SERIES

Geoscience Medallist 1. Understanding the Holocene Closed-Basin Phases (Lowstands) of the Laurentian Great Lakes and Their Significance*

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SUMMARY

The Laurentian Great Lakes are a chain of five large water bodies and connecting rivers that constitute the headwaters of the St. Lawrence River. Collectively they form one of the largest reservoirs of surface freshwater on the planet with an aggregate volume of >22,000 km^3. Early interpretations of the postglacial lake history implicitly assumed that the Great Lakes always overflowed their outlets. A study of Lake Winnipeg which concluded that lack of water in a dry climate had dried that lake for millennia led to re-evaluation of the Great Lakes water-level history. Using the empirical information of glacio-isostatic rebound derived from ^{14}C-dated and uptilted Great Lake paleo-shorelines, a method of computation was developed to test the paradigm of continuous lake overflow. The method evaluated site and outlet uplift independently, and low-level indicators such as submerged tree stumps rooted beneath the present Great Lakes were found to be lower than the lowest possible corresponding basin outlet. Results confirmed the low-level, closed-basin hydrological status of the early Great Lakes. This status is consistent with paleoclimatic inferences of aridity during the early Holocene before establishment of the present patterns of atmospheric circulation which now bring adequate precipitation to maintain the overflowing lakes. In a sense, the early to middle Holocene phase of dry climate and low water levels is a natural experiment to illustrate the sensitivity of the Great Lakes to climate change in this era of global warming, should their climate shift to one much drier than present, or future major diversions of their waters be permitted.

RÉSUMÉ

Les Grands Lacs Laurentiens sont une chaine de cinq grandes étendues d'eau connectées par des rivières, constituant la source du Fleuve St-Laurent. Collectivement, ils forment un des plus grands réservoirs d'eau douce de surface de la planète avec un volume total de plus de >22,000 km^3. Les premières interprétations de l'histoire postglaciaire des lacs supposaient implicitement que les Grands Lacs débordaient à leurs exutoires. Une étude du Lac Winnipeg, qui concluait qu'un déficit en eau durant un épisode de climat aride avait desséché le lac pendant des millénaires dans le passé, a mené à la réévaluation de l'histoire du niveau de l'eau des Grands Lacs. En utilisant des données empiriques du relèvement glacio-isostatique, dérivées de littoral anciens surélevés datés au ^{14}C, une méthode de calcul a été développée pour tester le paradigme d'une décharge lacustre continue. La méthode a évalué le soulèvement des sites et des exutoires indépendamment, et il a été constaté que les indicateurs de bas niveau tels que des troncs d'arbres submergés, enracinés en dessous des Grands Lacs actuels, étaient en fait sous le niveau de l'exutoire correspondant le plus bas. Les résultats confirment le bas niveau et le statut de basin hydrologique fermé des Grand Lacs dans le passé. Ce statut est cohérent avec des évidences paléoclimatiques d'aridité au début de l'Holocène, avant l'établissement des modes de circulation atmosphérique actuels qui apportent des quantités de précipitation adéquates au maintien des

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décharges lacustres. Dans un sens, la période climatique aride du début et du milieu de l'Holocène, et les bas niveaux d'eau constituent une expérience naturelle qui illustre la sensibilité des Grands Lacs aux changements climatiques, pertinent dans le contexte actuel de réchauffement global, surtout s'il s'avérait que leur climat devienne plus aride que présentement, ou que des diversions majeures des eaux soient permises.

INTRODUCTION

The Laurentian Great Lakes in eastern North America are a chain of five large water bodies totalling 244,160 km^2 in surface area with a land drainage area of 521,830 km^2. These lakes constitute the headwaters of the St. Lawrence River which drains to the Atlantic Ocean (Fig. 1). Collectively the lakes form one of the largest reservoirs of surface freshwater on the planet with an aggregate volume >22,000 km^3 (United States Environmental Protection Agency and Government of Canada 1995), similar to that of Lake Baikal in southern Siberia (Galazy 2015).

The Great Lakes today are open overflowing lakes (Fig. 2a) which receive adequate water supply to fill their basins and overflow their basin outlets into downstream rivers. The predecessor glacial lakes were also open overflowing water bodies, and the immediate postglacial (early Holocene) Great Lakes were initially interpreted in the same way, although early Holocene water levels in small lakes in eastern North America were long known to have been reduced by the dry climate (Shuman et al. 2002). Only since the late 1990s with increasing awareness of differential lake-basin warping by glacial isostatic adjustment, have the early to middle Holocene (early postglacial) Great Lakes come to be understood as closed or 'terminal' lakes (here termed *lowstands*) whose water levels were generally at lower elevations than their basin outlets (Fig. 2b). The lake basins were then isolated from the outlet rivers.

In this paper the present Great Lakes and the types of evidence used to infer low water levels below the present lake surfaces are discussed. A short review of the glacial and early postglacial Great Lakes follows to reveal that the latter were previously interpreted with an implicit assumption that they were open, overflowing water bodies. This assumption was challenged when the large Lake Winnipeg, about 500 km northwest of the Great Lakes watershed, was found to have been forced by the dry climate into a closed condition for several millennia. The remainder of the paper describes the steps which led to recognition of the early to middle Holocene Great Lakes closed-basin lowstands, and discusses their significance.

THE LAURENTIAN GREAT LAKES OF TODAY

The five Great Lakes between 41.5º and 49ºN latitude in central eastern North America today each overflow into connecting rivers which ultimately discharge to the St. Lawrence River and Atlantic Ocean (Fig. 3a). This chain of large lakes begins with the deepest (406 m maximum depth) and highest water body, Lake Superior (183 m asl), which overflows via the St. Mary's River into water bodies in the basins of lakes Michigan (282 m deep), Huron (229 m deep) and Georgian Bay (168 m deep), which all sit at a common level of 176 m asl. These lakes then overflow via the connecting St. Clair and Detroit rivers, and Lake St. Clair, to Lake Erie (64 m maximum depth) at 172 m asl. Lake Erie then discharges over the 52-m high Niagara Falls via the Niagara River to Lake Ontario (244 m maximum depth) at 74 m asl. The Lake Ontario overflow supplies the St. Lawrence River with an approximate mean discharge of 7000

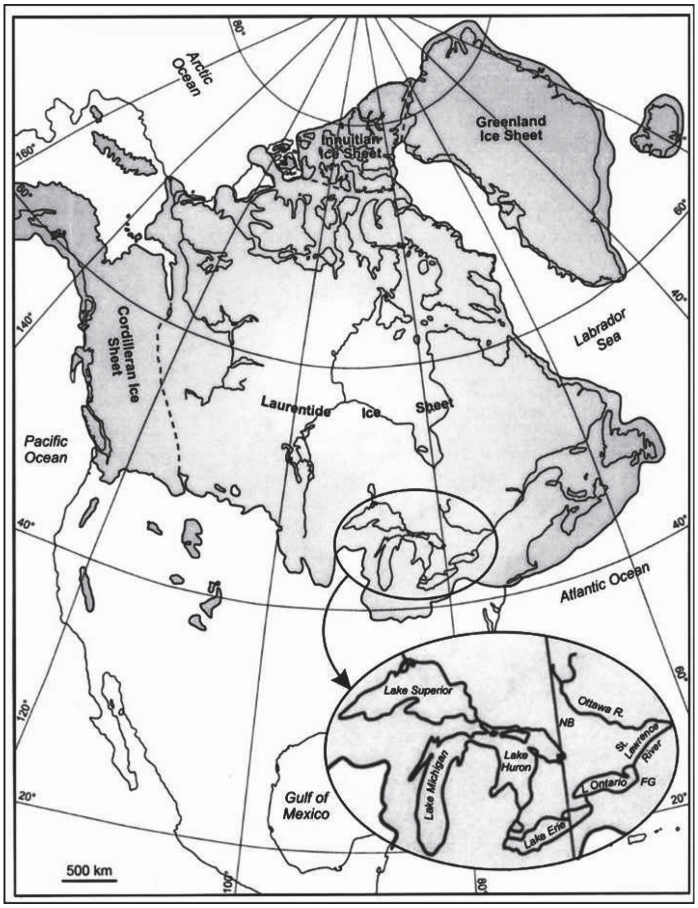

Figure 1. Map of North America showing the Laurentian Great Lakes (within the oval) draining northeastward via the St. Lawrence River to the Atlantic Ocean. Shaded area portrays the North American ice sheets at their maximum extent about 21,000 calendar years ago. From Lewis et al. (2010).

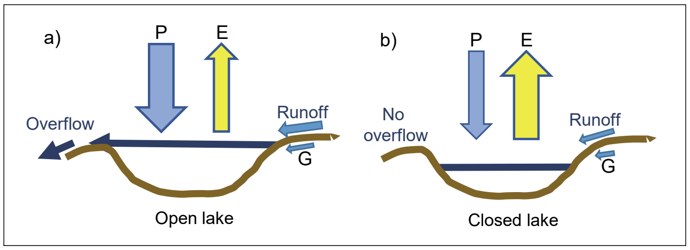

Figure 2. Schematic diagrams illustrating the types of water bodies that have occupied the Great Lake basins. P = precipitation, E = evaporation, G = groundwater. a) Open overflowing lake in which water supply by precipitation, runoff, inflowing rivers, and groundwater exceeds water loss by evaporation, and excess water overflows the basin outlet to supply a downstream river. b) Closed or terminal lake in which water loss by evaporation exceeds water supply by precipitation, runoff, inflowing rivers, and groundwater with the result that water level falls below the basin outlet and is isolated from a downstream river.

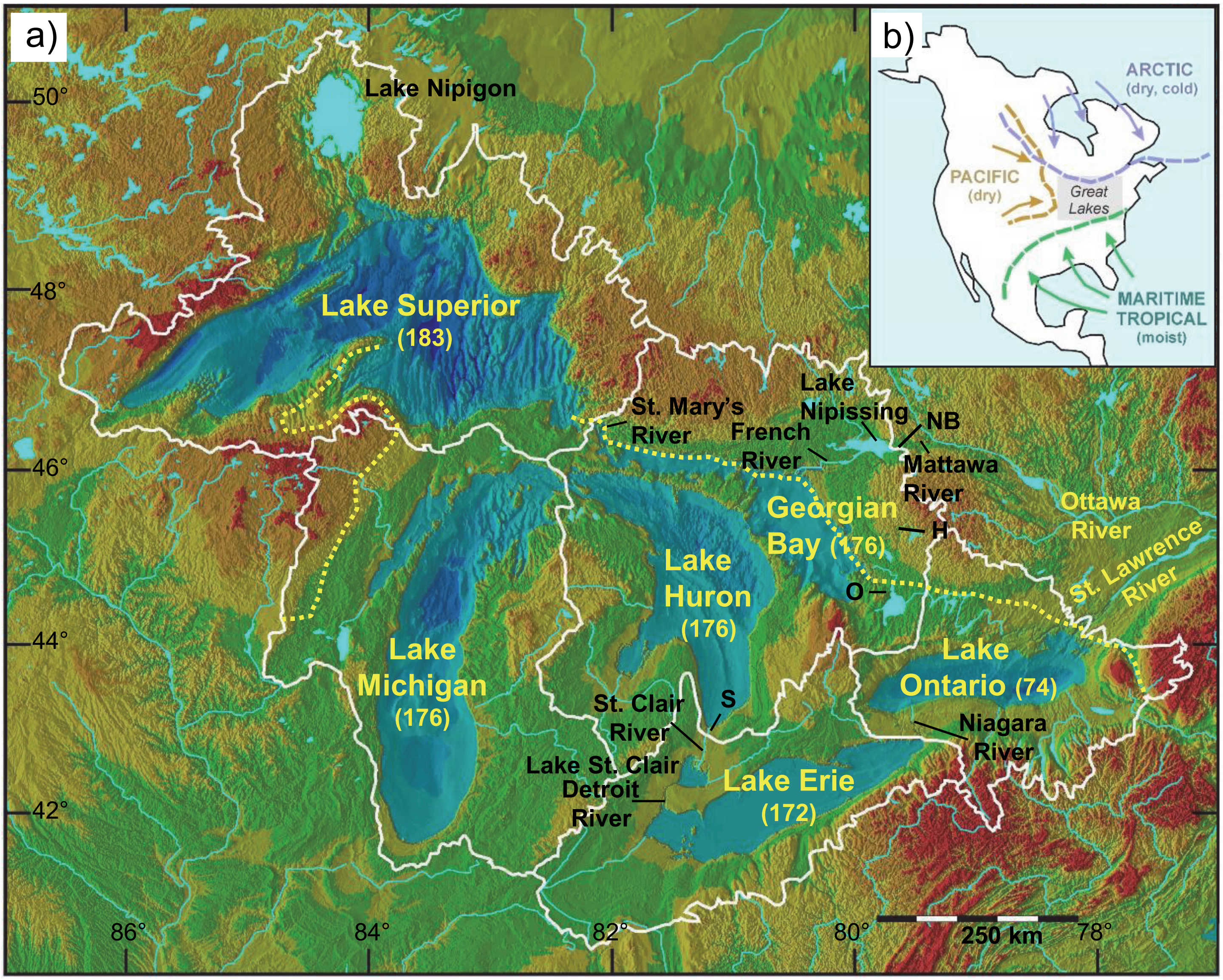

Figure 3. The Laurentian Great Lakes today. a) Shaded-relief map of the Great Lakes basin illustrating lake watersheds (white lines), lake elevations in metres, and generalized bathymetry. Areas north of the yellow dotted line near Georgian Bay, and west of the yellow dotted line near Lake Superior are underlain by harder rocks of the Precambrian Shield, and areas south of these dotted lines are underlain by softer Paleozoic sedimentary rocks. H = Huntsville, NB = North Bay, O = Orillia and S = Sarnia. Adapted from a relief map prepared by P. Gareau in Lewis et al. (2005). b) Map of North America showing the three main air masses whose periodic incursions over the Great Lakes influence their water supply. Adapted from Bryson and Hare (1974).

m^3s^{-1} (Mortsch et al. 2000). Also of importance is the Nipissing–Mattawa lowland northeast of Georgian Bay in the area of North Bay, Ontario, comprising the present Lake Nipissing and the French and Mattawa rivers, which drained the upper Great Lakes to valleys of the Ottawa and St. Lawrence rivers until about 6000 years ago (Fig. 3a).

The lakes occupy basins that were excavated during multiple glaciations, and are mostly underlain by the relatively soft Paleozoic sedimentary rocks that surround and overlap the harder metamorphic rocks of the Precambrian Shield (Fig. 3a). The Lake Superior basin was mainly excavated from Precambrian sedimentary and volcanic rocks which infilled an ancient mid-continent rift valley developed ca. 1.1 billion years ago (Hough 1958; Sutcliffe and Bennett 1992; Stein et al. 2015).

Water is supplied to each lake by direct rainfall and snowfall (precipitation), by runoff from adjacent land surfaces, and by inflow from upstream rivers and lakes. Apart from overflow, water is lost from the Great Lakes by evaporation from water surfaces (United States Environmental Protection Agency and Government of Canada 1995). Groundwater contributions to tributary streams of the Great Lakes range from 48 to 79% of their flows. Although total groundwater volume in the Great Lakes watersheds is estimated in the order of 4900 km^3, similar to the Lake Michigan volume (International Joint Commission 2010), groundwater input to the lakes is not well known.

Atmospheric circulation brings three major air masses over the Great Lakes (Fig. 3b). Incursions of Pacific and Arctic air are dry and enhance evaporation from the lakes. Incursions of moist subtropical air masses from the Gulf of Mexico and adjacent Atlantic Ocean deliver most of the precipitation in the Great Lakes region. Over all the Great Lakes, this water supply currently averages about 87.4 cm/yr (Croley and Lewis 2006), or less than 3% of the water volume stored in the Great Lake basins. Shifts in the relative periods of time that these contrasting moist and dry air masses overly the lake watersheds can change the water supply to the Great Lake basins, and affect their water balances significantly.

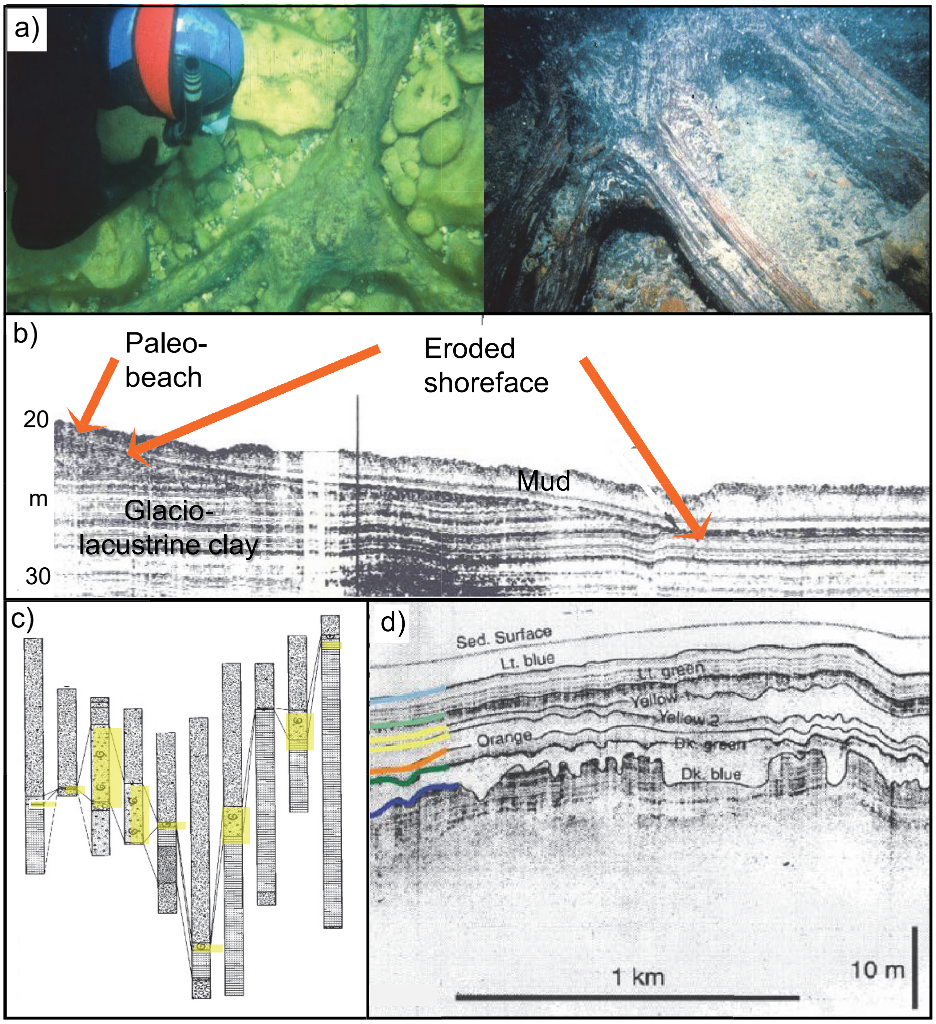

Figure 4. Some evidence indicating lake lowstands. a) Submerged tree stumps rooted in lake floor in Fathom Five National Marine Park between Lake Huron and Georgian Bay. Photos courtesy of S. Blasco. b) Seismic profile of mud-buried beach and shoreface beneath eastern Lake Erie. Adapted from Coakley and Lewis (1985). c) Shallow-water silt and sand with mollusc shells (yellow zones) in cores 3.5 to 11 m long under deep-water mud in Lake Ontario. From Anderson and Lewis (1985). d) Sedimentary unconformities revealed as acoustic reflections in a seismic profile from northern Lake Huron; the most obvious is the lowermost boundary, labelled dark blue. From Moore et al. (1994).

TYPES OF EVIDENCE FOR LOWSTANDS

The most convincing evidence of former low lake levels below the present water surfaces comes from tree stumps that are rooted into the lake floor in growth position (Fig. 4a). The two illustrated stumps are from a set of tree stumps in Fathom Five National Marine Park on the submerged Niagara Escarpment between Lake Huron and Georgian Bay in water depths from 3 to 43 m, which range in age from 7200 to 9600 ^{14}C years BP (Blasco 2001). Other sets of rooted tree stumps are: the Olson Forest in Lake Michigan offshore of Chicago, where stumps are dated at 8100 and 8400 ^{14}C years BP in 24 m water depth (Chrzastowski et al. 1991); two tree stumps in the Straits of Mackinac in 37 m water depth dated at 9800 and 8200 ^{14}C years BP (Lewis et al. 2005, their Table II); and the Sanilac Forest in southern Lake Huron, which ranges in age from 7900 to 6600 ^{14}C years BP in 13 m water depth (Hunter et al. 2006). A rooted spruce dated 7960 ^{14}C years BP was found in southern Lake Huron also, at 35 m water depth, on a submerged cross-lake ridge (O'Shea et al. 2014).

Other evidence for lowstands includes a seismic profile of a mud-buried beach and shoreface in 21 m water depth in eastern Lake Erie (Fig. 4b; Coakley and Lewis 1985), and shallow-water silt and sand with shells under deep-water mud in Lake Ontario at water depths ranging from 20 to 90 m (Fig. 4c) (Anderson and Lewis 1985).

Striking evidence for lowstands is provided by sedimentary unconformities documented in seismic reflection profiles, for example, from northern Lake Huron (Moore et al. 1994). These unconformities, seen in the seismic profile (Fig. 4d) as highlighted reflections labelled dark blue to light blue, signify lowstand wave erosion of previously-deposited sediment in an offshore basin. The yellow to light blue lowstands were dated in sediment cores and ranged from 10,000 to 7800 ^{14}C years BP (Rea et al. 1994a).

Overall, 223 pieces of dated evidence of former lake levels were considered, of which 221 are radiocarbon-dated and two are based on paleomagnetic secular variation (Lewis et al. 2007, 2012; Brooks et al. 2012; Anderson and Lewis 2012; Lewis and Anderson 2012; O'Shea et al. 2014). Additional ages were estimated by correlation of offshore pollen assemblages to onshore dated assemblages. Other indicators of low lake levels such as deeply incised tributary streams, submerged deltas, submerged terrestrial peat deposits, and lowstand unconformities were recognized by Coakley and Lewis (1985), Moore et al. (1994), Karrow et al. (2007), Kincare (2007), Lewis and Anderson (2012), and Lewis et al. (2012).

THE GLACIAL GREAT LAKES

The Great Lake basins were completely covered by the Laurentide Ice Sheet at its maximum extent about 21,000 years ago (Fig. 1). A continuous succession of evolving meltwater lakes began to appear starting in the southern Lake Erie basin about 14,500 ^{14}C BP or 17,600 cal BP (Calkin and Feenstra 1985; Fisher et al. 2015), and continued to develop for about 9000 years during the oscillatory retreat of the ice margin until eventually ice receded northward out of the Lake Superior watershed.

Wave-formed coastal features, such as shorebluffs of the glacial lakes (Fig. 5a), were recognized as shorelines of former water bodies as early as 1818 (Calkin and Feenstra 1985). In the period prior to 1950, when radiocarbon dating became commonplace, at least 48 different investigators produced multiple papers describing the shoreline features and interpreting their origin. The number of new researchers grew to peaks of 7 and 11 per decade in 1890–1899 and 1900–1909, respectively (Fig. 5b). During the 19th century the shoreline features were described without there being a clear consistent concept of their origin. Only towards the close of the 19th century and the beginning of the 20th century were these features recognized as traces of glacial lakes linked to the former ice sheet (Calkin and Feenstra 1985). Mapping the lake shorelines across moraines permitted the correlation of the moraines to aid in the construction of former ice margin positions and reveal the pattern of recession of the former ice sheet.

Early Strandline Diagrams, Uplift, and Isobase Maps

Mapping and correlation of individual glacial lake shorelines also revealed that these formerly level water planes were uplifted towards the north with increasing amplitude. Profiles of the uplifted shorelines were displayed in classic strandline diagrams of elevation versus distance in the direction of maximum uplift (Fig. 5c), as shown in the work of J.W. Goldthwait (1910a). Contour lines joining points of equal elevation over the uplifted water planes were plotted in map form to produce isobase maps. Isobases were drawn on the deformed water planes of former high-level lakes, for example, glacial Lake Algonquin in the Huron and Michigan basins (Fig. 5d) (Goldthwait 1910a). Shorelines were found to rise in elevation towards the NNE mainly in the direction of ice retreat with older shorelines raised more than younger ones – leading to an understanding of isostatic crustal depression under the load of the former ice sheet, and that recovery (uplift) was differential – faster and of greater amplitude in the direction of thicker and longer-lasting ice. As was learned from later studies, the recovery was prolonged – continuing through time, up to and including the present, but at decreasing velocity (Gutenberg 1933; Mainville and Craymer 2005), and including the lesser effects of both water loading and a component of forebulge subsidence near the former ice sheet margin (Clark et al. 1994, 2007).

Understanding of the retreat of the ice margin and the succession of proglacial lakes developed rapidly in the early 1900s, and a major synthesis was published in 1915 by F. Leverett and F.B. Taylor in a 529 page monograph of the United States Geological Survey.

Recognition of Glacial Lake Phases Below Present Water Levels

A theoretical basis for predicting the occurrence of lowstand water levels below the surfaces of the present Great Lakes emerged in 1936 when G.M. Stanley completed mapping the post-Main Lake Algonquin series of lake levels southeast of Georgian Bay. In the Leverett and Taylor (1915) synthesis, the profiles of this series of glacial lake levels converged southward toward a single outlet in the southern part of the Huron basin (Fig. 6a). In their interpretation, an ice margin had blocked and supported the northern parts of these lakes and progressive differential uplift over time had caused shorelines to form at successively lower elevations on the emerging land surface while their outlet remained in the south.

However, Stanley's mapping (Stanley 1936) showed that the successive shorelines were nearly parallel in the strandline diagram (Fig. 6b) which implied that the succession of lowering lakes was rapidly drained eastward to the Ottawa River valley by the opening of lower northern outlets. The projected water planes of the lakes would have passed southward many tens of metres below the water surface of the present Georgian Bay and Lake Huron. This interpretation was demonstrated generally to be true by J.L. Hough in 1962, and the scenario of glacio-isostatically depressed outlets in the northern sectors of Great Lake basins was generally regarded as an explanation for lowstand lake evidence (Hough 1962). In other words, the lakes were still regarded as open, overflowing systems, but the outlets were inferred to be at significantly lower elevations than today.

Study of the Great Lakes region continued in the years following 1950, and with the benefit of ^{14}C-dated chronology, these studies further refined the early interpretations and syntheses. Notable post-1950 syntheses were published by J.L. Hough in 1958 in his book *Geology of the Great Lakes*, and by P.F. Karrow and P.E. Calkin acting as editors and authors in the 1985 book *Quaternary Evolution of the Great Lakes* published by the Geological Association of Canada. Later contributions were made by J.T. Teller in 1987 in a volume of the Decade of North American Geology series, by P. Barnett in 1992 in the Ontario Geological Survey book *Geology of Ontario*, and by Larson and Schaetzl in 2001 in the *Journal of Great Lakes Research*, among others.

By 1990, the glacial Great Lakes were understood to have been open overflowing lakes supplied with abundant meltwater from the retreating ice sheet. Changes in water levels were mainly attributed to outlet erosion or the opening and closing of topographically lower outlets and drainage routes by oscillations of the ice margin during the general deglaciation. Outlets and drainage routes also changed as crustal isostatic rebound progressed at differential rates across this wide area.

OVERFLOWING POSTGLACIAL GREAT LAKES

Until the late 1980s, efforts to extend the history of water levels into postglacial time in the Great Lake basins used an

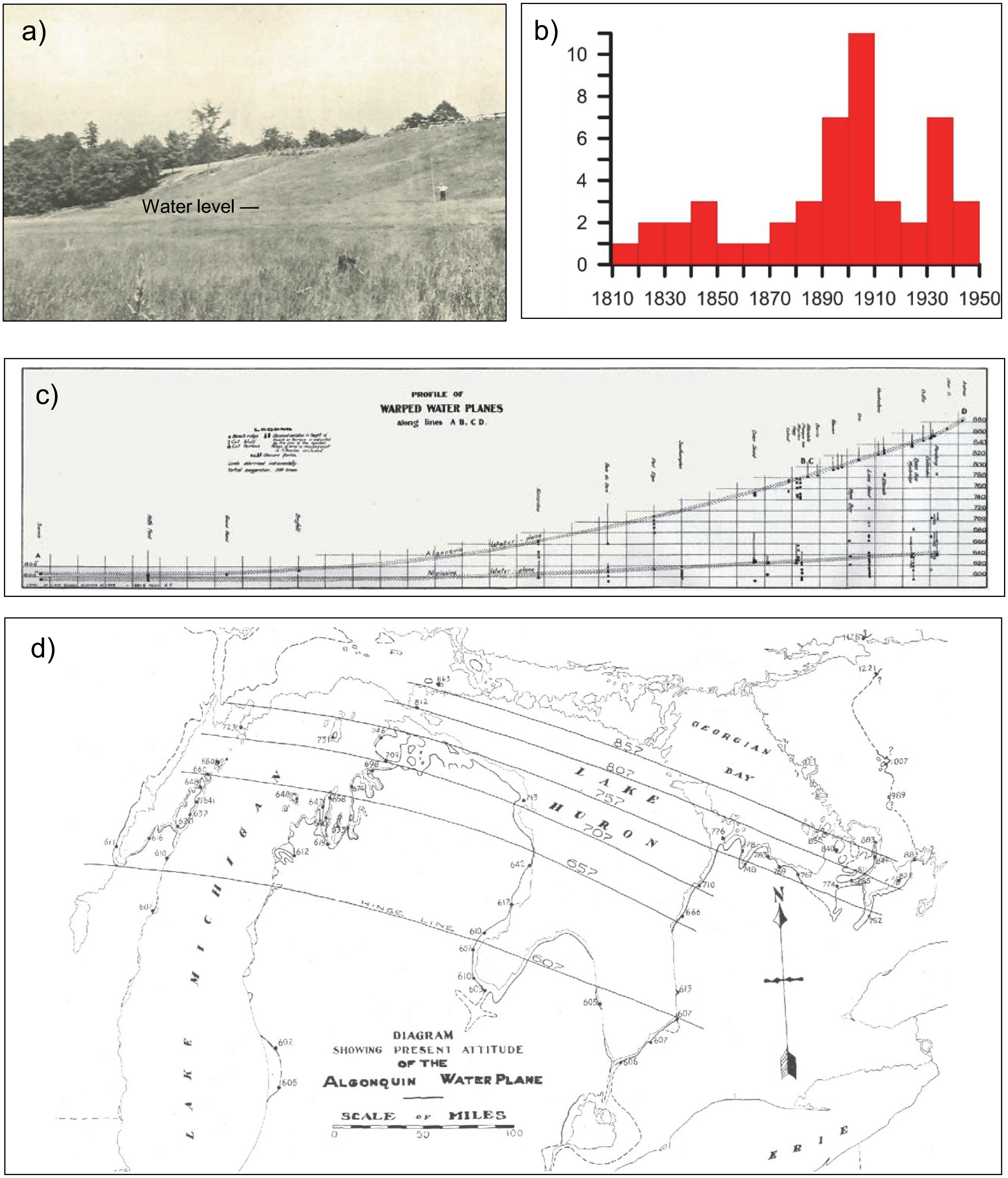

Figure 5. The glacial Great Lakes. a) Glacial lake shorebluff and nearshore terrace near Kettle Point on Lake Huron, Ontario, published by J.W. Goldthwait (1910a). b) Histogram of numbers of new authors per decade writing about the predecessor Great Lakes between 1818 and 1950 based on citations in Goldthwait (1910a, b), Hough (1958), and Karrow and Calkin (1985). c) Strandline diagram (elevation vs. distance) showing rises of 83 m for glacial Lake Algonquin (upper) and 15 m for the younger Nipissing Great Lake (lower) over 264 km in a NNE direction between Sarnia and Orillia, Ontario (Fig. 3). From Goldthwait (1910a). d) Contours of equal elevation or isobases drawn on the inferred waterplane of glacial Lake Algonquin (basins of lakes Huron and Michigan) (Goldthwait 1910a).

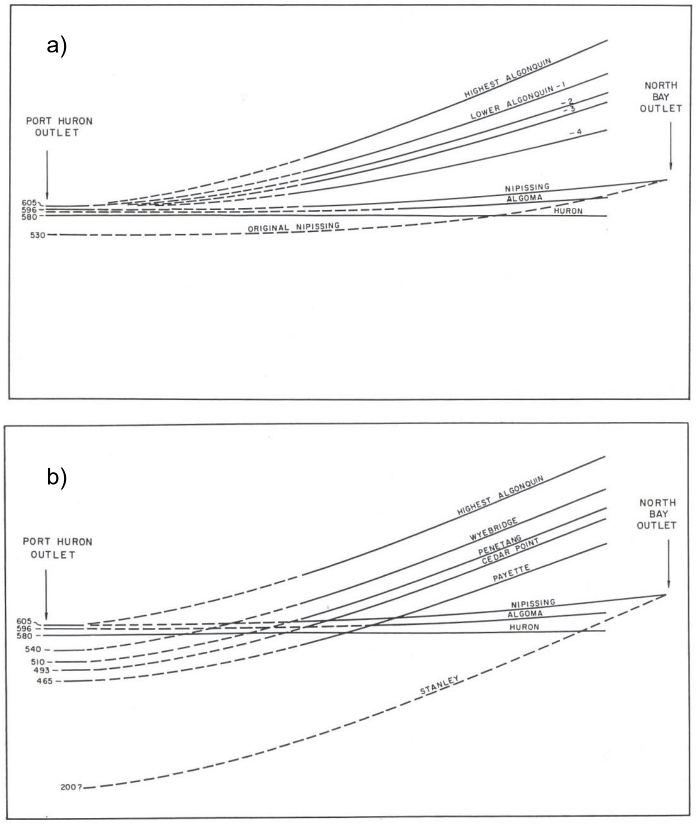

Figure 6. Recognition that 'lowstand' lakes could be caused by glacio-isostatic differential depression of outlets in northern sectors of the Great Lake basins. a) Leverett and Taylor (1915) synthesis of Post Algonquin glacial lakes in Huron and Georgian Bay basins. From Hough (1958). b) G.M. Stanley's (1936) revised synthesis of the Post Algonquin waterplanes. Elevations in feet. From Hough (1958).

implicit assumption that the postglacial lakes *always* overflowed their outlet sills, just as the Great Lakes do today, and as they did during deglaciation when they were supplied with abundant meltwater. Although a few indicators of past water levels lower than those of today were known, they were either ignored or considered explicable by lake outlets being relatively lower in the past due to differential glacio-isostatic depression. Two examples of this paradigm of interpretation are described from the literature.

Pausing Isostatic Rebound to Accommodate the Paradigm

In a 1962 milestone paper, J.L. Hough found a lowstand unconformity in the sediment sequence beneath northwestern Lake Huron which he believed was the evidence of the low water level as predicted by G.M. Stanley in 1936. Hough named the lowstand 'Lake Stanley' in honour of Stanley's insight. Hough reconstructed Lake Stanley with an overflowing outlet at North Bay, Ontario. The uptilted slope of the reconstructed Lake Stanley water plane was not as steep as the gradient of the earlier glacial Lake Algonquin paleosurface. Hough estimated that 25% of post-Algonquin uplift had been achieved by the time of Lake Stanley. His reconstruction met a problem, and he wrote "*In attempting to prepare a reconstruction of the outline of Lake Stanley … it was found that Lake Stanley could not have drained northeastward from Georgian Bay*." (In other words, it was lower than the North Bay outlet.) He went on "*Therefore the concept of rates of uplift was revised*." Hough proposed that much of the uplift was delayed until the time when Lake Stanley existed. In other words, to conform to the general assumption of overflowing lakes, Hough proposed a halt in uplift so that the North Bay outlet remained low enough to allow overflow from Lake Stanley. Although the evidence of a closed-basin lowstand was within his grasp, the paradigm that lakes always overflowed their outlets was too strong to overcome (Lewis et al. 2007).

Erie Lowstand Lake – Too Low to Overflow

In 1985, the present author with John Coakley (Coakley and Lewis 1985) attempted to fit a known trend of a submerged beach beneath eastern Lake Erie onto the strandline diagram of glacial lake shorelines in the region. The submerged beach trended up to the NNE as did the profiles of the earlier glacial lake water planes, but it projected to a position below the bedrock sill at the head of the Niagara River near Buffalo. Assuming that this low shoreline had to be part of an overflowing lake the authors declined to interpret the situation by writing "*Clearly, more information is needed before the significance of such features can be assessed further*." Again, the assumption of overflowing lakes was too strong to allow serious consideration of a closed-basin phase in Lake Erie.

CORRECTING THE IMPLICIT ASSUMPTION – THE LAKE WINNIPEG STUDY

The alternate interpretation of closed-basin large lakes in eastern North America became a reality when the Geological Survey of Canada and partners in Manitoba undertook a major study of Lake Winnipeg (Todd et al. 2000; Lewis et al. 2001). Lake Winnipeg is oriented with its long axis S to N, approximately in the direction of greater postglacial isostatic rebound (Fig. 7). It is generally less than 20 m deep, but its area is large, similar to that of Lake Erie. It overflows at the northern end of its basin into the Nelson River which drains to Hudson Bay. Like its predecessor glacial lake, Lake Agassiz, its basin has been warped upward to the NNE by differential crustal rebound (Johnston 1946; Teller and Thorleifson 1983).

After two seasons of field research and study of sediment architecture in hundreds of kilometres of seismic profiles, and investigation of sediment properties in more than 30 cores of both Lake Winnipeg and underlying Lake Agassiz sediments, it became clear that dry climate had greatly affected this water body. A strong unconformity, marked AU, between the Lake Winnipeg and Lake Agassiz sediments, was evident in seismic profiles in most areas of the lake (Fig. 7b). The surface of the Lake Agassiz sediments is dry and crumbly beneath the overlying Winnipeg sediments.

Pollen studies in the region revealed that a dry grassland climate had existed around most of the lake basin, shown in Figure 7a by the brown and red lines marked 6.5 (^{14}C ka), through most of early and middle Holocene time (Anderson and Vance 2000). Also, the basal ages of the Lake Winnipeg sediments south of the northern North Basin are all around 4 ^{14}C ka (Fig.

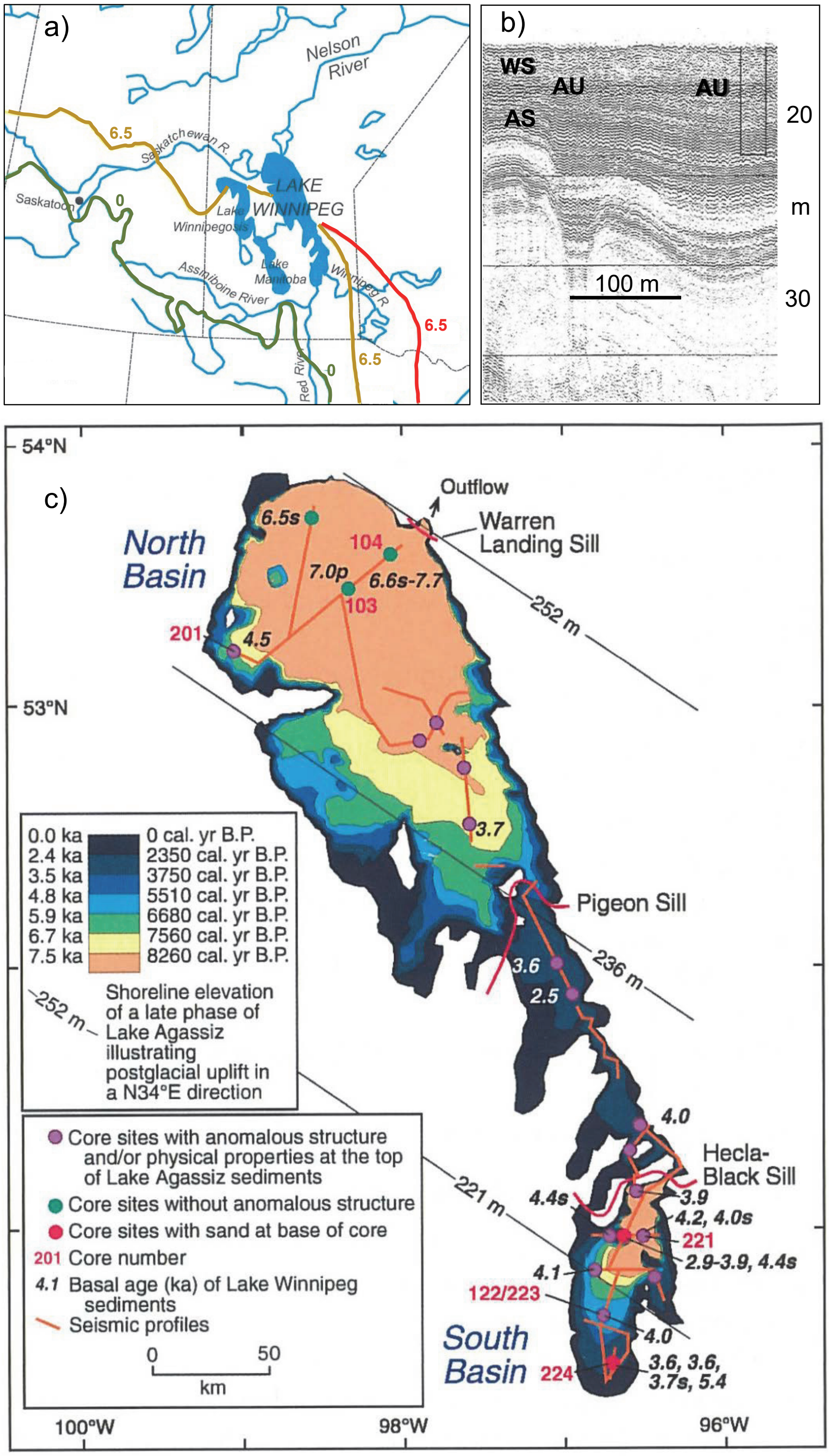

Figure 7. Lake Winnipeg, Manitoba. a) Location of Lake Winnipeg and the outflowing Nelson River. Also shown are the major inflowing rivers, and the northern and eastern boundaries of grassland (brown line) and parkland (red line) biomes at 6.5 ^{14}C ka compared with their present position (green line). From Anderson and Vance (2000). b) Typical seismic profile in Lake Winnipeg showing the Agassiz Unconformity (AU–AU) between Lake Winnipeg sediments (WS) and underlying Lake Agassiz (AS) sediments; black rectangle demarcates a core location. From Todd et al. (2000). c) Map of Lake Winnipeg showing areas that would have been inundated had it always been an overflowing lake; the colour-coded date of inundation applies to the lake area between the southern boundary of the indicated colour and the lake outlet or internal sill. Numbers beside core sites are the ^{14}C ka ages of basal Lake Winnipeg sediments. From Lewis et al. (2001).

7c), revealing that Lake Winnipeg sediments had not begun to accumulate until the late Holocene, even though the basin had been isolated from Lake Agassiz since the end of the early Holocene. A new analysis of uplift showed that had the lake always overflowed its fast-rising northern outlet, as it does today, the lake water would have back-flooded the basin several millennia earlier than the ages found for the basal Lake Winnipeg sediments. For example, the yellow area in Figure 7c would have been inundated by about 7 ^{14}C ka, yet the basal Winnipeg sediments there are only 3700 ^{14}C years old.

REASSESSMENT OF THE POSTGLACIAL GREAT LAKES

With the revelation that Lake Winnipeg had been a closed-basin lake for several thousands of years, a reassessment of the Great Lakes history in the time domain was begun by applying the method pioneered in the Lake Winnipeg study. The method computed independently the elevations of potential outlets and the elevations of sites that preserve evidence of lowstand lake levels through time. If a site with evidence for low water levels was ever *below* the corresponding basin outlet, the lake would then have been in closed-basin status (Lewis et al. 2005).

Since Andrews in 1970 showed that the uplift versus age curve of glaciated arctic sites was well-described by a negative exponential expression, a similar function was sought to fit uplift in the Great Lakes basin using available upwarped shorelines of known age, as shown in the two sketch maps of their isobases (contours joining shoreline sites of equal elevation) in Figure 8a, b.

Relative uplift, U, versus age, t, is described by the expression

$$U = A * (\exp^{(t/\tau)} - 1) \qquad (Eq.\ 1)$$

This expression from Peltier (1998) depends on two parameters: A is a site-specific amplitude factor, and τ is the relaxation time of the uplifting process. *Tau* (τ) is the period in years for which decelerating uplift is reduced by 1/e or 1/2.7183 or 36.8% in successive periods.

Upwarped shorelines of three high-level former lake phases of different age support the negative exponential expression for describing uplift through time – the Iroquois, Main Algonquin, and Nipissing Great Lake phases. The shoreline of glacial Lake Iroquois in the Lake Ontario basin formed about 13,500 cal BP, as lake levels fell when ice began retreating and lower outlets opened from the central St. Lawrence Lowland (Muller and Prest 1985; Anderson and Lewis 2012). Similarly, the shoreline of glacial Main Lake Algonquin formed throughout the basins of Lake Michigan, Lake Huron, and Georgian Bay about 12,500 cal BP as lake levels fell when lower outlets opened to the Ottawa River valley (Karrow et al. 1975). The shoreline of the postglacial Nipissing Great Lake, the last high stage of the upper Great Lakes, formed throughout the basins of lakes Superior, Michigan, and Huron and Georgian Bay between about 6000 and 4500 cal BP when drainage through the rapidly uplifting Nipissing–Mattawa lowland was gradually transferred to southern outlets (Eschman and Karrow 1985; Thompson et al. 2011). At two sites on the isobase maps (Fig. 8a, b), C and D between Lake Ontario and Georgian Bay, uplift of C relative to D was evaluated from extended isobases of these three former lake phases. As shown in Figure 8c, in the plot of relative uplift versus age, uplift for these three shorelines (solid red symbols) describes an exponential function reasonably well with relaxation times between 3000 and 5000 years, a wide range that indicates that uplift computations would not be overly sensitive to the τ parameter.

The relaxation time parameter was evaluated in transects where the ratio of uptilted slopes of two dated paleo-shorelines was known (Fig. 8d). A value of 3700 ± 700 years was obtained for τ from 20 transects (Lewis et al. 2005).

The exponential expression with τ evaluated allowed computation of isobase values at any age from known isobase values of a dated water plane. This property was used to convert water-plane isobase values of different ages to 10.6 ^{14}C ka or 12,500 cal BP, the age of glacial Main Lake Algonquin (Karrow et al. 1975). The Algonquin-age values were contoured to produce a surface of reference uplift throughout the entire Great Lakes basin (Fig. 8e). The uplift is relative to the area southwest of the Lake Michigan basin which was adjacent to the margin of the Laurentide Ice Sheet at its maximum extent, and south of glacial Lake Wisconsin (Fig. 8a, b). Then, for any site in the Great Lakes basin, the appropriate amplitude factor, A, was computed as

$$A = \mathrm{U_{ref}}/(\exp(12500/3700) - 1) \qquad (Eq.\ 2)$$

where $\mathrm{U_{ref}}$ is given by the reference uplift surface (Fig. 8e) for the site in question. The original elevations E_t for the site at any time t cal BP were calculated as

$$E_t = \mathrm{E_p} - A * (\exp(t/3700) - 1) \qquad (Eq.\ 3)$$

or in words: Site elevation at age t cal BP = Present site elevation ($\mathrm{E_p}$) – Site uplift since t cal BP.

This first-order expression enabled independent computation of the original elevations of outlet sills and sites with dated evidence for low (or high) water level in any basin for any age t cal BP. The lake level inferred from low water evidence could then be compared with outlet elevation through time. In this way, a quantitative estimate was obtained for the periods of time when water levels were below outlet elevations and lakes were in closed-basin status. The graph of elevation versus age (Fig. 8f) illustrates the typical trajectory of an uplifting lake-level indicator or an outlet sill with time.

DISCOVERING THE CLOSED LOWSTANDS

The original elevations of dated lowstand evidence and the uplift history of corresponding basin sills were computed and plotted on graphs of original elevation versus age for the Great Lake basins (Lewis et al. 2005, 2008). Closed-basin conditions were recognized in the Great Lakes (Lewis and King 2012), and results are summarized below.

Lake Ontario Water Level History

On the graph of original elevation versus age for the Lake Ontario basin (Fig. 9a) (Anderson and Lewis 2012), the water level history was inferred from the plotted array of lake-level evidence, and is shown by the thick blue line. Water levels descend on the right through the post-Iroquois glacial lake phases to a plateau between 12,900 and 12,300 cal BP or earlier, which was a near still-stand (a period of little relative movement of water level and lake basin) while the lake was at the same level as the Champlain Sea in the St. Lawrence Valley, as shown in the map of reconstructed shorelines (Fig. 9b). The black lines illustrate the rising sills of Lake Ontario (Fig. 9a). Clearly the blue line or lake level of early Lake Ontario fell below the outlet sills from about 12,300 to about 8300 years ago, defining a 4000-year period of closed-basin lowstand conditions. The lake lowstand reconstruction in Figure 9c for 10,500 years ago shows the lowstand shoreline well offshore from the present shoreline (black line).

A mud-buried paleo-barrier beach in the western end of the basin is shown in Figure 9d by the successive clinoform reflections in the seismic profile. The uplift history of the beach on the graph (labelled Grimsby-Oakville barrier beach in Fig. 9a) indicates that it was at lake level more than 12,300 years ago, and was likely built during the near still-stand at that time. The isotopic composition of shelly fauna (ostracodes and clams) in offshore sediment cores revealed an increase in $\delta^{18}\mathrm{O}_{\mathrm{lakewater}}$ after 12,900 cal BP from ~–14‰ to –9‰, signifying loss of glacial meltwater and hydrologic closure of Lake Ontario (Hladyniuk and Longstaffe 2016), consistent with the water level history in Figure 9a.

Lake Erie Water Level History

In the Lake Erie basin similar analyses of lowstand evidence and outlet sills plotted on a graph of original elevation versus age revealed a 6000-year period of closed-basin conditions, the longest in all of the Great Lakes, from about 12,500 to 6500 years ago (Fig. 10a) (Lewis et al. 2012). The lake level was defined in the central basin by its rise from the early Holocene lower limit of an offshore wave-cut terrace to middle Holocene buried lagoon sediments at the upper limit of the terrace at Rondeau Park (Fig. 10b). In the eastern basin the lake level was defined by a succession of dated mollusc shells in a

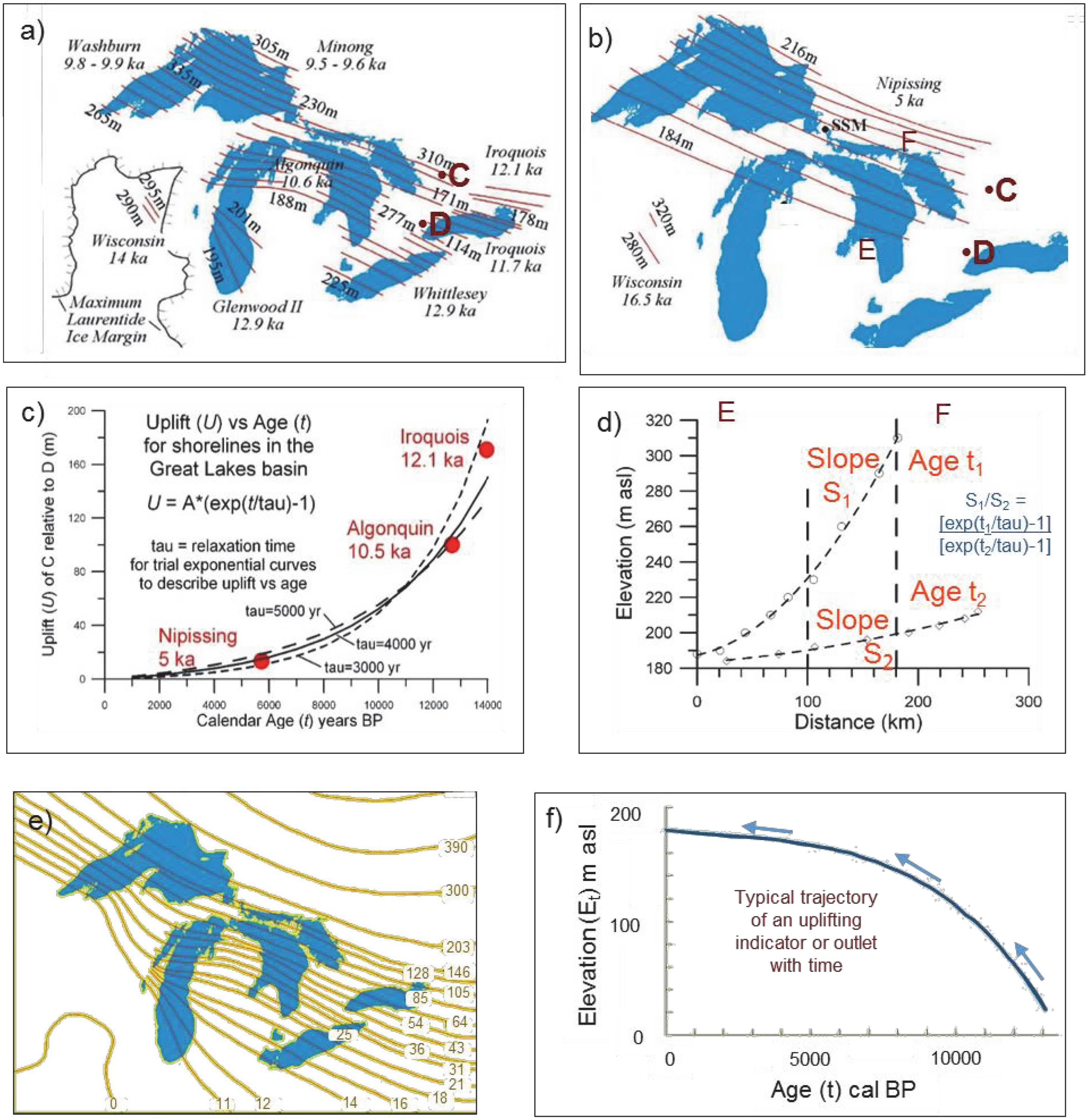

Figure 8. Computation of the original elevations of lowstand evidence and basin outlet sills independently. a–b) Sketch maps showing the age and isobase elevations of principal paleo-lakes in the Great Lakes region. From Lewis et al. (2005). c) Relative uplift of two locations, marked C and D (Fig. 8a b) versus age based on the differences in isobase values at C and D for the dated waterplanes of the Iroquois, Algonquin, and Nipissing paleo-lakes. From Lewis et al. (2005). d) Plot EF of elevation versus distance for isobases of two dated paleo-lake waterplanes (the higher Lake Algonquin and the lower Nipissing Great Lake shorelines) on the transect EF in Figure 8b; the ratio S_1/S_2 shows how τ, uplift relaxation time, is related to the shoreline slopes and ages. e) Reference uplift surface in metres describing glacial isostatic rebound throughout the Great Lakes basin since 12,500 cal BP, age of glacial Main Lake Algonquin, relative to the 0 m contour southwest of the Lake Michigan basin. From Lewis et al. (2005). f) Typical trajectory of an uplifting lake-level indicator or an outlet with time. See text for further explanation.

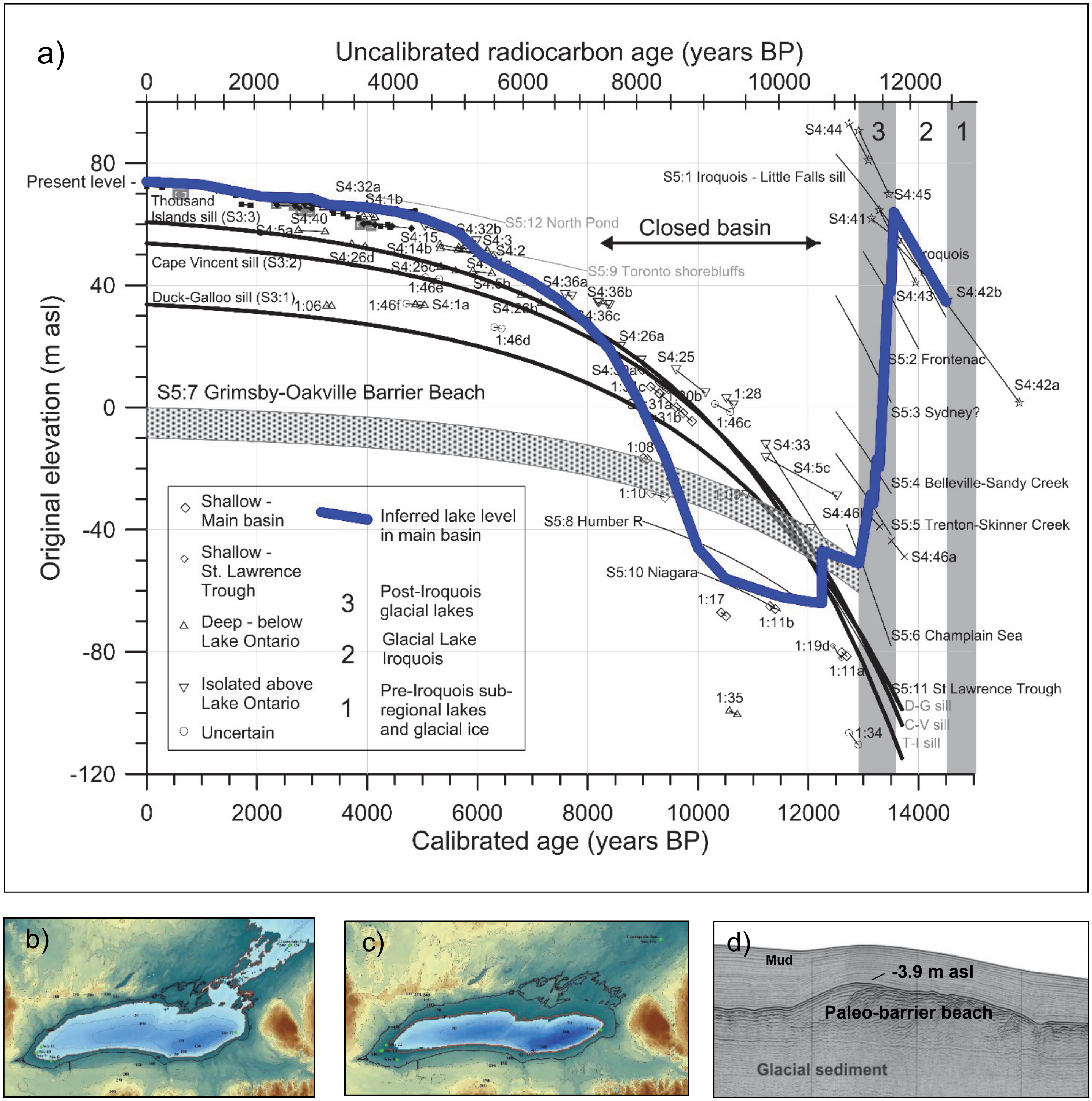

Figure 9. Lake Ontario basin water level history. a) Graph of original elevation versus age for an array of evidence of former water levels and the sills of the Lake Ontario basin (black lines). Inferred lake level is shown by the thick blue line. b) Map of reconstructed shorelines at 12,500 cal years BP showing confluent levels of early Lake Ontario and Champlain Sea in St. Lawrence River valley. Present Lake Ontario shore in black line. c) Map showing reconstructed shoreline of closed-basin Lake Ontario at 10,500 cal years BP. d) Seismic profile of a mud-buried paleo-barrier beach (Grimsby-Oakville Barrier Beach in Fig. 9a) in the western Lake Ontario basin, probably constructed during a near still-stand 12,900 to 12,300 cal years BP. Parts (a), (b) and (c) from Anderson and Lewis (2012), part (d) from C.F.M. Lewis unpublished data.

core of the mud-buried paleo-Nanticoke beach sediments. Between 12,500 and 6500 cal BP lake level was as much as 16 m below the outlet sills in the Niagara River. During this closed-basin phase, a map reconstruction of lowstand shorelines for 8500 cal BP (Fig. 10b) shows that Lake Erie was reduced to separate pools of water in its sub-basins.

Early and middle Holocene sediments in Lake Erie, from about 12,000 to 5000 cal BP, are consistent with a strongly

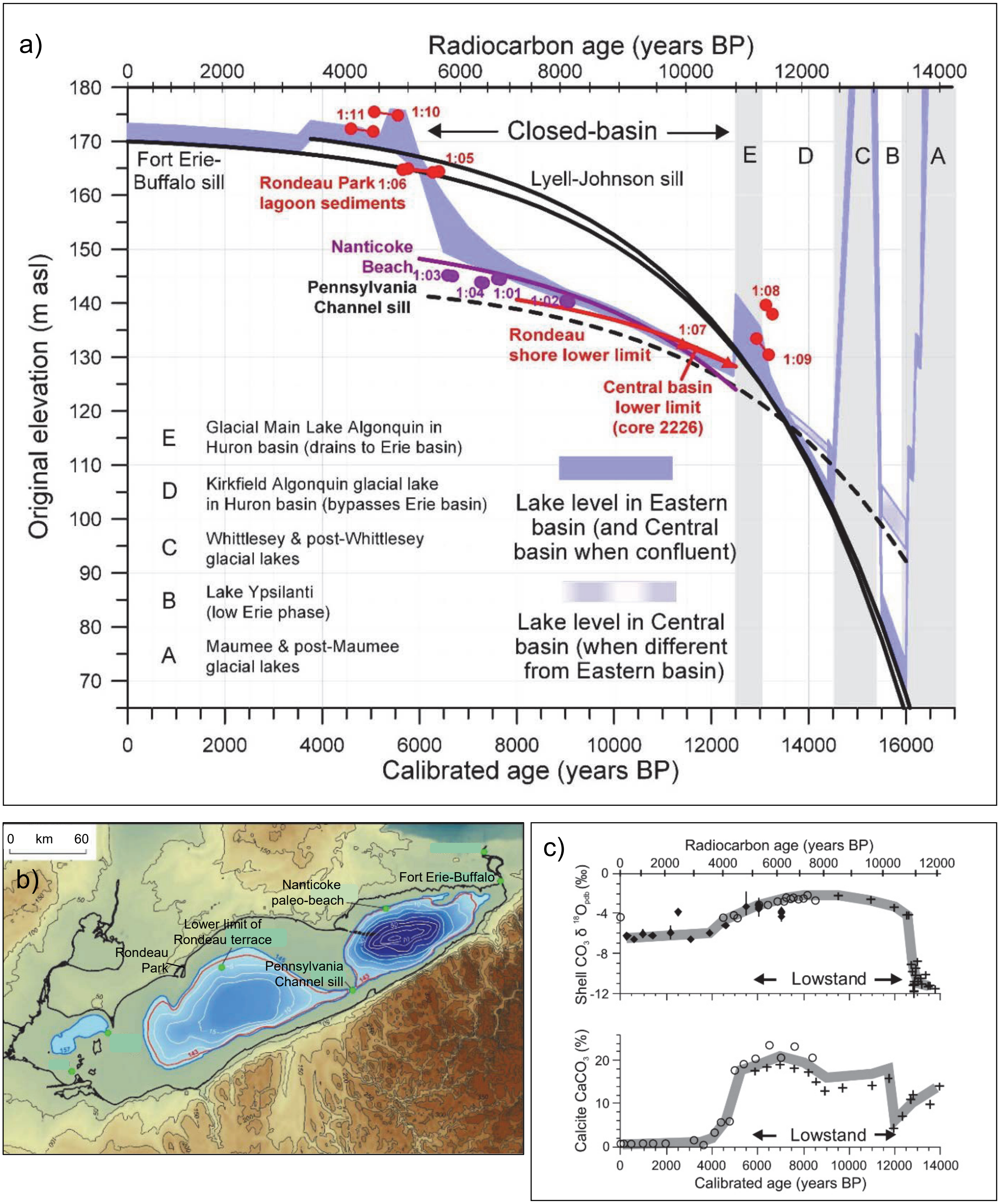

Figure 10. Lake Erie basin water level history. From Lewis et al. (2012). a) Graph of original elevation versus age for evidence of former lake levels and the outlet sills (black lines) of the Lake Erie basin. Inferred lake level is shown by the thick blue line. Key radiocarbon-dated evidence (site evidence numbered 1:11, as in Lewis et al. 2012, for example) is indicated by red and purple circles (red for evidence near Rondeau Park, and purple for evidence at Nanticoke paleo-beach, Fig. 10b); the circles at ends of lines bracket 2-sigma age ranges. b) Map showing shorelines of reconstructed closed-basin Lake Erie at 10,500 cal years BP. c) Sediment properties in offshore Erie basin sediments differentiate the lowstand (~12,000 to ~5000 cal BP) and open-lake (~5000 cal BP to present) conditions. Mollusc and ostracode δ^{18}O isotopic composition are shown in the upper graph and mineral calcite content is shown in the lower graph.

evaporative, calcite-saturated lowstand environment (Fig. 10c). The lowstand sediments are characterized by a highly positive $\delta^{18}O$ composition of ostracode and molluscan fossils, shown in the upper graph, and a high mineral calcite content, shown in the lower graph (Fig. 10c; Lewis et al. 2012).

Lake Huron and Georgian Bay, Lake Michigan, and Lake Superior Water Level History

In late glacial and early Holocene time, the overflow outlet for the Michigan, Huron and Georgian Bay basins was at North Bay, Ontario, via the Nipissing–Mattawa lowland. The uplift history of the elevation interval between the outlet sill and the full-discharge level at North Bay is shown in Figure 11a by the pale green band of rising original elevations while the water level history is portrayed by the thick blue line through the lake-level indicator data (Lewis and Anderson 2012). These data include complementary evidence of Georgian Bay lowstands in basins of the French River (Brooks et al. 2012), and in Georgian Bay (McCarthy et al. 2012). Tree stump data, always above the inferred lake level, are shown by the solid-coloured downward-pointing triangles, and their locations are plottted in Figure 11b. The lake-level history defines five lowstands with four below the North Bay outlet. Lowstands in solid blue line (Fig. 11a) are based on evidence in the Huron basin and are considered phases of low Lake Stanley. Lowstands shown with blue dots are based on evidence in the Georgian Bay basin and are named 'Lake Hough' after J.L. Hough. These lacustrine lowstands are largely contemporaneous with terrestrial evidence of dry climate and drought in eastern upper Michigan, USA, between the Lake Michigan and Lake Superior basins (Loope et al. 2012). Lowstands marked B, C_3, and D in Figure 11a are correlated with the Lt. Blue, Lt. Green1, and Lt. Green2 offshore sediment unconformities in the northern Lake Huron basin (Fig. 4d), marked by brown lines above the X-axis of Figure 11a.

The approximately 2500-year period of closed lowstands from about 11,000 to 8500 years ago was interrupted by at least four highstands. These lakes, collectively named 'Lake Mattawa,' would have overflowed the basin outlet valley at North Bay into the Mattawa and Ottawa River valleys. Currently they are variously attributed to outburst floods of surface water from glacial Lake Agassiz, meltwater from the Laurentide Ice Sheet (Breckenridge and Johnson 2009), or possibly, from unknown reservoirs. Recent dating of Lake Agassiz beaches in the Red River Valley (Fig. 7a) (Lepper et al. 2013), and boulders in outlet discharge channels north of Lake Superior (Kelly et al. 2016) suggests that the 10.7 cal BP Early Mattawa lake (Fig. 11a) could have been caused by rapid drainage from the Campbell beach level of Lake Agassiz through the basins of lakes Nipigon and Superior to the Lake Huron basin. Also, the Lake Mattawa phase about 9300 cal BP has been attributed to erosion of the morainic dam across the eastern Lake Superior basin and drainage of the impounded glacial Lake Minong (Yu et al. 2010; Lewis and Anderson 2012).

As measured in benthic ostracode fossils, the $\delta^{18}O$ isotopic composition of the Lake Mattawa highstand water was most similar to that of evaporated water or precipitation and runoff (Rea et al. 1994a, b; Dettman et al. 1995). It was more positive than that for the lowstand water which was quite negative, typical of glacial meltwater. Although more research is in order, the current data suggest the highstand lakes were filled with outburst floods from upstream stratified Lake Agassiz and the Superior basin lake during summers when the surface waters had undergone evaporation and mixing with summer precipitation and runoff (Buhay and Betcher 1998; Birks et al. 2007). The lowstand bottom waters, in which ostracodes lived, were possibly dominated by glacial groundwater, which drained from porewater in adjacent watersheds as base levels were lowered by evaporation (A. Smith personal communication 1996). The groundwater would have been charged by previous subglacial meltwater or glacial lakes. Clearly, the isotopic composition of surface waters in these Huron basin lake phases needs to be determined, as has been done for glacial Lake Agassiz (Buhay and Betcher 1998; Birks et al. 2007) to verify these suggestions.

In the Lake Michigan basin, low-level Lake Chippewa, following Lake Algonquin, was recognized by Hough (1955) on the basis of a sedimentary unconformity in which shallow-water sand and shells were overlain by deep-water clay. Hydrological closure of the basin was inferred at about 7 ^{14}C ka by Forester et al. (1994) and Colman et al. (1994) in a study of the ostracode fauna, and was confirmed later by a comparison of Holocene water level and outlet elevations in the Lake Michigan basin (Lewis et al. 2005). Multiple sites in the Lake Superior basin revealed a large drop during the Houghton phase and indicated that the water level was below the basin outlet between >9100 and 8900 cal BP (Boyd et al. 2012). Also, closed lake status is supported by a shift to more positive $\delta^{18}O$ isotopic values found in benthic ostracode fossils from the Lake Superior basin for the same period (Hyodo and Longstaffe 2012). Thus, the Superior basin lake was hydrologically closed during this period at least.

PALEOCLIMATE RECONSTRUCTIONS SUPPORT THE CLOSED-BASIN LOWSTANDS

Trends of annual temperature and humidity (moisture) obtained for the southern Ontario region from isotopic variations in terrestrial plant matter and lake sediments (Fig. 12a) show that the early Holocene climate was much colder and drier than at present, suggesting that dry Arctic air masses were initially prevalent over the Great Lakes basins followed by dry and warmer Pacific air masses (Edwards and Fritz 1986; Edwards et al. 1996). These trends are consistent with computation of the solar radiation reaching the northern hemisphere (Fig. 12b) (Kutzbach et al. 1998). During the period of the Great Lake lowstands, indicated by the grey band (Fig. 12b), summer insolation was more than 30 Watts/m^2 greater than present, signifying enhanced evaporation from summer water surfaces compared with present conditions.

Changes in the vegetative cover on land surfaces derived from pollen analyses also support an early Holocene dry climate. Pollen assemblage data have been correlated quantitatively to climate, and transfer function analyses of pollen

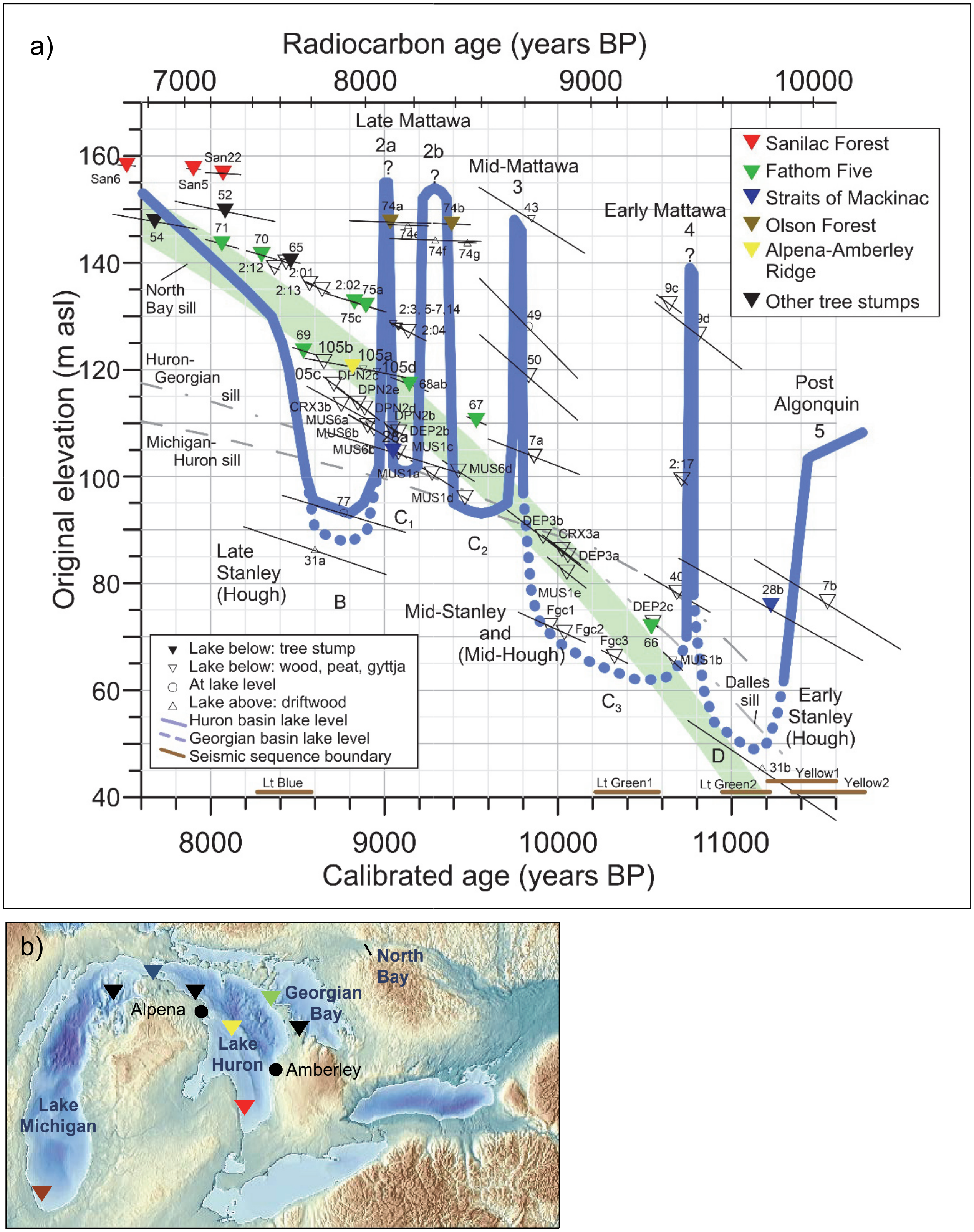

Figure 11. Huron and Georgian Bay basin water level history. From Lewis and Anderson (2012). a) Graph of original elevation versus age for evidence of former lake levels in the Huron and Georgian Bay basins and the elevation interval between outlet sill and full-discharge level (pale green band) at North Bay, Ontario. Inferred lake level is shown by the thick solid blue line in the Huron basin and by the blue dotted line in the Georgian Bay basin. b) Map showing locations of submerged tree stump data (legend on Figure 11a) and the North Bay outlet.

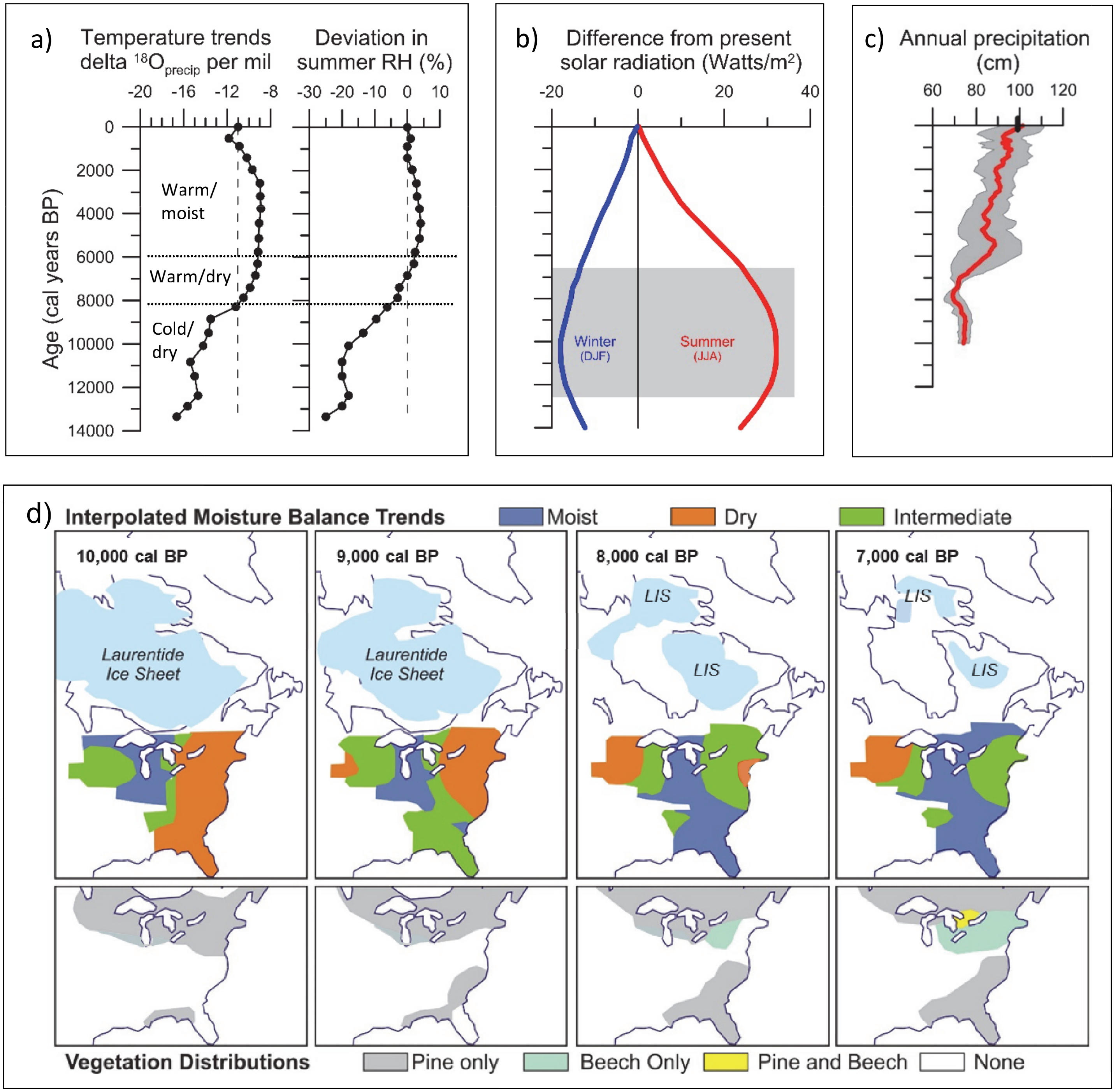

Figure 12. Paleoclimate proxy indicators. a) Mean annual temperature and summer humidity (moisture) trends in southern Ontario based on isotopic studies of terrestrial plant matter and lake sediments. Vertical dashed lines indicate present values. Data from Edwards et al. (1996). b) Solar radiation (insolation) in summer months (JJA) and winter months (DJF) for northern hemisphere. Grey band demarcates period of Great Lake lowstands. Data from Kutzbach et al. (1998). c) Results of transfer function analyses of pollen assemblage records from four small lakes near Huntsville, Ontario (Fig. 3), east of Georgian Bay showing a reduction of about 25–30 cm/yr in annual precipitation during the Great Lake lowstands; envelope of values in grey, and average values in red. Black line across X axis indicates present average precipitation. Data from McCarthy and McAndrews (2012). d) Early Holocene changes in moisture balance trends in small lake levels/areas and the relative presence of dry-tolerant pine and moisture-loving beech for the diminishing area of the Laurentide Ice Sheet (LIS) Adapted from Shuman et al. (2002).

records from small lake basins east of Georgian Bay (McCarthy and McAndrews 2012), for example, clearly show a reduction in early Holocene annual precipitation of about 25–30 cm/yr compared with present values (Fig. 12c).

The correlation of early Holocene climate change and deglaciation is well illustrated by Shuman et al. (2002) in snapshots from 10,000 to 7000 cal BP (Fig. 12d). In the upper series of maps showing a receding Laurentide Ice Sheet, changes in small lake levels and interpolated moisture balance trends show that dry conditions (orange areas) affected the eastern Great Lakes from 10,000 to 9000 cal BP, and the western Great Lakes from 8000 to 7000 cal BP. In the lower series of maps, the changing distribution of dry-tolerant pine and moisture-loving beech illustrates the increasing moisture availability through the early Holocene. At 10,000–9000 cal BP the Great Lakes were surrounded by dry-tolerant pine, but by 8000 to 7000 cal BP, the presence of moisture-loving beech appeared around the southern Great Lake basins.

In the absence of meltwater supply, the Great Lake lowstands resulted from a major incursion of dry climate induced by the residual presence of the retreating Laurentide Ice Sheet and its overlying anticyclonic atmospheric circulation, which prevented meridional (northward) flow of moisture (Shuman et al. 2002). The presence of aeolian deflation surfaces and terrestrial sand dune activity in the Great Lakes region attests to the late Wisconsinan and early Holocene dry climate, possibly aided by North Atlantic cool phases recorded in the Greenland ice core records (Campbell et al. 2011). The blockage of northward flows of moist subtropical air masses, likely also aided by southward shifts of strong temperature gradients and the atmospheric jet stream because of the residual ice sheet presence, enhanced the occurrences of dry Arctic air and later dry Pacific air masses over the Great Lake basins. The more frequent presence of dry air would have increased evaporation and reduced the lake levels. As the ice sheet diminished after 8900 cal BP and broke up over Hudson Bay at 8200 cal BP, northward advection of subtropical moisture increased (Shuman et al. 2002). With the increased water supply, lake levels rose and the closed-basin phases of the Great Lakes came to an end.

SIGNIFICANCE OF THE GREAT LAKE LOWSTANDS

Sensitivity to Climate Change

The Holocene lowstands outlined by this research can be viewed as a natural experiment to show that the Great Lakes are sensitive to climate change, particularly to climates drier than the present. This knowledge is important and such sensitivity may not be widely appreciated because the Great Lakes appear now to be relatively stable, as their mean monthly water levels have varied less than 2 m during the past 150 years of lake level monitoring (NOAA 2016).

From another viewpoint, Croley and Lewis (2006) have examined the question "How much climate change is required to reduce the present Great Lakes to closed-basin water bodies?" The change inputs are expressed in graphs of temperature change versus reductions in precipitation. The resulting changes in water level for specific lakes (Lake Superior and Lake Huron, for example, in Fig. 13) are expressed as elevation contours on the graph; the diagonally-ruled zones indicate where the lake levels fall to the outlet sills. As climate changes, contours to the left of the diagonally-ruled zones (outlet sills) illustrate the declining surfaces of the open lakes and those to the right of the same zones define the declining water surfaces when the lakes become closed. These lakes and the other Great Lakes (Croley and Lewis 2006) would become closed water bodies for large reductions in annual precipitation of 40 to 60% with present temperatures or small rises in temperature of < 2°C. In addition, evaporation and reduction of lake levels would be enhanced if wind speeds were faster (T. Croley personal communication 2010).

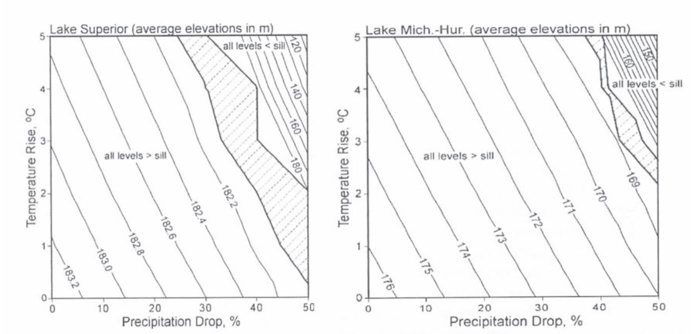

Figure 13. Climate change needed to drive the present Great Lakes into hydrological closure. These graphs of elevation contours (m asl) show how the lake surfaces decline from left to right as a function of changes in annual average values of temperature versus precipitation. Contours to the left of the outlet sills (ruled areas) indicate decline of the water surfaces while the lakes overflow their outlets, and those to the right refer to lowering of the water surfaces once the lakes are closed. From Croley and Lewis (2006).

Clearly, quite large reductions in climatic moisture to 40 to 60% of present precipitation are needed to drive the lakes into closure. This result is consistent with the conclusion of this paper that the lowstands were uniquely induced by severe dry climate related to the presence of the residual ice sheet during deglaciation.

The sensitivity of the Great Lakes water levels to past reductions in water supply implies that they would be sensitive also to future large water withdrawals and transfers to alleviate water shortages elsewhere in North America. Such a possibility should be taken into account in policy formulations regarding large water diversions from the Great Lakes.

What is the Future Outlook for the Great Lakes?

It is uncertain how climates will evolve over the Great Lake basins in this era of global warming. Kutzbach et al. (2005) explained by means of a plot of effective precipitation (P–E) versus Earth latitude, S pole to N pole, that warming is accompanied by an increase in total atmospheric vapour content in the tropics, and by an increase in poleward transport of water vapour (Fig. 14).

The boundary in the northern hemisphere, between northern areas which become wetter and southern areas which become drier, is about 42–43°N in the latitude of the southern Great Lakes for the average of seven global climate models driven by CO_2 greenhouse gas warming. However, individual climate simulations put this boundary as far south as the northern Gulf of Mexico, and as far north as James Bay. With this extent of variability, the future water supply of the Great Lakes is uncertain. Nonetheless, the early to middle Holocene phase of dry climate and closed-basin lowstands illustrates the sensitivity of the Great Lakes should their climate shift to one much drier than present, or future major diversions of their waters be permitted.

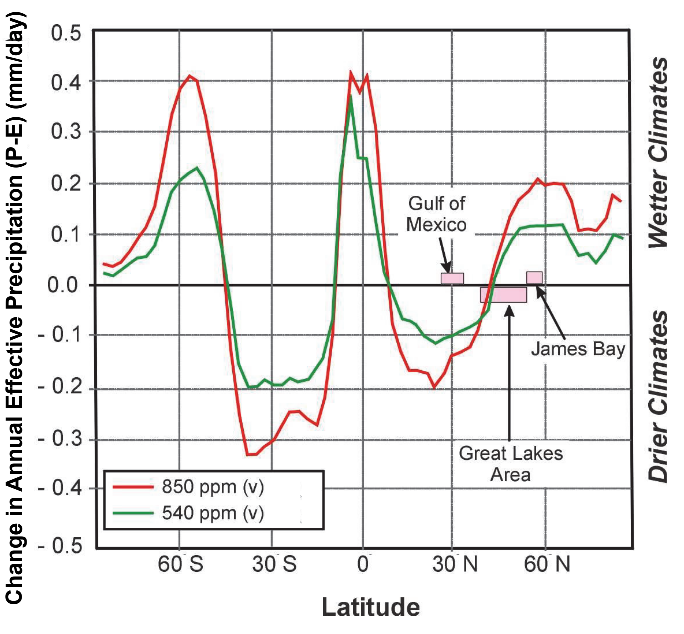

Figure 14. Future Great Lake climates. Graph of change in annual effective precipitation (precipitation – evaporation) versus Earth latitude for results from two groups of 7 climate models providing projections for the period 2089–2099, assuming either high-end (850 ppmv) or low-end (540 ppmv) greenhouse gas concentrations. The average boundary between future drier and wetter climates lies in the southern Great Lakes region, but individual model results position the boundary as far south as northern Gulf of Mexico and as far north as James Bay. Adapted from Kutzbach et al. (2005).

SUMMARY AND CONCLUSIONS

Hydrologically-closed lowstand lakes during the early to middle Holocene have been recognized in most Great Lake basins. An exponential model of glacial rebound and geological evidence of former water levels have shown that past lakes were closed when their water surfaces were lower than their corresponding overflow outlets.

The closed lowstands are the result of a past dry climate driven by the last deglaciation, and constitute an example of a severe response of the Great Lakes to a climate much drier than at present.

The recognition of the closed lowstand phases is important for

- outreach to raise awareness of the sensitivity of the Great Lakes to climate change.
- testing and validating climate-lake models by having them simulate the lowstands and thereby increase confidence in their projections of lake levels under future climates.
- policymaking that considers the implications of possible future large water diversions from the Great Lakes in the light of knowledge that the lakes have been hydrologically closed in the past and are sensitive to future changes in their water balance.

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Editor's Note:

For some years, Geoscience Canada has sought to publish papers by those who receive medals from the Geological Association of Canada for their scientific contributions. Many valuable overview papers and provocative treatments of issues in Earth Science have appeared in our Medallist Series. However, GAC is not the only geoscience organization that awards medals or recognizes excellent scientific research and in this issue it is our pleasure to extend this series to include the overview paper by Mike Lewis on the postglacial history of the Great Lakes.

Mike is the recipient of the 2015 W.A. Johnston Award of the Canadian Quaternary Association (CANQUA). The Award honours W.A. Johnston, an innovator in Quaternary studies in Canada who, in his years with the Geological Survey of Canada, developed many of the concepts of regional Quaternary studies used today. The first recipient of the Award was announced in 1987.

C.F.M. ("Mike") Lewis has worked in many areas over a long career with the Geological Survey of Canada in Ottawa and Burlington, Ontario, (Canada Centre for Inland Waters), and at the Bedford Institute of Oceanography since 1978. His central interest has been the history of the Great Lakes, a complex tale involving the interplay of the Laurentide Ice Sheet, its meltwater, isostatic rebound and shifts in the global climate. This work has revealed that these massive fresh water resources are highly sensitive, and not as perennial as we might have thought. They became shrunken, closed basins due to aridity following deglaciation, as a result of dry climate induced by the residual presence of the ice sheet north of the Great Lakes. Situated as they are in the boundary zone between differing climatic zones, the lakes remain sensitive to future anthropogenic shifts in our climate. The many lines of evidence that come together in understanding the history and perhaps the future of these iconic water bodies are explored in Mike's invited paper, based on a plenary address at the CANQUA conference in St. John's, NL, in 2015.

In future issues, we hope to honour other medal or award recipients from associated Geoscience Societies.

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