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C.F.M. Lewis

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Contributions to the glacial and postglacial history of Houghton Lake Basin in the northern part of the Lower Peninsula of Michigan, USA

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Abstract Two contributions were made to a study of the glacial and postglacial history of the Houghton Lake Basin in the northern Lower Peninsula of Michigan, USA. The first contribution describes the variation of water levels of Lake Huron (~130 m) and Lake Michigan (~100 m) which controlled the base levels for ground and surface water drainage in Lower Michigan during the past 14,000 years. These variations likely affected sedimentation within small lakes like Backus, Pup, and Marl, and partially with changes in the much larger Higgins Lake, all within the Houghton Lake Basin. The second contribution provides an estimate of differential crustal uplift in the Houghton Lake Basin north of a zone of crustal subsidence. These data suggest that the nature of crustal uplift in northern Lower Michigan is similar to uplift throughout the broader Great Lakes basin. Having only the elevations of fragments of a glacial lake shoreline throughout the Houghton Lake Basin, this estimate is based on trial elevations of the present-day elevation differences between the Lake Algonquin 190 m and 185 m isobases. A 15 m present-day elevation difference between the isobases suggests the 190 m and 185 m isobases were level, and the bowl-shaped Houghton Lake Basin probably supported a large lake, Glacial Lake Roscommon, between at least 16 and 15 ka BP. Glacial Lake Roscommon may nonetheless have existed earlier, as the Mackinac ice lobe is assumed to have begun its retreat at ca. 19 ka.

Introduction

At the invitation of R.J. Schaetzl of Michigan State University, the author prepared two contributions during 2023 to the glacial and post glacial history of the region, (Figure 1), in support of research that was being undertaken by members and associates of Michigan State University to better understand the evolution of landscapes in the Houghton Lake Basin. The basic research and analysis in chronology, glacial landform mapping, and lake sediment coring was performed by an association of American university scientists led by Schaetzl and funded by the United States National Science Foundation. I acknowledge, with pleasure, using the findings of these scientists during 2022 and 2023 in combination with my own background in Great Lake studies to make the following two contributions towards understanding the Houghton Lake Basin in the Lower Peninsula of Michigan.

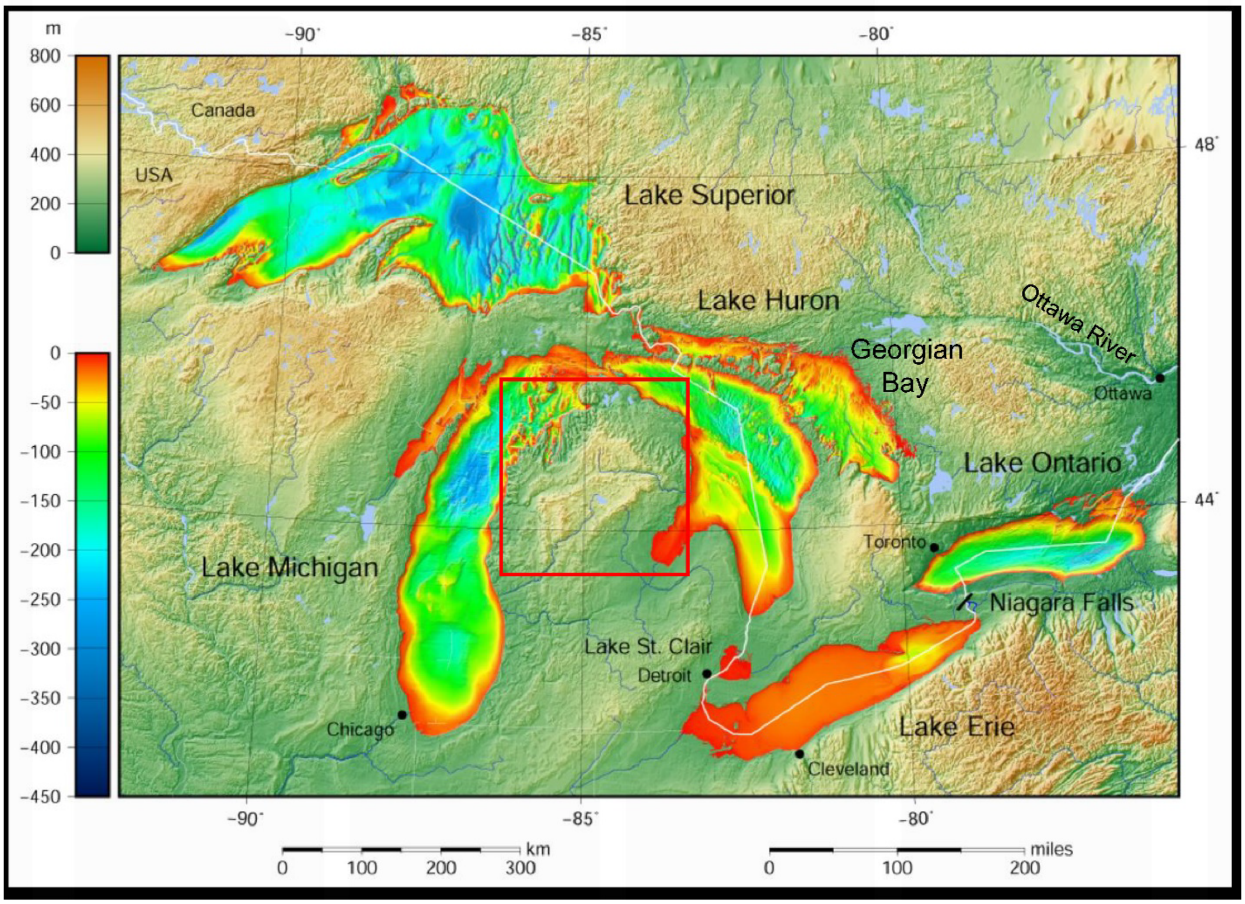

Figure 1. Great Lakes basin bathymetry and elevation. Red box between Lake Huron and Lake Michigan encloses the Houghton Lake Basin in the Lower Peninsula of Michigan. Elevation of land surface in m asl in upper palette at left. Bathymetry below individual Great Lake levels in m in lower palette at left. Image courtesy of United States National Oceanographic and Atmospheric Administration (1999).

Did variations in levels of the Great Lakes around Michigan affect sedimentation in the Roscommon lakes?

Surface elevations of the Great Lakes are the lowest levels to which terrestrial runoff and groundwater could drain in Michigan. Thus, as the Great Lake levels (surface elevations of Lakes Huron and Michigan) have fluctuated through late glacial and post glacial time, the base level for runoff and groundwater from adjacent terrestrial environments of the Lower Peninsula of Michigan (Houghton Lake Basin or Roscommon area) may have changed as well. If the base levels fell, so might the water table, tending to reduce water levels in small surface lakes, such as Backus, Pup, Marl and Higgins in the Houghton Lake Basin, depending upon the regional stratigraphy and groundwater transmissibility. Here, the results of Lake Huron and Lake Michigan water level variations are presented in Fig. 2 as are the observed elevations and durations of hiatus' in the smaller lakes of the Houghton Lake Basin. If severe enough, sedimentation in these lake basins may have reduced or stopped entirely, causing hiatus' in sediment accumulation while the lake basins were dry, as observed by other researchers (Fig.2) (Schaetzl et al. 2023). However, variations in base level are only one factor that may have influenced Roscommon lake levels; other factors such as paleoclimate, sediment supply, and runoff hydrology could also have been important.

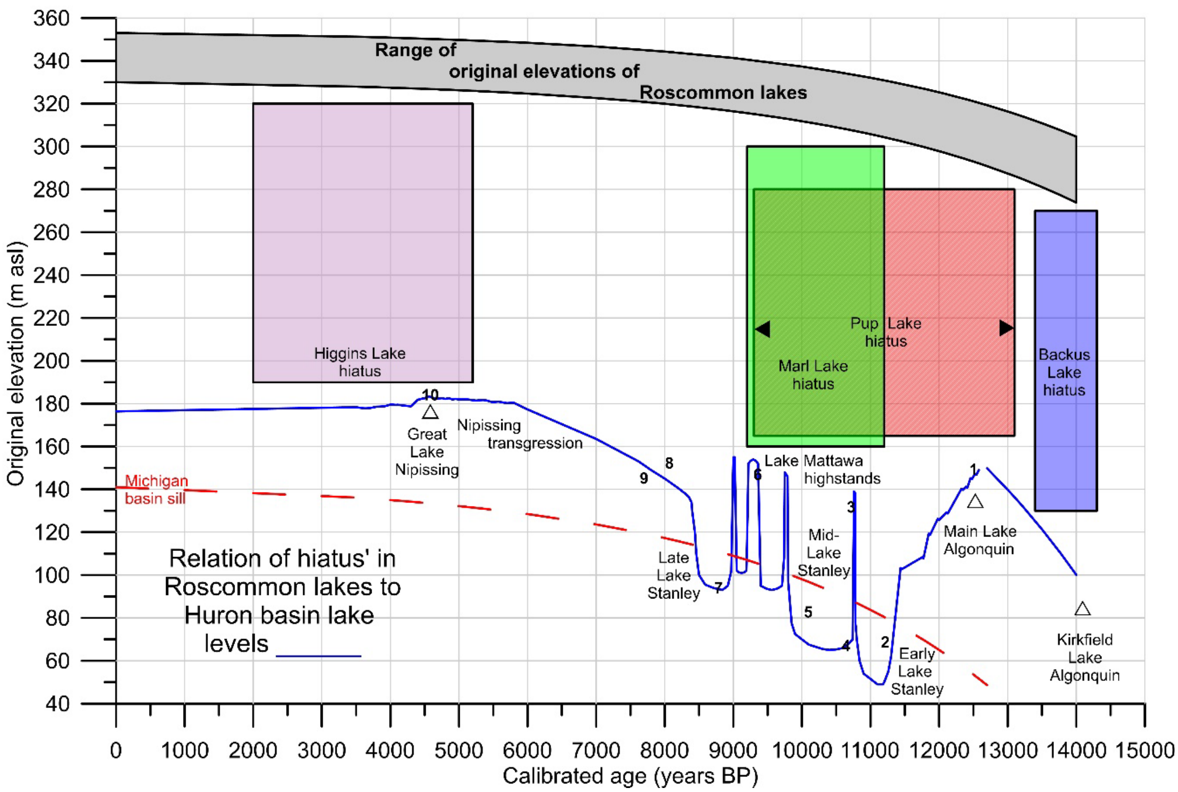

Figure 2. Plot of Lake Huron and Lake Michigan basin water level elevations and Roscommon small lake level elevations, also called Houghton Basin lakes, with age ranges of the lake's hiatus' indicated by coloured boxes. The blue line indicates lake levels in the Huron basin, and in the Michigan basin where it is above the dashed red line (sill in Straits of Mackinac between Lake Michigan and Lake Huron basins). Numerals 1 to 10 denote selected dates of water level features that confirm the history of Huron lake levels, mainly from Thompson et al. (2011), Lewis and Anderson (2012, 2017), and (Lewis et al. 2022).

Derivation of lake levels

Approximate surface elevations of lakes in the differentially uplifting Great Lakes region can be derived through time by computing the uplift of lake control sills when the lakes are open and overflowing. The age of the lake phases are confirmed by dating coastal landforms of the uplifted lake basins.

The uplift equation for the original elevations through time is (Lewis et al. 2005):

Et = Ep – A*(exp(t/*tau*)-1)

Stated conceptually: Past elevation of a site at t years ago = Present elevation – Uplift of the site over t years

where A = Ur/(exp(12400/3700)-1) and uplift values in metres, elevations in metres above sea level, t in years before present (1950 CE)

Et = the desired value, elevation of a sill or site at t years in the past, (i.e., t years older than 1950 CE or the present)

Ep = present elevation of a sill or site

A = an amplitude factor

exp = the exponential function, in which successively younger (elevation) values every *tau* years are 1/e or 1/2.7183 of the previous value

tau = relaxation time ~3700±700 years (Lewis et al. 2005). This value is assumed to be invariant throughout the Great Lakes region

Ur = reference uplift for a given sill or site location = uplift since 12,400 years ago relative to a zero reference area about 150 km west of Chicago, Illinois (Lewis et al. 2005).

The uplift equation is based on the finding that, for relative uplift in the region between Georgian Bay and Lake Ontario, to which strandline isobases of the uplifted Nipissing, Algonquin and Iroquois lakes could be projected, the relative uplift may be described by exponential curves with relaxation times between 3000 and 5000 years. As relaxation time could be computed for transects of isobases where the elevations and ages of two strandlines were known, an exploration of ~ 20 transects with these conditions throughout the Great Lakes region produced a value for *tau*, relaxation time, = 3700±700 years (Lewis et al. 2005). Because the reference uplift value is mainly based on the isobases of glacial Lake Algonquin (Lewis et al. 2005), and the southernmost Algonquin isobases are concave in the area of Lower Michigan (Lewis et al. 2022 fig. 9), it is likely that uplift owing to the enhanced load of ice in the Houghton Lake Basin has been taken into account by the uplift equation above.

For closed lowstand lakes that are not overflowing their basin sills, lake levels must be inferred from dated coastal landforms or dated features related to former lowstands, such as submerged forests where trees have been killed by rising lake levels. The original elevation of such trees is determined using the equation above.

Possible effects on sedimentation within lakes in the Houghton Lake Basin

In the accompanying plot (Fig. 2), the blue line represents water (base) level in the Lake Huron basin, and has been adopted from Huron basin paleo-lake levels in Lewis and Anderson (2012, 2017). This paleo-water level history has been extended from ~12,700 years to 14,000 years ago by computing early uplift of Lake Algonquin at the controlling sill at Kirkfield, Ontario. As water levels are commonly confluent in the Michigan and Huron basins, levels above the sill (Ep = 141 m above sea level, and A = 85 m) in the Straits of Mackinac between Lake Michigan and Lake Huron (see Fig. 1) are also the levels of paleo-lakes in the Lake Michigan basin. The grey band in the upper part of the accompanying plot (Fig. 2) represents the range of surface level variation due to uplift of the small lakes in the Roscommon basin. The reference uplift for these lakes ranges between 31 m and 36 m. The present elevations above sea level (asl) of these lakes are Higgins 352 m, Marl 330 m, Pup 343 m, and Backus 353 m (Schaetzl et al. 2023). The paleo-elevations of all these lakes would have varied within the grey band in Fig. 2.

According to the summary of the lake sediment core results (Schaetzl et al. 2023), each of these lakes showed pauses or hiatus' in sedimentation within the following periods, also illustrated by the width of the coloured boxes in the accompanying Fig. 2:

Backus Lake - from 14,300 years to 13,400 years ago

Pup Lake – from 13,100 years to 9300 years ago

Marl Lake – from 11,200 years to 9200 years ago

Higgins Lake – from 5200 years to 2000 years ago

Referring to the accompanying Fig. 2, there appears to be some relationship between paleo-lake level variations in the Huron and Michigan basins and the rate of sediment accumulation in the small lakes of the Houghton Lake Basin, i.e, Marl, Pup, Backus, and Higgins in part. There is an indication that when the large paleo-Lake Huon and paleo Lake Michigan base levels are low or lowering, sediment accumulation in the Houghton Lake Basin lakes slows or stops, forming a sedimentation hiatus. Such a hiatus may sometimes have occurred because the lake basins were dry.

The Backus Lake hiatus occurred during the Kirkfield phase of Lake Algonquin when the lake overflow sill at Kirkfield, Ontario, was isostatically depressed and water levels were low. The hiatus ends after a few hundred years as Lake Algonquin rises, owing to glacial isostatic adjustment, to the Main Algonquin level.

The hiatus in Pup Lake sediment accumulation appears to have formed about 12.4 ka BP (date 1 in the accompanying Fig. 2) as the Main Lake Algonquin began to drain to Ottawa River (adjacent to Ottawa in Fig. 1) and decline during the post-Algonquin lake series. The hiatus continued for several thousand years to about 9.3 ka BP. Perhaps the low Lake Stanley base levels in the Huron and Michigan basins lowered the water table so much, near this lake, that it may have dried up.

The hiatus in Marl Lake only began about 11.2 ka BP (date 2 in the accompanying Fig. 2), close to the onset of the extremely low water levels of the Early Stanley phase. Perhaps a longer period of lowered water tables locally, induced by the post Algonquin and Early Stanley phases of low lake level, was required to pause sedimentation in Marl and Pup lakes. Interestingly, the end of sedimentation hiatus conditions in both lakes began about 9.2 ka to 9.3 ka BP, at about the time of the rise of Huron basin lake level to the Lake Mattawa 2b highstand. The latter coincided with the death of trees about 9.3–9.45 ka BP in the Olson Forest in southern Lake Michigan, as indicated by date 6 in the accompanying Fig. 2. Other evidence of sediment drying may be noticed when cores of the lake's sediments are examined further, or if seismic profiles are obtained across the lakes.

The long (~3000 years) hiatus in the sediment record of Higgins Lake from 5.2 ka BP to 2.1 ka BP only poorly correlates with the history of Huron basin lake levels. Possibly a ~4 m drop in level over 500 years after the 4.5 ka peak (date 10 in the accompanying figure) of the Nipissing Great Lake (Thompson et al. 2011) caused a small decline in the Roscommon water table, and this event may have contributed to the Higgins Lake hiatus.

Differential uplift in lower Michigan in terms of uplift for the wider Great Lakes region and the probable age of Glacial Lake Roscommon

To assess the topics above, equations that describe the post-glacial differential uplift of the Great Lakes region are applied and the results compared with surveyed shoreline elevations in the Houghton Lake Basin. The southern isobases of paleo-Lake Algonquin of the Late Wisconsinan Great Lakes are curved, concave southward, around the Lower Peninsula of Michigan, which contains the Houghton Lake Basin. This situation suggests that Lower Michigan had borne overall (in addition to the Mackinac lobe) an unusually thick or longer-lasting load of Laurentide Ice than the load in adjacent regions (Fig. 3).

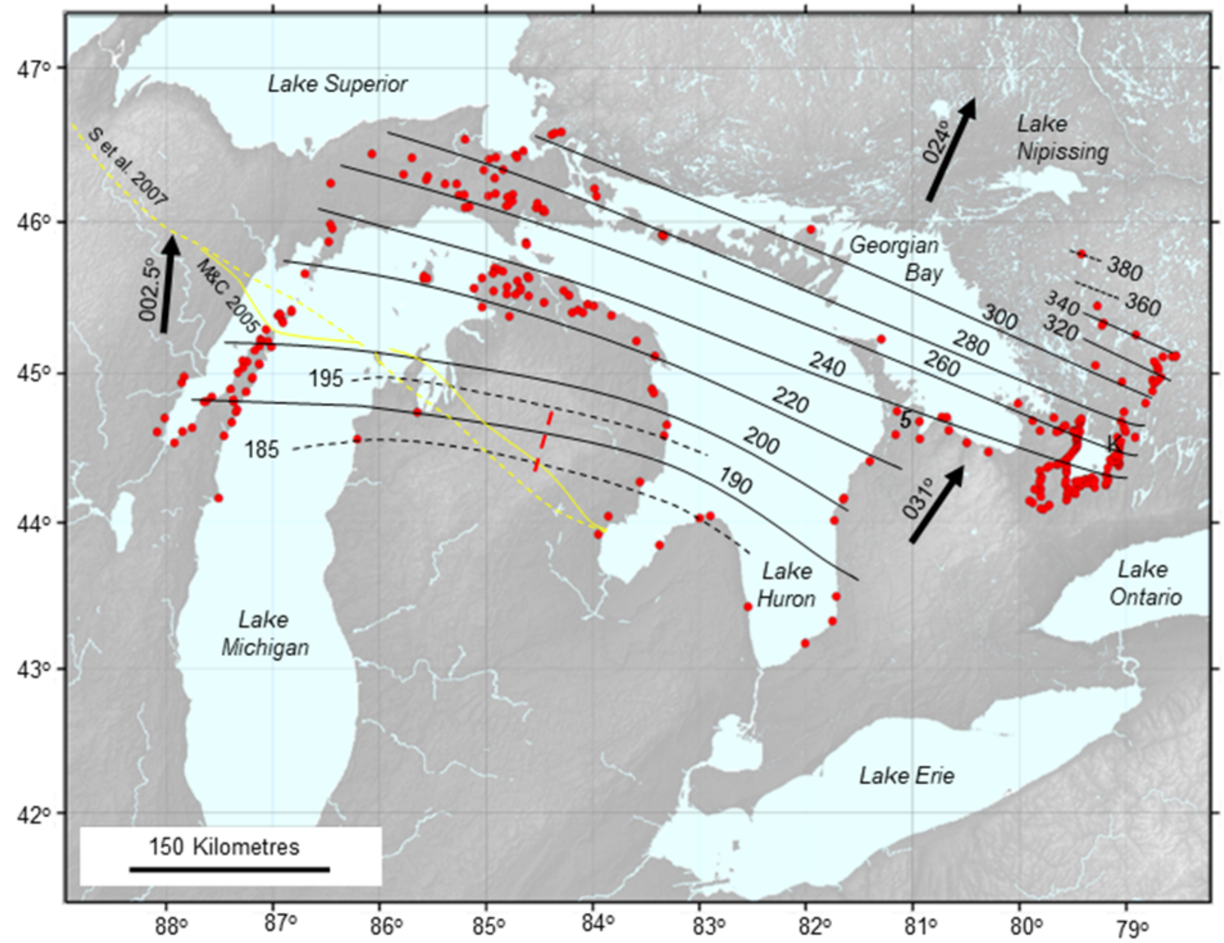

Figure 3. Isobases in metres above sea level for glacial Lake Algonquin, age 12,400 calibrated years BP. Solid red circles are positions of elevation measurements of the glacial Lake Algonquin strandline. Isobases at 185 m and 195 m above sea level were added to this figure from elevation data compiled for Lake Algonquin in Lewis et al. (2022). Yellow solid and dashed lines demarcate a boundary zone, south of which the crust is subsiding, and north of which the crust is rising (Mainville and Craymer 2005, also M&C 2005; Henton et al. 2006; and Sella et al. 2007 also S et al. 2007). Only the rising area is assumed to be uplifting differentially following crustal depression under the former ice load. The southern subsiding area possibly reflects a collapsing glacial forebulge. The dashed red line indicates the part of the rising section that was analysed for differential uplift.

The southwardly concave Algonquin isobases suggest that the unusually heavy ice load still existed during the time of Lake Algonquin about 12,400 years ago, causing excessive crustal depression, even though crustal irregularities were being smoothed during rebound (Walcott 1972). Isobases of the later Nipissing Great Lake about 4500 years ago pass smoothly through the Lower Peninsula of Michigan (Lewis et al. 2022), suggesting that the excessive crustal depression of the Houghton Lake Basin had been eliminated by that time (Fig. 4).

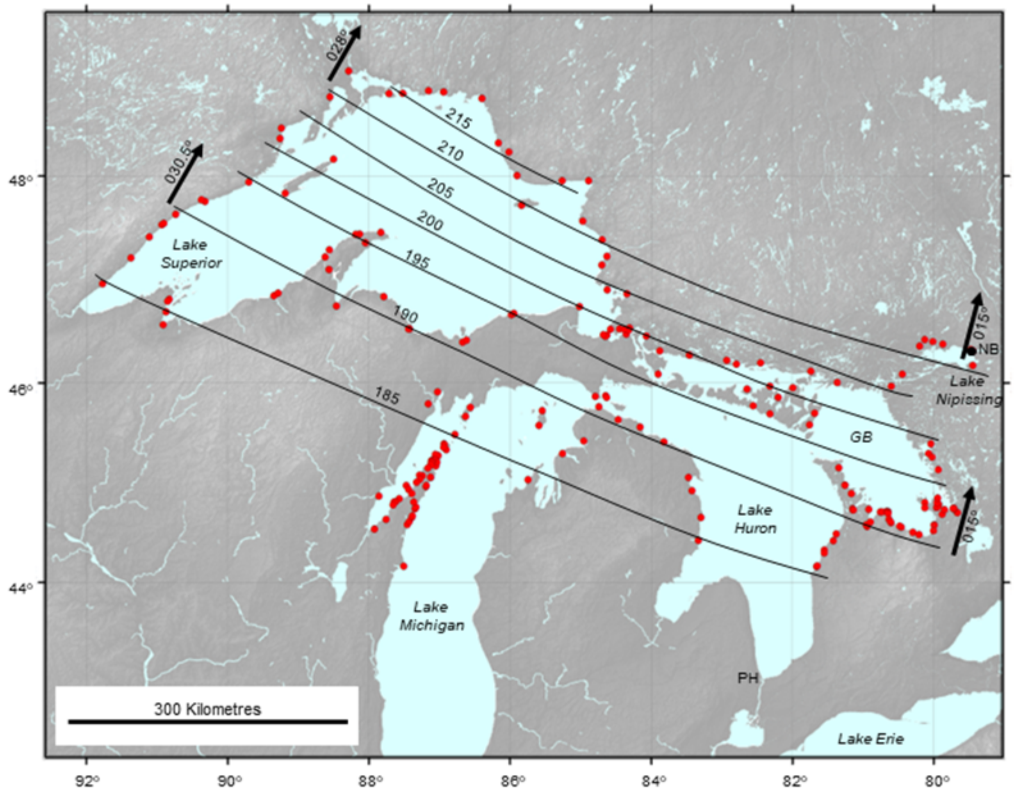

Figure 4. Isobases in metres above sea level on the Nipissing Great Lake strandline, age 4500 years (OSL). Solid red circles reflect the positions of elevation measurements of the strandlines of the Nipissing Great Lake. Note that the 185 m asl Nipissing isobase passes smoothly through the lower peninsula of Michigan between Lakes Michigan and Huron. From Lewis et al. (2022).

The ice load that caused the excessive depression was probably the aggregate loads of the Lake Michigan, Saginaw, and Mackinac lobes of the Laurentide Ice Sheet (LIS) (Schaetzl et al. 2023). The advancing ice margin of the Mackinac lobe in the Houghton Lake Basin has been documented by moraines dating from the Red Oak (Bucks) Ridge about 40 ka (OSL) in the northern sector to the Lake City-Harrison Ridge about 19 ka (OSL) in the southern sector (Fig. 5). The initiation of this advance preceded the LIS glacial maximum by about 10,000 years. Shore features of Early Lake Roscommon, inferred in the Schaetzl et al. (2023 fig. 36) model, were probably destroyed by the advancing ice.

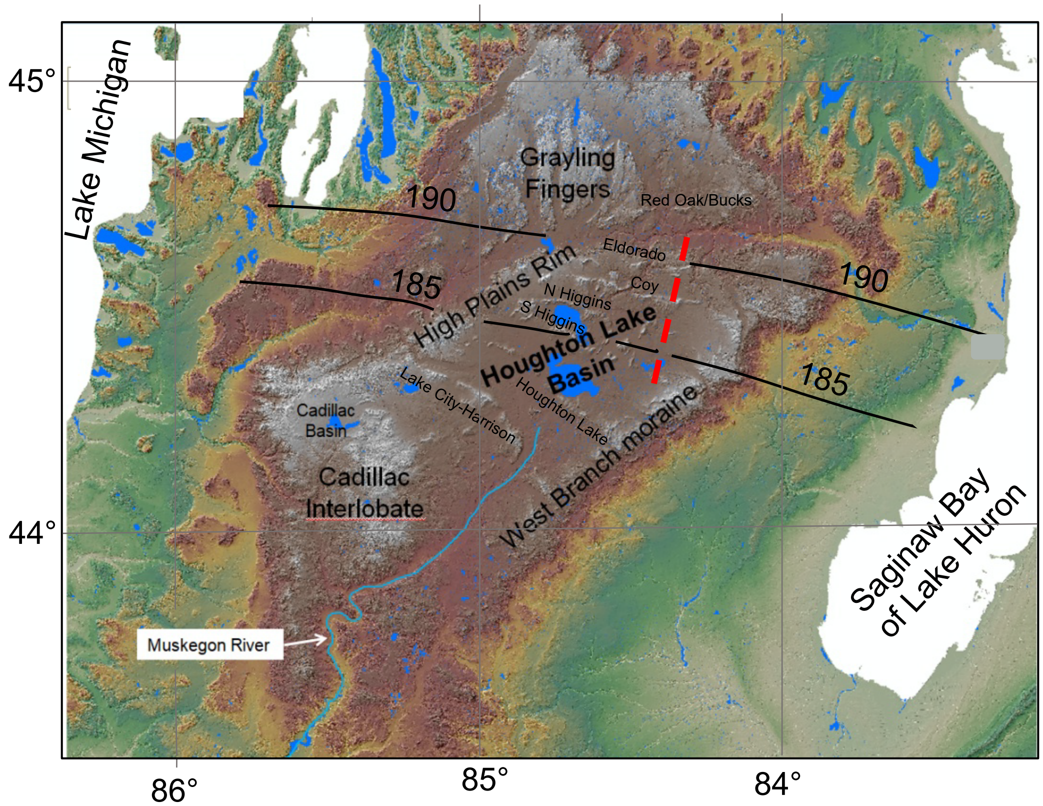

Figure 5. Map of the Houghton Lake Basin in the Roscommon County area of Michigan showing names of features (large font). Ridges (moraines) exclusive of Cadillac Basin are shown in small font; South Higgins Lake ridge and northern ridge labels appear above each ridge, Houghton Lake ridge and Lake-City Harrison ridge labels appear below the ridges. Lake Algonquin isobases at 5 m interval of elevation from 185 m to 190 m above sea level (asl) are superimposed on the map from Fig. 3. The dashed red line is the section that was analysed for differential uplift of the Houghton Lake Basin. (base map from Schaetzl et al. 2023 with permission)

An expanding Glacial Lake Roscommon after 20 ka (OSL) would likely have existed, caused by the retreat of the Mackinac lobe through the Houghton Lake Basin (Schaetzl et al. 2023). Observable fragments of shore features formed by this lake phase were found in the landscape at elevations ranging between 328 m asl and 368 m asl (Fig. 6) (Schaetzl et al. 2023).

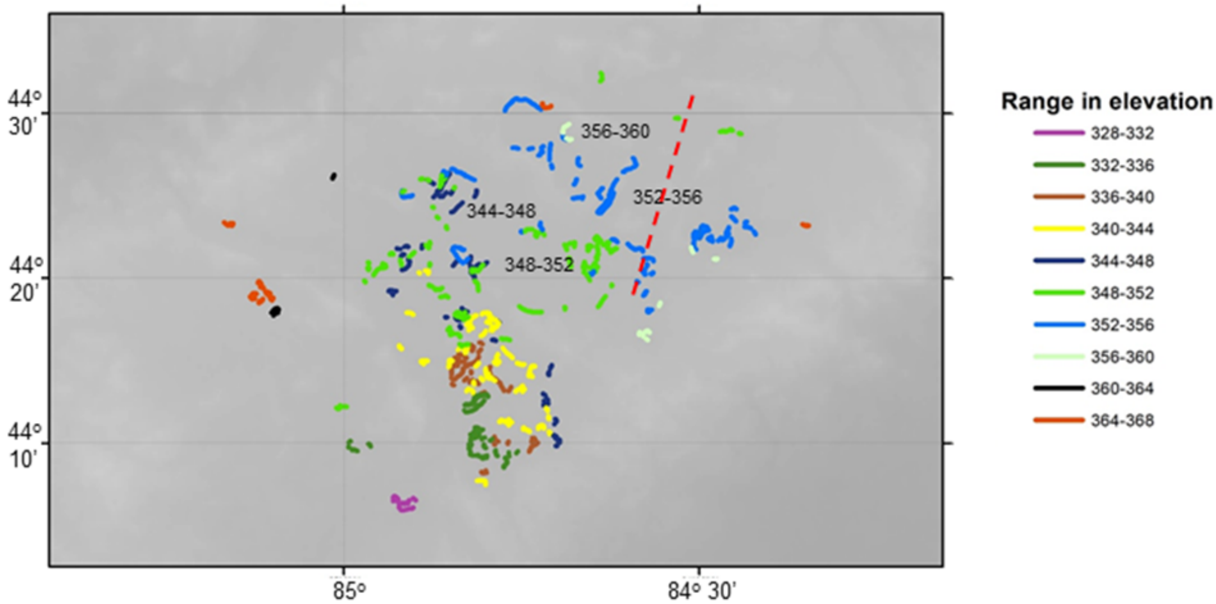

Figure 6. An example of some of the shoreline fragments in the Houghton Lake Basin (data from Schaetzl et al. 2023). Shoreline elevations, against a grey background keyed to the Houghton Lake Basin indicated by latitude and longitude, in groups spanning 4 m are colour-coded to the legend at right. Only shoreline fragments in the northeast sector of this map are in the area of modern uplift. See Figure 3 for the location of the boundary zone between areas of uplift and subsidence. The dashed red line is the section that was analysed for differential uplift of the Houghton Lake Basin. (Shoreline data from Schaetzl et al. 2023.)

The southern peninsula of Michigan is traversed by a boundary zone between uplift to the north and subsidence to the south, evidenced by long term measurements of Great Lakes water levels (Mainville and Craymer 2005), and by Global Positioning System vertical earth measurements (Fig. 3) (Henton et al. 2006, Sella et al. 2007). The subsidence may demarcate areas of a collapsing crustal peripheral forebulge that was forced upward by the previous ice load. Only areas to the north of the boundary zone where uplift is still in progress can be assessed in terms of the present knowledge of glacio-isostatic differential uplift for the Great Lakes basin. By comparing Figure 3 and the figure of shoreline fragment elevations (Fig. 6) (Schaetzl et al. 2023), it appears that only the northeast sector of the area in which Lake Roscommon shore features are visible is undergoing uplift. Shorelines with elevations ranging from 344 m to 360 m above sea level occur in this area between the 185 m and 190 m Algonquin isobases.

Background of differential uplift in the Great Lakes region

The differential uplift of the Great Lakes region was derived from observation that relative uplift for paleo-lakes Iroquois, Algonquin, and Nipissing between Georgian Bay and Lake Ontario could be described using exponential curves with relaxation times of 3000 to 5000 years, as explained in Lewis et al. (2005), and Lewis (2016). Further analysis of 20 paleo-shoreline transects in basins containing two dated strandlines of different age determined the mean and standard deviation of the Great Lakes relaxation time to be 3700±700 years. A response surface for uplift since Lake Algonquin, 12,400 cal years ago, relative to a zone of inferred zero uplift about 150 km west of Chicago, IL, was developed using Lake Algonquin deformation, and that of other paleo-lake shorelines after they were adjusted to the currently accepted age of Lake Algonquin (12,400 cal years BP) (Lewis et al. 2005). Contours of uplift in the response surface are shown in Fig. 6 of Lewis et al. (2005). Results of the glacioisostatic analysis are shown in Figure 7 and Table 1 below.

Application of Great Lakes differential uplift to the Houghton Lake Basin

Contours of 30, 36, 39.5 and 43 m of uplift since 12,400 cal years follow the 185 m, 190 m, 195 m, and 200 m Algonquin isobases (above sea level) approximately (Fig. 2) through the Lower Peninsula of Michigan. The response surface values of post-Algonquin uplift for the 185 and 190 m isobases modified by amplitude factors were employed to compute elevations of sites on the isobases for a range of ages (Table 1) using the equations for differential uplift in Lewis et al. (2005). Only elevations between the 185 and 190 isobases were used owing to the restricted distribution of observed Glacial Lake Roscommon shore fragments in the zone of modern uplift. Trial modern shore elevations were postulated for sites on the 185 and 190 m isobases and elevations of the sites were computed for a wide range of ages from 10,400 to 25,000 years ago (Table 1). When the computed elevation differences between the adjacent 185 m and 190 m contours (isobases) switched from positive to negative, or became zero, a level surface was detected between sites on the adjacent isobases, and this condition was assumed to signal the potential presence of Glacial Lake Roscommon. This level condition indicated when the bowl-shaped attitude of the basin that included the 185 m and 190 m isobases was well suited to hold the waters of the lake. The isobases are separated by about 24 km. The age of the level condition was identified in the computations by yellow cell colour (Table 1). If the observed range of trial modern shore elevations could accommodate or led to equal elevation differences at adjacent Algonquin isobases, Glacial Lake Roscommon was inferred to have been present at the indicated age of level conditions. If the age of the computed level surface also agreed with the inferred probable age of ice retreat or the inferred presence of Glacial Lake Roscommon from other data, confidence was gained for the idea that the parameters of differential uplift in the wider Great Lakes region applied also to the restricted Houghton Lake Basin area.

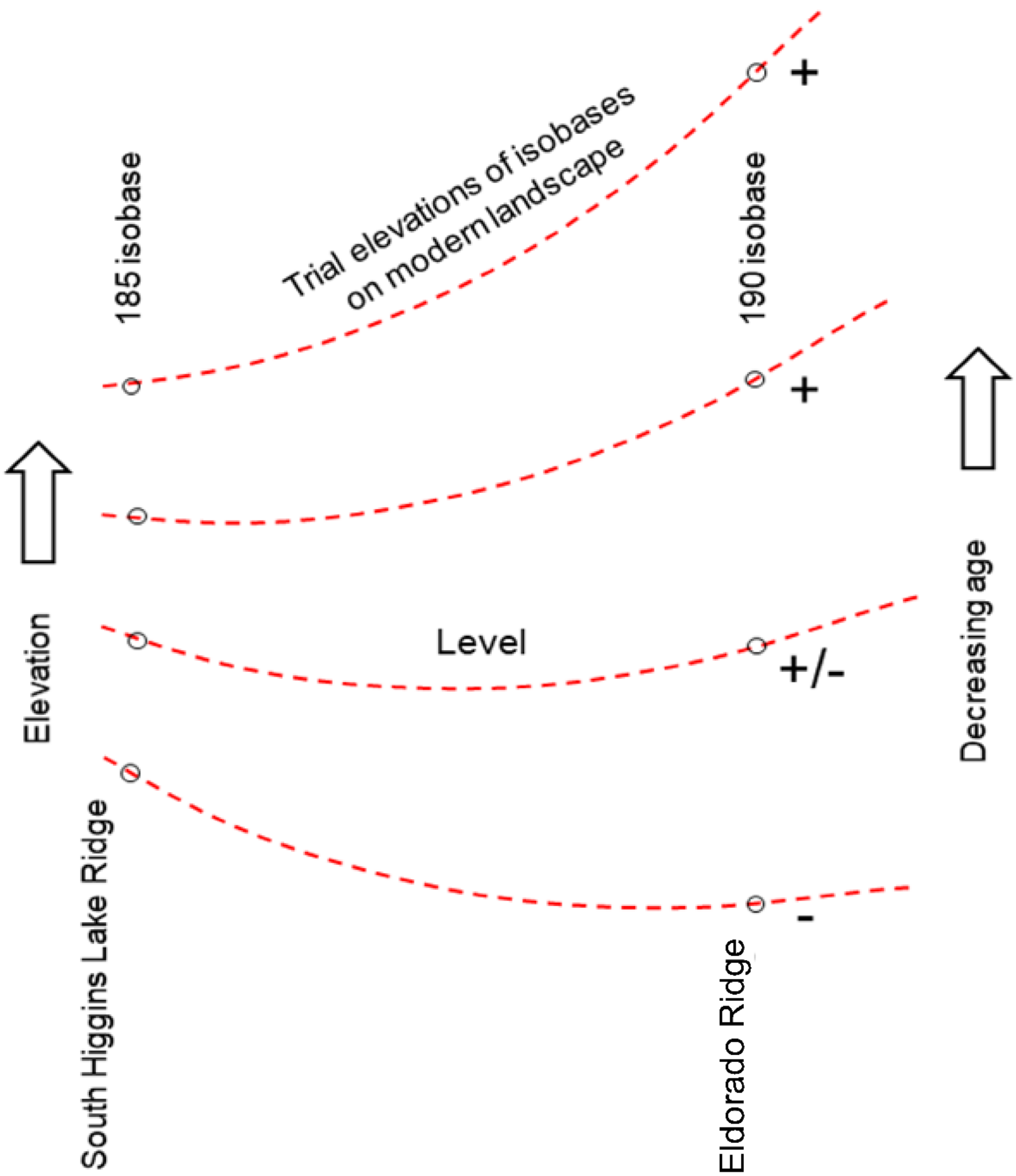

Figure 7. Sketch of differential uplift for sites on the Algonquin 185 m and 190 m (above sea level) isobases (open black circles) in the Houghton Lake Basin during ice retreat. The isobases are separated horizontally by about 24 km. Location of the uplifted section is shown by a dashed red line in Figures 3, 5, and 6. Dashed red curves above from base to top represent successive positions of the ground surface and sites on the 185 m and 190 m isobases during postglacial uplift. The uplift is differential as the 190 m isobase was rising faster than the 185 m isobase. The uppermost dashed red curve represents the present-day landscape, with a postulated trial elevation difference. Examples of the computed elevations for each isobase and their differences are provided in Table 1. *The elevation differences, rather than the individual isobase elevations, are important in this study*. The elevation difference between the 190 m

isobase elevation and the 185 m isobase elevation is negative when the basin was most deeply depressed by the ice load and the 190 m isobase was below the 185 m isobase (lowest dashed red curve). Then, the differentially rising isobases pass through a level condition and the difference becomes positive as differential uplift continues to raise the northern part of the basin relative to its southern part. The level condition and its age are interpreted as a signal for the presence of Glacial Lake Roscommon in the Houghton Lake Basin.

Table 1. Calculations of elevations and elevation differences for sites on the Algonquin 185 m and 190 m isobases while Laurentide Ice (Mackinac lobe) was retreating from Glacial Lake Roscommon using a 15 m trial present-day elevation difference. Bolded digits in the heading (columns 2 and 3) indicate an example of assumed present-day site (trial) elevations on the 185 m and 190 m Algonquin isobases needed for level conditions at the 16 ka to 15 ka age range indicated by yellow cell colours in columns 1 and 4.

Mackinac ice lobe retreating			
Age cal years BP	I85 m isobase[a] sites, ref elevation **340** m asl	190 m isobase[a] sites, ref elevation **355** m asl	Elevation diff of sites: 190 m iso – 185 m iso
10400	322.98[b]	334.57[c]	11.59[d]
10800	320.91	332.09	11.18
11200	318.61	329.33	10.72
11600	316.04	326.25	10.20
12000	313.18	322.82	9.63
12400	310	319	9
12800	306.45	314.74	8.29
13200	302.49	309.99	7.49
14000	293.18	298.81	5.63
15000	278.31	280.97	2.66
16000	258.83	257.6	-1.23
17000	233.30	226.96	-6.33
18000	199.86	186.83	-13.02
19000	156.03	134.24	-21.79
20000	98.60	65.33	-33.27
21000	23.36	-24.96	-48.32
22000	-75.23	-143.27	-68.04
23000	-204.42	-298.30	-93.88
24000	-373.70	-501.44	-127.74
25000	-595.52	-767.62	-172.10

[a] Separation of the 185 m and 190 m above sea level isobases = 24 km

Example calculations for the first line of computations above are given below:

[b] 340-(30/(EXP(12400/3700)-1)*(EXP10400/3700)-1))

[c] 355-(36/(EXP(12400/3700)-1)*(EXP10400/3700)-1))

[d] 334.57 – 322.98 = 11.59

Glacial Lake Roscommon

Modern shore fragments with a wide range of elevations, between 344 m and 360 m above sea level, were measured for Glacial Lake Roscommon (named after Roscommon County in the Houghton Lake Basin) in the area of modern uplift (Fig. 5) (Schaetzl et al. 2023, this volume). The fragments could not be correlated into long sets of shorelines, as was done for the major strandlines in the Great Lakes region, possibly because the Roscommon water level was fluctuating widely, because conditions for coastal feature construction were not available in the landscape over long distances, or because of their ephemeral nature. Trial modern sites on the 190 m isobase exceeded trial elevations of sites on the 185 m isobase by 13 to 15 m for a 'level' surface at 16 ka to 15 ka (Table 1). As this range of elevation (13 to 15 m) is well accommodated by the range of the observed shore feature elevations (344 m to 360 m) (Fig. 5), it is probable that Earth properties and crustal differential uplift in the northern Houghton Lake Basin were similar to uplift in the wider Great Lakes region. The modern and theoretical gradients for the Lake Roscommon basin, about 0.5 to 0.6 m/km (13/24 to 15/24 m/km), are within the range of proglacial lake strandline gradients for the Great Lakes basins, 0.1 to 1.4 m/km (Lewis et al. 2022). However, they are greater than the minimum Great Lakes paleo-strandline gradients (0.1 to 0.3 m/km) measured in the Erie basin for Lake Warren in Lewis et al. (2022).

Early Glacial Lake Roscommon

The ages for level conditions during Early Glacial Lake Roscommon, when Mackinac Lobe ice was advancing into the Houghton Lake Basin, theoretically would have resulted in much greater trial present shore elevations and gradients. Early Glacial Lake Roscommon was inferred in the model for ice advance into the Houghton Lake Basin (Schaetzl et al. 2023, fig. 36). Shore features would have been constructed when the basin crust was deeply depressed under the advancing and long-lasting load of ice. Recovery of the shore features by differential uplift from this deep depression would have raised them significantly more than those raised later during ice retreat. Unfortunately, the shore features of Early Glacial Lake Roscommon were probably destroyed by the advancing ice.

Conclusions

This analysis suggests that the northern part of the Houghton Lake Basin was uplifted differentially with uplift parameters similar to those controlling the Earth's crust in the wider Great Lakes region. More evidence is desirable, and could be available when more fragments of the Glacial Lake Roscommon shoreline are dated.

Measured elevations of Glacial Lake Roscommon shore fragments range overall from 328 m to 368 m above sea level. In the northeast sector of the area of measured shore fragment elevations where uplift is occurring today, the elevations range from 344 m to 360 m above sea level. Trial elevation differences of 13 m to 15 m for sites on the 185 m and 190 m Algonquin isobases, yield an age of 16 ka to 15 ka BP using calculations and crustal properties that describe differential uplift in the broader Great Lakes region. Because the range of trial elevations to achieve this result is accommodated by and similar to the actual range of Lake Roscommon shore fragment elevations, confidence is gained that the probable age of the lake ranges during ice retreat from about 19 ka to about 16 ka to 15 ka BP.

The modern and theoretical gradients for the Houghton Lake basin, about 0.5 to 0.6 m/km, are within the range of proglacial lake strandline gradients for the broader Great Lakes basins, 0.1 to 1.4 m/km. They are greater than the minimum Great Lakes proglacial paleo-strandline gradients (0.1 m/km to 0.3 m/km) despite their southern location (Lewis et al. 2022), possibly because of the extended recovery of the Houghton Lake Basin from its excessive and long-lasting depression under the former ice load, thought to have resulted from the aggregate load of the Lake Michigan, Saginaw, and Mackinac ice lobes.

Acknowledgements

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