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A 4,700-Year Record of Lake Level and Isostasy for Lake Michigan

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ABSTRACT. *Four relative lake-level curves (RLLCs), produced from five sites bordering Lake Michigan, show similar timings of high and low lake-levels during the late Holocene. However, glacial isostatic-adjustments and possibly tectonism experienced at each site are superimposed on these records of relative lake-level change. This effect causes the RLLCs to diverge from each other with time. The absolute magnitudes of lake-level fluctuations for the late Holocene can only be determined by quantifying and subtracting the component of vertical ground-movement from each RLLC.*

Both an exponential rate and a constant-rate equation for a shoreline undergoing isostatic adjustment were used to model vertical movement for each site. Results show that for at least the last 4,000 calendar years (cal BP) of record, vertical movement in Lake Michigan has obeyed both types of equations. The two models yield similar results because rates of vertical movement of the shorelines around Lake Michigan are small and the time frame for which lake-level data are available is so short that the exponential nature of isostatic change is not expressed. Except for the southern shore of Lake Michigan, all the study sites have experienced uniform isostatic uplift consistent with trends reported by the Coordinating Committee on Great Lakes Basic Hydraulic and Hydrologic Data (1977) and Tushingham (1992). The southern shore of Lake Michigan, however, experienced a change in uplift rate relative to the Port Huron outlet about 1,400 cal BP.

The residuals between the calculated rates of vertical movement at each site and its corresponding RLLC are a record of water-level change experienced at each site. Within the resolution of the technique used to construct the RLLCs, all the residual curves should be, and are, similar. A Fourier smoothing of the combined residual curves yields a "eustatic" lake-level curve for Lake Michigan over the past 4,700 cal BP. The results of the Fourier smoothing identify major lake-level fluctuations such as the Nipissing II and Algoma phases of ancestral Lake Michigan. The technique also resolves lower magnitude and shorter duration quasi-periodic lake-level fluctuations of about 160 years (120 to 200 years).

INDEX WORDS: *Lake level, Lake Michigan, isostasy, Holocene.*

INTRODUCTION

Thompson and Baedke (1997) produced four graphs of late Holocene lake level for Lake Michigan by examining the internal architecture and timing of development of strandplains of beach ridges in five embayments of the lake (Fig. 1). These curves show physical and temporal scales of paleo lake-level fluctuation at each study site (Fig. 2). Although similar lake-level trends occur in all the curves, differential vertical ground-movement between sites from crustal isostatic adjustments owing to glacial and hydrostatic loading and unloading or by possibly tectonic movement causes the elevations recorded in the curves to diverge from each other. This separation, commonly, increases with age. Consequently, lake level defined in each curve is relative only to the immediate vicinity of each study area (relative lake-level curve [RLLC]). A single curve that describes the absolute elevation of Lake Michigan throughout the late Holocene cannot

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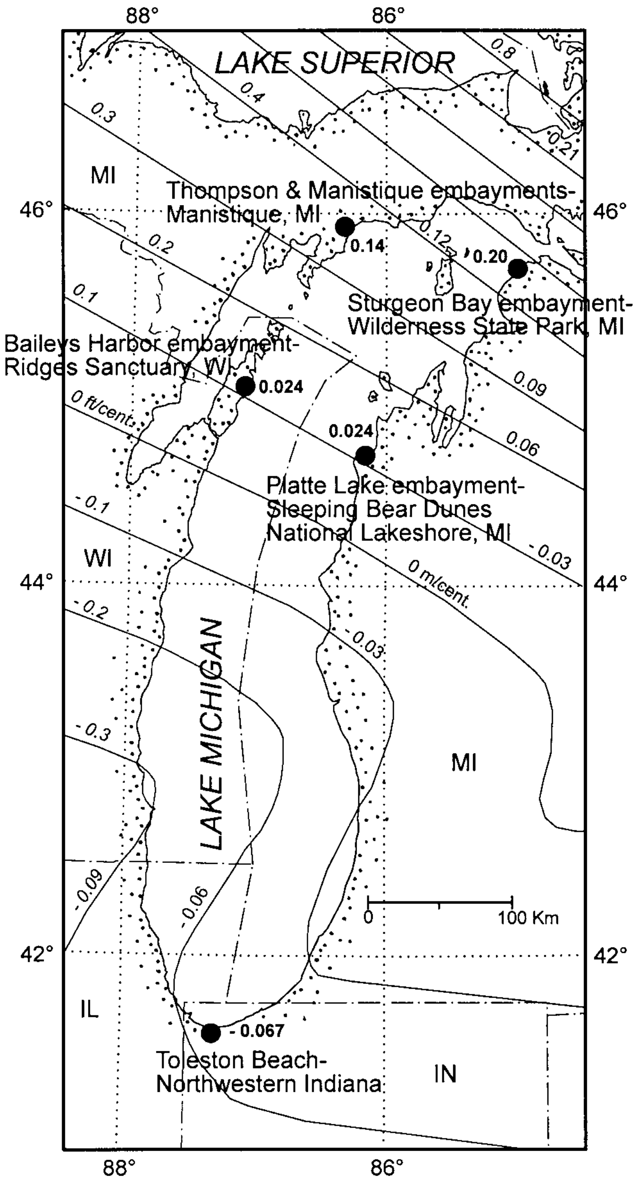

FIG. 1. Map of Lake Michigan showing the study areas, rates of apparent vertical movement based on lake-level gauges, and calculated rates of late Holocene vertical movement from the RLLCs. Data from the CCBHD (1977) were adjusted to fit a zero isobase through the Port Huron outlet.

be directly created by any one RLLC or by combining data from several of the RLLCs without removing the effects of vertical movement.

The purpose of this study is to: (1) quantify long-term vertical ground-movement preserved in each RLLCs of Thompson and Baedke (1997), (2) subtract this component from each RLLC, and (3) produce a residual lake-level curve that represents the fluctuation of Lake Michigan water level during the late Holocene. The residual lake-level curve describes the changing elevation of a water plane that intersected the Port Huron outlet, and for a short time the Chicago outlet, for Lakes Michigan and Huron. The curve can be used as a proxy for climatic conditions in the Great Lakes region and may be useful in predicting the magnitude and timing of future lake-level variations. Moreover, the calculated rates of vertical movement extracted from the RLLCs provides a means to test the rates of vertical movement calculated from subsets of the historical lake-level record by the Coordinating Committee on Great Lakes Basic Hydraulic and Hydrologic Data (1977) [CCBHD] and Tushingham (1992). It is not an intent of this paper to address all geophysical issues and modeling related to isostatic and tectonic vertical ground-motion in the Lake Michigan basin. More recent discussions are in Clark *et al.* (1990, 1994), and Tushingham (1992). We also will not address all issues related to the interpretation of late Holocene lake level in the upper Great Lakes. Such an analysis awaits more sedimentological studies of beach-ridge complexes in the Lake Superior and Lake Huron basins (e.g., Johnston *et al.* 2000) that will better define long-term rates of vertical ground-movement and outlet use. Reviews specific to the late Holocene of Lakes Michigan and Huron are by Eschman and Karrow (1985), Hansel *et al.* (1985), and Larsen (1985b, 1994).

METHODS

Changes in water level in the absence of any vertical movement between shorelines are experienced equally by all the shorelines and, therefore, should be apparent in each of the RLLCs. That is, changes in the total supply of water to the lake basin caused by an increase or decrease in precipitation, evaporation, or runoff should be coincident between RLLCs if all sites have similar preservation potential. Similarly, if the elevation of the outlet is changed by erosion or damming without any warping of the basin, all shorelines should experience and possibly record the same water-level change. Vertical movement between the shorelines and the basin outlet can cause each shoreline to behave differently from the others, resulting in differences between RLLCs. If the vertical movement produces warping of the entire basin, a systematic relationship of vertical ground-motion should exist between shorelines. The RLLCs of Thompson and Baedke

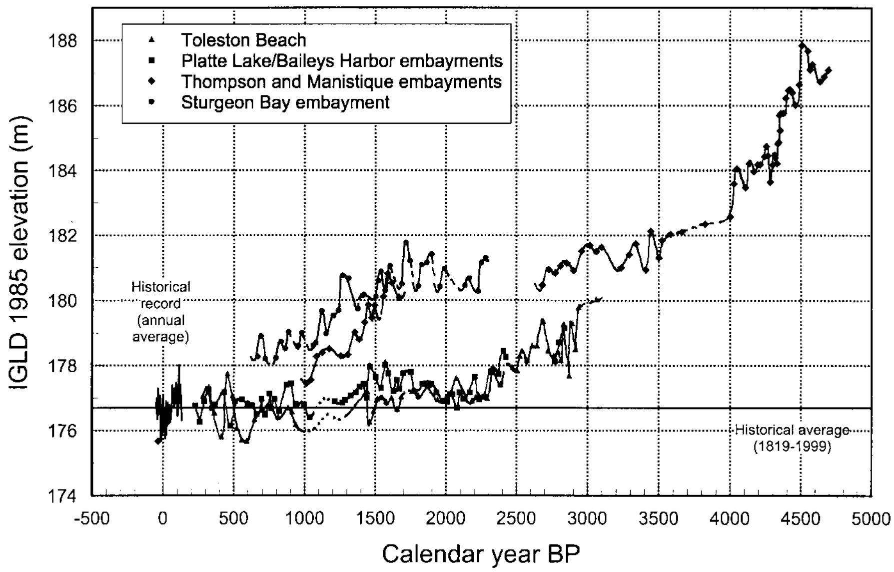

FIG. 2. Relative lake-level curves for Lake Michigan from Thompson and Baedke (1997). Data points are basal foreshore elevations for individual beach ridges at the five sites shown in Figure 1.

(1997) clearly show the long-term change in the elevation of the surface of the lake and a superimposed vertical movement between sites (Fig. 2). In the Lake Michigan basin, long-term and short-term water-level changes are interpreted as a product of changing climate (Fraser *et al.* 1975, 1990), and the vertical movement of the ground surface has been identified as a product of isostatic rebound following deglaciation of the basin (Clark *et al.* 1990, 1994; Tushingham 1992; Larsen 1994).

Conceptually, the problem of removing the effect of isostasy from the RLLCs can be illustrated mathematically. One equation, corresponding to lake-level elevations for each strandplain, is defined by two variables: (1) Lake Michigan water level at the time each beach ridge formed, and (2) isostatic movement of the shoreline following beach-ridge formation. With two unknowns and only one equation, there are infinite solutions to this problem; therefore, the problem is underdefined. By considering two or more RLLCs that overlap in time, two or more equations can be created making it possible to converge to a better solution through an iterative process. The iterative process consists of subtracting hypothetical rates of isostatic movement, based on an uplift model, from each RLLC until the difference between residuals are minimized. Curves of the residuals should be nearly identical. If significant dissimilarities exist between the residual curves then: (1) the technique used by Thompson and Baedke (1997) does not produce adequate RLLCs, (2) the rates of isostatic uplift removed from the RLLCs are overestimated or underestimated (Fig. 3), (3) the uplift model used to calculate rates of vertical movement is inappropriate, and/or (4) local tectonism has modified the RLLCs enough to mask the isostatic signature.

Andrews (1970a, b) presents a mathematical model that describes post-glacial behavior of shorelines as a result of isostatic rebound. A simplified version of the Andrews model from Larsen (1994) can be presented in the form:

$$\log(Alt) = ax + b \tag{1}$$

where *Alt* is the altitude of the shoreline, *x* represents either distance from the relict shoreline to the modern shoreline or age of the relict shoreline, *a* is a constant, and *b* represents the intercept of the modern shoreline with the y axis (altitude). In this study, *Alt* are lake elevations from the RLLCs of Thompson and Baedke (1997), *x* is the corresponding age from the same source, and *b* is the elevation 176.96 m IGLD 1985 (International Great Lakes Datum of 1985). The constant *b* is the average elevation of the last ~33-year quasi-periodic lake-level

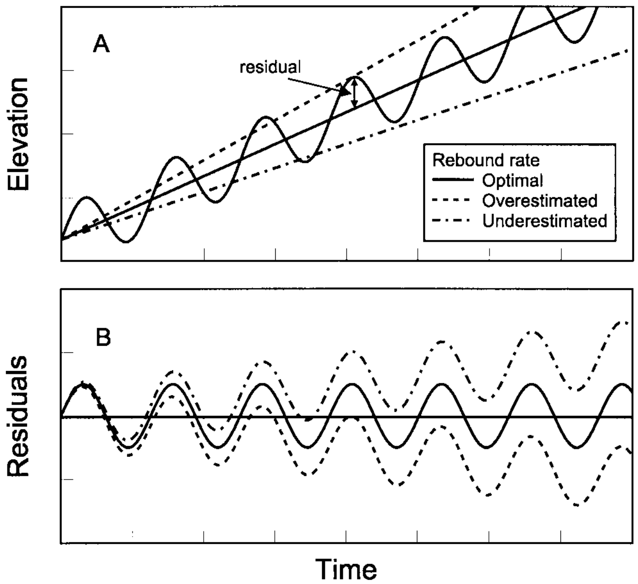

FIG. 3. Schematic diagrams illustrating the fitting of rates of vertical ground movement to a RLLC. A. RLLC with several potential rates of rebound fitted to the data. B. Residuals based on the potential rates of rebound in A. Overestimated rates produce residual that are too low and underestimated rates produce residuals that are too high. When multiple datasets are considered, the rate of rebound can be adjusted to produce similar residuals for all datasets.

fluctuation in Lake Michigan (Thompson 1992, fig. 7). The coefficient *a* can be systematically adjusted until a best fit, determined by a least-squares method, is obtained. The resulting value of *a*, therefore, represents the long-term vertical movement due to isostatic adjustment for each site.

The Andrews model is based on an exponential-rate equation. Rates of vertical shoreline movement, therefore, can only be calculated for instantaneous points on the curve. To establish long-term rates of vertical movement, best-fit lines as defined by a constant-rate (i.e., linear) equation were calculated through the RLLCs (Fig. 4). The Andrews and constant-rate models produce nearly identical lines of best fit and are so similar that it is not possible to distinguish the two rebound lines when plotted together. The similarity of these two models is due to the very low rates of vertical movement experienced in the Lake Michigan basin and the short duration of our uplift records (< 5,000 years). Lewis (1969) saw a linear uplift relationship at Manitoulin Island, Ontario, suggesting that the uplift rates observed for Lake Huron represent the near-straight portion of an exponential decay curve. Larsen (1994) discounted the Andrews model of vertical movement in favor of a linear model in his geomorphological study of beach ridges in Lakes Michigan and Superior. Other workers, such as Mörner (1980) and Coakely and Lewis (1985), have found that some rebounded areas respond both linearly and exponentially. We suggest that the Andrews and constant rate models of isostasy give similar results for the areas studied in Lake Michigan. They can, therefore, be used interchangeably to explain isostatic uplift for at least the last 4,000 calendar years before 1950 AD (cal BP, see Thompson amd Baedke 1997).

The difference (residuals) between the lines of best fit given by the Andrews equation and the elevations of the RLLCs is a record of long-term lake-level fluctuation for Lake Michigan and Lake Huron (Fig. 4). Within the accuracy of the data collection technique used by Thompson and Baedke (1997), all residual lake-level curves should show similar timings and magnitudes of lake-level fluctuations. Combining overlapping residual curves, a lake-level curve can be created that represents the elevation of a water plane that extended through the Port Huron outlet, and for a short time the Chicago outlet, for Lakes Michigan and Huron during the late Holocene. Although the Port Huron outlet is rebounding, it acts as a datum to which all residual lake-level curves are referenced. The lake-level curve produced by combining all the residual curves would be correlative to a eustatic sea-level curve for ocean coasts (see Kendal and Lerche 1988 for a discussion of eustasy). The Port Huron outlet curve will be referred to as a "residual lake-level curve" to avoid confusion with ocean terminology.

ANALYSIS

The scenario that a uniform rate of vertical isostasy can be identified for each site by calculating best-fit curves through the entire lake-level records was initially assumed. For the Baileys Harbor/Platte Lake and Sturgeon Bay curves, rates of vertical movement (given by the constant rate model) of 0.024 and 0.2 m/century, respectively (see Figs. 4B and 4D, and Table 1), produce residuals that are consistent with each other. However, for the Toleston Beach site this assumption causes residuals between 500 and 2,500 cal BP to be significantly lower than the residuals for Baileys Harbor/Platte Lake and Sturgeon Bay embayments.

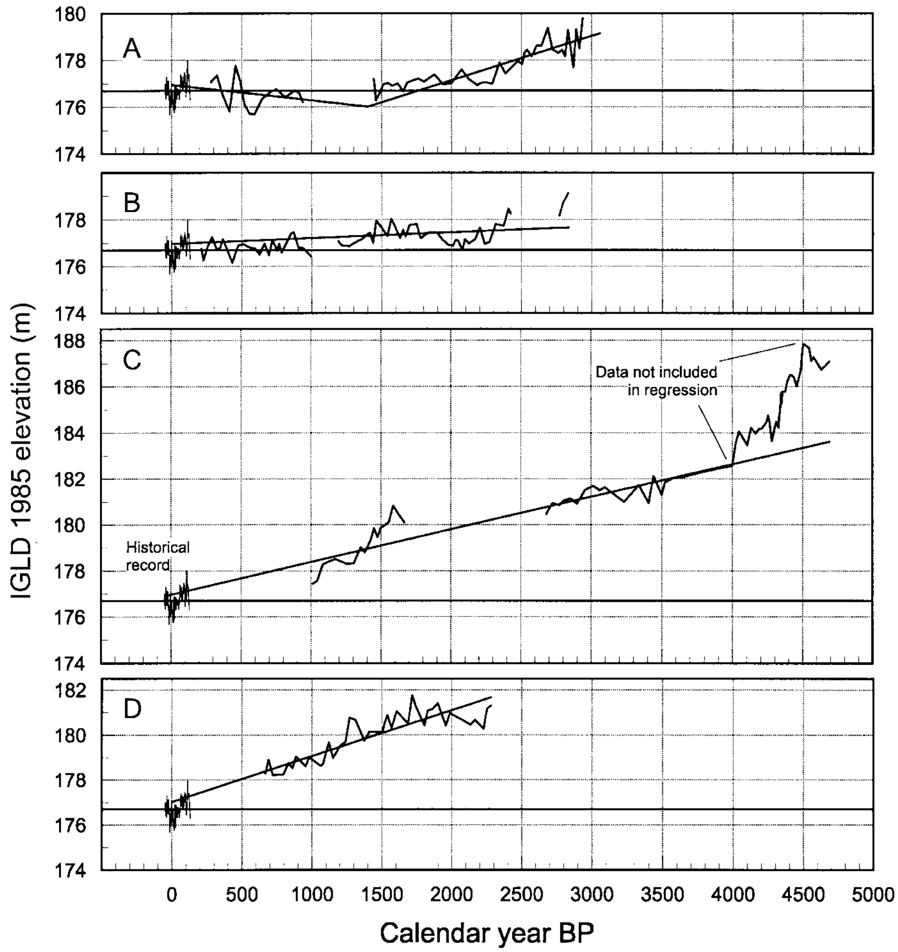

FIG. 4. Relative lake-level curves with lines of best fit from the linear model. A. Toleston Beach, B. Baileys Harbor/Platte Lake embayments, C. Manistique/Thompson embayments, and D. Sturgeon Bay embayment. See Table 1 for a summary of calculated rates of apparent vertical movement.

Thompson and Baedke (1997) note that the southern shore of Lake Michigan experienced a long-term relative lake-level fall prior to 1,400 cal BP, followed by a long-term lake-level rise to the present. This behavior is not seen at any other of the Thompson and Baedke (1997) data sets. Splitting the Toleston record into two data sets (1,400–3,100 cal BP and 0–1,400 cal BP) and calculating corresponding rates of vertical movement (Fig. 4A) resolves this discrepancy and produces results that are consistent with trends observed in the Baileys Harbor/Platte Lake and Sturgeon Bay residuals. These observations suggest that the southern shore of Lake Michigan is not responding to simple constant-rate or exponential vertical isostasy. Thompson (1992) suggested that local tectonism or differential compaction may be responsible for an east-to-west tilting of the shoreline along the southern shore of Lake Michigan. Tushingham (1992) indicated that subsidence in the southern half of Lake Michigan is related to the collapse of a peripheral bulge that formed from ice loading.

If any of these mechanisms are valid, then this treatment of the Toleston Beach data suggests that the change in uplift pattern with respect to the outlet occurred about 1,400 cal BP. At this time, the Port Huron outlet was rising more rapidly than the southern shore of Lake Michigan—a pattern observable today in lake-level gauge data (CCBHD 1977, Tushingham 1992). Prior to 1,400 cal BP, the

TABLE 1. Rebound rates from this study and the CCBHD (1977). CCBHD (1977) rates are interpolated to a zero isobase projecting through Port Huron, Michigan.

Embayments	Record Limit (cal BP)	Rebound Rate (m/century) this study	Rebound Rate (m/century) CCBHD (1977, fig. 2)
Toleston Beach	3100–1400	0.19	
Toleston Beach	1400–250	–0.067	~ –0.061
Bailey Harbor/Platte Lake	2800–200	0.024	~ 0.03
Manistique/Thompson	4700–present	0.14	~ 0.12
Sturgeon Bay	2300–700	0.20	~ 0.15

southern shore of Lake Michigan was rising more rapidly than the outlet. Larsen (1994) suggested that the Port Huron outlet was eroding up to 2,000 years ago, creating the appearance that the southern shore of Lake Michigan is rising more rapidly than the outlet because of a basinwide loss of water. Under this scenario, all the RLLCs for Lake Michigan should show a lake-level fall to about 2,000 cal BP followed by a change in slope grading to today. The Toleston Beach, Baileys Harbor/Platte Lake, and Sturgeon Bay RLLCs show a low phase of the lake from about 2,000 to 2,300 cal BP (Figs. 4 A, B, D), however this low is followed by a persistent high phase. No distinct change in slope is apparent at 2,000 cal BP in any of the RLLCs. Larsen's (1994) interpretation of an eroding outlet at 2,000 cal BP is partially based on shifting the Toleston Beach curve about 1,000 years older. Not using the time shift, his model would suggest that erosion occurred up to 1,400 cal BP. The other RLLCs also do not show a change in slope at this time. More RLLCs for Lakes Michigan and Huron are needed to evaluate erosion of the Port Huron outlet up to 2,000 cal BP.

The Manistique/Thompson lake-level curve was also separated into two data sets, because the Manistique/Thompson curve shows that relative lake-level fell about 5 m from 4,500 to 4,000 cal BP (Fig. 4C). This fall reflects a large water loss in the Lake Michigan basin following the Nipissing Phases at approximately 3,800 cal BP and subsequent isostatic rebound of the area. Because the largest amount of vertical movement in the lake-level record during 4,500 to 4,000 cal BP is due to water loss, long-term rates of isostasy would be overestimated (more than 5 times greater) if this part of the data set were included in the calculation of the best-fit line. Therefore, the best-fit line was calculated using only the data from 4,000 cal BP to the present (Fig. 4C). This treatment of the data produces residuals consistent with all other sites for data post 4,000 cal BP.

The rate of vertical movement calculated for the Sturgeon Bay embayment is higher (0.20 m/century) than the rate calculated by the CCBHD (1977, 0.15 m/century) (Fig. 1 and Table 1). Although this difference may be an artifact of the technique of data collection, this large discrepancy is not seen in any of the other sites. This discrepancy may be due to the much longer record considered by this study than the CCBHD. The higher rate in this study may be a better estimate of long-term rebound experienced at the Sturgeon Bay embayment for the past 2,300 calendar years.

LATE HOLOCENE LAKE LEVEL OF LAKE MICHIGAN

The residual lake-level curves produced from the Thompson and Baedke (1997) data covers a time frame from 200 to 4,700 cal BP (Fig. 5). With vertical isostasy removed from the RLLCs, the magnitude and timing of lake-level fluctuations are readily apparent. To illustrate the trends in late Holocene Lake Michigan lake level, the data sets of all sites were combined and a 20 percent Fourier smoothing was applied (using Jandel Scientific, TableCurve 2D, v. 3.0). Fourier smoothing is one of the most reliable illustrative techniques for data that may contain periodicity (Anderssen and Seneta 1971) and filters out the high frequency components of the data based on a smoothing percentage. The average error for the smoothing of the residual lake-level data is ± 0.28 m with a resultant noise reduction of approximately 13 percent. The 20 percent smoothing was specifically selected to show the 120- to 200-year quasi-periodic fluctuation (~160 year) observed by Thompson and Baedke (1997) that is defined by groups of four to six beach ridges that show an increase and decrease in fore-

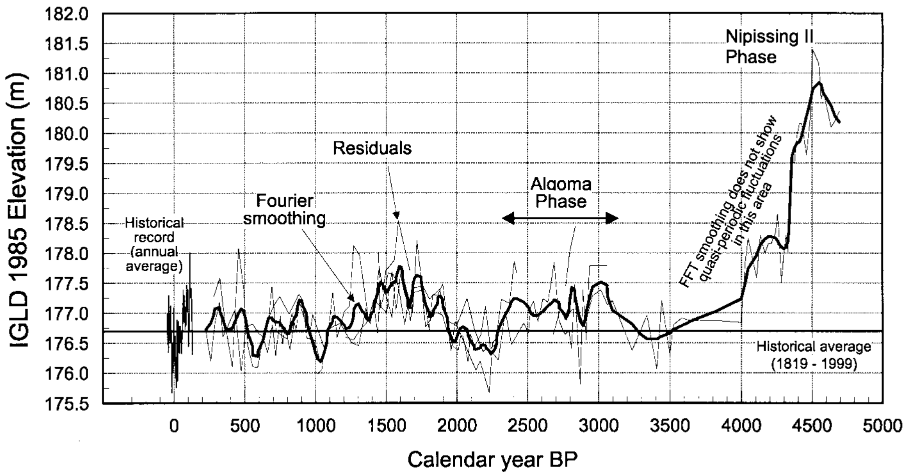

FIG. 5. Residual lake-level curves with vertical movement removed. A 20 percent Fourier smoothing is added to illustrate common lake-level fluctuations observed in all sites.

shore and dune crest elevation within each group. Other smoothing techniques, such as a linear moving average or Fourier smoothing's with greater or lesser smoothing percentages, will modify the appearance of the derived lake-level curve. For example, Fourier smoothings less than 13 percent contain too much noise to recognize 160-year fluctuations, and smoothings greater than 26.5 percent remove 160-year fluctuations from the curve. Additionally, it is not possible to smooth the data to bring out the ~30-year quasi-periodic fluctuation recognized by Thompson (1992) and Thompson and Baedke (1997). The upper limit of this fluctuation is represented by the individual data points in the residual lake-level curve (Fig. 5). Owing to the decreased data density for the record prior to 3,000 cal BP, the 20 percent Fourier smoothing of the Manistique/Thompson embayment data does not adequately show a 160-year variation, although it is apparent in the residual data. More data sets from 2,500 to 5,500 cal BP are needed to better define the older part of the lake-level record. Thompson *et al.* (1991) and Thompson (1992) suggested that a 600-year fluctuation may occur in Lake Michigan, however with isostatic rebound removed from the dataset, this fluctuation is not observed.

The older part of the residual lake-level curve shows a lake level high at 4,500 cal BP (Fig. 5). Larsen (1994) places the age of the Nipissing I Phase of ancestral Lake Michigan at 5,300 cal BP, so this high probably represents Larsen's Nipissing II Phase. At this time both the Port Huron and Chicago outlets were actively discharging from Lakes Michigan and Huron (Lewis 1969, 1970). Following the 4,500 cal BP high, lake level underwent a rapid fall of about 4.1 m to a low at 3,400 cal BP. This rapid fall may be related to erosion of the Port Huron outlet or to a long-term loss of water volume to the basin. There does not appear to be any evidence that points to either scenario or both scenarios to account for a water-level fall that is more than five times greater than the rate of rebound. More data sets are needed to better define this part of the lake-level record. The projected elevation of the low at 3,400 cal BP in the Toleston Beach RLLC is 180 m. This level is the elevation of a bedrock sill in the Chicago outlet (Leverett 1897). The cessation of rapid lake-level lowering appears to be related to the beginning of the abandonment of the Chicago outlet from ancestral Lake Michigan.

The smoothed residual lake-level curve shows a significant rise in lake-levels from 3,300 to 3,000 cal BP that probably marks the beginning of the Algoma Phase of ancestral Lake Michigan (Fig. 5). High lake levels, dominated by four peaks, continued until about 2,400 cal BP when lake level fell 1 m. At this time, the Chicago outlet was probably completely abandoned (Chrzastowski and Thompson 1992). Falling lake levels from 2,400 to 2,250 cal BP were followed by rising lake levels after about 2,100 cal BP. Lake levels rose about 1.5 m to a maximum high at about 1,600 to 1,700 years ago. The 160-year quasi-periodic fluctuation is well expressed across this high, and Thompson and Baedke (1997) noted that beach ridges formed at this time are the most continuous and well-formed in their study areas. Lake-level fell from 1,600 to 1,000 cal BP at which time Lake Michigan began fluctuating in a range very similar to the historical record.

Several late Holocene relative lake-level curves have been produced for Lakes Michigan and Huron (Lewis 1970; Fraser *et al*. 1975, 1990; Larsen 1985a,b; Larsen 1994; Dott and Michelson 1995) and Lake Ontario (Dalrymple and Carey 1990). All the curves show similarities, and there is general agreement on major lake-level trends (Fig. 6). However, different approaches, assumptions, treatment, and time frame covered in the development of the curves precludes one-to-one comparison. This study has established a resolution of lake-level events on a time scale that is much finer in detail than these previous works.

USING THE LAKE-LEVEL CURVE

Because the beach ridges used by Thompson and Baedke (1997) preserve high stands of lake level (Thompson and Baedke 1995), the smoothed residual curve approximates the upper limit of late Holocene lake level in the Lakes Michigan and Huron basins. Thompson and Baedke (1997) indicate that a beach ridge is formed approximately every 33 years (32 ± 6.6 years, Thompson and Baedke 1997, fig. 7F) in response to a fluctuation of about 0.5 to 0.6 m. The smoothed residual lake-level curve (Fig. 5) is the upper limit of this 33-year quasi-periodic fluctuation. Foreshore deposits consist primarily of horizontal and lakeward-dipping subhorizontal parallel-laminations (Thompson and Baedke 1997) and are interpreted as primarily winter storm deposits. Basal foreshore elevations probably record winter lake levels early in the development of each beach ridge. Although there is no way to collect the low stands of lake level from a strandplain of beach ridges, it is possible to estimate low late Holocene lake levels by mirroring the resultant curve 0.6 m lower (Fig. 7). We suggest that late Holocene lake level may have fluctuated between these two boundaries.

The smoothed residual curve shows late Holocene lake level for the Port Huron outlet over the past 4,700 cal BP. Lake-level elevations in the curve cannot be directly applied to coastlines of Lakes Michigan and Huron without adding isostatic rebound back into the curve. Unfortunately, no single model adequately defines isostatic deformation in the Great Lakes (Clark *et al.* 1994), and maps of vertical movement are generally not referenced to the Port Huron outlet. It is possible, however, to interpolate Port Huron referenced rates of vertical movement from maps of CCBHD (1977), Tushingham (1992), Clark *et al.* (1994), and Larsen (1994).

CONCLUSIONS

Four relative curves of late Holocene lake level were produced from five sites around Lake Michigan by studying the internal architecture and timing of development of strandplains of beach ridges (Thompson and Baedke 1997). All curves show similar lake-level variations but have recorded different rates of vertical movement caused by isostasy and/or tectonism. Although trends in high and low water levels and rates of isostatic movement can be determined from these combined lake-level and isostatic-adjustment curves, it is not possible to determine absolute magnitude of lake-level or isostatic rebound without determining the absolute magnitude of each factor at each site.

All RLLCs show that rates of isostasic uplift obey both exponential and linear-rate equations for a deformed shoreline. This implies that the rates of rebound in Lake Michigan are so small and the time frame for which lake-level data are available is so short that the exponential nature of the Andrews equation is not expressed. Long-term rates of isostatic adjustment in Lake Michigan are similar to those calculated from historical data except along the southern shore. The Toleston Beach has not been isostatically rebounding as rapidly as the Port Huron outlet for the past 1,400 calendar years (–0.067 m/century). Prior to 1,400 cal BP, the southern shore was rebounding more rapidly than the Port Huron outlet at a rate of 0.19 m/century. These findings give new estimates of the amount of vertical ground-movement experienced along the southern shore of Lake Michigan. When incorporated into rebound models, these estimates of the timing and rates of rebound may provide better results for the past elevations of southern Lake Michigan shoreline features than the values used to date.

Subtracting best-fit rates of rebound from relative lake-level curves of all sites produces residual lake-level curves that are similar. After combining the residual lake-level curves, the timing and magnitude of the prominent lake-level events during the last 4,700 cal BP were determined as: (1) the end of the Nipissing phases as shown by a rapid fall of 4.1 m from a high at 4,500 to about 3,400 cal BP, (2)

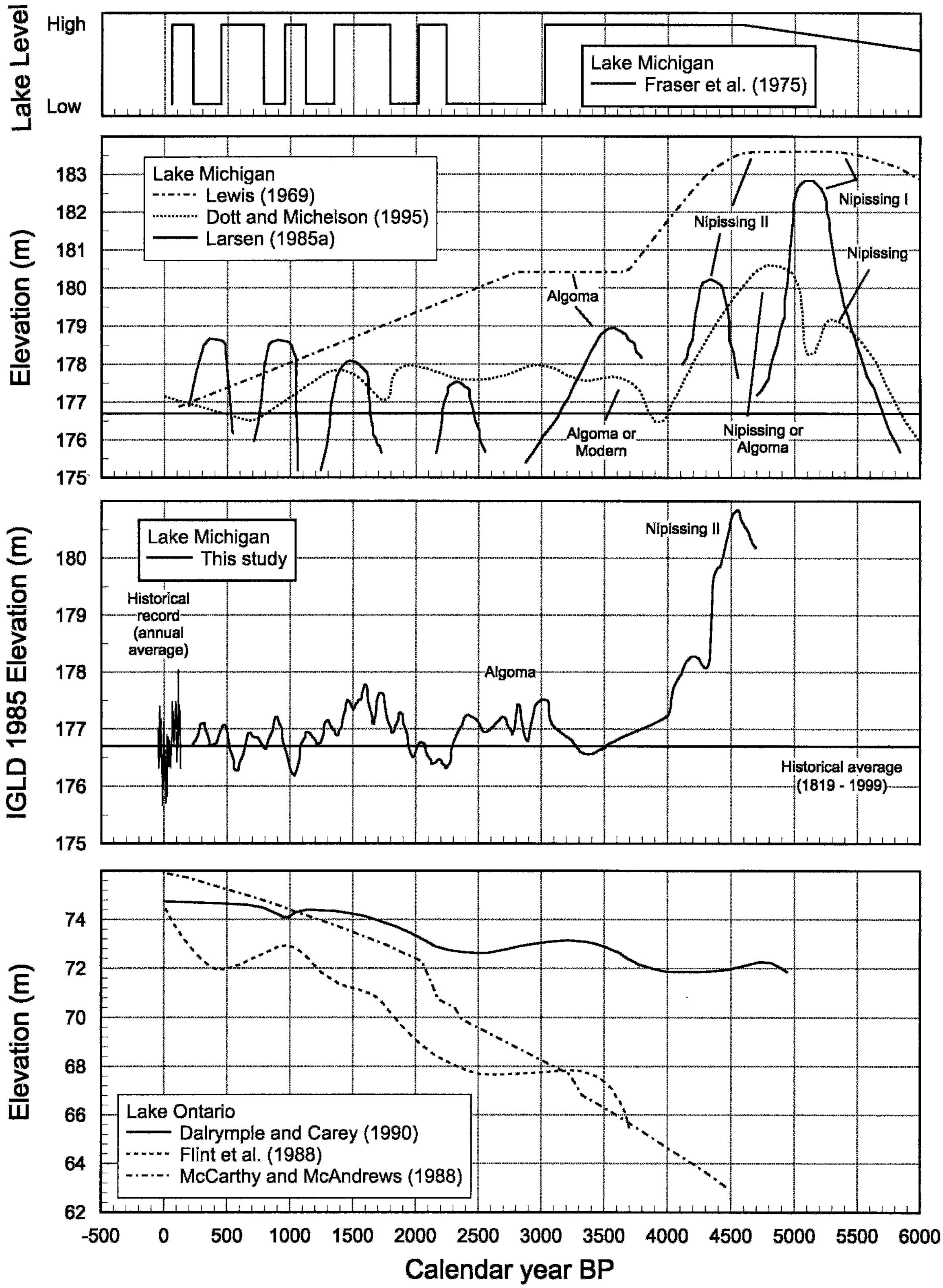

FIG. 6. Graphs of late Holocene relative lake level for Lakes Michigan, Huron, and Ontario and the residual lake-level curve for Lake Michigan.

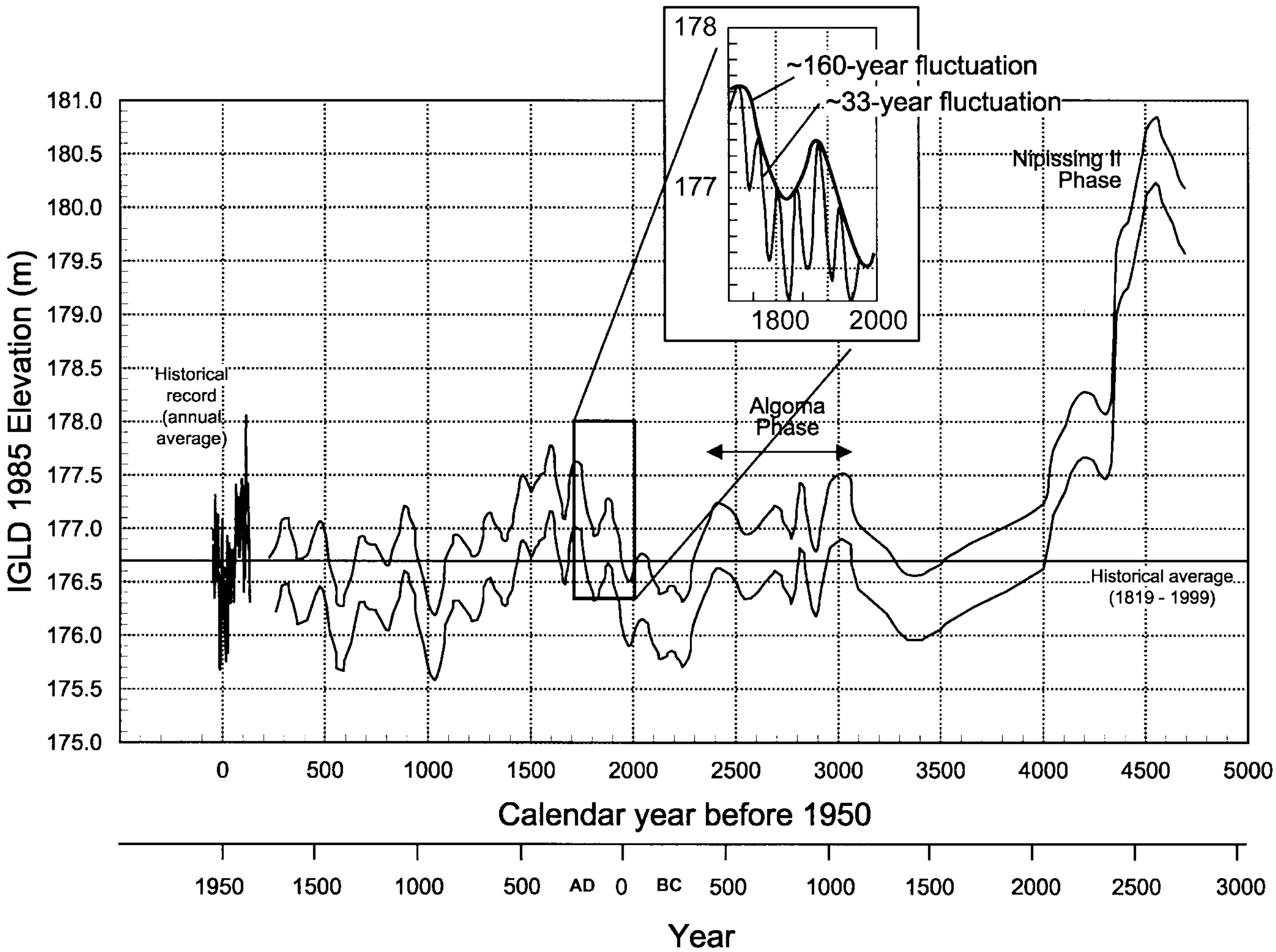

FIG. 7. Graph of late Holocene and historical lake level for Lake Michigan. Late Holocene lake-level curve was mirrored 0.6 m lower to indicate possible extremes of low lake level.

the Algoma Phase from 3,400 to 2,300 cal BP, and (3) a long-term lake-level high centered at about 1,700 cal BP. A resolution of lower-magnitude lake-level events not previously achieved also was established.

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