



Reconstructing paleo lake levels from relict shorelines along the Upper Great Lakes

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Shorelines of the upper Great Lakes include many embayments that contain strandplains of beach ridges. These former shoreline positions of the lakes can be used to determine changes in the elevation of the lakes through time, and they also provide information on the warping of the ground surface that is occurring in the Great Lakes after the weight of glacial ice was removed. Relative lake-level hydrographs can be created by coring the beach ridges to determine the elevation of basal foreshore (swash zone) deposits in each ridge and by obtaining radiocarbon dates of basal wetland sediments between ridges to generate an age model for the ridges. Because the relative-level hydrographs are the combination of lake-level change and vertical ground movement (isostatic rebound), the rebound must be removed to produce a graph that shows only the physical limits and timing of past lake-level fluctuations referenced to a common outlet. More than 500 vibracores of beach-ridge sediments were collected at five sites along Lake Michigan and four sites along Lake Superior. The cores showed a sequence of dune deposits overlying foreshore deposits that, in turn, overlie upper shoreface deposits. The base of the foreshore deposits is coarser and more poorly sorted than an overlying and underlying sediment and represents the plunge-point sediments at the base of the swash zone. The plunge-point deposits are a close approximation of the elevation of the lake when the beach ridge formed. More than 150 radiocarbon ages of basal wetland sediments were collected to produce age models for the sites. Currently, age models exist for all Lake Michigan sites and one Lake Superior site. By combining the elevation data with the age models, six relative lake-level hydrographs were created for the upper Great Lakes. An iterative approach was used to remove rebound from the five Lake Michigan relative hydrographs and merge the graphs into a single hydrograph. The resultant hydrograph shows long-term patterns of lake-level change for lakes Michigan and Huron and is referenced to the Port Huron outlet. When the age models are completed for the Lake Superior sites, a hydrograph will be created for the entire lake.

Keywords: Lake Superior, Lake Michigan, beach ridge, lake level, sedimentology

Introduction

Fluctuations in lake level are a primary control on shoreline behavior throughout the Great Lakes (Hands, 1983). Management, protection, and development of Great Lakes shorelines and paralic settings require an understanding of how lake level varies through time. The physical limits, timing, and rates of lake-level change can be determined from historical gage records that begin for most lakes in 1860. Unfortunately, these records are too short to determine statistically if longterm patterns (greater than a decade or two) of lakelevel change exist. Additionally, the historical record may underestimate the range of lake-level rise and fall that occurred in the past several thousand years (Larsen, 1985). Therefore, an alternative source of information is needed to extend the length of the historical record beyond the 140 years of gage data.

Numerous relict shorelines that occur inland from the modern shore are found around the upper Great Lakes. Many of the higher-elevation shorelines formed when glacial ice remained in the basin (Larsen and Schaetzl, 2001), while shorelines at lower elevations formed over the past 6,000 years under more modern lake configurations and environmental conditions (Larsen, 1985, 1994; Johnson et al., 1990; Dott and Michelson, 1995; Lichter, 1995; Petty et al., 1996; Thompson and Baedke, 1997). These former shoreline positions of the lakes can be used to determine changes in the elevation of the lakes through time, and they also provide information on the warping of the ground surface (isostatic rebound) that is occurring in the Great Lakes after the weight of glacial ice was removed (Larsen, 1994; Baedke and Thompson, 2000). Both long-term lake-level data and improved understanding of isostatic rebound are critical to governments, hydropower and shipping industries, shoreline property owners, recreational boating enthusiasts, and natural resource managers. These data enhance the ability to forecast future water-level changes by constraining past lake-level extremes, demonstrating natural variability and periodicity, and correlating to climate change.

This paper will discuss how a specific type of shoreline depositional feature, beach ridges (Figure 1), can be used to reconstruct past lake levels in the upper Great Lakes. Beach ridges are a common coastal feature along the shores of lakes Michigan, Huron, and Superior; where they occur as a set of 25 or more ridges, a detailed lake-level hydrograph can be constructed. Hydrographs created for a single site, however, contain information that is relative only to that site because of differential vertical ground movement between that site, other sites, and the outlet for the basin.



Figure 1. Oblique aerial photograph of beach ridges in the Manistique embayment, southwest of Manistique, Michigan. The modern lake is to the right and dark arcs extending to the top of the photograph are individual ridges. The ridges are tree-capped, and the low areas between the ridges are sedge-covered wetlands.

Overlapping data sets from several sites are needed to remove the vertical ground movement component of the individual relative hydrographs incrementally and collapse them into a single graph that represents longterm lake-level change at the basin's outlet (Baedke and Thompson, 2000).

Beach ridges

Beach ridges are curvilinear ridges of sand that parallel or sub-parallel the modern shoreline. They commonly occur in embayments of the lakes, but they also occur as fingers of sand spits and the arcuate flanks of tombolos. In embayments, they are typically capped with 0.25 to 5 m of dune sand. In many parts of the Great Lakes, the swales between beach ridges contain wetlands. If several beach ridges occur in the same embayment, they form what is termed a 'strandplain.'

Strandplains of beach ridges (Figure 2) are common along the northern and southern shores of the upper peninsula of Michigan (Petty et al., 1996; Thompson and Baedke, 1997), the northwestern and northeastern coasts of the lower peninsula of Michigan (Lichter, 1995; Thompson and Baedke, 1997), the Door

Peninsula of Wisconsin (Larsen, 1994; Thompson and Baedke, 1997), and parts of the Niagara escarpment extending into Ontario (Lewis, 1969). Other strandplains occur at the southern tip of Lake Huron, along the eastern coast of Lake Superior, and on the Apostle Islands in western Lake Superior. Most embayments contain several beach ridges, but some of the largest have 50 to 80 beach ridges. The largest strandplain of beach ridges occurs at the southern tip of Lake Michigan. Here, more than 100 ridges arc across northwestern Indiana into northeastern Illinois (Thompson, 1992). Unfortunately, little of this strandplain remains owing to late twentieth century urban and industrial growth in the area. The large number of strandplains in the upper Great Lakes, however, provides ample sites to study past shoreline behavior and lake-level change.

Although the surface expression of beach ridges is the long linear dune cap, beach ridges have a core of water-lain sediments that is several meters thick and can extend for a kilometer offshore (Fraser and Hester, 1977; Thompson, 1992). Beach ridges form in areas having a positive rate of sediment supply and in the final stages of a lake-level rise (Thompson and Baedke, 1995). When the water-level rise slows as it



Figure 2. Map of the upper Great Lakes showing embayments containing late Holocene strandplains with several or more beach ridges (dots), study areas (rectangles, squares), and additional sites mentioned in the text. TB = Toleston Beach, PL = Platte Lake, SB = Sturgeon Bay, MT = Manistique and Thompson, BH = Baileys Harbor, GTB = Grand Traverse Bay, ATB = Au Train Bay, TAB = Tahquamenon Bay, BAB = Batchawana Bay.



Figure 3. Schematic diagram, illustrating the development of a beach ridge. (A) During a lake-level rise (1 to 2 to 3) the shoreline is eroded landward. (B) As the rising lake level slows and eventually stops (4), a topographic high (called the 'berm') forms at the top of the swash zone. Water-lain sediments underlay the berm, and grasses colonize the berm crest, and subsequently traps wind-blown sediments, causing the dune to grow in height. (C) With falling lake level (5 to 6 to 7), the shoreline progrades lakeward. If the shoreline receives enough sediment and the beach ridge grows sufficiently in height, this beach ridge will not be completely eroded during the next lake-level rise.

approaches its highest elevation, the coast undergoes a brief period of aggradation (Figure 3). This aggradation creates a water-lain berm at the crest of the swash zone. This berm and associated nearshore sediments form the core of the beach ridge. Colonization of the berm by grasses traps wind-blown sediment along the berm crest, producing a linear dune cap parallel to the modern shoreline. The dune cap grows in height and width with time, and the shoreline progrades toward the lake during the subsequent fall from the high stand. If the shoreline receives a sufficient supply of sediment, the beach ridge will not be completely eroded during the next lake-level rise. Through time, a chronosequence of beach ridges is created and preserved, recording high stands in lake level.

Shorelines in areas of positive sediment supply are dominated by these depositional processes and have similar coastal geomorphic features. These features and corresponding sedimentary deposits differ in scale and composition between sites and also differ seasonally at a single site. The main elements are the dune, backshore, foreshore, and upper shoreface (cf. Reinick and Singh, 1980). Onshore- to offshore-oriented topographic profiles of a modern beach cross all of the major geomorphic elements of a beach ridge and can be used to illustrate spatial differences between each shoreline depositional environment (Figure 4).

The dune (sometimes called the foredune) occurs in the most landward and highest topographic part of the profile (Figure 4). In the upper Great Lakes, dunes are colonized by plants such as marram grass (Ammophila breviligulata Fern.) and eastern cottonwood (Populus deltoides Marsh.) that trap and stabilize sand blown landward from the beach (Olson, 1958). Although the actual grain size and sorting of shoreline deposits are dependent on the grain size of sediment delivered to them from the littoral system, dune deposits commonly consist of moderately to well-sorted, medium- to upper fine-grained sand. Most dunes are linear or curved parallel to the shoreline, with a uniform height along their length. Blowouts may occur along coasts with limited sediment supply. Lakeward of the dune is the backshore (Figure 4). The backshore extends from the base of the dune to the berm at the top of the swash zone. This horizontal to lakeward-sloping surface is a minor depositional area, where windblown sediment rests in transit during its transport from the swash zone into the dune. Backshores commonly contain wind ripples and small wind-transported bedforms less than 0.5 m in height. The swash zone, or foreshore, of the beach is where waves break and rush up the beach face (Figure 4). The foreshore is the coarsest and commonly the most poorly sorted part of the shoreline system, consisting of medium-grained sand to granular sand with pebbles and cobbles; the base of the foreshore is the coarsest and most poorly sorted part of the entire foreshore. Onshore transport from shoaling waves and offshore transport from the backwash concentrate the largest size



Figure 4. Graphs showing the topographic profile and grain-size distribution for modern shorelines in areas of beach-ridge development. Note that profiles C and E do not cross the entire width of the dune. (A) Peterson Beach, Sleeping Bear Dunes National Lakeshore, Michigan; (B) Baileys Harbor, Ridges Sanctuary, Door Peninsula, Wisconsin; (C) Lake Street Beach, Indiana Dunes National Lakeshore, Indiana; (D) Sturgeon Bay, Wilderness State Park, Michigan; (E) Au Train Bay, Au Train, Michigan; (F) Tahquamenon Bay. Geomorphic features: d = dune, bs = backshore, fs = foreshore, us = upper shoreface. Grain size abbreviations: vf = very fine-grained sand, f = fine-grained sand, m = medium-grained sand, c = coarse-grained sand, vc = very coarse-grained sand, g = granule, p = pebble.

fraction at the base of the foreshore (Fox et al., 1966; Fraser et al., 1991; Komar, 1998). This coarse-grained plunge-point (also called a plunge-step) deposit occurs at or very near the still-water elevation of the lake. Lakeward from the plunge point and extending to the depth of average fair-weather wave-base is the upper shoreface (Figure 4). In the upper Great Lakes, the upper shoreface commonly contains one or more longshore bars with intervening troughs. Upper shoreface deposits range in grain size from medium- to lower fine-grained sand and become finer grained and more poorly sorted with depth. The upper shoreface may also contain coarser-grained horizons associated with sediment transported in rip channels during storm conditions. A variety of two-dimensional and threedimensional bedforms occur in the upper shoreface (Davidson-Arnott and Greenwood, 1979).

Shoreline progradation and depositional regression place the onshore dune deposits over foreshore deposits that, in turn, overlie the upper shoreface deposits. The vertical sequence of sediment types and structures that is produced through lakeward translation of the shoreline mimics the horizontal sequence observed in the onshore- to offshore-oriented topographic profile. Within this vertical sequence, the elevation of the plunge-point sediments at the base of the foreshore deposits approximates the elevation of the lake when the foreshore deposits accumulated.

Reconstructing paleo lake levels

Reconstructing past lake level requires data to be collected on the elevation of the lake and the time period when the lake was at that elevation. Strandplains of beach ridges are an ideal area to collect both types of information because the beach ridges form a chronosequence that internally contains plunge-point deposits that can be used to determine the elevation of the lake. Basal foreshore deposits, however, are several meters below the ground surface, and they must be recovered carefully to produce accurate elevation data. A landbased vibracorer (Lanesky et al., 1979; Finklestein and Prins, 1981; Thompson et al., 1991) is a useful tool for recovering a relatively undisturbed 7.5-cm-diameter sample of mud to sand to gravel, ranging to depths of 5 m (Figure 5). Vibracorers also are portable and can be used in remote areas of the Great Lakes. Lastly, vibracorers produce minimal land and vegetation disturbance relative to truck-mounted drill rigs and can be used in environmentally sensitive areas where foot traffic is permitted.

More than 500 vibracores were collected along the lakeward margin of beach ridges in five strandplains of Lake Michigan and four strandplains of Lake Superior (Figure 2). The vibracores were collected at the change in slope that occurs along the lakeward side of the beach ridge, between the dune cap and the adjacent swale. At this position, foreshore deposits are recovered at their highest elevation, and the amount of dune sand collected is minimized. The core sites were surveyed using an optical transit at a precision of 0.003 m. All elevations were referenced to the International Great Lakes Datum of 1985.

In the laboratory, cores were cut on both sides using a circular saw, and a wire was pulled along the length of the cores to split them into two halves. The cores were described, sampled, and photographed. One half of each core was used to make a thin peel (1- to 5-mm thick) using Rub-R-MoldTM latex and MasoniteTM. The peel enhances the visibility of sedimentary structures and makes a semi-permanent copy of the core. All samples were sieved using ¹/₂ PHI intervals, and statistical parameters (mean, sorting, and skewness) were calculated using the method of moments (McManus, 1988). An additional parameter, coarsest one-percentile, was determined from plots of cumulative grain-size distribution and used to determine the relative importance of traction load in the grain-size distribution. Physical and biological sedimentary structures, grain-size characteristics, fossils, and colors were used to distinguish three facies that represent deposits that accumulated in the dune, foreshore, and upper shoreface environments. Particular attention was placed on accurately determining the base and top of the foreshore deposits. Commonly, numerous sediment samples were collected at these boundaries to determine the basal elevation and thickness of the foreshore deposits accurately.

Cores collected in lakes Michigan and Superior ranged from 1.5 to 4.5 m in length. The upper limit was constrained by the length of core tube used. Most cores reached depths that penetrated upper shoreface deposits, but some cores stopped in gravelly plungepoint deposits at the base of the foreshore. All cores showed a similar pattern, with dune deposits overlying foreshore deposits that overlie upper shoreface deposits (Figure 6). Facies characteristics, however, varied between sites and from beach ridge to beach ridge throughout the strandplains.

Dune deposits consist of moderately to well-sorted upper medium- to lower fine-grained quartz sand. Most dune deposits are unstratified, but some low- to highangle parallel laminae occur in the lower part of the dune sequence. Rootlets and soil horizons are common. There is a sharp or gradational contact between the dune deposits and the underlying foreshore deposits. Where gradational, this contact is difficult to establish with certainty. Foreshore deposits are highly variable in grain size, ranging from moderately to poorly sorted medium-grained sand to gravels. Laminae and beds alternate between a finer-grained background sediment and coarser-grained horizons. Horizontal and lakeward-dipping subhorizontal laminations are common. Most laminae are ungraded or normally graded, but some laminae are inversely graded. Foreshore sands are composed primarily of quartz and lithic fragments, but shell debris, plant fragments, and charcoal grains are also present at some sites. Clasts consist of siltstone, shale, limestone, and dolostone. The contact between the foreshore deposits and underlying upper shoreface deposits is sharp, sometimes with an abrupt change in grain size that is easily recognizable without the need for grain-size determinations.

The age of each beach ridge is the second piece of information required for reconstructing paleo lake levels. It is not possible to form a beach ridge landward from a previously formed ridge without eroding the older ridge. Consequently, the relative age of the beach ridges in a strandplain must be younger with proximity

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Figure 5. Photograph of land-based vibracorer used to collect onshore and nearshore deposits from strandplains of beach ridges. The vibracorer recovers relatively undisturbed samples of clay, slit, sand, and gravel to depths of about 4.5 m.

to the lake. This relative age relationship, however, provides no calendar control on the age of the ridges. Two possible methods can be used to estimate the calendar age of a beach ridge: dating wetland sediments that accumulate landward of the ridges and dating sand grains within the ridges.

The age of organic deposits in the swales between ridges can be used to approximate the age of the ridges. That is, radiocarbon age determinations can be made on basal wetland sediments between ridges and the ages applied to the ridges. An assumption is made with this method that the wetland was established and began accumulating organic material soon after the lakeward beach ridge formed. Although we have not rigorously tested this assumption, rhizomatous sedges and other graminoids with a few small tree seedlings were observed landward of a newly formed beach ridge in the Thompson embayment near Manistique, Michigan. The beach ridge formed during the high lake levels of 1986, and our observations were made in 1991. At this time, a thin (2-mm) detrital organic layer was observed across the swale. Kormandy (1969) reported that submerged wetland vegetation occurs in ponds between beach ridges of the Presque Isle Peninsula sandpit, Pennsylvania, within three to five years, followed by taller plants within 10 years. Thompson and Baedke (1997) argued that the assumption that a wetland formed soon after the beach ridge is most valid



Figure 6. Schematic diagram, illustrating a typical sequence of lithologies, sedimentary structures, and grain-size trends that occur in vibracores from beach ridges. See Figure 4 for grain-size abbreviations.

in embayments where ground-water focusing has produced a water table elevated above lake level. In this scenario, ponding, or at least a water table near the ground surface, occurs in the swale during the early stages of beach-ridge development. Hydrophytic plants colonize the swale, and organic material begins to accumulate. Through time, sufficient organic material accumulates that can be radiocarbon-dated. More recent accelerated mass spectrometry techniques have reduced the amount of organic material needed for dating to a single pine needle or seed (cf. Muzikar et al., 2003).

A second approach to dating beach ridges is to date the sand grains within each ridge. This technique, optically-stimulated luminescence (OSL), has only recently been applied to Great Lakes shorelines (Argyilan et al., 2002), and few data sets are available at this time.

More than 150 hand-augured cores and vibracores (both 7.5-cm diameter) were collected from the embayments in lakes Michigan and Superior. Where possible, a core was collected from every third swale. The cores were returned to the laboratory, split, and a roughly 2-cm-thick sample of peat or organic-containing sand was recovered from the base of the wetland sequence. All samples were sent to GeoChron Laboratories for conventional bulk ¹⁴C age determination with delta ¹³C correction. The age determinations were converted to calendar years using the program and data sets of Stuvier and Reimer (1993). Because of variability in the data and because only about one-third of the wetlands were sampled, an age model, using a least-squares regression between calendar age and distance landward to each ridge, was created. The age model, therefore, creates an age for every beach ridge in the strandplain with regard to its distance landward. All sites in Lake Michigan have age models (Thompson and Baedke, 1997); however, at this time, Tahquamenon Bay (Johnston et al., 2004) is the only site in Lake Superior for which an age model has been constructed. Opticallystimulated luminescence methodology is currently being explored for use in the other Lake Superior sites where poor peat preservation in the wetlands has hindered the radiocarbon-dating approach.

A lake-level hydrograph can be created by combining the foreshore elevations from the vibracores with the beach ridge ages assigned by the age model. A comparison of site-specific hydrographs of Lake Michigan shows that the sites experienced similar lake-level rises and falls, but the absolute elevations are not the equal (Figure 7). Divergence of hydrographs indicates that there has been differential vertical ground movement between sites through time and that the lake-level hydrograph created for each site shows lake-level change 'relative' only to that site. In the Great Lakes, this vertical movement is commonly attributed to isostatic rebound (Clark et al., 1990, 1994; Tushingham, 1992; Larsen, 1994) in response to the removal of ice following the last glacial retreat. In the upper Great Lakes, the rate of crustal rebound increases to the northeast, but the rebound is complicated because some sites (e.g., Ludington, Michigan) are rising at rates that are much slower than surrounding areas (Figure 8). In general,



Figure 7. Hydrographs of relative lake level for Lake Michigan from Thompson and Baedke (1997).

a greater amount of crustal warping is expected with increasing latitude.

Strandplains of beach ridges surrounding the upper Great Lakes are rebounded at the same rate as the underlying crust. Beach ridges that formed 2,000 years ago at a common lake level have experienced longer periods of rebound, and also greater amounts of rebound, than younger beach ridges. Therefore, the older beach ridges occur at higher absolute elevations than the younger beach ridges (Figure 9A). Some researchers (Andrews, 1970; Larsen, 1994) suggest that the elevation of beach ridges should increase exponentially with distance from the modern shoreline. Our study suggests that due to the low rates of rebound experienced in Lake Michigan and the relatively short duration of our record sets (<4,500 year), the effect of isostatic rebound on the elevation of beach ridges can adequately be described with a linear equation (Baedke and Thompson, 2000). This may not be true for sites in northern Lake Superior that have experienced greater amounts and rates of uplift than Lake Michigan.

A complicating factor in this simple rebound scenario is that the elevation of the water in the lake, and ultimately the basal foreshore elevations in the beach ridges, is referenced to the elevation of the dominating outlet (Larsen, 1994). For lakes Michigan and Huron, the dominating outlet for the past 5,000 years is the Port Huron outlet at the southern tip of Lake Huron. This outlet is rebounding with the rest of the basin. The elevation of this outlet is the zero isobase for lake-level elevations over the past 5,000 years. The zero isobase extends westward and crosses Lake Michigan near Sleeping Bear Dunes National Lakeshore in Michigan and the Door peninsula in Wisconsin (Figure 8). The actual position of the zero isobase crossing Lake Michigan can only be approximated from historical gage data and may be migrating northward with time. North of this zero isobase, the crust is rebounding more rapidly than the Port Huron outlet; south of the zero isobase, the crust is rebounding slower than the outlet. Consequently, shorelines north of the zero isobase experience a long-term lake-level fall, whereas shorelines south of the zero isobase experience a long-term lakelevel rise (Figure 9A). Because of this crustal warping through time, lake-level curves created for any site are 'relative' only to the site and nearby areas.

The relative lake-level hydrographs produced for each site contain information on past lake-level changes and vertical ground movement. To produce a graph of only past lake-level change, the



Figure 8. Map of the upper Great Lakes, showing modern rates of ground warping (isostatic rebound) based on the data and maps of Coordinating Committee on Great Lakes Basic Hydraulic and Hydrologic Data (2001).

rebound within each relative hydrograph must be removed. Baedke and Thompson (2000) used an iterative approach, subtracting rates of rebound from all relative lake-level hydrographs until differences between their residuals were minimized (Figure 9B). If rebound is extracted correctly for each relative hydrograph, the resulting lake-level hydrographs should show similar timing and magnitudes of fluctuations. To highlight the trends in the resulting lake-level hydrographs, a Fourier smoothing was calculated through the combined data sets. The result is a lake-level hydrograph for lakes Michigan and Huron that represents the upper limit of long-term lake-level change at the Port Huron outlet (Figure 10).

Current understanding and needs

The hydrograph for lakes Michigan and Huron shows that lake level was very high 4,500 years ago (Figure 10). This high stage is often called the Nipissing II phase of ancestral Lake Michigan. Between 4,500 and about 3,500 years ago, lake level fell more than 4 m to an elevation that is similar to the mean elevation of the historical record from 1819 to 1990. During the past 3,500 years, the upper Great Lakes experienced three long-term highs: the Algoma phase (2,300 to 3,300 cal. yr. B.P.), and two unnamed high phases (1,100 to 2,000 and 0 to 800 cal. yr. B.P.). The

most recent high phase corresponds to a cool period known as the Little Ice Age.

Superimposed on these long-term trends are two quasi-periodic fluctuations with periodicities of about 160 and 33 years in duration. The 160-year quasiperiodic fluctuation is pervasive throughout the last 3,500 years of data and can be directly connected into historical gage data for the basin. The 160-year quasiperiodic fluctuation also occurs in the older part of the hydrograph, but the Fourier smoothing could not pick it out from the single data set that defines this part of the graph. The 33-year quasi-periodic fluctuation cannot be shown in the hydrograph for lakes Michigan and Huron because these fluctuations are the points that define the 160-year fluctuations. The 33year fluctuations, however, are observable in the historical data for lakes Michigan and Huron (Thompson, 1992).

This high-resolution residual hydrograph does have its problems. More data sets are needed, especially in the older part of the graph. Several relative lakelevel hydrographs end in the Algoma phase, and only one hydrograph extends back in time to the Nipissing phases. Additional data sets are also needed to refine the younger end of the hydrograph and better attach it to the historical data. Because all of the data for the residual hydrograph are from Lake Michigan, a map showing long-term rates of rebound for lakes Michigan



Figure 9. Schematic diagrams showing the effect of vertical ground movement on relative lake-level hydrographs and residual hydrographs with vertical ground movement removed. (A) Rebound scenario for lakes Michigan and Huron. (B) Residual hydrograph scenario for lakes Michigan and Huron. (C) Rebound scenario for Lake Superior. (D) Residual hydrograph scenario for Lake Superior.

and Huron cannot be constructed with any degree of certainty. Five to six additional sites are needed along the shores of Lake Huron to define long-term rates of crustal warping more accurately.

Reconstruction of past lake levels in Lake Superior is more complicated. Lakes Superior, Michigan, and Huron were combined into one large lake during the Nipissing and Algoma phases. Farrand (1962) calculated that the outlet for Lake Superior at Sault Ste. Marie rebounded above the elevation of lakes Michigan and Huron about 2,200 years ago. Lake Superior, therefore, used the Port Huron outlet until about 2,200 years ago and experienced lake levels similar to lakes Michigan and Huron (Figure 9C). After 2,200 years ago, Lake Superior would have a new zero isobase through the Port Huron outlet and a different lake-level record (Figure 9C). Regardless of the outlet and differential vertical movement, a hydrograph can be created by minimizing the residuals between relative lake-level hydrographs (Figure 9D). It is important to note that the switching of outlets from Port Huron to Sault Ste. Marie created a new set of hydrologic conditions in the Lake Superior basin because the drainage basin became smaller and the outlet became bedrock-controlled. Thus, Lake Superior may not show the same quasi-periodic lake-level fluctuations as lakes Michigan and Huron after they split from each other.

The relative lake-level hydrograph for Tahquamenon Bay shows the expected long-term lake-level patterns for a site near the Sault Ste. Marie outlet that is rebounding slightly less than the outlet (Figure 11). Nipissing II phase deposits occur in the older and higher elevation part of the graph. These deposits are younger (200 to 300 years) than corresponding deposits in Lake Michigan. The age model for Tahquamenon Bay, however, does not take into account missing ridges formed during the post-Nipissing fall at Tahquamenon Bay that were eroded by later high lake levels (Johnston et al., 2004). Adding these ridges would place the Nipissing deposits at Tahquamenon Bay in the same age range as Lake Michigan. The Tahquamenon hydrograph shows a long-term lowering from 3,800 to 2,400 cal. yr. B.P. that extends below the historical average lake level for



Figure 10. Hydrograph of late Holocene lake level for Lake Michigan at the Port Huron outlet. This graph was generated by removing long-term rates of vertical ground movement from the relative hydrographs (Figure 7).

Lake Superior. An upward bowing during the long-term fall is the Algoma phase of ancestral Lake Superior. This high lake stage will be more pronounced when rebound is removed. At 2,400 cal. yr. B.P., the hydrograph shows a change from a long-term lowering to a slight rise that occurs when the Sault outlet begins to control Lake Superior water levels. The switch of outlets is older than Farrand's (1962) calculation, but Johnston et al. (2004) suggest that erosion or nondeposition may have occurred at this time. In all, the Tahquamenon Bay site follows the pattern expected for Lake Superior. A residual lake-level hydrograph will be created when age models are completed for the three other sites studied along the southern and eastern shores of Lake Superior.

Application of lake-level hydrographs to other research in strandplains

Wetland plant communities of the Great Lakes are dependent on water-level fluctuations to maintain di-

versity of both plant species and the faunal habitats they provide (Keddy and Reznicek, 1986; Wilcox, 1995; Wilcox and Meeker, 1995; Maynard and Wilcox, 1997). Therefore, researchers and natural resource managers require knowledge of the amplitude and frequency of high and low lake-level events that drive changes in wetland vegetation. The modern record is too short to provide an adequate understanding of these events, especially when the effects of long-term climate changes are considered. The lake Michigan-Huron hydrograph of Baedke and Thompson (2000) that covers several thousand years and contains century- and decade-level resolution helps explain the evolution of coastal wetland systems.

Studies of long-term lake-level records preserved in individual strandplains also provide a history of the developmental processes of these chronosequences of ridges and intervening wetlands and attach time scales to them. The strandplains thus serve as opportune sites to study successional processes in biological communities. The extensive strandplain at the southern end of Lake Michigan has a rich history of such studies. Following the lead of Cowles



Figure 11. Hydrograph of relative lake level for the Tahquamenon Bay embayment from Johnston et al. (in press).

(1899), who studied plant succession on dunes, Victor Shelford used the ridges and ponds in the nearby strandplain to study the distribution and succession of animal communities in terrestrial and aquatic habitats (Shelford, 1907, 1911, 1913). Olson (1958) later used the same strandplain to identify correlations among dune-building, soil development, and plant succession. More recently, successional processes in wetland and aquatic plant communities were studied in this chronosequence of dune ponds by Wilcox and Simonin (1987) and Jackson et al. (1988). Singer et al. (1996) then evaluated the effects of long-term climate change on wetland successional processes, and Doss (1993) investigated ground-water contributions to the ponds. A similar suite of biological studies is currently underway in strandplains of northern Lake Michigan and Lake Superior (e.g., Booth, 2001; Booth et al., 2002).

Additionally, shoreline dunes of the Great Lakes also respond to long-term lake-level changes that determine sand supply. Loope and Arbogast (2000) showed that perched dunes that dominate the eastern shore of Lake Michigan formed during century-level highstands over the past 1500 years that correspond to the Baedke and Thompson (2000) hydrograph. A detailed hydrograph based upon data taken from strandplains of beach ridges currently exists only for Lake Michigan. The forthcoming Lake Superior hydrograph (Johnston et al., 2004) will be of great value as regulation of Lake Superior water levels is reconsidered. A similar hydrograph for Lake Ontario is needed to provide information on the decade-level frequency of high and low lake levels necessary to restore natural hydrologic conditions on regulated Lake Ontario (Wilcox and Whillans, 1999). A long-term hydrograph for Lake Erie would assist in wetland restoration efforts that are dependent on both periodic flooding and dewatering of sediment, which drive changes in vegetation (Kowalski and Wilcox, 1999; Wilcox and Whillans, 1999).

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