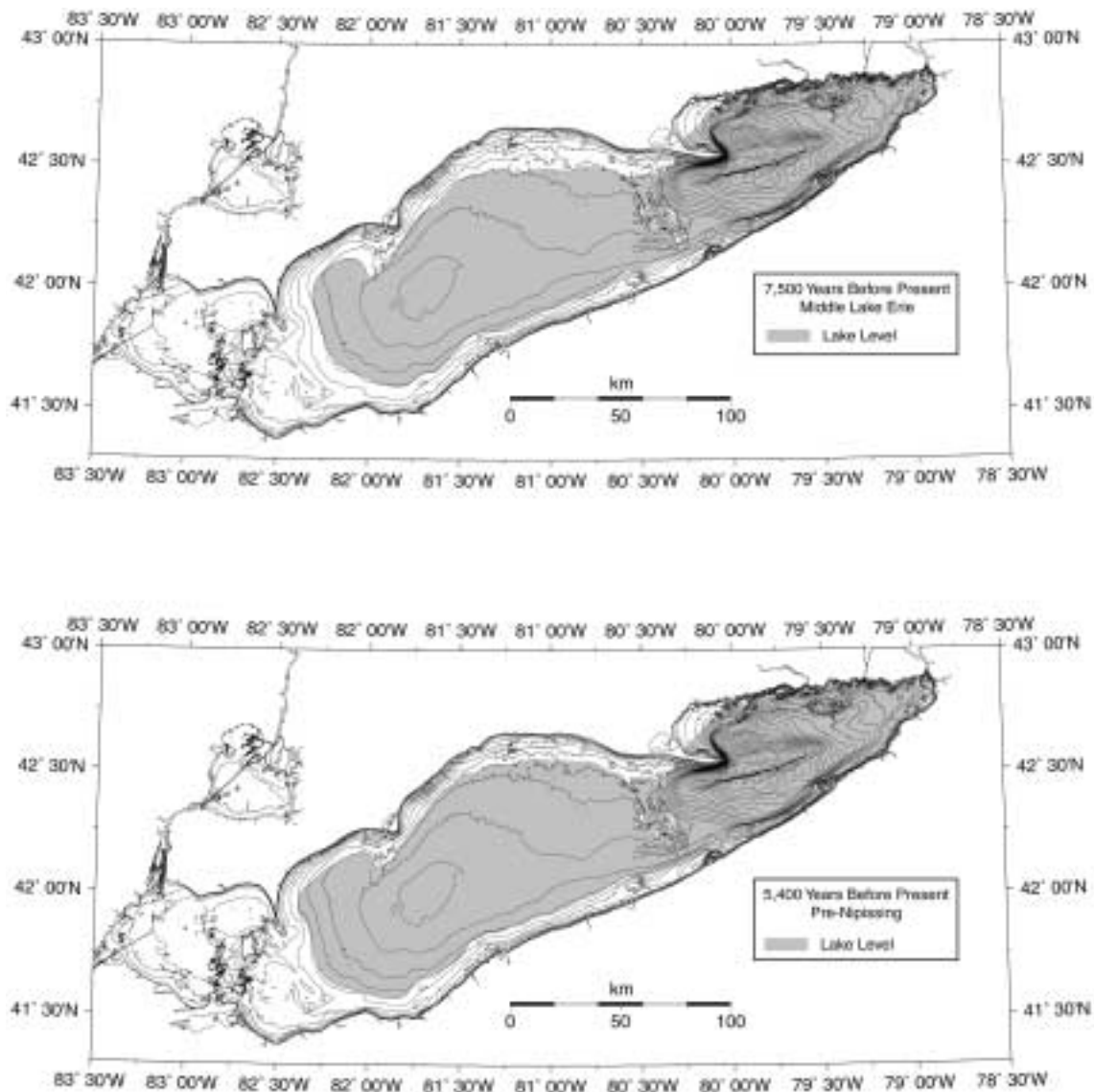


FIG. 10. *Continued.*

3. Lake level fell below the level of the outlet sill during substantial intervals of the first half of Holocene time, 10,300–5,400 ya, most likely during the period 9,000–6,000 ya, when climate was warmer and drier than at present.
4. Also contributing to a low water level during about 9,000–6,000 ya was flooding of the central basin of Lake Erie as isostatic rebound continued, greatly increasing lake surface area (Fig. 2) and concomitantly increasing lake surface evaporation (the negative term in the water budget).
5. The early Nipissing Rise (Nipissing I), about 5,400 ya (?), resulted when lake level, which formerly had fallen below the level of the outlet sill, was restored to the level of the Lyell-Johnson outlet sill, as climate became less arid and the water budget became positive. Small and variable influx of upper Great Lakes water may have entered the Lake Erie basin at times over the next thousand years. Low-water depositional features previously formed in Lake Erie (Bay bars off Buffalo, Clear Creek Ridge, Long Point–Erie Ridge, Conneaut Bank, Fairport Ridge, Cleveland Ridge) were flooded at this time. Water circulation patterns changed, and Long Point Spit began to form.
6. Later, about 4,000 ya (?), an additional rise in

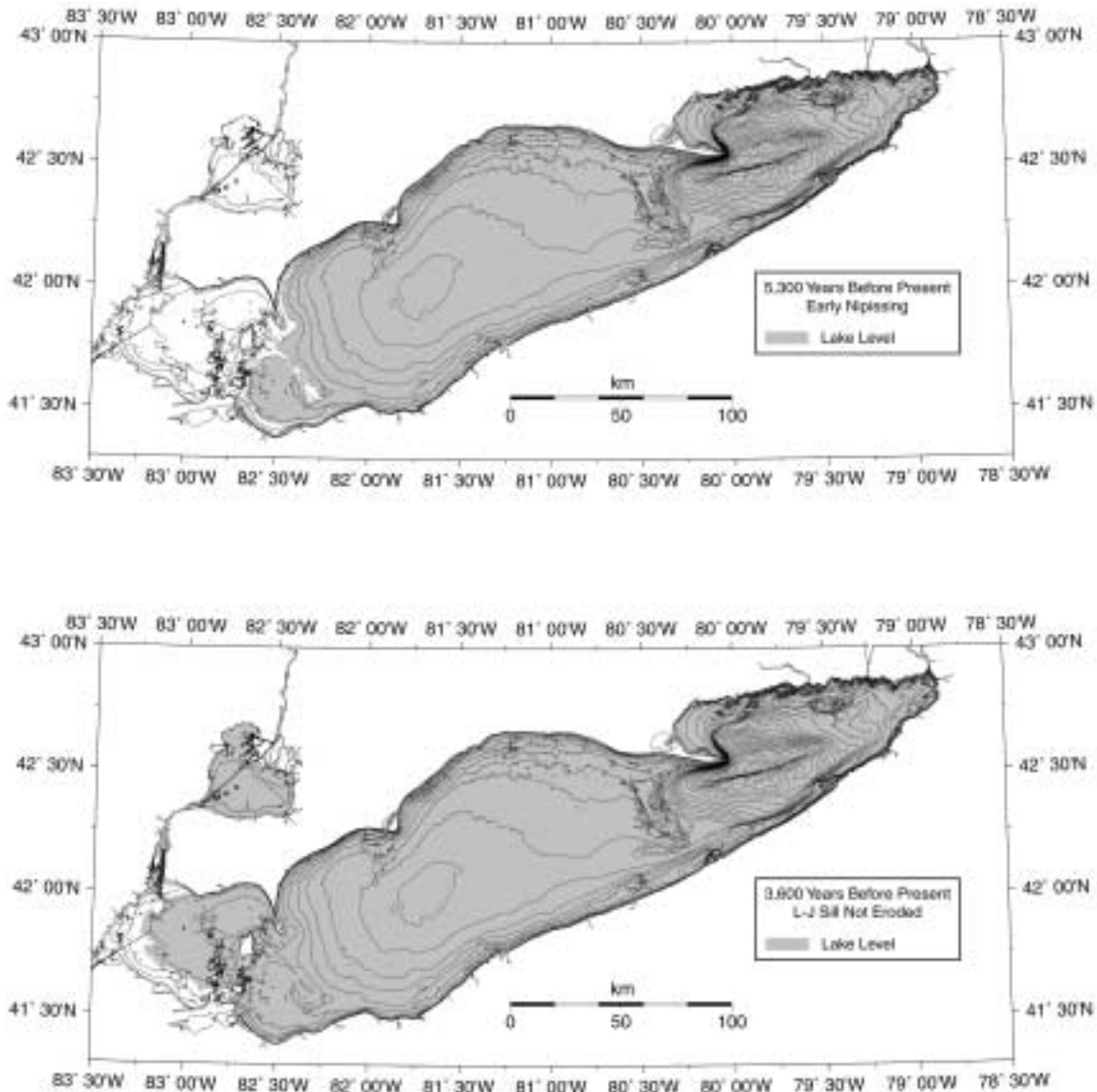


FIG. 10. Continued.

lake level (Nipissing II) resulted from the final introduction of large volumes of upper Great Lakes water into Lake Erie. At this time the western basin of Lake Erie was flooded. Also flooded were the younger and shallower depositional features which had formed in central and western Lake Erie (Pelee-Lorain Ridge, Point Pelee Fan, Lorain Bank, Presque Isle Bank). The youngest, and presently active, depositional features of Lake Erie began to form at this time (Point Pelee, Pointe aux Pins, St. Clair Delta, Maumee Spit).

7. Water levels in eastern Lake Erie were slightly higher than at present. Lake level was lowered

several meters during the interval 3,600–3,000 ya by headward erosion of the Niagara gorge. Erosion of the Lyell-Johnson outlet sill returned Lake Erie to the level of the Niagara River at Fort Erie. In the western basin, water level did not fall significantly because lower water level at the sill was partially compensated by differential isostatic rebound in the west.

This Holocene lake level model for Lake Erie is illustrated in Figure 8b, which like Figure 8a is also a topographic section through the deep axis of Lake Erie as shown in Figure 7. In Figure 8b, the inferred

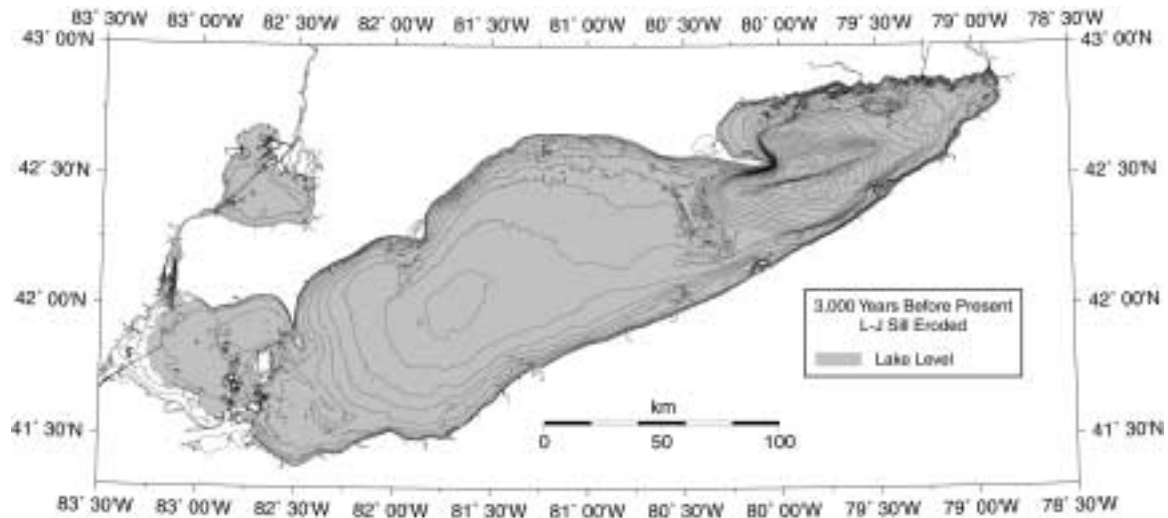


FIG. 10. Continued.

present position of water planes relative to the topography are sketched in for nine representative time intervals of the Holocene. Figure 9 shows schematic diagrams of inferred lake level history at four locations shown in Figure 7. These schematic diagrams illustrate rather large differences in lake level history between each of the four locations.

Differential isostatic rebound (Clark *et al.* 1994, thin-ice model) between each Figure 9 locality and the outlet sill varies in proportion to distance from the sill. According to the Clark model, the rate and amount of differential isostatic rebound decrease non-linearly with increasing distance from the sill. Applying the Clark model, the outlet sill rose less than 10 m in the last 10,000 years relative to the location near the sill (diagram EE). During the same period the outlet sill rose 10–20 m relative to the eastern basin locality (diagram E), 20–30 m relative to the central basin locality (diagram C), and 40 to 50 m relative to the western basin locality (diagram W).

According to the model the outlet sill moved eastward twice, first from the Dunkirk Sill to the Fort Erie Sill, and later from the Fort Erie Sill to the Lyell-Johnson Sill, as isostatic rebound elevated downstream sills at a higher rate than those upstream. Still later the Lyell-Johnson Sill was eroded (Pengelly *et al.* 1997) and the Sill shifted back upstream to the Fort Erie Sill. During the earliest low-water period (Ypsilanti Low), when the Dunkirk Sill was presumed to be active, location EE, near the Fort Erie Sill, was probably dry land. According

to the model, location E, in the eastern basin, was water-covered during the entirety of the Holocene. Location C, in the central basin, was the site of a small lake impounded by the Pennsylvania Sill until the central basin was flooded about 10,500 ya. Location W, in the western basin, remained the site of dry land or small marsh/ lake basins until it was finally flooded about 5,400 ya.

According to the model, during the highest level reached by the Nipissing Rise about 3,600 ya, lake level was 4 m above present lake level at locality EE; 1 m above present lake level at locality E; 1 m below present lake level at locality C; and 3 m below present lake level at locality W.

The model does not predict shorter term fluctuations in lake level, such as annual and decadal changes which have occurred in response to the changing water budget. Such changes have undoubtedly occurred throughout the Holocene and continue at present. Shorter term variations in lake level would have been greater during times when lake level dropped below the level of the outlet sill. However large variations, when lake level is lower than the outlet sill, may be the exception rather than the norm, since most of the bathymetric features which record low lake levels are indicative of a specific depth range. Variability in lake level may have been larger during the early Nipissing Rise, during a time of delicate balance between the water budget and the introduction of water from the upper Great Lakes.

### LAKE ERIE PALEOGEOGRAPHY

Paleogeographies of the nine episodes of Lake Erie lake level history depicted in the model (Fig. 10) are shown as nine separate overlays to the bathymetry. Details of Holocene shoreline configurations, to the extent that the model is accurate, are revealed, thanks to the detailed bathymetric mapping. Figure 10 shows reconstruction for times that correlate with inferred water levels 1 through 9 shown in Figure 8b; these times illustrate the postulated Lake basin(s) and outlet sill(s) during: 1) the Ypsilanti Low (13,400 ya); 2) the unnamed low episode (12,000 ya); 3) main Lake Algonquin (10,400 ya); 4) at the beginning of the pre-Nipissing lowstand (10,300 ya); 5) about the midpoint of pre-Nipissing Lake Erie time (7,500 ya); 6) just prior to the early Nipissing Rise (Nipissing I) (5,400 ya); 7) just after the early Nipissing Rise (5,300 ya); 8) following introduction of a significant volume of upper Great Lakes water via the Detroit River (3,600 ya); and 9) following erosion of the Lyell-Johnson Sill (3,000 ya).

During the first postglacial lowstand (13,500–13,000 ya) two small lakes existed, one behind the Pennsylvania Sill, the other behind the Dunkirk Sill. During the second postglacial lowstand (12,500–12,000 ya), the two small lakes persisted, one still behind the Pennsylvania Sill, the other now impounded behind the Fort Erie Sill. The lakes were larger during the second lowstand. During the main Algonquin Highstand (11,000–10,300 ya), when upper Great Lakes water was coming through Lake Erie, the central basin sill and the Long Point-Erie Ridge were inundated, and a large lake formed in the central basin. After initiation of the lengthy early/ middle Lake Erie lowstand (10,300–5,400 ya), when upper Great Lakes water again bypassed Lake Erie, the central basin sill was barely flooded, and a smaller lake in the central basin was very shallow.

Snapshots of the paleogeography at 7,500 and 5,400 ya show a large shallow lake now largely filling the central basin, but with the Clear Creek Ridge and Long Point-Erie Ridge exposed as peninsulas. The lake in the eastern basin is almost as large as it is at present, and the Long Point Spit had not yet begun to form. Following the early event (s) of the Nipissing Rise (5,300 ya), configuration of the lake in the eastern basin was approximately the same as it is at present but at a slightly higher level near the Lyell-Johnson Sill, and beyond in the Niagara River. The Clear Creek Ridge and Long Point-

Erie Ridge were flooded, the central basin was about as extensive as it is at present, and water had not yet entered the western basin. At this time the Pelee-Lorain Ridge became a spit, and the Point Pelee Fan began to form. At the height of the Nipissing Rise in the time interval 4,000–3,600 ya, the Detroit River had received the full and sustained influx of upper Great Lakes water, and erosion of the Lyell-Johnson Sill had begun. The eastern end of the lake was 4–5 m above present level, and the eastern and central basins were about the same extent as at present. The western basin was flooded though water level was several meters lower than at present. Following erosion of the Lyell-Johnson Sill (3,000 ya), lake configuration was only slightly less extensive than at present. The largest difference is that the western basin was less extensive at its extremely shallow western end.

### CONCLUSIONS

Eighteen Lake Erie and Lake St. Clair lakefloor bathymetric features are interpreted as indicators of present and former lake levels (Fig. 1). Of these six are presently active features adjusted to present lake level, and twelve were apparently formed at lower lake levels and later abandoned. These features include six deltas/fans, eight spits, one cusped foreland, two bay bars, and one morainic ridge.

Around the eastern extremity of the lakes, the Buffalo Ridges occur at a depth of 10–12 m (Fig. 1a). These are provisionally interpreted as shoreline features consisting of a line of several spits and bay bars. This line is continuous across several eroded headlands truncating NE-SW ridges. Other interpretations for these features include end moraine, or formation at present depth during strong storms, effects of which are magnified in the eastern extremity of the lake. If the first interpretation is correct, the Buffalo Ridges document the existence of lake levels which had fallen below the level of the outlet sill in middle Holocene time.

Lake surface area and lake water volume as a function of lake level in the present Lake Erie, have been computed using present bathymetry, and are illustrated graphically (Figs. 2 and 3). Notwithstanding constraints imposed by not considering differential isostatic rebound and sediment infilling of lake basins, two episodes of lake level history are apparent. At lower water levels Lake Erie was small and largely confined to the eastern lake basin. Lake area and water volume did not increase at a high rate with respect to increasing lake level. At

higher water levels, lake area and water volume increased at a very high rate with respect to increasing lake level, as the much larger central basin of Lake Erie was flooded.

Annual totals of the water budget terms evaporation (evp), runoff (run), and over-lake precipitation (plk) were compared with the amount of water necessary to raise present Lake Erie lake level by 1 m, based on measurements and estimates from 1950–1990 (Figs. 4 and 5). Detroit River throughput is ignored. The three water budget terms (evp, run, and plk), the net basin supply (nbs), and the volume of water contained in 1 m of lake water, all lie within the narrow range of 20–25 billion cubic meters (Fig. 6).

Features of the present water budget are instructive regarding the water budget of early Holocene Lake Erie. Two conclusions: 1) without Detroit River input, Lake Erie's present water budget could go negative during extremely dry and windy years; and 2) changes in lake levels in response to changes in water budget would occur very rapidly. At present, the entire volume of Lake Erie is supplied by the Detroit River in about 3 years, or would be supplied by the local drainage basin in about 20 years.

In the scenario where lake level falls below the level of the outlet sill, lake level ceases to be controlled by sill depth and passes primarily to the climate-driven water budget. Large increases in lake surface area as a function of lake level would have the effect of increasing evaporation, the negative term in the water budget, without significantly affecting the positive terms, over-lake precipitation plus runoff. Increased evaporation concomitant with rising water levels would tend to prevent lake level from rising beyond a certain point. Conversely, falling lake level would decrease the evaporation term, which would prevent lake level from falling beyond a certain point at which the water budget becomes positive. An equilibrium lake level would be maintained as governed by the water budget. Seasonal, annual, and longer-term changes in the water budget would raise or lower lake level, introducing a "noise level" which is not easily quantified.

During the middle Holocene (9–6 ka) climatic optimum, warmer temperatures and greater aridity characterized the climate of the region. Considering the present water budget, Lake Erie may have fallen below sill depth for a long period of time between 10 and 5 ka. Following the climatic optimum, lower temperatures and higher rainfall may have returned Lake Erie to the level of the outlet sill, possibly before introduction of significant amounts of upper

Great Lakes water. An early episode of the Nipissing Rise could have been the result.

A provisional model of lake level history is proposed, notwithstanding all its uncertainties (Figs. 7 and 8). Taken into consideration are: 1) lake floor features, described in detail by recent bathymetry, which are indicators of present and past lake levels, 2) differential isostatic rebound, (3) water budget data, (4) past climate information, and (5) previous investigators' interpretations of lake level history derived from radiocarbon dates on materials indicative of lake level. Also considered are geological evidences of higher and lower lake levels from the surrounding land areas, including downcutting of stream valleys below present lake level, and beach ridges above present lake level. The model is illustrated by water-plane sketches (Fig. 8b) which depict nine episodes of lake level history, all plotted against a longitudinal section of lake floor topography.

In an isostatically rebounding lake, lake level history varies with location, especially as a function of distance from the outlet sill. A new feature of the model are lake level histories which are location-specific, as illustrated by schematic diagrams (Fig. 9) of lake level history for four locations: near the outlet sill; and in the eastern, central, and western basins. Another new feature of the model is the proposed extended period of low lake level in the middle Holocene, when lake level was controlled not by the level of the outlet sill, but by climate and the water budget. Still another new feature of the model are water-level rises associated with the Nipissing Rise which occur rapidly (1–20 yrs) and may amount to 10 m or more. What the model cannot show are short-term, cyclic variations in lake level brought about by seasonal/ annual/ decadal variations in climate and the water budget.

Based on the model of lake level history, Lake Erie paleogeography varied spectacularly during the Holocene, as illustrated (Fig. 10) for the nine episodes of lake level history shown in Figure 8b. Shoreline configurations for each episode are depicted as overlays on the bathymetry.

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