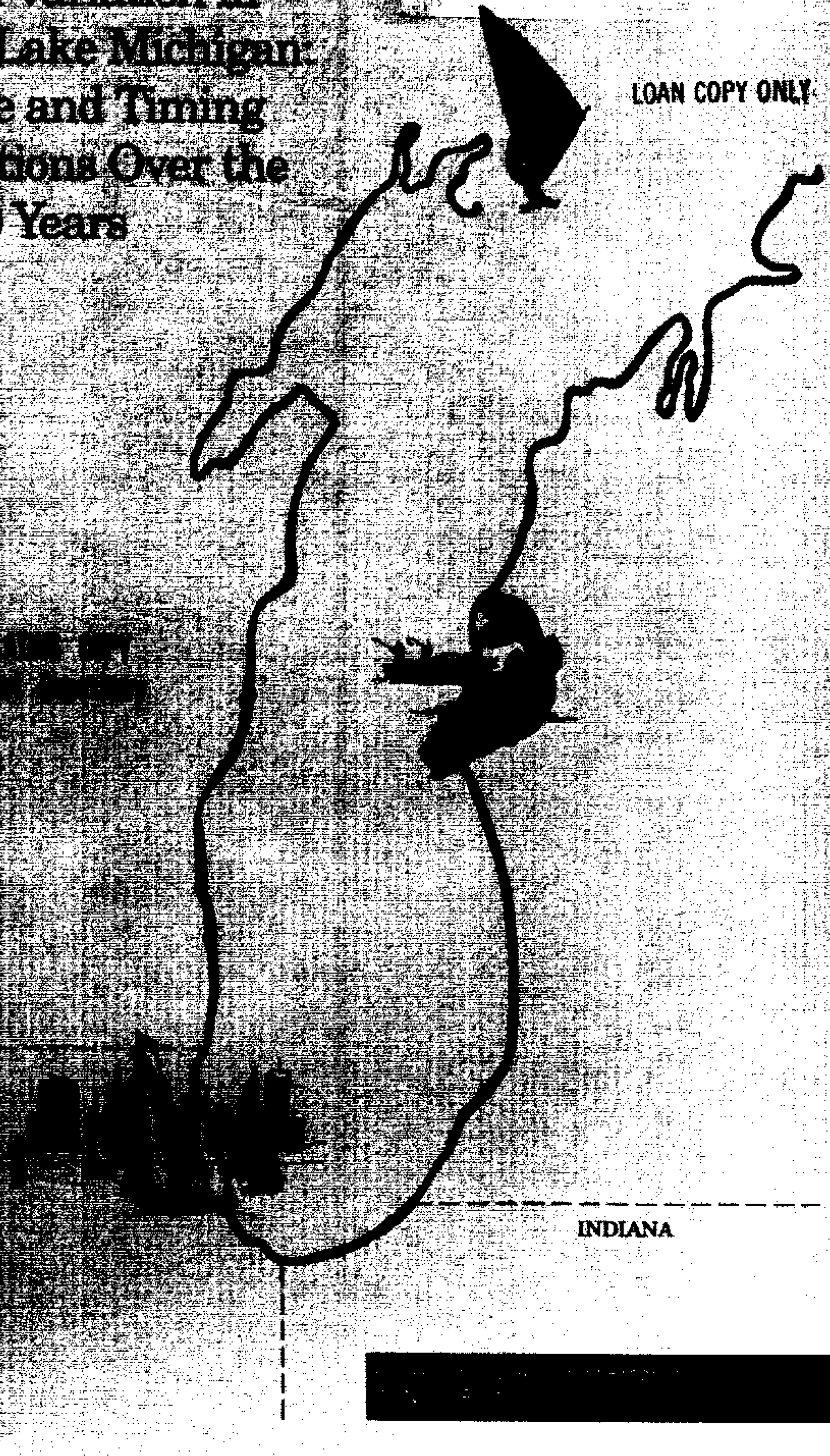
Lake-level Variation in Southern Lake Michigan: Magnitude and Timing of Fluctuations Over the Past 4,000 Years

Todd A. Thompson
Gordon S. Fraser
Norman C. Hester



IL-IN-SG-R-91-2
200 April 1991
COMM-NA89AA-D-SG058

Published by the Illinois-Indiana Sea Grant Program with funding from the National Sea Grant College Program, National Oceanic and Atmospheric Administration, U.S. Department of Commerce.

This work is a result of research sponosored by NOAA, National Sea Grant College Program, Department of Commerce, under Grant COMM-NA89AA-D-SG058. The U.S. Government is authorized to produce and distribute reprints for governmental purposes not withstanding any copyright notation that may appear hereon.

Issued in furtherance of Cooperative Extension Work, Acts of May 8 and June 30, 1914, in cooperation with the U.S. Department of Agriculture. Donald L. Uchtmann, Director, Cooperative Extension Service, University of Illinois at Urbana-Champaign.

Lake-Level Variation in Southern Lake Michigan: Magnitude and Timing of Fluctuations over the Past 4,000 Years

Todd A. Thompson

Gordon S. Fraser

and

Norman C. Hester

Indiana Geological Survey
Bloomington, Indiana

For additional copies of this publication, contact:

Office of Agricultural Communications and Education
University of Illinois
69SG Mumford Hall
1301 West Gregory Drive
Urbana, IL 61801
Attention: Cyndi Moore

ABSTRACT

The southern shore of Lake Michigan was an area of sediment accumulation throughout the late Holocene. Sediment accumulated in a 20 mi long, 5.5 mi wide, and 50 ft thick (32 km x 9 km x 15 m) wedge of beach/dune ridges that arcs across northwestern Indiana. The ridges are a record of past lake-level fluctuations in the Lake Michigan basin, recording about 5,000 years of lake level. Vibracores from the lakeward margin of about 60 of the ridges and radiocarbon dates on peat and organic-rich sediments from the base of wetlands between ridges were collected to construct curves of late Holocene lake-level variation in two areas of the Toleston Beach. These curves are useful in defining the upper physical limits of lake level and indicating patterns of past lake-level fluctuation along the southern shore of Lake Michigan for the past 4,000 years.

In the Miller Woods area of the Indiana Dunes National Lakeshore, a record of long-term and large-scale lake-level change is preserved. Beach ridges were formed about every 150 years. The elevation of foreshore deposits in these ridges indicates a long-term relative drop of about 15 ft (4.6 m) in the upper limit of lake level. Perturbations from this long-term fall occurred as high stands about 600, 1,700, and 2,300 years ago, and possibly 1,175 years ago. These highs are consistent with the pattern of late Holocene lake-level and climate variations observed in other studies and suggest a long-term recurring lake-level variation of 500 to 600 years in the Lake Michigan basin. In the Gary Airport area, a smaller-scale and shorter-term record of lake-level variation is superimposed on the long-term and intermediate-term variations observed in the Miller Woods area. Beach ridges were formed in the Gary Airport approximately every 30 years during a slight relative lake-level rise.

KEYWORDS: Lake Michigan, Lake Level, Stratigraphy, Sedimentology, Shoreline Behavior, Toleston Beach, Indiana

CONTENTS

FIGURES

TABLE

ACKNOWLEDGMENTS

Many research assistants worked on this project, and their help is gratefully acknowledged. In order of time spent on the project, they are: Linda D.P. Thompson, Paul K. Doss, Zinta Smidchens, Steve J. Baedke, Charlotte Tanner, and Al Archer. Special thanks is extended to the Indiana Dunes National Lakeshore, Lake County Parks and Recreation Department, Gary Parks and Recreation, IDNR Division of Nature Preserves, and the Chicago South Shore and South Bend Railroad for permission to collect vibracores and peat cores on their properties. The Indiana Dunes National Lakeshore was also helpful in providing temporary storage for core tubes, cores, and the vibracorer, and in logistical support throughout the several field seasons. Reviews of earlier versions of this manuscript were provided by Drs. Mike Chrzastowski, Lloyd Furer, Curt Larsen, and Greg Olyphant. The figures in this report were drafted and reproduced by the Drafting and Photography Sections of the Indiana Geological Survey. Approval to publish was granted by the Publications Committee of the Indiana Geological Survey.

INTRODUCTION

Effective management of Great Lakes shorelines requires a knowledge of how these coasts respond to the various factors that influence shoreline behavior. Some of these factors are weather-generated waves and currents, sediment budget, and location and type of man-made structures along the coast. But the most important factor influencing shoreline behavior in the Great Lakes is fluctuation in lake level.

High lake levels that occurred throughout the Great Lakes from 1985 to 1987 demonstrated the problems caused by an elevated water surface. Erosion and inundation of public and private lands occurred along United States and Canadian coastlines, and many shoreline structures failed. Even minor storms caused the flooding of large expanses of low-lying areas. Although high lake levels are dramatic in their effects, low lake levels generate their own environmental problems that range from the siltation of harbors and navigation channels to the undercutting of seawalls and other nearshore structures.

Park and industry managers, local, state and federal planners, and coastal engineers, charged with determining how coasts of the Great Lakes are managed, maintained, developed, and protected, need information about the physical limits of lake-level variation and the timing of lake-level events. These variables are generally determined from the historical record of lake levels, but studies in the Lake Michigan basin (Fraser and others, 1975, 1990; Larsen, 1985) suggest that large-magnitude variations in lake level occurred in the past and that the short historical record for Lake Michigan does not accurately represent lake-level maxima. These studies suggest that lake levels higher than the historically recorded levels did occur.

The purpose of this report is to describe the history of lake-level fluctuation in the southern part of the Lake Michigan basin during the late Holocene based on an examination of the internal structure and timing of development of beach ridges in northwestern Indiana. These ridges record about 5,500 years of lake-level variation. This paper presents information indicating the pattern of lake-level behavior of only the past 4,000 years in two parts of Indiana's shoreline.

STUDY AREA

The study area lies at the southern end of Lake Michigan and east of the Indiana-Illinois state line (Fig. 1). It covers an area of approximately 50 mi^2 (130 km^2) and includes the cities and towns of Gary, Whiting, Hammond, Indiana Harbor, Hessville, Aetna, and Miller. The study area is part of the Toleston Beach, a late Holocene strand plain that arcs across northwestern Indiana. The Toleston Beach began to form about 6,500 years ago, following a large scale transgression of the lake across the southern shore of Lake Michigan (Thompson, 1987a, 1987b, 1989). The Toleston Beach contains over 150 beach ridges in its western part that increase in relief and merge eastward into about 40 ridges near Miller, and finally coalesce into a single, 150 ft (46 m) high, dune ridge east of the study area.

During the late Holocene, the southern coast of Lake Michigan was a sediment sink that was supplied by net southward-directed beach and longshore drift, first from the eastern margin of the lake and after 2,500 years ago combined with sediment from the western margin. Because the southern shore of Lake Michigan was at the end of the transport path, the sediment accumulated along the shorelines of Indiana and Illinois. Olson (1958) has shown that this sediment forms dune capped beach ridges during a drop from a lake-level high. Thus, ridges in the Toleston Beach record high stands in Lake Michigan. Because the area was sediment rich and responded depositionally to variations in lake level, the potential for the preservation of a complete and easily interpreted record

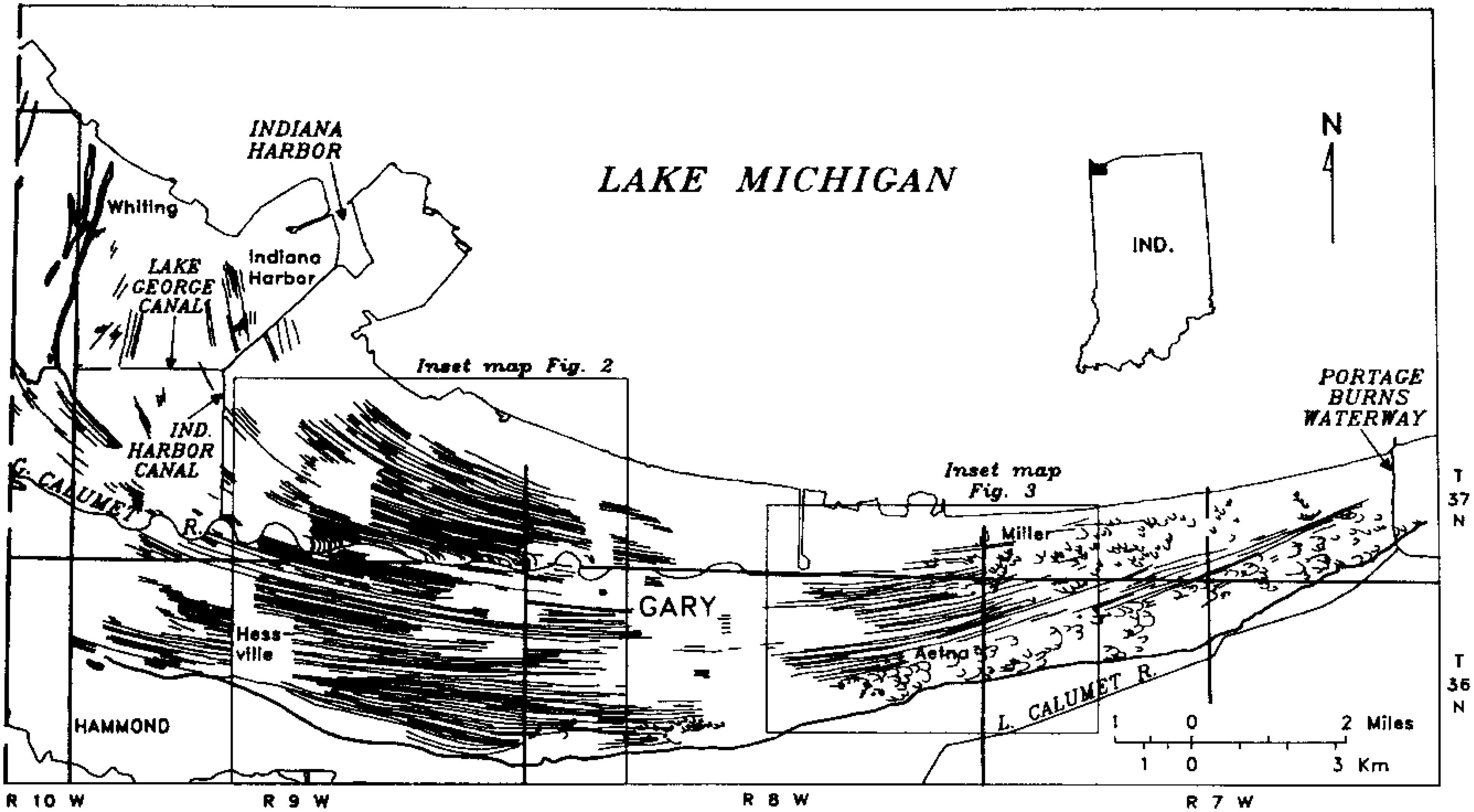


Figure 1. Map of the southern shore of Lake Michigan, showing areas studied, physical and cultural geographic features, and beach ridges (arcs) in the Toleston Beach. See Figures 2 and 3 for vibracore locations.

of lake-level fluctuation is greater here than along other reaches of Great Lakes' coastline.

The pattern of beach-ridge development in the Toleston Beach, whereby small beach ridges in the western part coalesce eastward, indicates that the rate of shoreline progradation and potential for a complete preservation of lake-level fluctuation is greatest in the western part of the Toleston Beach. Here, small-scale and short-term variations are preserved, whereas eastward, only larger-scale and longer-term fluctuations are recorded.

To document both the small- and large-scale variations, two parts of the Toleston Beach were studied (Fig. 1): (1) several locations near the Gary Airport (Gibson Woods Nature Preserve and Shell Addition, Ivanhoe property of the Chicago South Shore and South Bend Railroad, Clark Street property of Bongi Trucking, and Clark and Pine Nature Preserve); and (2) the Miller Woods and Inland Marsh Units (not shown on Fig. 1) of the Indiana Dunes National Lakeshore. These two areas are referred to here as the Gary Airport and Miller Woods areas, respectively.

Near the Gary Airport, individual beach ridges are about 8 ft (2.5 m) high and separated by wetlands (Fig. 2). The beach ridges occur in groups of four to five ridges that are, in turn, separated by slightly wider wetlands. Aerial photographs from 1938 show the ridges to be traceable for 2.5 to 3.1 mi (4-5 km) sub parallel with the modern shoreline. The ridges coalesce eastward, or they curve along their eastern end into the Grand Calumet River. The ridges that curve toward the Grand Calumet River record successive positions of the mouth of the river through time as new beach ridges were added to the shoreline. The recurved ridges show that the mouth of the Grand Calumet River was systematically forced eastward during the late Holocene by the accretion of longshore drift from the western margin of the lake on the western side of the river mouth.

At Miller Woods (Fig. 3), the beach ridges form several composite structures consisting of a main ridge with minor ridges on the lakeward side of the main ridge. The minor ridges decrease lakeward in height. Like the groups of ridges at the Gary Airport area, the composite structures are separated by wider-than-average wetlands. Individual ridges rise 12 to 20 ft (3.7-6.1 m) above the wetlands, and there is a decrease in ridge height (approximately 5 ft/mi [0.9 m/km]) to the west along each ridge crest. The main ridges represent deposition during a long-term and large-scale fall in lake level, and the minor ridges reflect a superimposed shorter-term and smaller-scale variation (Thompson, 1988). Some of the minor beach ridges that formed during low-water periods or during the next period of lake-level rise to a major high stand may have been eroded or stacked, but the record is probably largely intact with respect to the larger-scale variations. The decrease westward in ridge height and relief above the wetland is a result of decreasing dune thickness above nearshore sediments in the ridges but may also indicate differential subsidence, compaction, or isostatic adjustment along Indiana's shoreline.

METHODS

Reconstruction of a lake-level record requires information on how the lake's water surface varied with time. This information can be determined from the beach ridges in the Toleston Beach by noting the altitude of the deposits that accumulate at the swash zone (foreshore deposits) in each ridge, and by dating peats from the basal part of the wetland landward of each ridge (Thompson and others, 1987). By dating the basal part of the wetlands, we assume that each wetland formed soon after the beach ridge lakeward of it.

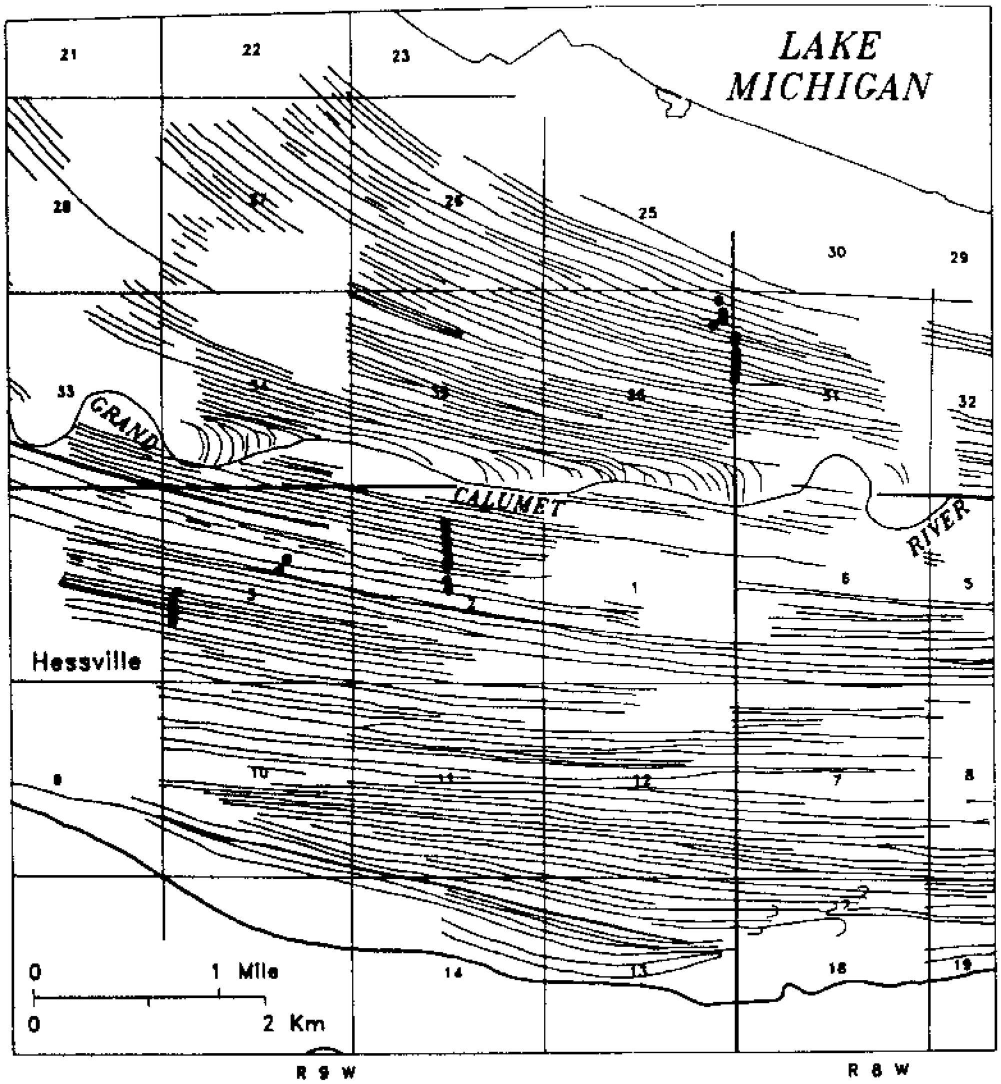


Figure 2. Map of Gary Airport study area. East- and west-oriented black lines are the positions of the crests of beach ridges. Dots are vibracore locations.

The plunge point at the base of swash zone along the southern shore of Lake Michigan is granular and pebbly. In a foreshore sequence, the plunge point occurs at the base of the foreshore sediments as a coarse-grained bed. The altitude of this bed is the approximate altitude of the lake surface and is the closest approximation of actual lake level when the beach ridge formed that can be obtained from stratigraphic and sedimentologic data (Thompson and others, 1987).

Sixty-eight, 3-in (7.6 cm) diameter, oriented vibracores were collected along the lakeward margin of 59 beach ridges in the springs of 1988, 1989, and 1990 (Figs. 2 and 3). All vibracores were collected at the intersection of the lakeward slope of the beach ridge and the wetland lakeward of it to obtain foreshore deposits below the ground surface. An additional 23 cores were obtained from the crest and landward side of the ridges and from the center of wetlands between ridges to determine the stratigraphy of the ridges and wetlands. The elevation of the ground surface at the core sites was

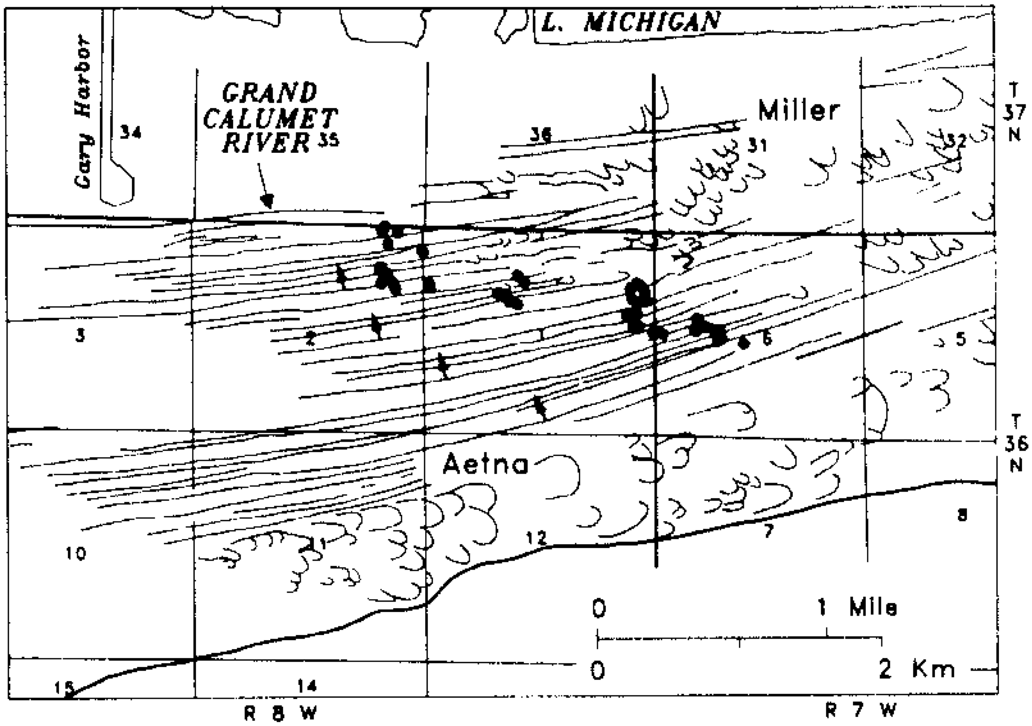


Figure 3. Map of Miller Woods study area, showing beach ridges (arcs) and vibracore locations (dots). Arrows indicate groups of beach ridges that decrease in relief toward the lake.

established by leveling from U.S. Geological Survey and National Park Service benchmarks and from U.S. Geological Survey water wells. These sources of altitude are referenced to the National Geodetic Vertical Datum (NGVD) of 1929.

All vibracores were returned to the laboratory, split normal to the ridge axis, described, photographed, and sampled. Latex peels were made of each core to preserve the core and to enhance stratification. Inclined strata were divided into: (1) subhorizontal parallel-stratification (< 5° dip), (2) low-angle parallel-stratification (5-15° dip), and high-angle parallel-stratification (> 15° dip). Over 1,000 sediment samples from the cores were wet and dry sieved at ½ϕ intervals. Graphs of grain size distributions were constructed to facilitate identification of foreshore sediments. These data were compared to the physical characteristics of grab samples (Indiana University Sedimentology Seminar, 1989; and Fraser and others, in press) and 6 cores from the modern beach.

Radiocarbon dates were obtained from 48 peat and organic-rich sand samples from the basal part of wetlands between ridges, and from 12 peat and wood samples from within wetland and coastal sequences. The organic samples from the wetlands were obtained by hand auguring or vibracoring with a 3-in (7.6 cm) aluminum core pipe at the deepest part of the wetland (determined by probing). The samples from the base of the wetland sequence were removed from the core and dried. All samples were sent to Geochron (Krueger Enterprises) for radiocarbon dating. At Geochron, the samples were examined for contamination by modern rootlets. All observable modern rootlets were removed. The samples were treated with a hot solution of HCl to remove carbonates, and a $\delta^{13}C$ correction was performed on each sample. To correct for variations in atmospheric carbon and to convert to calendar years, the radiocarbon dates were calibrated with a bidecadal dataset from 1950

AD to 7210 BC (Stuiver and Reimer, 1986, Revision 2.1). *All radiocarbon dates and beach ridge ages in this report are reported in calendar years before present (BP) with 1950 as 0 years BP.*

RESULTS

Sediment Characteristics

Description

Most of the vibracores collected along the lakeward margin of the beach ridges recovered a sequence of dune sand overlying foreshore sand and sandy gravel. Many of the cores in the Gary Airport area also penetrated upper shoreface sand below the foreshore sediments.

The dune sands are composed of well-sorted to moderately well-sorted, lower fine- to upper fine-grained sand in fining upward sequences (Fig. 4). Commonly, the dune sands are unstratified; however, zones with abundant heavy minerals display primary structures consisting of low- and high-angle parallel-laminations (Fig 5). Dip directions between sets are highly variable. Rootlets and root mottles occur in the upper part of the dune sequence to depths of 3.5 ft (1.1 m).

The foreshore deposits in the study area consist of moderately sorted, upper fine- to lower medium-grained sand with laminae and beds (0.3 to 4 ft thick [0.1-1.2 m]) of upper medium- to upper very coarse-grained sand (Fig. 4). Laminae are defined by variations in grain size that produce horizontal laminae and lakeward-dipping subhorizontal parallel-laminae (Fig. 5). High-angle, landward-dipping, parallel-laminae may occur at the base or near the top of the foreshore sequence, but basal landward-dipping laminae are rare. Laminae are commonly ungraded, but normally graded and inversely graded laminae are present. Although primarily composed of quartz sand, foreshore sediments also contain lithic fragments, shell and plant debris, and charcoal. These constituents may be concentrated in laminae and beds, but commonly are dispersed throughout the foreshore sequence.

The foreshore sequence is generally 4.5 to 5.5 ft (1.4-1.7 m) thick with a range from 3 to 7 ft (0.9-2.1 m). Most foreshore sequences are ungraded, but it is common for the base (plunge point) and the top of the sequence to be more coarsely grained and more poorly sorted. The coarsest beds (very coarse-grained sand to sandy gravel) generally occur at the base of the foreshore sequence.

The upper shoreface deposits consist of lower fine-grained to upper very fine-grained sand with interbeds of lower medium- to upper coarse-grained sand (Fig. 4). Primary structures include horizontal to high-angle parallel-laminae, ripples, and micro-troughs that are defined by grain-size variations with occasional organic-rich mud laminae and flasers. Like the foreshore deposits, the upper shoreface sediments are rich in lithic fragments, charcoal, and plant and shell debris.

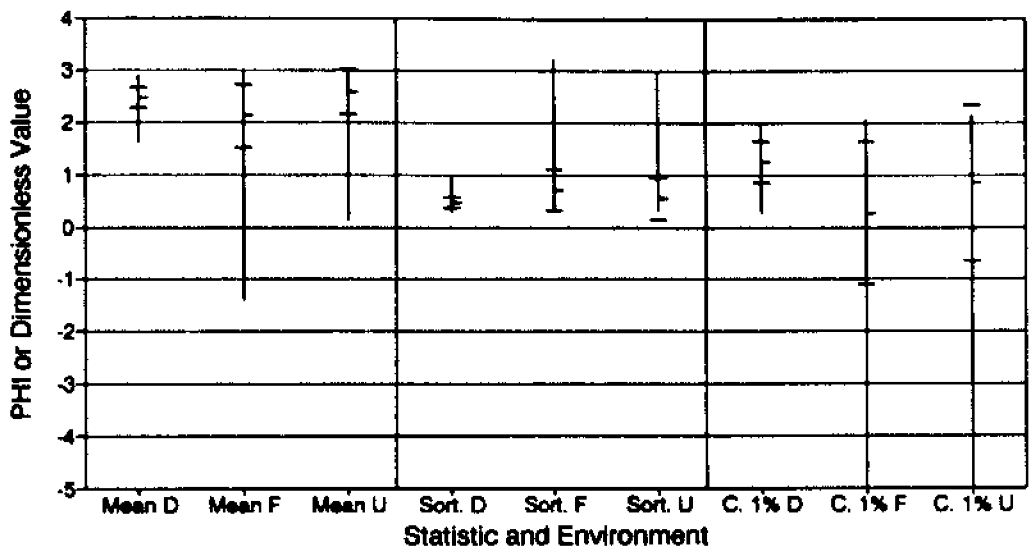


Figure 4. Summary of grain size statistics for dune (D), foreshore (F), and upper shoreface (U) deposits. Vertical lines define the range of measurements with one standard deviation (solid bars) around the mean (tick mark).

Discussion

Important to the construction of a lake-level curve is the identification of foreshore deposits in cores and the recognition of the contacts of the foreshore sediments with overlying dune and underlying upper shoreface deposits. The contact between foreshore and dune sediments is sharp and marked by a change in grain size. Plots of mean grain size and sorting indicate that the foreshore deposits are coarser and more poorly sorted than the dune sediments (Fig. 6). Furthermore, a distinct deflection toward coarser sizes in the coarsest one-percentile occurs at the contact, representing the traction-transport load in the water-laid foreshore sediments. Skewness is commonly used as an indicator of eolian or water-laid deposits with positive skewness suggesting wind transport (Friedman, 1961), but we have found that skewness is not a reliable indicator of mode of transport or deposition in the sediments along the southern shore of Lake Michigan. The upper contact of the foreshore deposits is also defined by a change in composition. The foreshore sediments contain lithic fragments, shell and plant debris, and charcoal. These constituents are not present in the dune deposits. This compositional change creates a sharp change in color in a wet core from light yellow-brown dune sands to gray brown foreshore deposits at the upper contact.

The contact between foreshore and upper shoreface sediments also is marked by a grain size variation from the coarser foreshore deposits to the fine- to very fine-grained upper shoreface sediments. The upper shoreface deposits are slightly better sorted than the foreshore sediments, but the range of variation is large (Fig. 4). Although the coarsest one-percentile increases at this contact, it does not become as fine as the dune sediments above the foreshore deposits. These vertical grain size trends observed in core have a one-to-one correspondence to trends observed across environments in the modern beach (Fig. 7). No consistent composition or color change occurs at the foreshore-upper shoreface contact, but the change in primary sedimentary structures is helpful in selecting the basal foreshore contact.

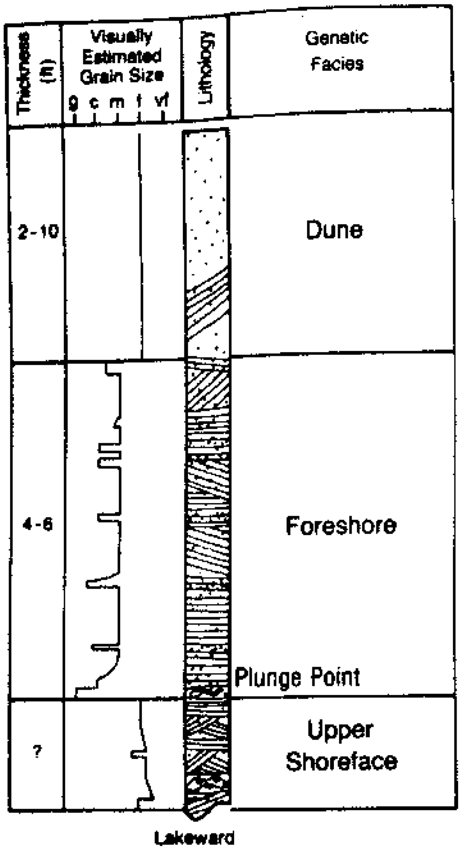


Figure 5. Idealized stratigraphic column, illustrating the characteristics of typical dune, foreshore, and upper shoreface sediments recovered in core.

Foreshore Elevations

Compaction Considerations

Foreshore elevations were determined by subtracting depth to the top and bottom of the foreshore deposits in the core from the altitude of the ground surface at the core site. An important consideration is where to apply the compaction that occurs during the collection of the vibracore. The methods commonly used are: (1) adding the compaction mathematically (linearly, logarithmatically, exponentially, etc.) along the length of the core, (2) adding the compaction to areas of disturbance within the core, (3) adding the compaction to the top or bottom of the core, and (4) ignoring all compaction. Our experience with hand augering in the wetlands is that the upper part of the peat column may compact more than 50%, suggesting that most compaction observed in the vibracores is related to the compaction of the peat column at the top of the core. In addition to the compaction in the peat column, most vibracores collected within the study area have some disturbance between 3 and 5 ft (0.9-1.5 m) below the surface. Compaction can also occur in these areas. Our observations indicate that most of the compaction occurs in the upper part of the core (< 5 ft [1.5 m] with most < 2 ft [0.6 m]). Consequently, we have added the compaction at each site to the top of the core. To determine the altitude of the foreshore deposits, the depths in the core to the foreshore contacts were subtracted from the altitude of the ground surface.

Miller Woods Area

Foreshore deposits were collected in 22 cores in the Miller Woods area (Fig. 8). Only half of the cores, however, penetrated the entire foreshore sequence. Many of the cores, collected during the drought of 1988, stopped in the gravelly base (plunge point) of the foreshore and were unable to penetrate into the upper shoreface sediments. Consequently, the base of the foreshore is not well represented in the cores obtained in the Miller Woods area. Trends in lake-level behavior, however, can be determined from the top of the foreshore, and the base of the foreshore can be approximated by subtracting the average foreshore thickness (5 ft [1.5m]) from the top of the foreshore sequence or by noting the altitude of the base of the core tube.

In the Miller Woods area, the foreshore deposits commonly occur from 16 to 22 ft (4.9-6.7 m) below the dune crests of the beach ridges (Fig. 8). The thickness of the dune deposits above the foreshore sediments increases landward between ridges, artificially suggesting higher foreshore elevations in the more landward ridges than those observed in the cores. Thus, the altitude of the crest of the beach ridge should not be used as an indicator of actual lake level.

The altitudes of the foreshore deposits indicate a long-term fall in the level of Lake Michigan since the early development of the Toleston Beach. Basal foreshore deposits decrease in elevation from 591 ft (180 m) above MSL in the landward part of the Toleston Beach. The most landward core in the Miller Woods transect did not penetrate the entire foreshore sequence. However, the average thickness of the foreshore sequence (5 ft [1.5 m]) subtracted from the altitude of the dune-foreshore contact that was recovered in the core yields an altitude of about 595 ft (191 m). Applying the same technique to the most lakeward core yields an altitude of about 583 ft (177.7 m). This elevation is comparable to the highest lake levels in the historical record (Quinn and Sellinger, 1990).

Several upward deflections of 3 to 6 ft (0.9-1.8 m) occur on the long-term lake-level fall (Fig. 8). These deflections correspond to the composite structures of ridges in the Miller Woods area that were described earlier.

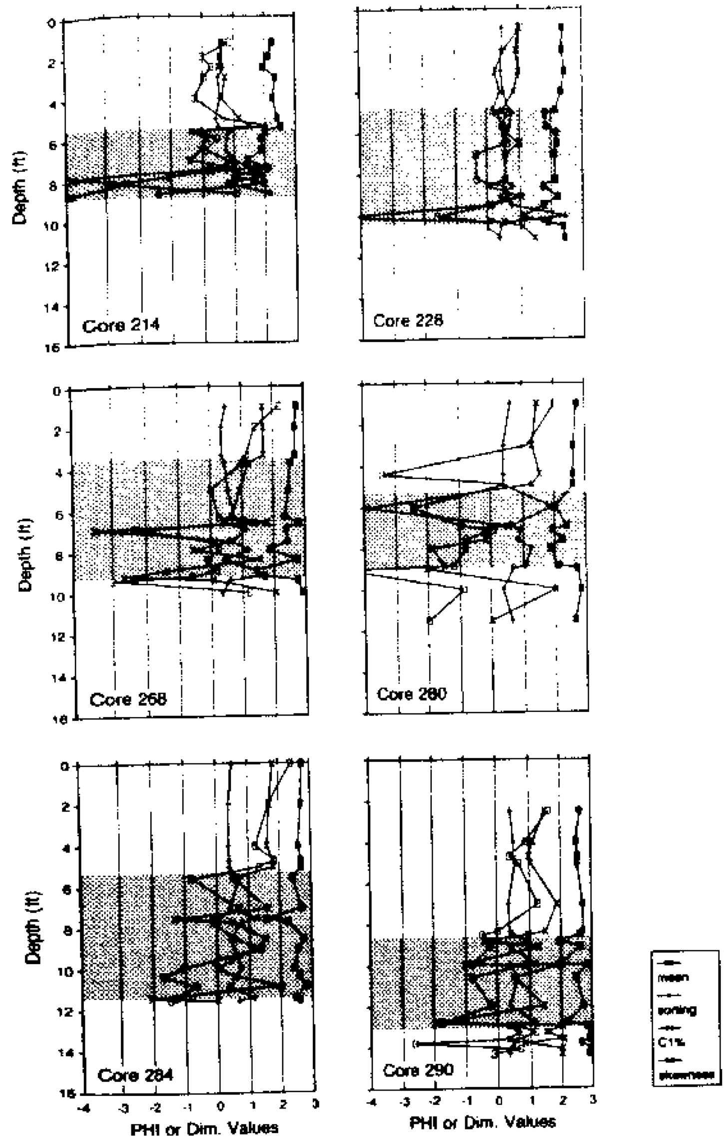


Figure 6. *Grain size distributions of selected cores. Foreshore sediments are stippled.*

Gary Airport Area

Foreshore deposits were collected in 34 cores in the Gary Airport area along several offset transects (Fig. 9). We were unable to construct a complete transect in the Gary Airport area because of man-made disturbance and urban development. Unlike the Miller Woods area, most of the cores penetrated the entire foreshore sequence. Elevations of the foreshore deposits show less variability and range in altitude from 583 to 576 ft (177.7-175.6 m) above MSL. Like the Miller Woods area, there are several upward and downward deviations in the elevation of the foreshore deposits.

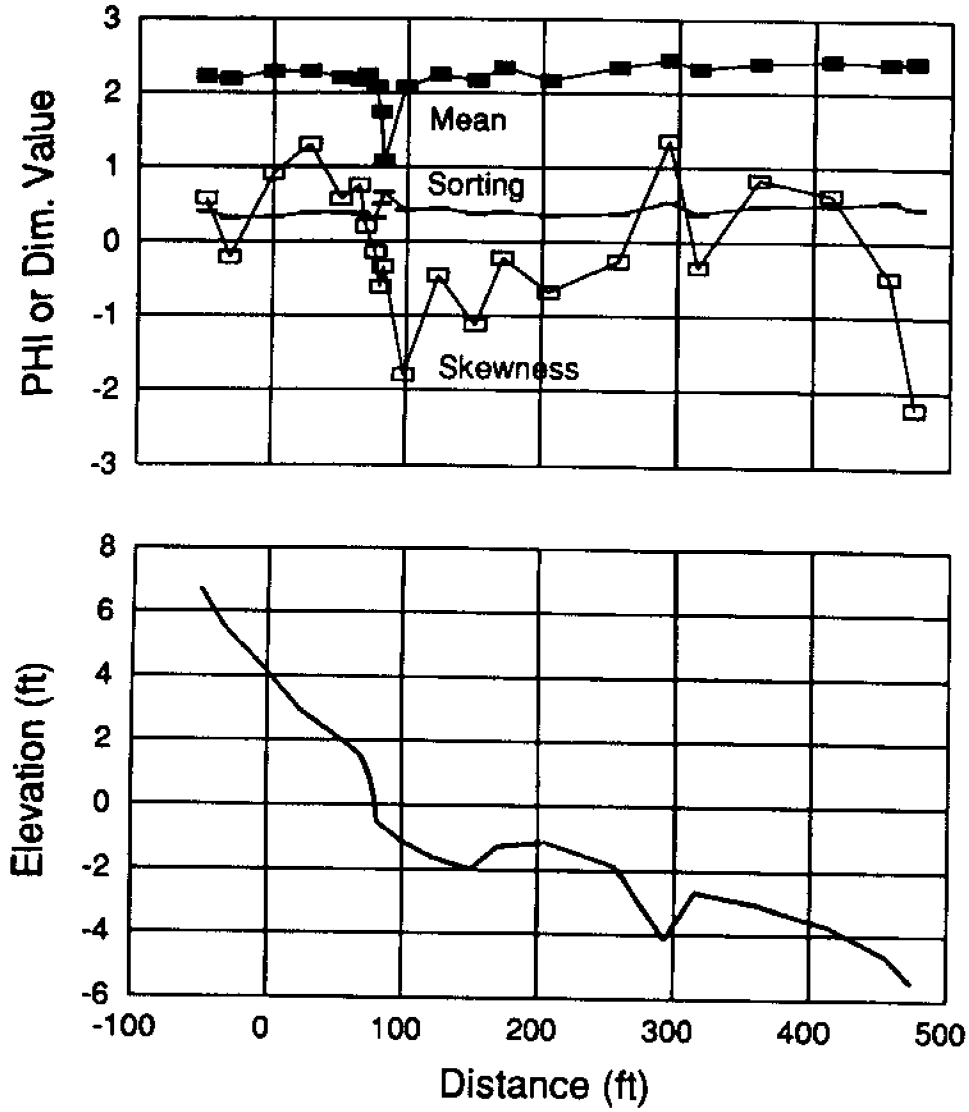


Figure 7. Grain size distributions along an onshore-offshore transect of the modern shoreline at the Miller Woods area. Upper diagram shows grain size parameters along the transect shown in the bottom diagram.

Shoreline Ages

Assumptions

The relative ages of the beach ridges along the southern shore of Lake Michigan follow a simple pattern. The oldest ridges occur in the landward part of the Toleston Beach and become sequentially younger lakeward. This horizontal stratigraphy is useful for correlation throughout the Toleston Beach but provides little information on the absolute age of the ridges and timing of their development. Although the nearshore deposits contain shell and plant debris, this organically-produced material is too sparse for radiocarbon dating. Moreover, it is difficult to determine the

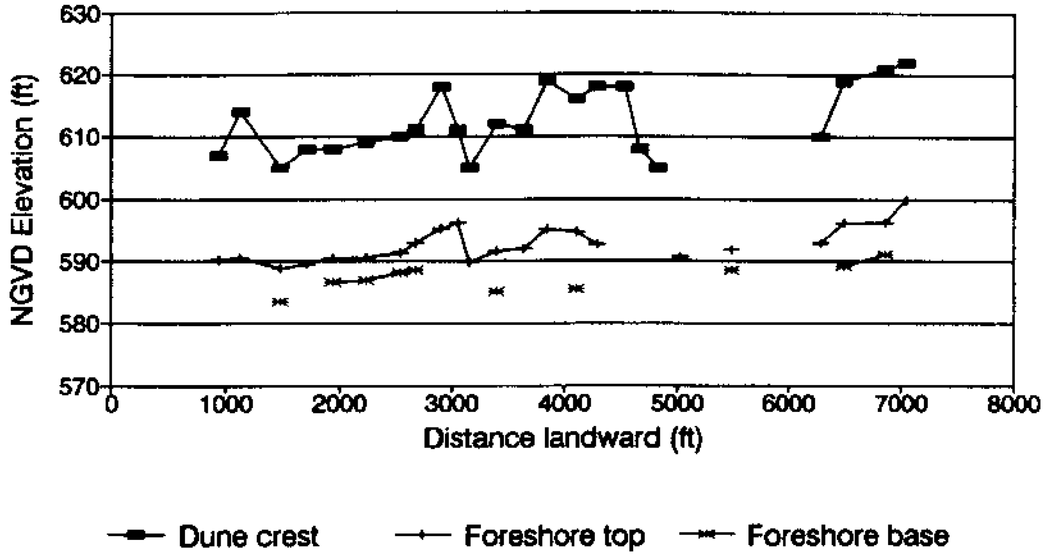


Figure 8. Beach ridge crest and foreshore elevations in the Miller Woods area.

source of this material because the erosion of older sedimentary deposits that occur along the margins of the lake introduces "old" carbon into the nearshore system. The only other available source of material for radiocarbon dating in the Toleston Beach is the peat, organic mud, and organic sand in the wetlands between ridges.

We have made the assumption that the wetland formed and began to accumulate vegetable matter in the swale between beach ridges soon after the beach ridge lakeward of it was created. Under this assumption, a radiocarbon date on the basal organic sediments in the wetland should provide a close approximation to the time that the beach ridge lakeward of it formed. This assumption is valid if organic material accumulates in the swale within 40 to 120 years, the laboratory error on all standard radiocarbon dates (Hedges, 1985). Given the length of time encompassed by the laboratory error, this assumption is probably valid. Exceptions occur for the wetlands between ridges in the higher elevations of the composite structures in Miller Woods. In these areas, the swales between ridges contain isolated wetlands that may not have been in contact with the water table throughout their history, precluding the development of wetland vegetation and its subsequent accumulation in the swale. These wetlands radiocarbon date significantly younger than wetlands lakeward of them.

Miller Woods Area

The ages of 23 beach ridges were determined in the Miller Woods area (Fig. 10). The dates show an overall lakeward decrease in the age of the ridges that reflects the progradational nature of the shoreline. However, variability does occur within the data. This variability is especially apparent in the three most landward dates that are from 800 to 1,500 years younger than dates that are immediately lakeward of them, and the single date at about 1,700 ft landward of the shoreline that is more than 1,000 years older than laterally adjacent dates.

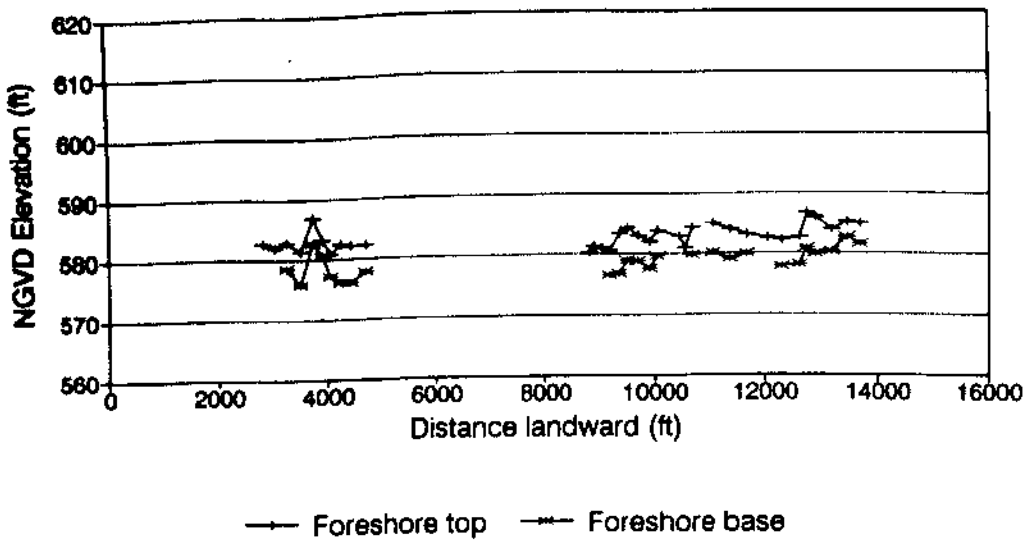


Figure 9. Foreshore elevations in the Gary Airport area.

Because a relationship exists between the ages of the beach ridges and their distance landward from the shoreline, a weighted least-squares line of best fit of age versus distance was calculated to reduce the variability in the data set (see Till, 1973, for a discussion of least-squares assumptions). Six age determinations associated with isolated wetlands in the higher elevations of composite structures and the anomalously old date at 1,700 ft were not included in the calculations (ovals in Fig. 10). This linear regression yields a slope of 0.56 yr/ft (Table 1). The inverse of the slope is an approximation of the rate of shoreline progradation in the central part of the Toleston Beach. This long-term rate is 1.8 ft/yr (0.5 m/yr).

To determine the approximate time between beach ridge formation, a weighted least-squares regression was calculated between the age of the ridges and a beach-ridge number assigned sequentially to the ridges. The dates deleted from the age versus distance regression were not included in these calculations. The slope of the best fit line of age and beach-ridge number in the Miller Woods area is 151 yr/ridge (Table 1). This slope and its standard error indicate that beach ridges were formed on an average in the Miller Woods area every 137 to 164 years.

Table 1. Summary of weighted least-squares regressions for determining the age of the beach ridges and timing of beach ridge development.

	Slope	R^2	Std. Err.
Miller Woods area			
Age vs. Distance	0.56 yr/ft	0.89	0.025
Age vs. Ridge #	151.0 yr/#	0.89	13.9
Gary Airport area			
Age vs. Distance	0.17 yr/ft	0.73	0.012
Age vs. Ridge #	30.5 yr/#	0.49	7.5

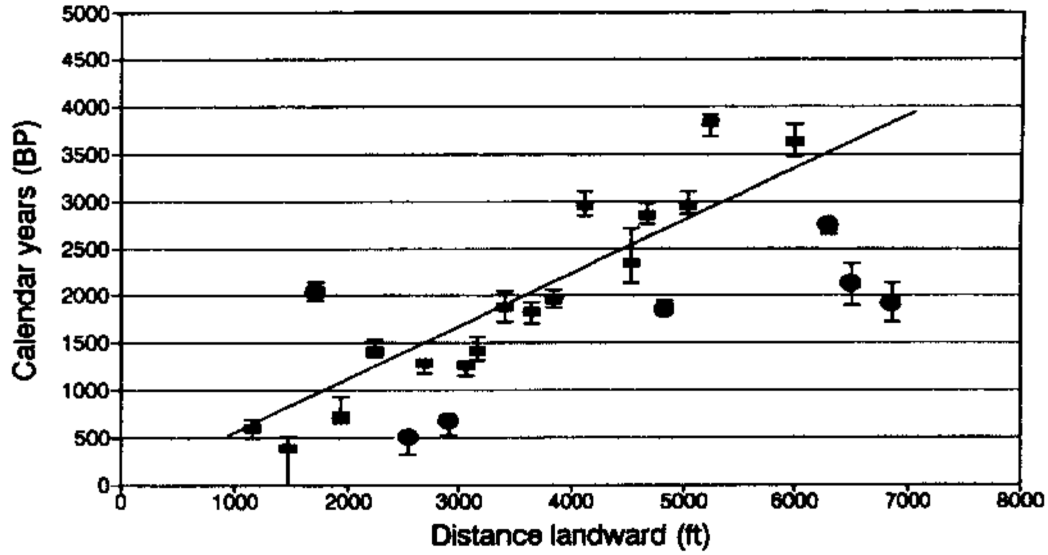


Figure 10. Graph of calibrated ridge ages in the Miller Woods area.

Gary Airport Area

In the Gary Airport area, the ages of 19 beach ridges were determined (Fig. 11). Like the Miller Woods area, the dates show a lakeward decrease in the age of the ridges, but the trend is less well defined. A weighted least-squares line of best fit of age versus distance landward of the modern shoreline has a slope of 0.17 yr/ft (Table 1), yielding an average rate of shoreline progradation for the western part of the Toleston Beach of 5.8 ft/yr (1.7 m/yr). This rate of progradation is more than three times greater than the rate calculated for the Miller Woods area.

A weighted least-squares regression of age versus ridge number landward from the modern shoreline has a slope of 30.5 yr/ridge (Table 1). Although there is a large scatter about the regression line, this slope and its standard error suggest that beach ridges were added to the shoreline in the Gary Airport area every 23 to 38 years. Groups of four to five of these beach ridges coalesce eastward to form a single ridge in the Miller Woods area.

DISCUSSION

Late Holocene Lake-Level

Curves of late Holocene lake level for the Miller Woods and Gary Airport areas can be constructed from Figures 8 and 10 and Figures 9 and 11, respectively, by using the linear regression lines in the age versus distance graphs as real time and plotting foreshore elevations on these curves. An adjustment from NGVD to the International Great Lakes Datum (IGLD) is also necessary to compare the graphs to the historical record for Lake Michigan. This adjustment applied to NGVD is -1.452 ft [0.44 m] for northwestern Indiana, yielding an elevation in IGLD (U.S. Corps of Engineers, personal communication; Indiana Department of Natural Resources - Division of Water Resources, personal communication).

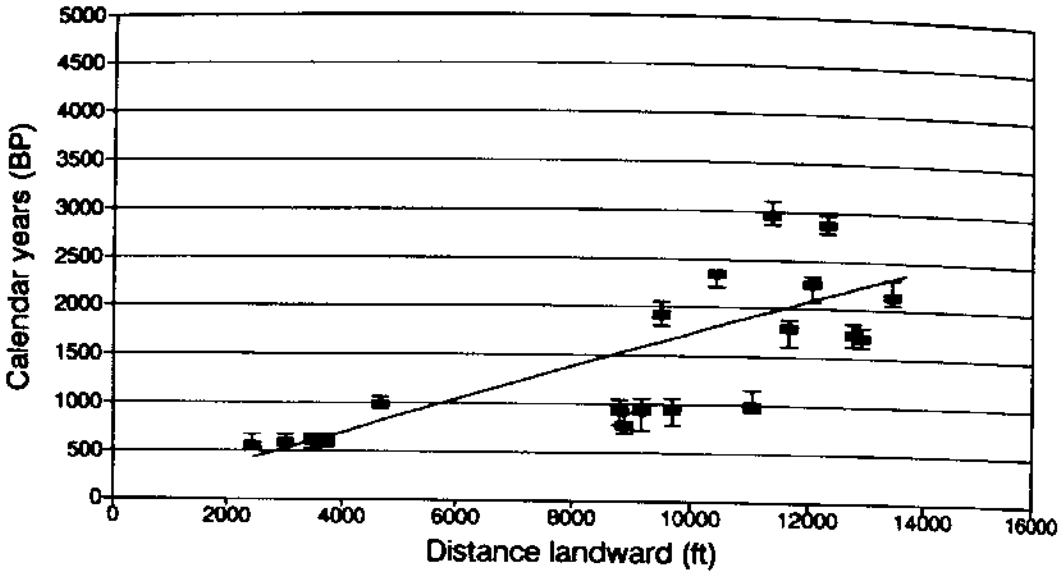


Figure 11. Graph of calibrated ridge ages in the Gary Airport area.

The derived graph for the Miller Woods area shows a long-term lake-level fall of 15 ft (4.6 m) (Fig. 12) from about 4,000 years ago. To determine the average relative rate of lake-level fall, a best fit was calculated through the basal foreshore deposits with an elevation of 578.91 ft (176.45 m) at zero calendar years. This elevation is the annual average of monthly lake level from 1819 to 1989 (see below). Anchoring the regression on this value assumes that lake-level variations in the historical record are representative of variations that occurred during geologic time. Over the time period covered by the study, the regression yields a relative rate of lake-level fall for the Miller Woods area of 0.00315 ft/yr (0.96 mm/yr). During this lake-level fall, beach ridges in the Miller Woods area were formed and preserved every 140 to 160 years.

High stands on the long-term fall occurred 600, 1,700, and 2,300 years ago (Fig. 12). The latter two highs match the timing of highs in Lake Michigan's level noted by Larsen (1985) and Fraser and others (1990). Their studies suggested a rising or high lake level from 1,150 to about 1,300 years BP. This lake-level event was not recognized in the Miller Woods area; however, there is a flattening of the Miller Woods curve from 1,250 to 1,100 years ago (Fig. 12). If a high stand occurred at this time, it was not as extreme as the high stands at 600, 1,700, and 2,300 years BP.

The high lake levels at 600, 1,700, and 2,300 years BP and possibly at 1,175 years BP suggest that long-term high lake-level episodes occur about every 500 to 600 years in the Lake Michigan basin. The past high-level episodes were 3 to 6 ft (0.9-1.8 m) above the mean of the long-term fall. Because only high stands are preserved along the southern shore of Lake Michigan, the range in variation from one high stand to a low stand may be double the observed variation (6 to 12 ft [1.8-3.7 m]).

The curve for the Gary Airport area shows many of the basal foreshore altitudes to be below annual elevations of the historical record (Fig. 13). The best fit of basal foreshore deposits from 500 to 2,400 years ago and passing through the average of the historical record yields a slope of -0.00094 ft/yr (-0.29 mm/yr). At this slope, the Gary Airport area experienced an extremely slight relative lake-level rise over the past 2,400 years.

Because beach ridges were created in the Gary Airport area every 25 to 35 years, the curve for this area is more detailed than the curve for Miller Woods. The high levels in the Miller Woods

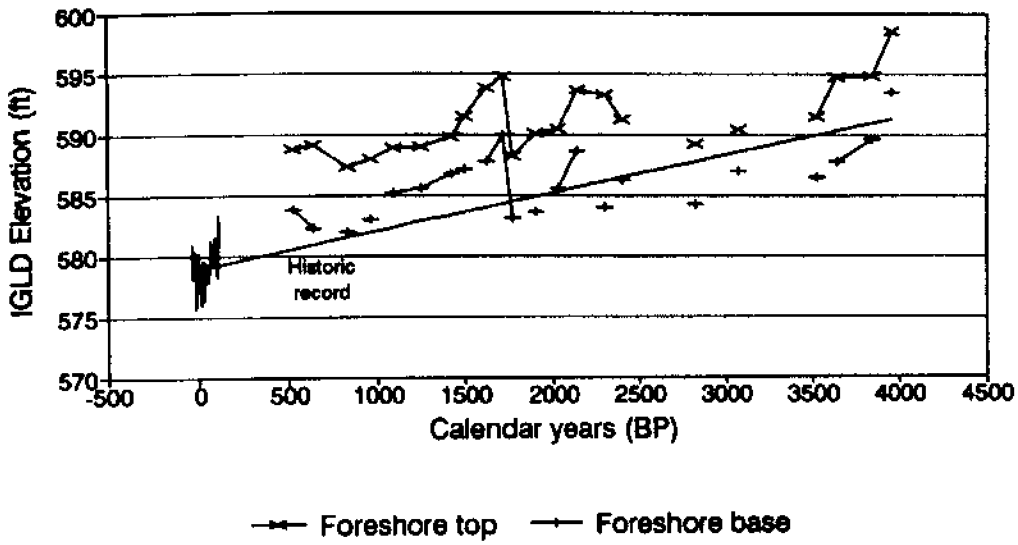


Figure 12. Late Holocene lake-level curve from the Miller Woods area and historical record for Lake Michigan. Where not present, the foreshore base is estimated. Best-fit line passes through basal foreshore elevations.

curve at 1,700 and 2,300 years ago are represented in the Gary Airport curve by a broad hump between 1,500 to 2,000 years and the high levels before 2,200 years (Fig. 13). The gap in the Gary Airport curve from 800 to 1,500 years, however, misses the possible high that occurred at 1,200 years suggested in the Miller Woods curve. The high at 600 years ago is recorded, however. Smaller-scale variations comprised of groups of four to five ridges occur on these long-term variations. They represent the partial preservation of the 140 to 160 year fluctuation recognized in the Miller Woods area.

The lake-level curves for the Miller Woods and Gary Airport areas show similar patterns of lake-level events (i.e. similar high and low phases), but opposite patterns of long-term lake-level behavior. The divergence of relative lake-level curves over a distance of only 7 mi (11.3 km) is surprising for an area generally considered to be tectonically and isostatically stable. Clark and others (1990), however, show that the southern shore of Lake Michigan has undergone isostatic subsidence in historical time of about 0.0034 ft/yr (1.04 mm/yr) relative to a lake-level gauge at Goderich, Ontario, and that isobases for Lake Michigan are roughly perpendicular to Indiana's shoreline. The study of Clark and others (1990) implies that lake level along the southern shore of Lake Michigan during the late Holocene should be rising, and that the rate of relative lake-level rise should increase westward along Indiana's coast.

The relative lake-level curve for the Miller Woods area, in contrast shows a long-term lake-level fall. If the southern shore of Lake Michigan was subsiding during the late Holocene, water level in the Lake Michigan basin must have been falling at a rate that exceeded the rate of subsidence in the Miller Woods area. Westward, the rate of subsidence was slightly greater than the rate of lake-level fall in the Lake Michigan basin, producing the small relative lake-level rise observed in the Gary Airport curve. Assuming that the lines of best fit are representative of the two relative lake-level curves, the rate of vertical movement between the two areas is 0.0041 ft/yr (1.2 mm/yr). This rate of adjustment is considerably larger than the estimates of Clark and others (1990).

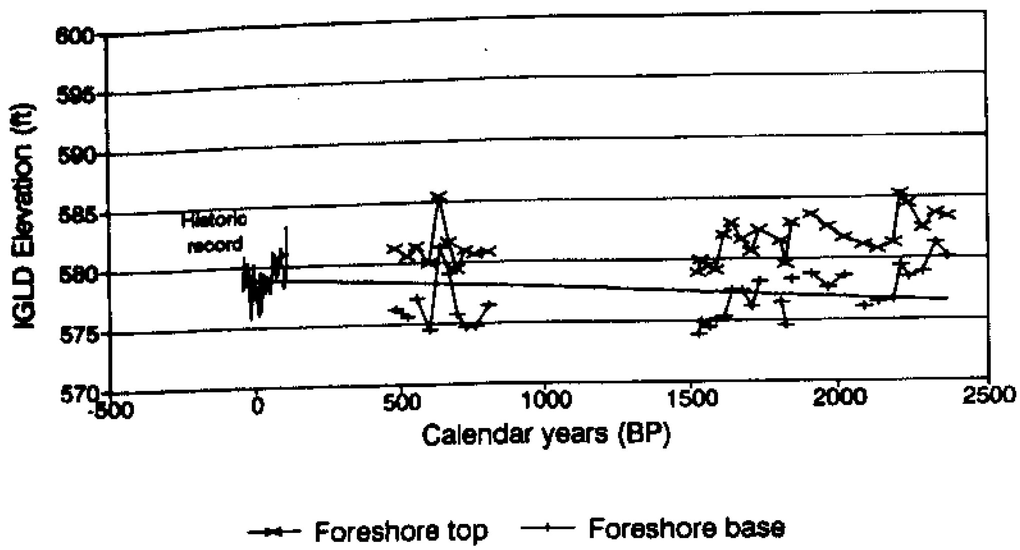


Figure 13. Late Holocene lake-level curve from the Gary Airport area and historical record for Lake Michigan. Best-fit line passes through basal foreshore elevations.

If the rates of isostatic subsidence of Clark and others (1990) are accurate for the southern shore of Lake Michigan and representative of vertical movement throughout the late Holocene, some other mechanism or mechanisms were active to produce the differences observed between the two study areas. Two possible mechanisms are faulting and differential compaction. No data is currently available to evaluate these possible processes. Without better knowledge of isostasy between the southern shore of Lake Michigan and the outlet at Port Huron, Michigan, tectonism in the southern part of Lake Michigan, and differential compaction along Indiana's shoreline, neither of these factors can be removed from the relative lake-level curves for southern Lake Michigan. The study of other coastal features in the Lake Michigan basin are needed to reconstruct water planes across Lake Michigan that can better define long-term rates of vertical movement.

Historical Lake Level

The continuous historical record of lake level for Lake Michigan begins in 1860; however, Quinn and Sellinger (1990) have presented intermittent data that extends the historical record to 1819 (Fig. 14). A 50-year smoothing of the average summer lake level shows that lake level was on the average very high in the 1850s and fell to a low in the 1930s. Following the 1930s and except for a brief fall in the early 1960s, lake level has steadily risen with each successive high above the previous high period. The observed pattern is suggestive of a long-term quasi-periodic behavior of about 160 years with a range in variation of 2.5 to 3 ft (0.8-0.9 m). This period is within the 151 ± 14 years noted between beach-ridge formation in the Miller Woods area, and we suggest that the historical record appears to reflect the lake-level behavior observed in the geological record.

A shorter-term smoothing of the historical record (15 years) shows a distinct secondary quasi-periodic behavior with a scale of 1.5 to 2 ft (0.5-0.6 m) and a period of about 28 years (Fig. 14). Liu (1970) suggested that a similar low-frequency cycle existed in Great Lakes water levels at a period of about 27 years, and Cohen and Robinson (1976) indicated the presence of 22- and 36-year periodicities for all of the Great Lakes. These periods are within or near the range of the 31 ± 8 years between beach ridges that was observed by the study of the beach ridges in the Gary

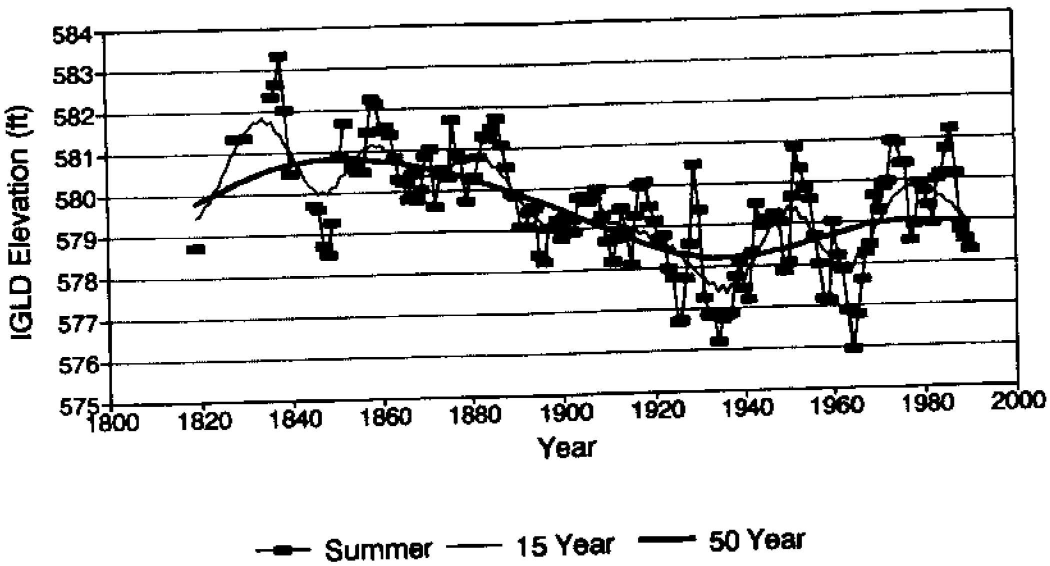


Figure 14. Summer average of lake level for Lake Michigan from 1819 to 1989 with 15-year and 50-year smoothings.

Airport area. Although the periods described above are at the limit of being statistically valid (see Currie and Fairbridge, 1985), their combination with the information gained from the geologic record strongly implies that a quasi-periodic behavior at about 25 to 35 years occurs in the Lake Michigan basin.

Summary

The geologic record indicates a long-term fall in the level of Lake Michigan throughout the late Holocene. The relative rate of this fall in the Miller Woods area is 0.00315 ft/yr (0.96 mm/yr). Westward where the rate of subsidence exceed the rate of lake-level fall, a relative lake-level rise of 0.00094 ft/yr (0.29 mm/yr) was observed. During the overall lowering of the level of Lake Michigan, high lake levels from 3 to 6 ft (0.9-1.8 m) above the mean of the lake-level fall occurred at 600, 1,175, 1,700, and 2,300 years BP. The timing of these high stands suggests a quasi-periodic behavior of 500 to 600 years with a range in variation of 6 to 12 ft (1.8-3.7 m). Superimposed on this large-scale variation are two smaller-scale fluctuations that are reflected in the historical record. Both variations appear to be quasi-periodic with timings of about 140 to 160 and 25 to 35 years and ranges of 2.5 to 3 ft (0.8-0.9 m) and 1.5 to 2 ft (0.5-0.6 m), respectively.

CONCLUSIONS

Lake-level variations are a primary control on shoreline behavior. This is especially true for the sandy coasts of the Great Lakes where variations in lake level are an order of magnitude larger than sea level variations. High lake levels not only inundate land, but they permit storm surge to impinge on man-made and natural features well above the altitude of the lake. Knowledge of the physical limits and timing of lake-level events is paramount in managing these shorelines. This study is an initial attempt quantify lake-level behavior in Lake Michigan during the Late Holocene.

This study shows that lake level during the late Holocene was not static and reached altitudes above those observed in the historical record for Lake Michigan. Furthermore, this study suggests that lake level may be quasi-periodic with 500-600, 140-160 and 25-35 year variations. The ranges of variation are estimated at 6 to 12 ft (1.8-3.7 m), 2.5 to 3 ft (0.8-0.9 m) and 1.5 to 2 ft (0.5-0.6 m), respectively. The study of additional ridge and swale areas in the Lake Michigan basin is needed to verify the existence of these quasi-periodic lake-level variations and to better understand vertical movements.

REFERENCES

Clark, R.H., Pranger, H.S., Walsh, J.K., and Primus, J.A., 1990, A numerical model of glacial isostasy in the Lake Michigan basin: *Geological Society of America, Special Publication 251*, p. 111-123.

Cohen, B.P, and Robinson, J.E., 1976, A forecast model for Great Lakes water levels: *Journal of Geology*, v. 84, p. 455-465.

Currie, R.G., and Fairbridge, R.W., 1985, Periodic 18.6-year and cyclic 11-year induced drought and flood in northeastern China and some global implications: *Quaternary Science Reviews*, v. 4, p. 109-134.

Davis, R.A., Jr., Fox, W.T., Hayes, M.O., and Boothroyd, J.C., 1972, Comparison of ridge and runnel systems in tidal and non-tidal environments: *Journal of Sedimentary Petrology*, v. 42, p. 413-421.

Fraser, G.S., Larsen, C.E., and Hester, N.C., 1975, Climatically controlled high lake levels in the Lake Michigan and Lake Huron basins: *An. Acad. Brasil. Ciencia*, v. 47, p. 51-66.

Fraser, G.S., Larsen, C.E., and Hester, N.C., 1990, Climatic control of lake levels in the Lake Michigan and Lake Huron basins: *Geological Society of America, Special Publication 251*, p. 75-89.

Friedman, G.M., 1961, Distinction between dune, beach, and river sands from their textural characteristics: *Journal of Sedimentary Petrology*, v. 31, p. 514-529.

Hedges, R.E.M., 1985, Progress in radiocarbon dating: *Science Progress, Oxford*, v. 69, p. 409-427.

Indiana University Sedimentology Seminar, 1989, Sedimentation along a barred shoreline, southern Lake Michigan: *Geological Society of America, Abstracts with Programs*, v. 21, p. 31.

Indiana University Sedimentology Seminar, in prep, Sediments and sedimentary structures of a barred, atidal coastline, southern shore of Lake Michigan.

Larsen, C.E., 1985, A stratigraphic study of beach features on the southwestern shore of Lake Michigan: new evidence of Holocene lake level fluctuation: *Illinois State Geological Survey, Environmental Geology Notes 112*, 31 p.

Liu, P.C., 1970, Statistics of Great Lakes levels: *Proceedings of the 13th Conference on Great Lakes Research*, p. 360-368.

Olson, J.S., 1958, Lake Michigan dune development. 3. Lake-level, beach, and dune oscillations: *Journal of Geology*, v. 66, p. 473-483.

Quinn, F.H., and Sellinger, C.E., 1990, Lake Michigan Record Levels of 1938, a present perspective: *Journal of Great Lakes Research*, v. 16, p. 133-138.

Stuiver, M., and Reimer, P.J., 1986, A computer program for radiocarbon age calibration: *Radiocarbon*, v. 28, p. 1022-1030.

Thompson, T.A., 1987a, Development of the late Wisconsinan to early Holocene Calumet and Toleston dune/beach complexes in the Indiana Dunes National Lakeshore: *Proceedings of the First Indiana Dunes Research Conference, Symposium on Shoreline Processes*, p. 1-4.

Thompson, T.A., 1987b, Sedimentology, internal architecture, and depositional history of the Indiana Dunes National Lakeshore and State Park: Unpublished Ph.D. thesis, Indiana University, 295 p.

Thompson, T.A., 1988, Shoreline behavior, sediment accumulation, and the scale of lake level fluctuation along the southern shore of Lake Michigan: *Society of Economic Paleontologists and Mineralogists, Annual Midyear Meeting Abstracts*, v. 5, p. 54.

Thompson, T.A., Wood, W.L., and Davis, S.E., 1989, Shoreline deposition and erosion in northwest Indiana: *Field Guide for the 1989 Meeting of the North-Central Section of the Geologic Society of America*, p. 95-171.

Thompson, T.A., 1989, Anatomy of a transgression along the southeastern shore of Lake Michigan: *Journal of Coastal Research*, v. 5, p. 711-724.

Thompson, T.A., Fraser, G.S., and Olyphant, G., 1988, Establishing the altitude and age of past lake levels in the Great Lakes: *Geological Society of America, Abstracts with Programs*, v. 20, no. 5., p. 392.

Till, R., 1973, The use of linear regression in geomorphology: *Area*, v. 5, p. 305-308.