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COASTAL STUDIES PROGRAM

COASTAL SEDIMENTARY PROCESSES IN SOUTHERN LAKE MICHIGAN: THEIR INFLUENCE ON COASTAL EROSION

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Edited by

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Preface

This open-file report is a collection of short papers, extended abstracts, and progress reports reviewing the first year of ongoing work on coastal processes research sponsored by the US Geological Survey in southern Lake Michigan. The research on processes is part of a five-year USGS study directed toward a better understanding of the relationship between high lake levels and coastal erosion in southern Lake Michigan. Other aspects, framework and lake level, are addressed in a companion open-file report (No. 90-272).

Coastal processes studies are attempting to understand the sources, pathways and sinks of sediments passing through the coastal zone. Therefore, the enclosed reports cover aspects of coastal bluff composition and stability, coastal and beach sediment stability and dynamics, along-shore transport processes and rates, offshore lake bed stability, and the role of ice in protecting and eroding coastal sediments as well as rates and processes implied from signatures in the stratigraphic record.

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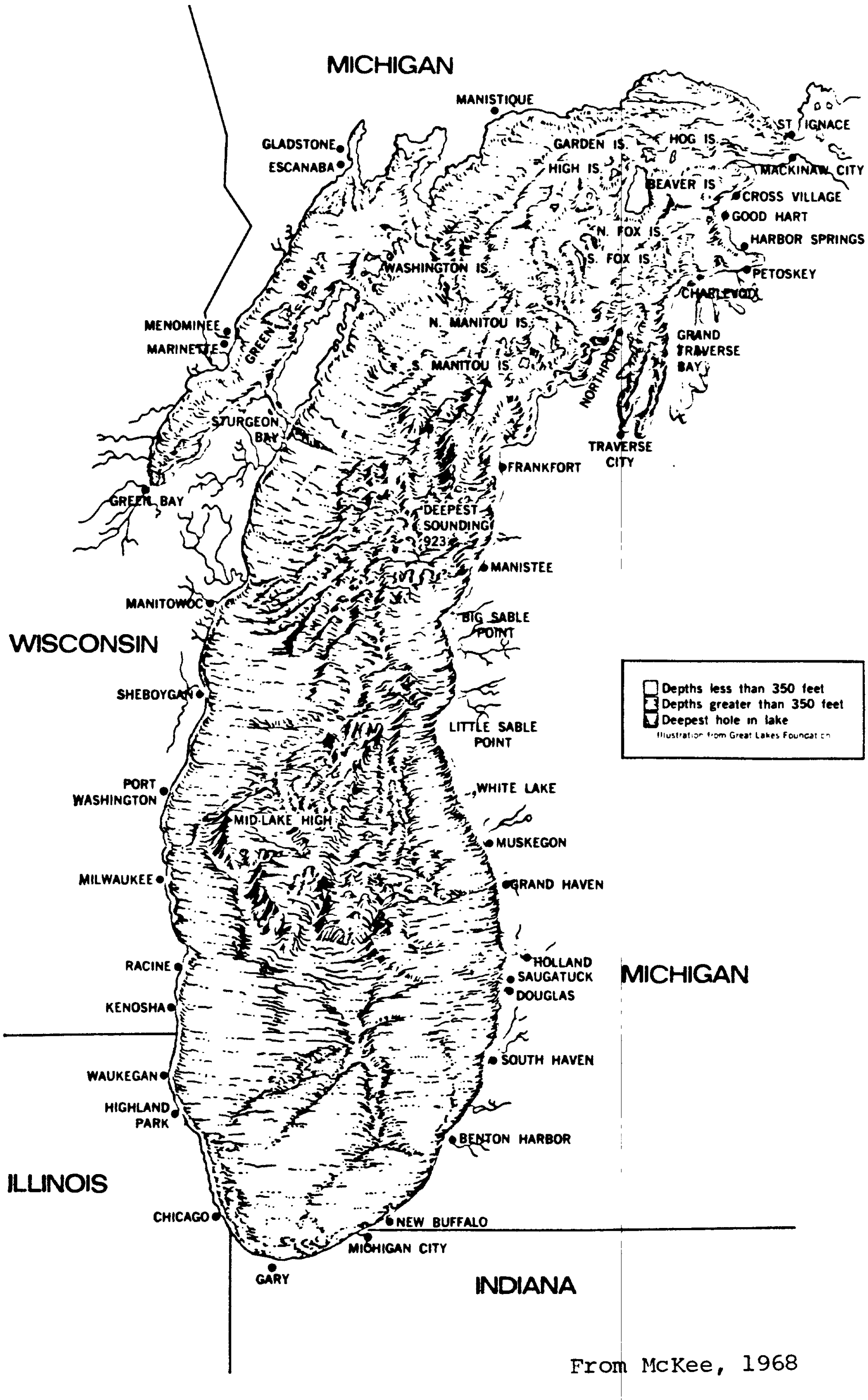

From McKee, 1968

SEDIMENT CONTENT AND BEACH PROFILE MODIFICATION BY ICE ALONG THE COAST OF SOUTHERN LAKE MICHIGAN

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Sea ice is known to influence the bottom topography of high latitude coastal marine environments (Barnes et al., 1988). In the Great Lakes, studies of the influence of lake ice on the lake bed and coast have focussed on its protection of beaches (O'Hara and Ayers, 1972; Marsh et al, 1973; Davis, 1973; Seibel et al., 1976; Evenson and Cohn, 1979), its role in erosion (Bajorunas and Duane, 1967), and ice morphology in relation to lakebed morphology. Several studies have described the nearshore ice regime, its development, and its decay (Kivisild, 1970; Miner, 1989).

Lake ice is present along the coast of Southern Lake Michigan for only 2 to 4 months per year (Assel et al., 1983). However, the presence of ice corresponds to periods of high wave energy associated with winter storms, therefore measurable coastal effects attributable to the presence of ice might be anticipated. This report discusses preliminary observations of ice zonation, coastal profiles, and sediment content in the coastal ice belt based on field work undertaken in February, 1989 at 9 locations along the coast of Southern Lake Michigan (Figure 1).

Ice Zonation

The ice zonation we observed at the coast agrees with that reported by Seibel (1986 , after O'Hara and Ayers, 1972, and Kivisild, 1970, and Figure 2). We use the terminology from Kivisild (1970) which follows that developed and widely accepted for the arctic marine environment (Reimnitz et al., 1978). The zonation was most completely developed along the southeastern coast of the lake, and least well developed along the western shore. The zonation was similar at all the sites although portion of the zonation may have been absent at different locations and times.

The coastal ice regime consisted of an ice foot at the shoreline and a lakeward sequence of wave-generated ice ridges with intervening shore-parallel troughs (Figure 2). At the shoreline an ice foot is built of ice and sediment where the subaerial beach is exposed to freezing temperatures and wave swash. The ice foot may build to a height of 1 m and usually extends several meters shoreward from the shore line. Immediately lakeward of the ice foot are a series of one or more grounded ice ridges often separated by ice filled troughs (lagoons in Figure 2). The surface of the ice in the troughs was rough, with relief of 10 to 30 cm depending on the size of ice blocks crowded here during formation. Water depths in most lagoons we studied was less than a meter deep and commonly the ice extended nearly to the lake bed.

The grounded ice ridges were coast parallel and composed of adjoining ice cones (volcanos) with steep sometimes vertical lakeward slopes and more gentle shoreward slopes (Marsh et al., 1973 and Figure 2). The ridges were composed of millimeter size ice granules more-or-less frozen together. The consistency of the fast ice complex on the whole was that of hard snow and was very rapidly augered with a power auger or a spiked pole. The below-lake-level portions of these ridges were water saturated and poorly indurated. Ridge heights were commonly about a meter (Figure 3), but several reached heights of 5 to 7 meters. Ridges were absent along engineered coasts. The ridges were restricted to within 25 m of the coast along the western and southern shores in Illinois and Indiana, but occurred out to about 100 m along the southeastern shore.

Lakeward of the ridges, two ice regimes were observed. Congealed pancake and slush ice similar to the lagoonal ice and uncongealed slush and brash-ice which were found to be up to 60 cm thick against the vertical face of the ice ridges. The uncongealed material was readily driven against the ridges by the wave regem, supplying ice and sediments to the ridges through the cone (volcano) conduits (Marsh et al., 1973).

Coastal Profiles of Ice and Lake Bed

Coastal profiles were surveyed using an integrated total station which was referenced to previously established profiles at seven locations. We estimate that the vertical errors in the profile measurement due to rod placement are less than 10 cm. Profiles were referenced vertically to lake level and to temporary bench marks established by previous surveys in all cases except Gillson Beach. Our measured lake levels were referenced and interpolated to actual elevation based on the lake level elevation at Milwaukee, Wisconsin, Calumet Harbor, Illinois, and Holland, Michigan during the time of survey.

Comparisons of fall (open water) and winter coastal profiles indicated that both erosion and deposition had occurred since the fall (Figure 4). Ice ridges are almost always associated with an underlying bar on the lake floor (Siebel et al., 1976). An erosional trough up to 50 cm deep was commonly associated with the lakeward edge of the coastal ice ridges (Figure 3a). These changes are believed to reflect lakeward displacement of wave energy dissipation by the belt of coastal ice.

Sediment Content of Lake Ice

Analysis of ice samples from the shore ice indicated a broad range of sediment content (Table 1). Sediment content of the ice ranged from less than 0.01 g/L to 866g/L; the latter being a ball-shaped mass rolling along the lake bed. Apart from the ice balls, sediment contents were highest in ice foot samples, with average concentrations of nearly 40 g/L (Table 1), and were least in the drift ice lakeward of the ridges. The one water sample contained very little sediment (0.03g/L), but even less was found in several offshore ice samples (0.003g/L).

The sediments entrained in the shorefast and drifting brash ice consisted primarily of well sorted medium-grained (.25mm) beach sand (Figure 5) with occasional bimodal admixture of gravel, especially along the Illinois shoreline. The source of this material is presumed to be the subjacent shoreface (Miner, 1989). Silt and clay size material was observed on filters from the water sample and the offshore ice samples where very small quantities of sediment were found.

Estimations of the width of the coastal ice zones based on aerial observations documented on video (February, 1989) and width and thickness measurements based on the profiles form the basis for estimating the volume of ice of different types along the coast (Table 2). Using these data, the sediment load in the coastal ice ridge complex can be estimated. Using the average values in Table 2 most of the sediment contained in the ice is found in the ridge and lagoon complex and an average of about 360 g of sediment are contained in the ice for each meter of coastline (or about a third of a ton per kilometer). We note that at the time of our observations sediments in the fast ice were not being transported by ice rafting, nor readily available for transport. However, this sediment-rich ice might be transported during periods of ice decay and break-up.

Rapid southward, alongshore ice drift (30 cm/sec) including sediment-laden ice blocks was observed during strong northeasterly winds on the Illinois coast. Conservative estimates of an average width (20 m) and thickness (0.3 m) coupled with sediment content for active drift ice (25 g/L) suggest that longshore transport by ice rafting would be as much as 2×10^{3} tons per day if the assumed conditions persisted. Transport by ice rafting, compared to wave and current transport, commonly results in longer sediment trajectories because grains are locked in the ice cover, moving wherever it goes, and do not have to be repetitively eroded and resuspended by waves along the shoreface.

Preliminary Conclusions

The presence of ice influences coastal erosion by entraining significant quantities of sediment primarily from the beach face, transporting it alongshore and locking a portion in the fast ice on the shoreface. The coastal ice foot and ice ridges force waves to expend their energy further lakeward, eroding and modifying the lake bed (Nielsen, 1988). We do not yet have information on ice rafted sediment depocenters nor on the offshore transport of sediments by ice.

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Table 1. Sediment concentration in Lake Michigan Coastal Ice, (grams per liter of water plus sediment)

No. of Samples	Location	Average Sediment Concentration	Range
FAST ICE			
4	Ice foot	39.2	9.2-56
8	Ice ridges	9.1	1.0-32
1	Ice troughs	10.7	----
6	Undifferentiated fast ice	10.5	4.7-25
AVERAGE		16.5	1.0-56
DRIFT ICE			
6	Offshore	0.22	0.003-1.2
10	Nearshore inactive	1.0	0.01-2.0
8	Nearshore active	25.0	3.0-79
MISCELLANEOUS SAMPLES			
3	Offshore (anchor ice??)	2.3	0.11-6.4
3	Sediment laden ice blocks	445	179-866
1	Water sample	0.032	----

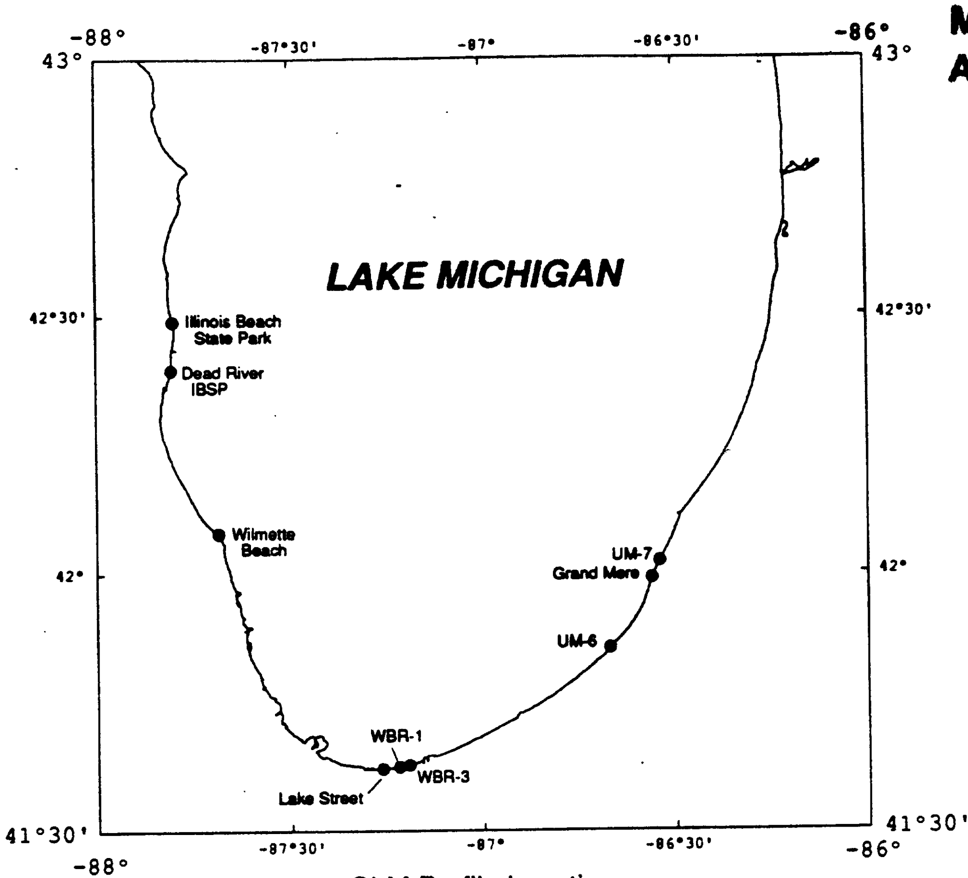


Figure 1. SLM Profile Locations

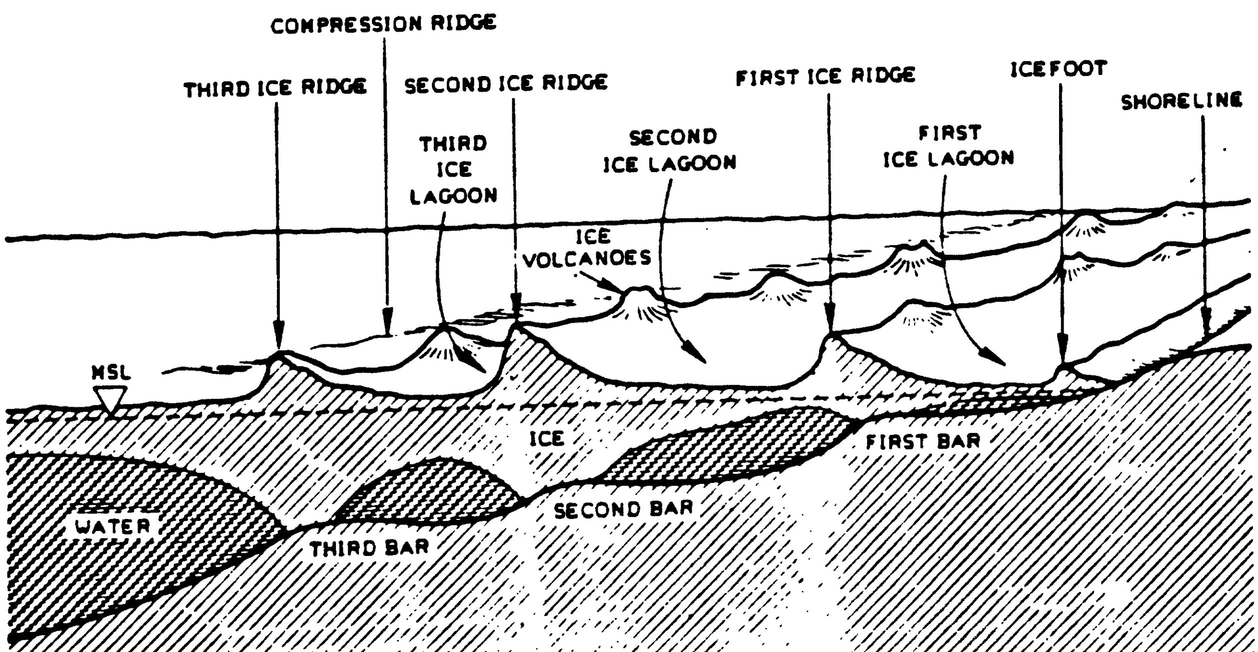
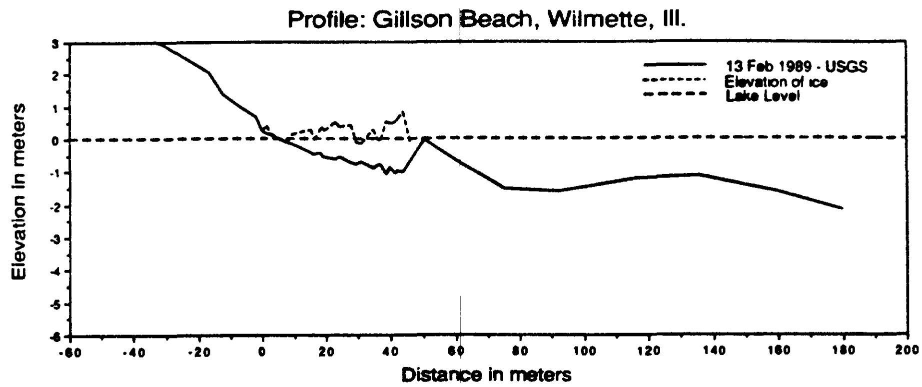
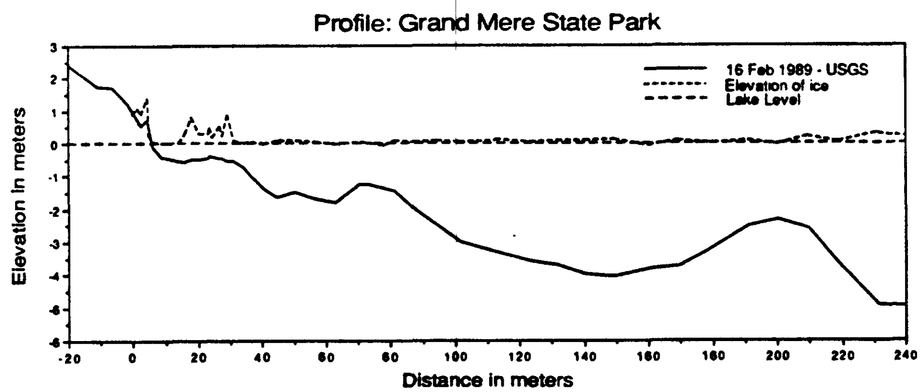
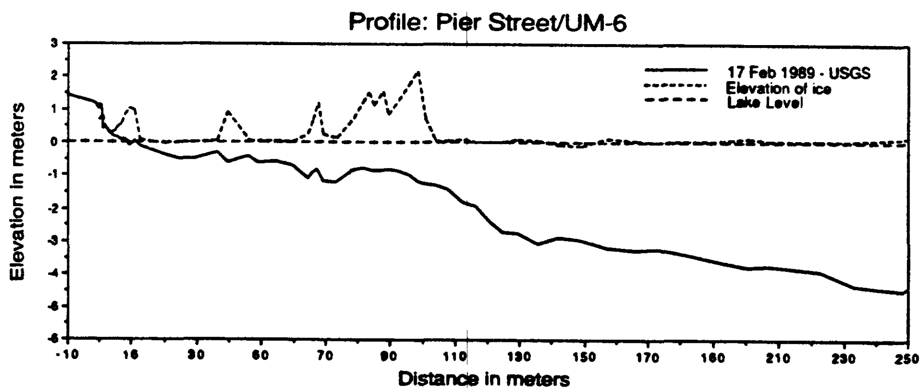


Figure 2. Coastal Ice Zonation (after Seibel, 1986)







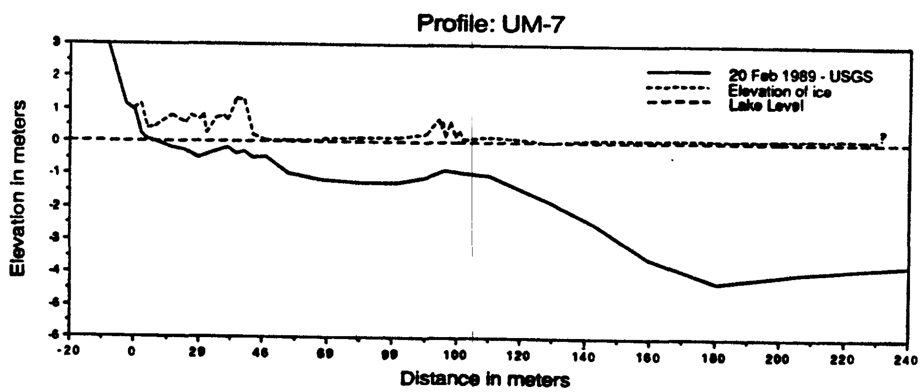
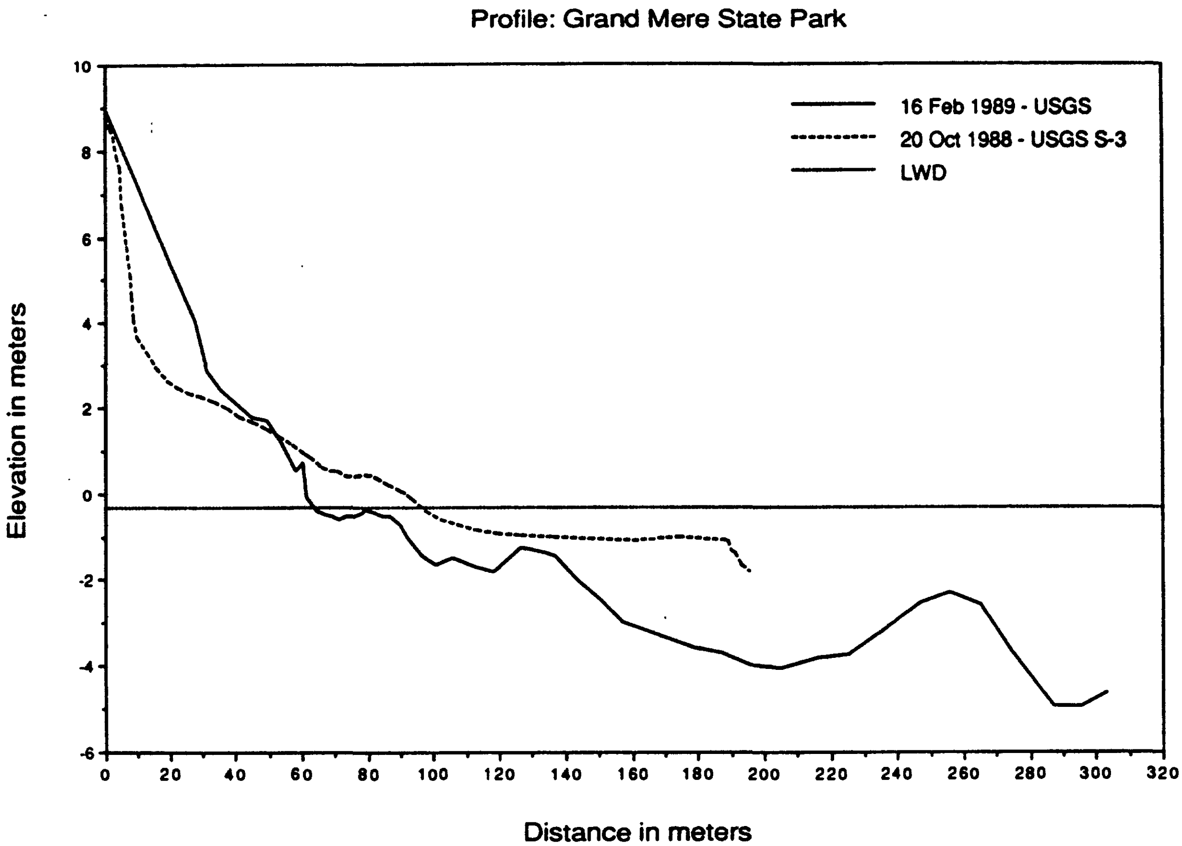


Figure 3. February 1989 coastal profiles and ice profiles. Locations on Figure 1.



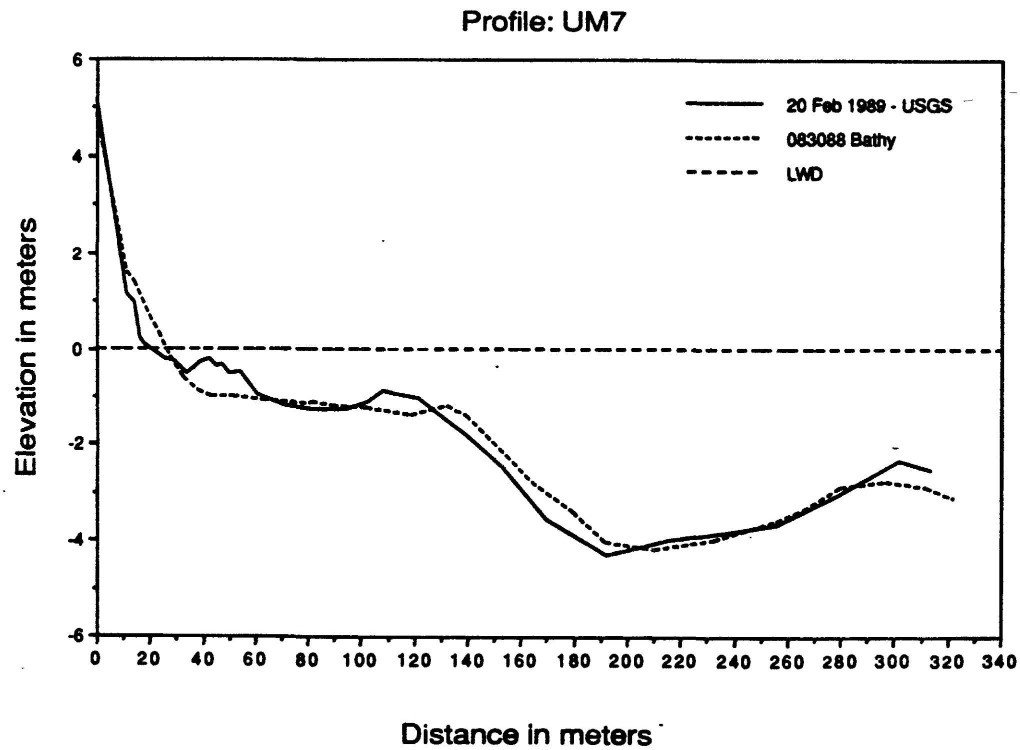


Figure 4. Comparative profiles, fall - winter (1988,89). Profile locations on Figure 1.

Table 2. Volume and sediment content of southern Lake Michigan Coastal Ice

	Ice foot		Ridges and Trough		Adjacent Ice	
	Width	Thickness	Width	Thickness	Width(>)	Thickness
Wilmette	12	0.1	40	1	0	0
Lake Street	14	0.1	50	0.6	20	0.4
WBR-1	0	0	38	0.3	20	0.5
WBR-3	5	0.2	15	0.4	50	0.5
UM-6 Pier Street	12	0.4	91	1	260	0.3
Grand Mere	6	0.2	25	0.5	220	0.3
UM-7 Chalet	7	0.5	35	0.7	260	0.4
Average	8	0.21	42	0.64	118.57	0.34
Vol/m of coast	1.71		27.0		>40.7	
Sed. content (g/l)	39.2		9.8		0.71	
Sed. cntnt (g/m of coast)	67.2		263.8		>28.9	
TOTAL (gm of coast)	359.9					
Tons/km	0.36					

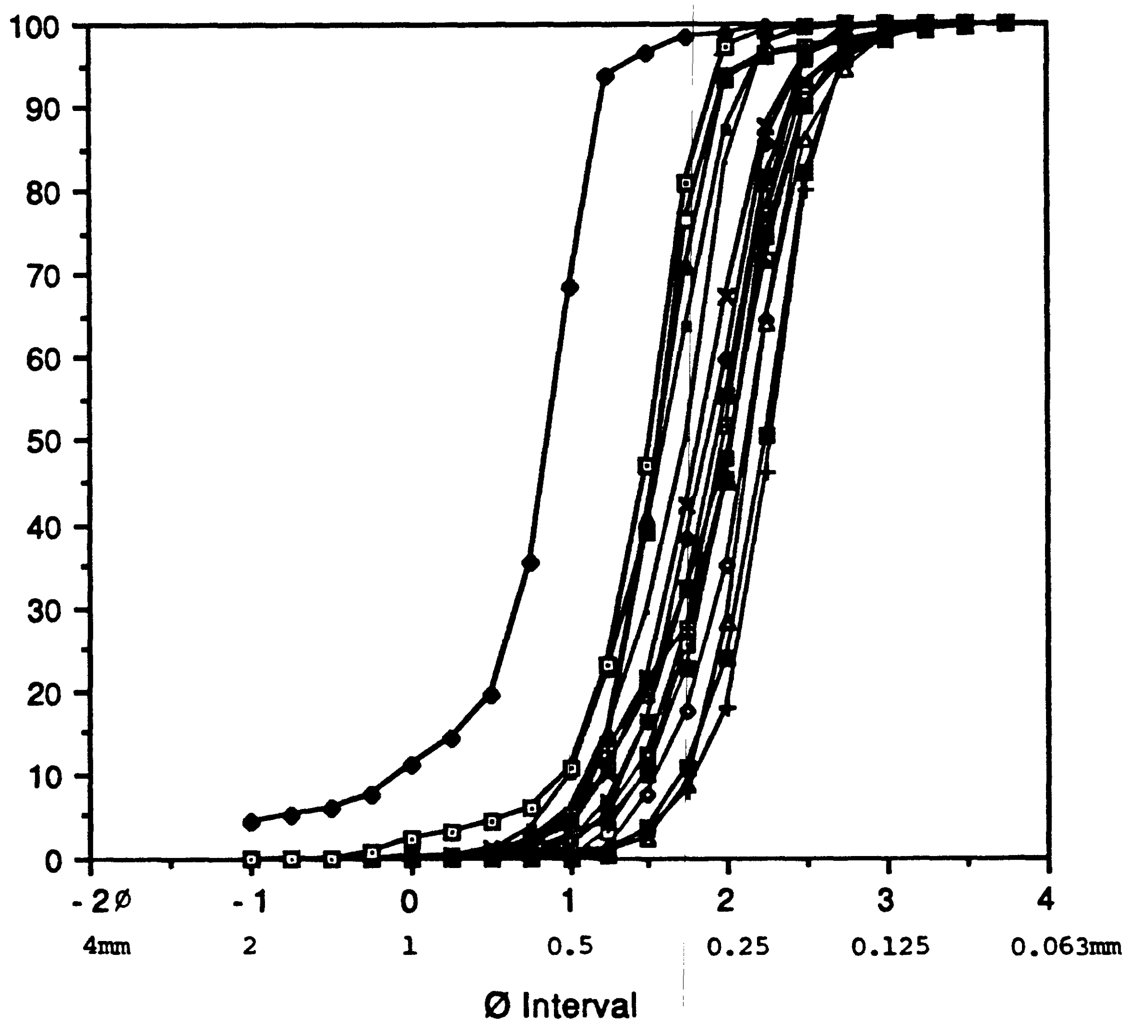


Figure 5. Cumulative percent size distributions of sediment entrained in lake ice, February, 1989.

NEARSHORE ZONE OF LAKE MICHIGAN NORTH OF FORT SHERIDAN, ILLINOIS: PRELIMINARY RESULTS OF BATHYMETRIC AND GRAIN SIZE DISTRIBUTION SURVEYS

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The 1 km length of lake front immediately north of Fort Sheridan, Illinois is typical of the Lake Michigan shoreline environment: it is constantly subjected to fluctuations in lake level, attacks by winter storm waves, ice action, and other dynamic processes or agents. Paradoxically, as shown on maps produced by the Illinois State Geological Survey, the area contains both a zone of rapid bluff retreat (southern section) and an adjacent zone that has shown little or no change in shoreline position during the past century (northern section). As a part of the southern Lake Michigan Program of the U. S. Geological Survey, the nearshore zone off this stretch of lake front is being investigated to ascertain possible relationships between lake bed characteristics and the observed differences in the rate of shoreline retreat.

The initial field work was of reconnaissance nature: a recording fathometer, a small grab sampler, and Loran navigation were used to conduct a general survey of a corridor approximately 0.8 km wide (shore-parallel) by up to 8 km long (shore-normal) (Figure 1 shows approximate positions of tracklines). Spacing between lines extending offshore was about 80 m. During the sampling phase of the field work, 32 stations were occupied; 28 samples were recovered. Sampling was not attempted in depths greater than about 6 m. All samples were described on board the research vessel (the R/V Chippewa). Grain size analyses of the coarse fraction are being conducted in the laboratory using sieves and a rapid sediment analyzer (settling tube). Fine-grained sediment (till?) will be analyzed with a coulter counter.

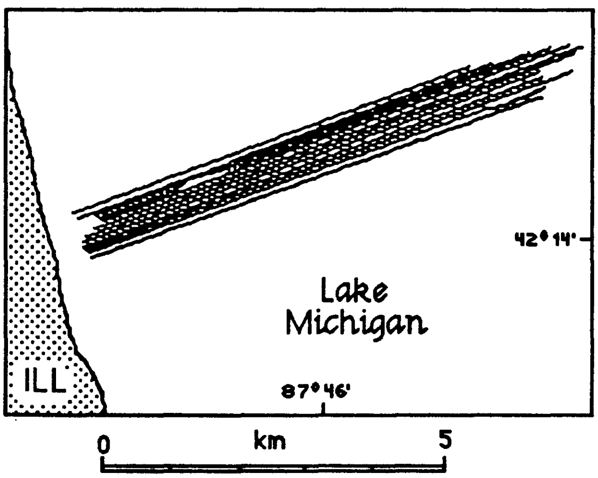


Fig. 1— Tracklines of bathymetric survey

Results of the bathymetric survey show that the lake floor is morphologically complex. Specifically, a representative profile (refer to Figure 2) would contain the following features or characteristics: (a) one or two broad bars (?) of low relief lakeward of the foreshore zone, then (b) a zone of rough terrain characterized by narrow ridges and troughs having about or less than 1 meter of relief, and (c) another mound or terrace-like feature in about 7–8 m of water. Farther offshore, a second zone of rough terrain of about 1 m relief (d) is present, then, starting approximately 2 km offshore (in depths of 8–12 m) , a 2-km-wide zone of hummocky terrain is present. This zone is often distinguished by twin ridges (e) that rise

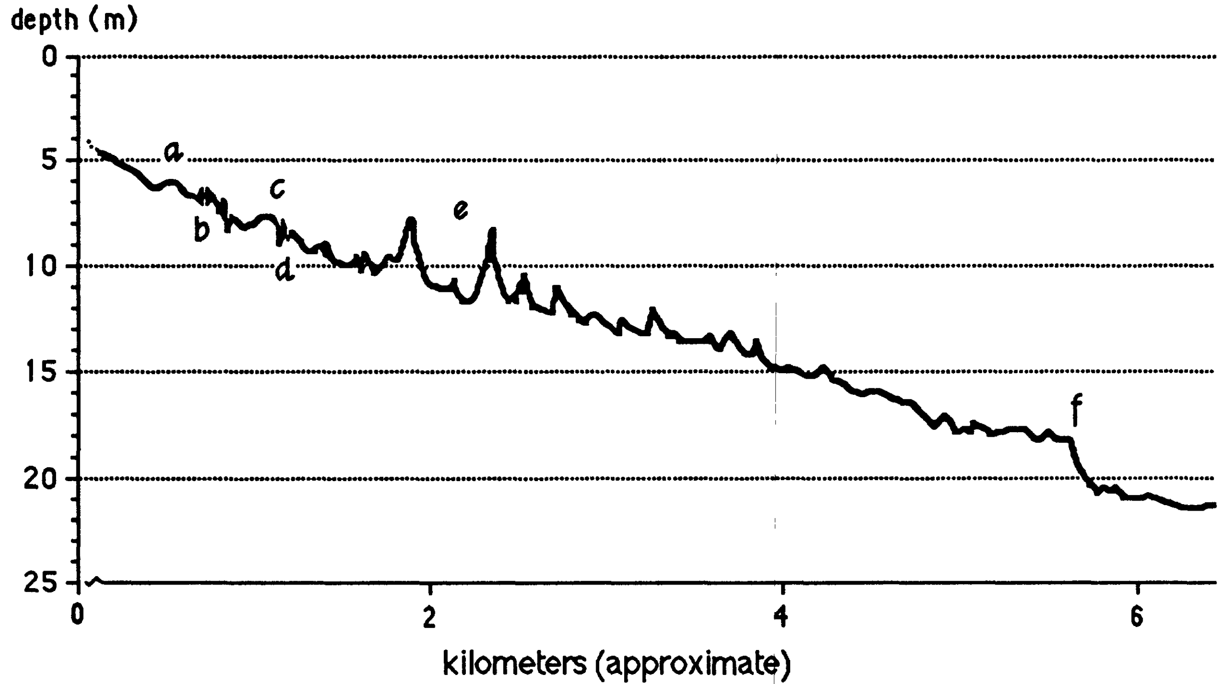


Fig. 2—Representative shore-normal bathymetric profile of Lake Michigan nearshore zone immediately north of Fort Sheridan, Illinois

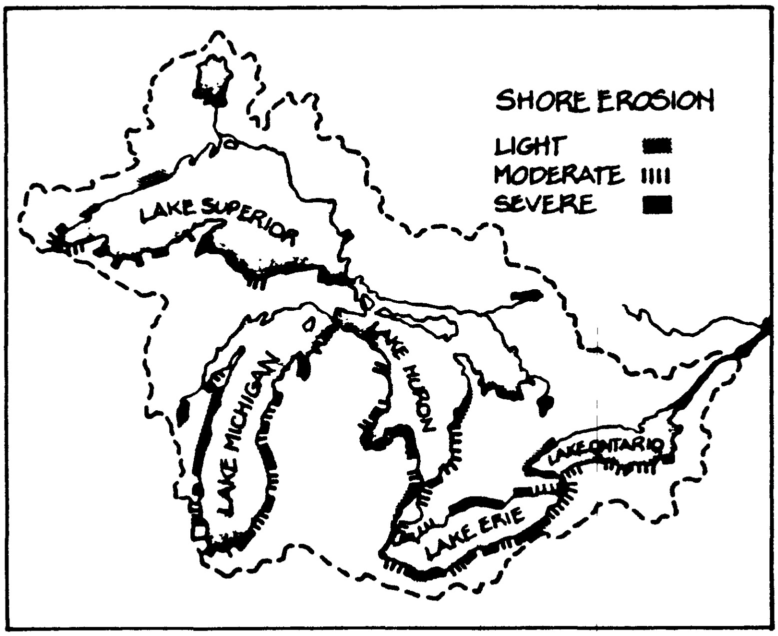
often distinguished by twin ridges (e) that rise up to 4 m above the surrounding lake floor and trend shore-parallel. The morphology becomes more subdued farther offshore, where, approximately 7 km from the shoreline, a ramp (f) separates the landward side of the profile from a deeper zone that extends toward the southern Lake Michigan basin.

There are apparent differences in the shallow water morphologies of the northern and southern sections of lake floor. For example, in about 7 m of water, rough terrain in the northern section gradually changes to smooth or mounded terrain in the southern section. In addition, Work in progress is examining other zones of micro-relief and the possibility that differences in foreshore slope angles exist. The effects of engineering structures, summer-winter beach cycles, and changes in lake level are also being considered.

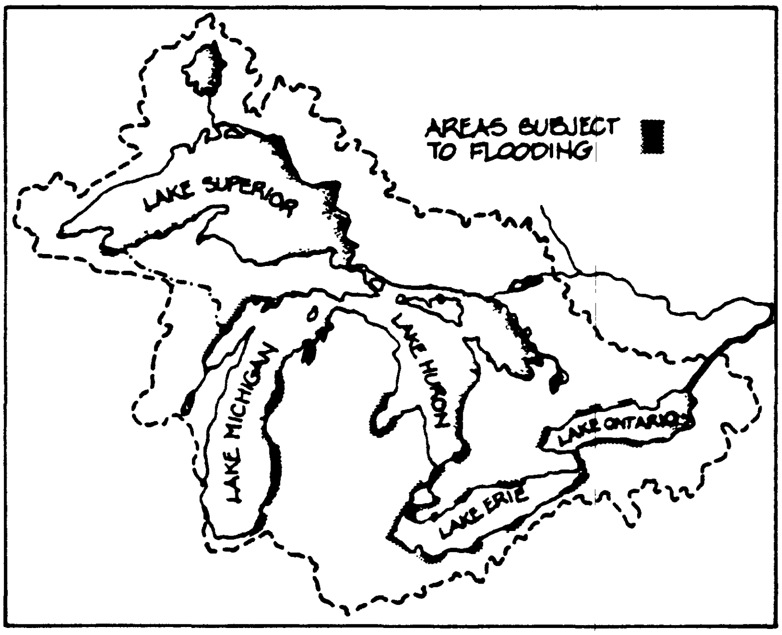
The shallow water sediments are typically fine to very fine sands. Gravel and hard clay are also present. Distribution of sediment types is patchy, but a "hard bottom" tends to be more prevalent in the southern section. A general trend toward a hard clay lake bed in deeper water (> 6 m) seems to be present: the presence of sand, at least in appreciable quantities, appears to be restricted to shallower depths. Whole shells and shell fragments were identified in many samples and sand-sized ash particles were present in most samples.

In addition to detailed analyses and descriptions of the bathymetry and grain size distribution, wave rays typically associated with winter storms will be plotted to analyze wave energy distribution at the shoreline at representative lake levels. Future work will focus directly on possible wave—lake bed relationships. The nearshore zone off Illinois Beach State Park is composed of sand to a depth of 10-15 m. A previous survey

(Graf, 1976) exists for bathymetry and grain size distribution comparisons, and in situ density determinations, in situ cone penetrometer measurements, and core data coupled with new bathymetric and textural information will provide a basis for examining possible process-response relationships between wave-induced bottom currents and the lake floor sediments.



GREAT LAKES SHORELINE SUSCEPTIBLE TO EROSION



GREAT LAKES SHORELINE SUSCEPTIBLE TO FLOODING

LATE WISCONSINAN AND HOLOCENE LITTORAL DRIFT PATTERNS IN SOUTHERN LAKE MICHIGAN

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Introduction

The purpose of this study is to summarize the late Wisconsinan and Holocene littoral-drift patterns and coastal evolution in southern Lake Michigan. This is a new synthesis of existing data since previous discussions of lake-level history and lake-margin deposits have not necessarily focused on coastal processes. The data base for this study consists of historical topographic maps, surficial geologic maps, and early aerial photographs. The littoral-drift patterns are interpreted based on the geomorphic indicators of net drift-direction summarized by Hunter and others (1979) and Jacobsen and Schwartz (1981). This is part of a continuing study to summarize past and present littoral-drift processes in southern Lake Michigan.

Background

During each of a series of successively lower lake-level maxima between 14,000 and 4,000 YBP, an embayment of the ancestral Lake Michigan formed in the present area of Chicago and northwestern Indiana. The western end of the embayment led to the Chicago Outlet where lake water drained into the Mississippi River system. This Chicago Outlet embayment isolated littoral drift from the western and eastern lakeshores. Drift from these two shores terminated in spits built into the north and south sides of the embayment as shown in Figure 1. Fetch and shoreline orientation were favorable for northerly waves to produce southerly drift along the western lakeshore, and northeast to southwest drift along the southern lakeshore. Sediment supplies to the Glenwood, Calumet and early Toleston beaches of the southern lakeshore were primarily derived from erosion along the eastern shore of the lake (Chrzastowski, 1989).

With successively lower lake-level maxima the position of spits and drift-aligned beaches translated lakeward and to lower elevation on the gently sloping former lake bottom. During late Nipissing Phase (approx. 4,000 YBP), lake level at about 180.5 m reduced the Chicago Outlet embayment to a small area straddling the Illinois-Indiana state line (Fig. 1 D). Continued lake level decline brought the lake below the 180 m sill elevation of the Chicago Outlet (Hansel and others, 1985). Lake flow toward the outlet was then eliminated, and drift along the western lakeshore resulted in a lakeward succession of baymouth barriers and barrier spits that reached the southern lakeshore. The plan-view configuration of the remnants of these barriers is recorded on surficial geologic maps of the southern Chicago lakeshore prepared by Bretz (1943a, b) (Fig. 2).

Figure 3 identifies several of the coastal geographic features related to the evolution of the southern lakeshore during the past 3,000-4,000 years. Lake Calumet and Wolf Lake are apparently the remnants of lagoons formed behind baymouth barriers and barrier spits that built to the south and southeast. As additional beach accretion occurred along this southwestern corner of the lake, the result was a complete reversal in net drift direction along the western Indiana lakeshore. This drift reversal is recorded in the geomorphology of the series of more than 150 beach ridges across this area as shown on early aerial photographs. Recurves at the eastern ends of these ridges document the southeasterly transport direction (T. Thompson, Indiana Geological Survey, pers. commun.). This reversal is also prominently recorded in the stream pattern of the Little and Grand Calumet Rivers. The Little Calumet River originates in north central Indiana about 14 km south of Michigan City. The river mouth was deflected westward by growth of the Toleston beaches and spits. When these beaches and spits reached their maximum westward extent the Little Calumet River entered the south end of the Chicago Outlet embayment about 6.4 km west of present Lake Calumet. Lowered lake level, combined with spit and beach ridge development from littoral drift of the western lakeshore, eventually deflected the stream mouth eastward. East of the divergence of the Calumet River, this eastward-flowing reach is called the Little Calumet/Grand Calumet River. Over the past 3,000-4,000 years the outlet of the Grand Calumet River into Lake Michigan was deflected approximately 34 km eastward to its present position in east Gary, Indiana (Fig. 2).

Conclusions

This study provides at least three perspectives on littoral-drift processes along the south lakeshore.

1. Within rather well-defined limits, it is possible to define the zone of net convergence of littoral drift that existed along the southern lakeshore prior to urban devlopment. Historical maps of the Michigan City vicinity indicate a prominent westward deflection of Trail Creek, and thus net littoral transport was westward at this point of the Indiana shore. The stream-mouth deflection of the Grand Calumet River documents net littoral transport in an eastward direction for the shore to the west of the stream mouth. Thus the zone of net convergence of littoral drift along the south shore was the approximate 31.5 km reach between the mouths of the Grand Calumet River and Trail Creek.

2. During the past 3,000 to 4,000 years, two distinct sediment sinks have existed along the south lakeshore. One was the area of beach-ridge accretion to the west of the eastern city limit of Gary, Indiana. This accretion represents a smoothing of the plan form of the shore across this area of former shoreline embayment. The source of littoral sediments for this accretion area was primarily from the western lakeshore. The other sink was the Indiana Dunes lakeshore area, which corresponded to the zone of drift convergence. The sediment sink at Indiana Dunes emphasizes the importance of the beach-to-dune transport process in the analysis of sediment budgets along this coast. Nearly all littoral sediment supplied to this shore is medium sand or finer, a size range susceptible to local aeolian transport. Landward transport into the dunes explains why this drift convergence is not marked by progradational features such as one or more cuspate forelands or cuspate spits.

3. During the past 3,000-4,000 years, the 6- to 10-m depth bathymetric high known as Indiana Shoals has not been related to any convergence and offshore deflection of littoral drift, nor have these shoals apparently been of any consequence to regional drift patterns. During this time the littoral drift terminated south and east of the Indiana Shoals. The shoal area would be significant to littoral transport processes at lake levels lower than present. At lake levels 6- to 10-m lower than present the shoal area likely corresponded to the net-drift convergence on the south lakeshore.

Acknowledgments

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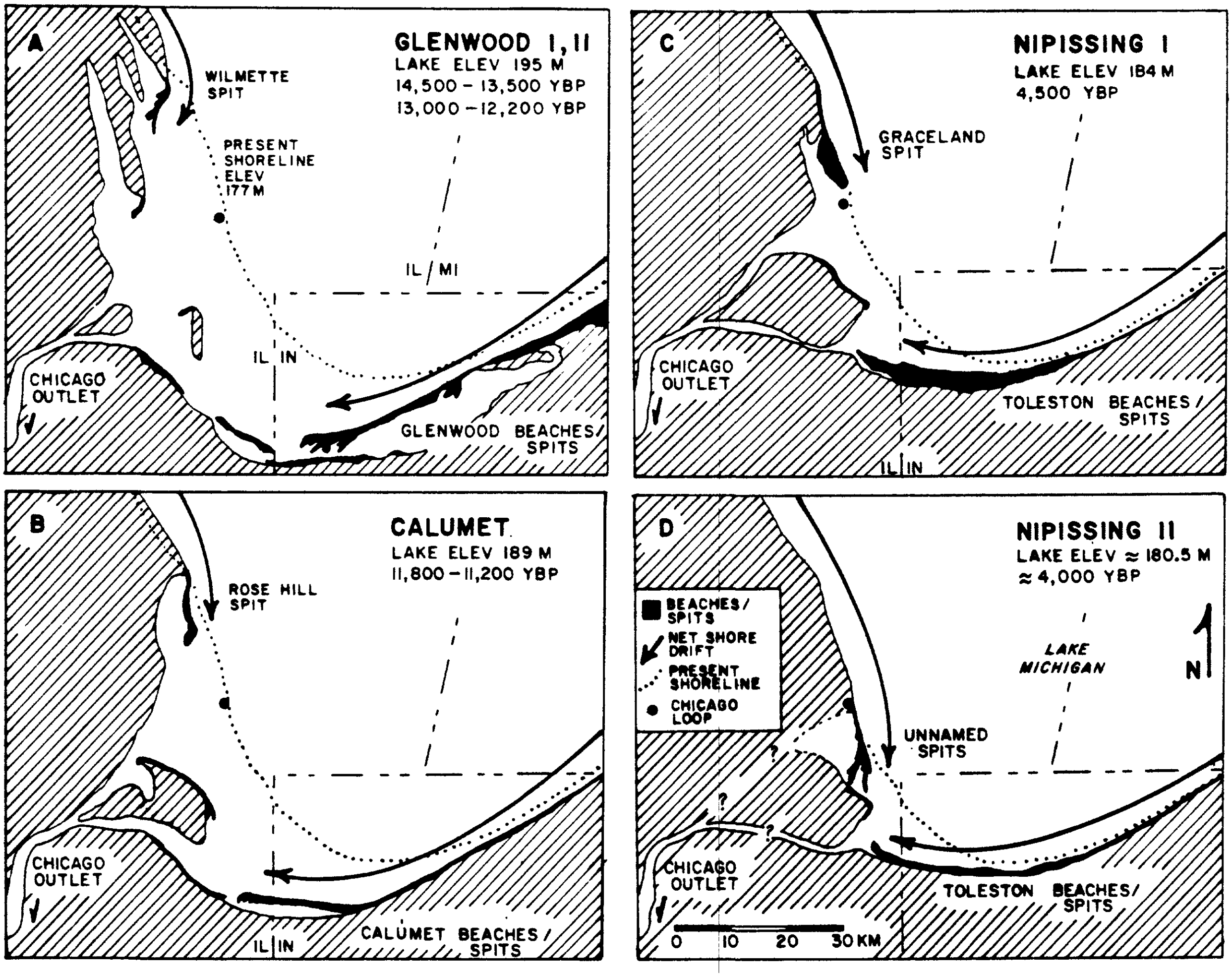

Figure 1. Coastal paleogeography and net littoral drift patterns of southern Lake Michigan during peak lake levels of high lake phases between 14,500 YBP and about 4,000 YBP (after Hansel and others, 1985; Schneider and Keller, 1970; Alden, 1902).

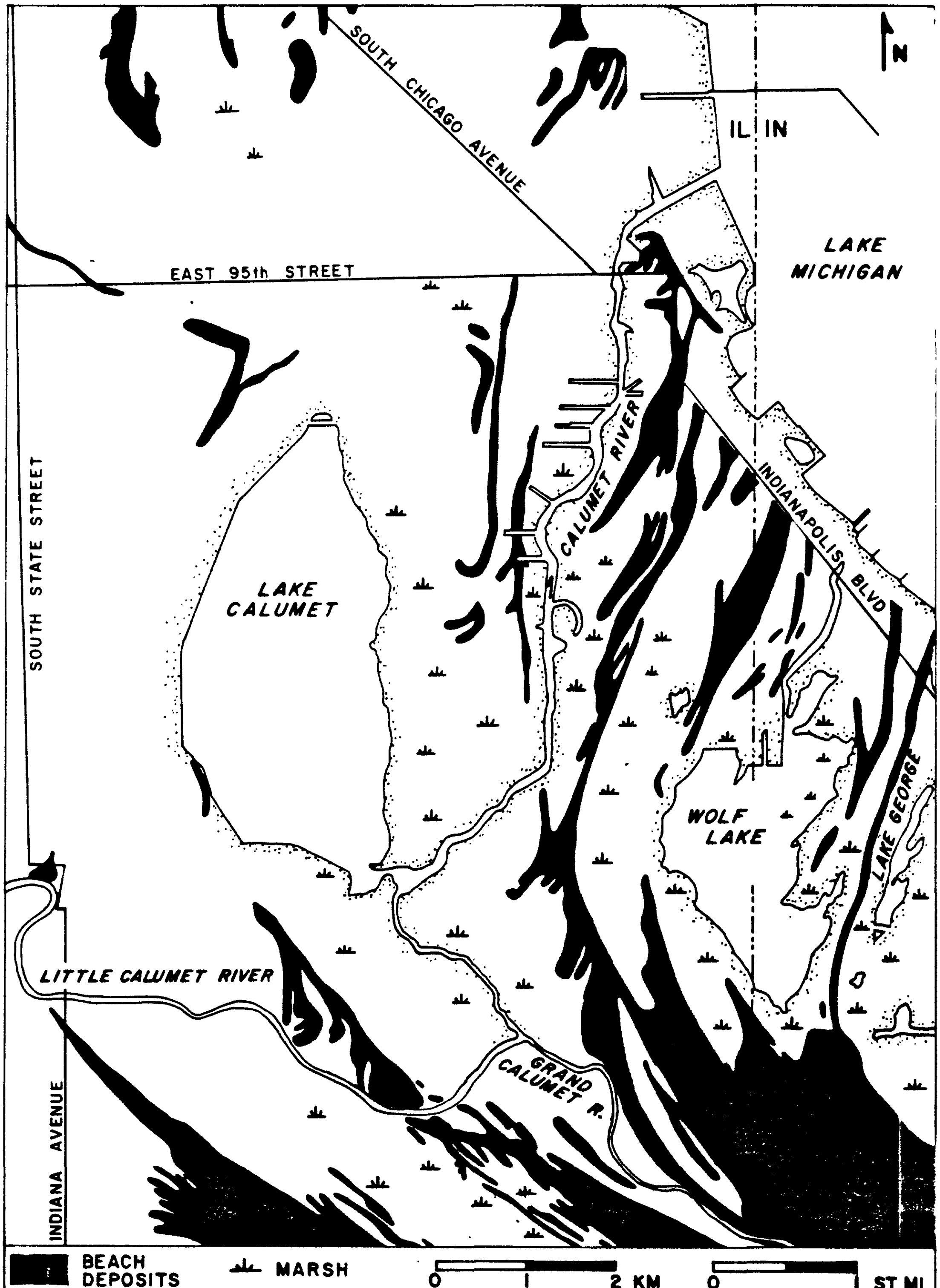

Figure 2. Map showing surficial remnants of barrier spits, baymouth barriers and beach ridges in the Lake Calumet and Wolf Lake vicinity as mapped in 1930-1932 by Bretz (1943b).

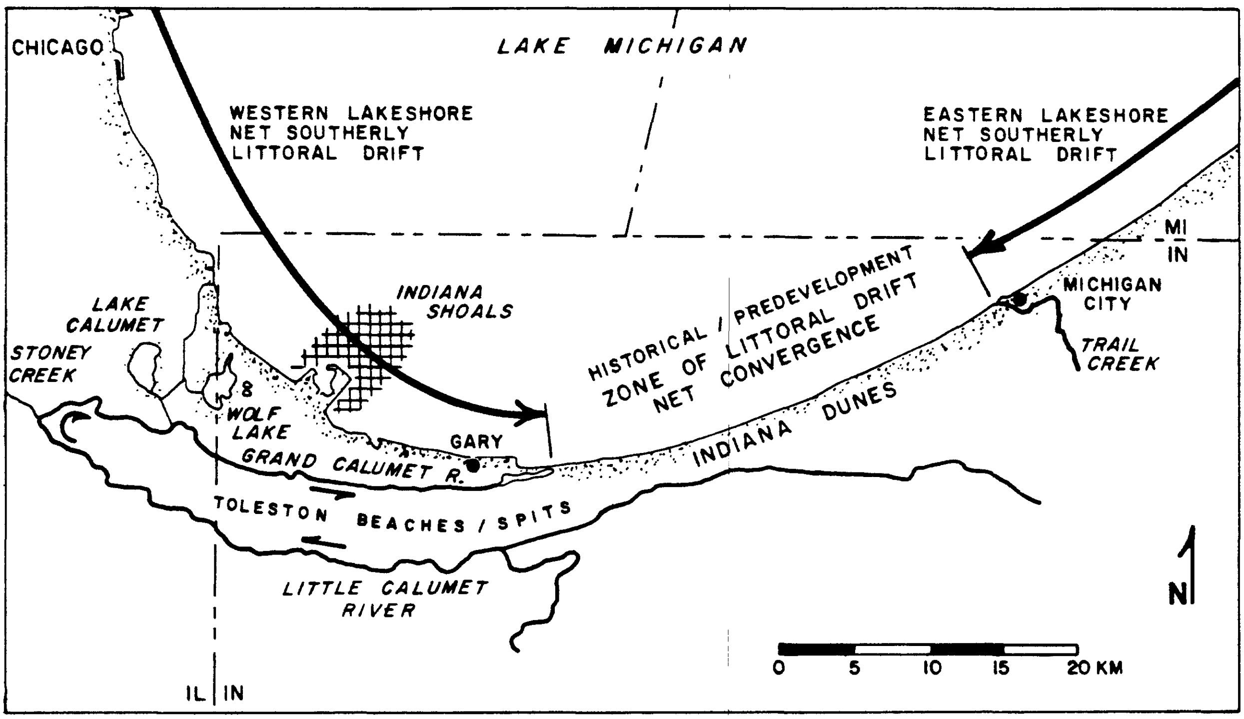

Figure 3. Select coastal-geographic features of the southern lakeshore related to the littoral drift history over the past 3,000-4,000 years.

ESTIMATE OF THE NATURAL-STATE LITTORAL TRANSPORT ALONG THE CHICAGO LAKESHORE

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Introduction

One of the consequences of urban development along the Illinois shore of Lake Michigan has been the gradual depletion of sand in the littoral sediment stream. The principal cause has been construction of shore defenses which limited or locally eliminated sediment supply derived from bluff and beach erosion. In addition, lakefills and shore-normal structures formed drift barriers that caused deflection of sediment offshore and subsequent downdrift starvation. In any effort to quantify historical littoral-sediment depletion rate, an important baseline reference is the transport rate prior to shore development. The purpose of this study was to estimate that natural-state littoral transport along the Chicago lakeshore. The method was to compute the volume of beach accretion against timber and quarry-stone jetties started in 1833 and 1834 at the mouth of the Chicago River. These were the first shore structures built along the Chicago lakeshore as well as the entire western shore of Lake Michigan. Construction was by the U.S. War Department for the purpose of forming a harbor along the lower reach of the Chicago River. The north jetty was an effective barrier to the net southerly littoral transport. Rapid updrift accretion, channel shoaling, and the need for several extensions of jetty length to halt bypass were continuing problems that led to frequent shoreline surveys by War Department Engineers.

Methods

Figure 1 shows the shoreline positions from 1834 through 1869 against the north (updrift) jetty, then called North Pier. The bends in North Pier correspond to pier extensions with different orientations. The waterworks breakwater and the basin were parts of a facility begun in 1852. The 1854 shoreline presumably documents the erosion that likely resulted from littoral sediment starvation south of the waterworks.

In this study the historical shorelines were digitized and area between successive shorelines was computed. Accretion thickness was based on an estimate of the depth of closure for this coastal setting. Depth of closure is dependent on local wave climate and is generally slightly more than twice the extreme annual significant wave height (Hallermeier, 1977, 1981, 1983; Hanson, 1989). Using 3 m as an extreme annual significant wave height (U.S. Army Corps of Engineers, 1953), the depth of closure estimate is 6 m. Historical profile comparisons along the Illinois shore generally support a 5.5 to 6 m closure depth (U.S. Army Corps of Engineers, 1953).

Figure 2 shows the model used in the volume calculations. Since the shoreline positions were not corrected to a common datum, a correction was made to adjust the map-view accretion area for differences in lake level between successive shorelines. The assumption is that if the lake level for the younger of two shorelines is higher, then some accretion area is submerged and needs to be added. Conversely, for a lower lake level, the accretion area in map view is exaggerated and an area correction needs to be subtracted.

A lake-level curve was derived for average summer (June-July-August) lake levels through the accretion history (Fig. 3). Since U. S. Lake Survey records do not predate 1860, this curve is primarily based on the pre-1860 lake-level observations made by several early settlers skilled in surveying techniques. These observations are summarized by Angell et al. (1897) and tabulated by Fisk (1904) as monthly average elevations above Mean Tide New York (MTNY).

A foreshore/upper shoreface slope of 1:20 was assumed, which is typical of present-day Chicago beaches (U.S. Army Corps of Engineers, 1953). The difference in shoreline lake levels between succesive shorelines (W) was multiplied by the 1:20 slope to give a width of shoreline translation (T) resulting from lake level difference (Table 1). This, multiplied by shoreline length (L), provides an area correction (Ac) to be added to or subtracted from the map area (Am). The accretion volume between successive shorelines was computed by

$$V=Dc(Am+Ac)$$

where: V=accretion volume; Dc=depth of closure; Am=map-view accretion area; and Ac=accretion area attributed to lake-level change. The sign of Ac is dependent on whether the younger shoreline corresponds to a lake level higher (+) or lower (-) than the older shoreline. The model ignores sediment accumulation in the dunes and berm.

Results and Discussion

Table 1 summarizes the computed annual-accretion volumes. Figure 4 compares a histogram of the accretion volumes and the derived lake-level curve. The histogram includes notation of significant events in the pier construction and beach accretion history.

Although the accretion record begins in 1833-34, construction history indicates that the pier had a rather short offshore extent, and considerable sediment bypass was likely. Therefore the 1833-34 accretion is dismissed for computing an annual transport rate. The 1852 start of construction on the waterworks affects the 1850-1854 accretion record, and in later years it is uncertain to what degree the waterworks facility restricted accretion at North Pier. Thus for this analysis the post-1850 record is dismissed.

The accretion record of interest is the 15-year record of 1835 to 1850. The histogram shows considerable variation in the accretion volumes during this 15-year period, but this variation can be explained by considering lake-level history and pier construction history. For example, an interval of peak accumulations between 1836 to 1839 initially corresponds to high lake levels and increased sediment supply from shore erosion, and pier extension which increased the pier-end depth and reduced the potential for bypass despite the 1838-39 falling lake level. Diminished accretion from 1839 to 1844 corresponds to low lake levels, possible reduced sediment input, and increased potential for sediment bypass of the pier end. A peak in the accretion record from 1844-45 corresponds to the final pier extension. The peak at 1849-50 is unrelated to a significant lake-level change or pier extension and possibly results from an excessive map-view accretion area due to the foreshore welding of a bar.

The accounting of accretion volume on a yearly basis is subject to over- or under-estimate, depending on whether shoreline surveys included or excluded emergent bars in the process of welding to the foreshore. However, the long-term yearly mean accretion should be relatively insensitive to these year-to-year variations.

The total beach-accretion volume from 1835 to 1850 is 1,142,000 m^3, which gives a 15-year mean accretion rate of 76,000 m^3/yr. This is an underestimated transport rate since some bypass occurred, as indicated by the history of channel-entrance shoaling and bar development south of the pier end. Apparently most of the bypassed sediment remained in an offshore bar and only a small volume migrated landward since shore erosion south of the river was extreme. Historical bathymetric surveys provide for an estimated shoal volume of 30,000 m^3 (Turnbull, 1844). Adding this to the accretion record, the estimated mean transport rate is 78,000 m^3/yr. Unaccounted bypass could raise this transport rate by one or more thousand m^3.

Since this accretion is against the first structures built along the Chicago lakeshore, 78,000 m^3/yr is an estimate of natural-state littoral transport. Because of the location near the southern extent of the western shore, the accretion corresponds to entrapment of the final flux of the littoral stream before reaching the drift terminus along the southern margin of the lake. The accretion record thus also provides an estimate of natural-state littoral transport from the western lakeshore to the drift terminus along the south lakeshore.

Conclusions

This estimate of a natural-state, littoral-transport rate will be revised as assumptions are refined in the volume calculation model. As a first approximation, however, a mean-annual transport rate of 78,000 m^3/yr is considered a reasonable estimate. This is less than the typical littoral transport rates of 100,000 to 250,000 m^3/yr along sandy ocean coasts (U.S. Army Corps of Engineers, 1984, pp. 4-91) and reflects the lower wave energy of this Great Lakes shoreline. It is likely that above-average frequency and intensity of storm events combined with high lake levels intermittently resulted in a robust littoral transport comparable to some ocean-coast settings.

Data summarizing present-day littoral transport along the Illinois shore are being compiled as part of this study. Preliminary comparisons suggest that on the northern-most Illinois lakeshore, along the southern half of Illinois Beach State Park, littoral transport may still be comparable to this computed natural rate. Elsewhere on the Illinois shore littoral transport is negligible or at most about half of this rate.

One of the applications of computing this drift accretion at North Pier is the study of sediment budgets and shore erosion along the Indiana lakeshore. Specifically, the 1834 start of drift entrapment at North Pier essentially marks the beginning of the end of littoral-sediment supply from the western lakeshore to the southern lakeshore. With time, increasing development of the western lakeshore resulted in a growing number of drift barriers and other shore defenses to halt erosion. Considering 156 years of interrupted transport (i.e., 1834-1990), and a transport rate of 78,000 m^3/yr, then the historical development of the Illinois lakeshore has potentially deprived the southern lakeshore of 12.2 million m^3 of littoral sediment. Much of this sediment likely never entered the littoral stream since it still resides in erosion-defended bluffs. Some of this sediment was trapped against drift barriers; some was possibly deflected offshore.

Table 1. North Pier shoreline accretion parameters and computed annual-accretion volumes.

Shoreline Accretion Interval	Mapped Accretion Area (Am) $m^2 \times 10^2$	Shoreline Length (L) $m \times 10^2$	Difference in Shoreline Lake Levels (W) m[1]	Lake Level Shoreline Translation (T) m[2]	Accretion Area Correction (Ac) Ac = LxT $m^2 \times 10^2$	Annual Accretion Volume (V) V = Dc(Am + Ac) m^3/yr[3]
1834-35	28.5	1.7	+0.04	+ 0.8	+ 1.4	18,000
1835-36	65.0	2.6	+0.04	+ 0.8	+ 2.1	40,000
1836-37	338.5[4]	11.2	+0.12	+ 2.4	+ 27.1	219,000[4]
1837-38	220.0	5.7	+0.18	+ 3.6	+ 20.5	144,000
1838-39	200.1	6.3	-0.41	- 8.2	- 51.7	89,000
1839-43	285.1	11.6	-0.55	-11.0	-127.6	24,000*(95,000)
1843-44	79.7	6.1	-0.03	- 0.6	- 3.7	46,000
1844-45	175.5	9.5	-0.04	- 0.8	- 7.6	101,000
1845-49	383.8	12.2	-0.20	- 4.0	- 48.8	50,000*(210,000)
1849-50	295.6	9.1	+0.27	+ 5.4	+ 49.1	207,000
1850-54	86.5	9.8	+0.20	+ 4.0	+ 39.2	19,000*(75,000)
1854-62	260.8	9.4	+0.22	+ 4.4	+ 41.4	23,000*(81,000)
1862-64	64.0	4.6	-0.22	- 4.4	- 20.2	13,000*(26,000)
1864-65	68.5	5.5	-0.12	- 2.4	- 13.2	33,000
1865-68	137.9	10.2	-0.13	- 2.6	- 26.5	22,000*(67,000)
1868-69	76.1	10.1	+0.02	+ 0.4	+ 4.0	48,000

[1]Positive sign indicates lake level of younger shoreline is higher (lake-level rise); negative sign indicates lake level of younger shoreline is lower (lake-level fall).

[2]Lake level shoreline translation (T) equals difference in lake levels between successive shoreline surveys (W) multiplied by 1:20 slope (i.e., Wx20).

[3]Annual accretion volumes to nearest thousand m^3. Value of Dc (Depth of Closure) equals 6 m. Asterisks indicate that the annual accretion volume is an average over two or more years. Volume in parenthesis is the total for the years spanned.

[4]Accretion area and volume for the interval 1836-37 is based on the more lakeward of the two shorelines recorded for 1837.

Acknowledgments

Special appreciation is extended to Keith Ryder of the U.S. Army Corps of Engineers, Chicago District Office, who graciously assisted in providing copies of that agency's historical maps and surveys. Paul D. Terpstra of the Illinois State Geological Survey digitized the shorelines and calculated areas. This paper is a contribution to the International Geological Correlation Programme (IGCP) Project 274, Coastal Evolution in the Quaternary.

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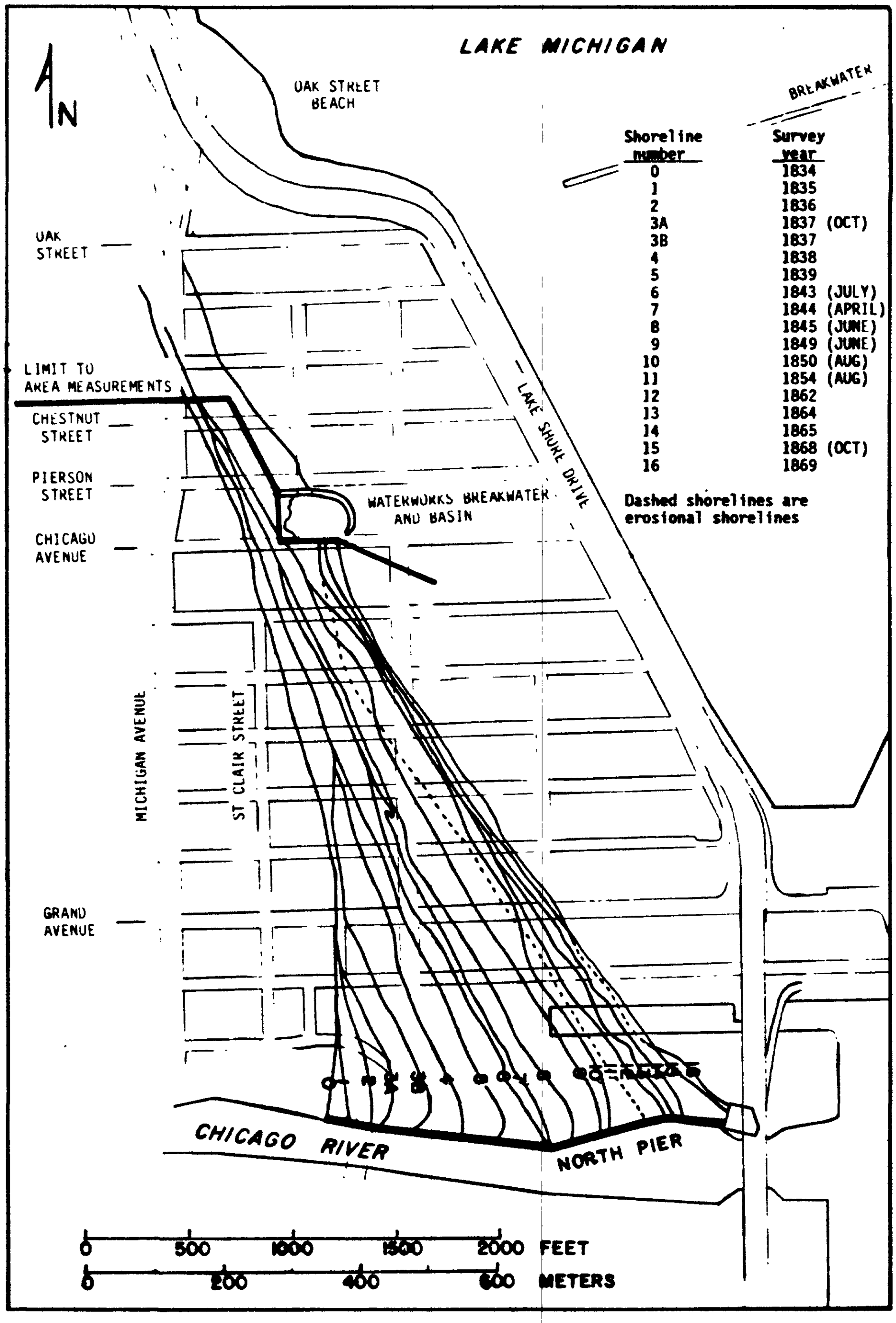

Figure 1. North Pier accretion shorelines superimposed on the present-day street grid (historical shorelines from Lipencrantz, 1876).

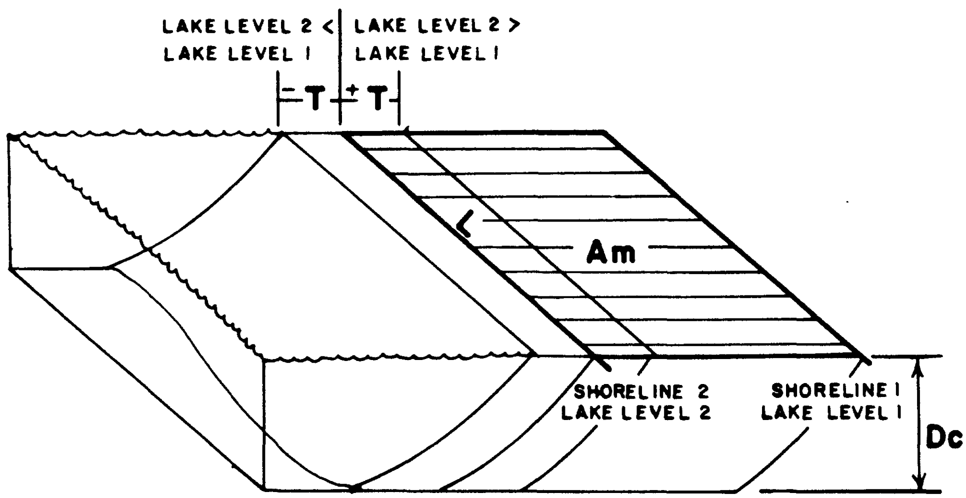

Figure 2. Model for the accretion volume calculation.

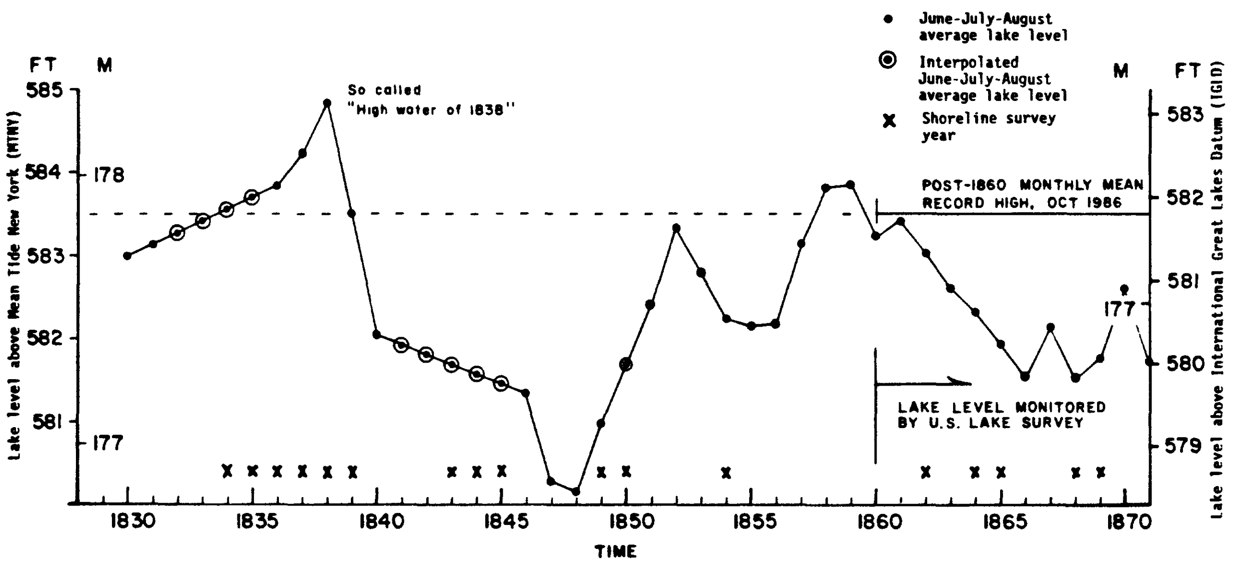

Figure 3. A derived lake-level curve encompassing the North Pier accretion history. The yearly lake levels are the mean of monthly means for the three month period June-July-August for years with data for at least one of these months (after Fisk, 1904).

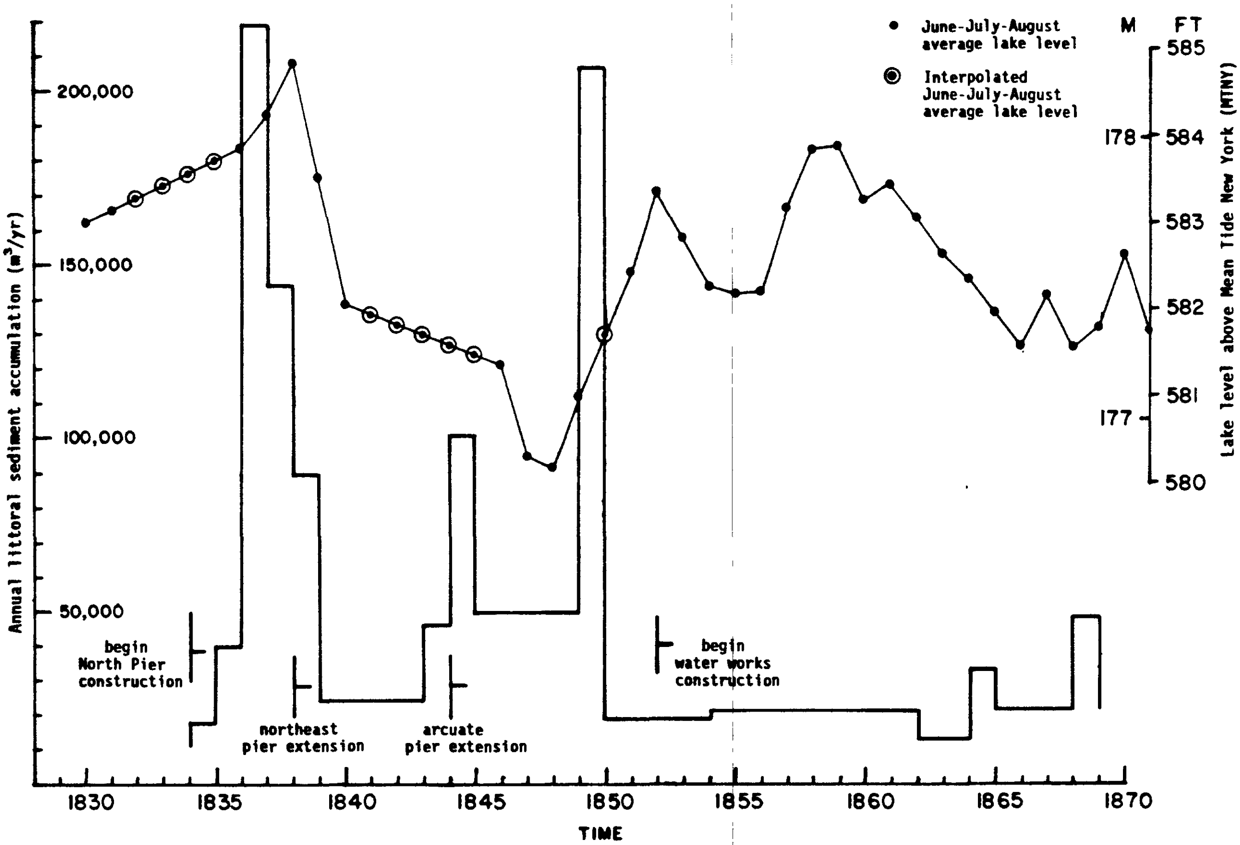

Figure 4. Histogram of annual littoral sediment accretion volumes (from Table 1) compared to the mean summer lake-level curve (from Figure 3).

1989 SHORE EROSION AND RAPID DEVELOPMENT OF LOGARITHMIC-SPIRAL RECESSION AT NORTH POINT MARINA, LAKE COUNTY, ILLINOIS

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Introduction

Since 1988 the Illinois State Geological Survey (ISGS) has conducted a monitoring program to document bathymetric and beach changes associated with the construction of North Point Marina (Chrzastowski and Riggs, 1989; Chrzastowski and Terpstra, 1990). During 1989 the most severe erosion on the Illinois Lake Michigan shore occurred in undefended lakefill at the marina facility. During a nine-month period, maximum shoreline recession was approximately 61 m. This erosion resulted in emergency construction of shore defense to protect a parking lot, access roads and a restroom/shower facility. Erosion monitoring documented the rapid development of a logarithmic-spiral shoreline, and provides a case history of the potential rapid rate at which undefended gravelly sand lakefill can be eroded elsewhere on the Illinois shore.

Background

North Point Marina is a state-owned, 1500-slip marina located at the Illinois-Wisconsin state line in the North Unit of Illinois Beach State Park. The marina basin straddles the preconstruction shoreline, with a pair of arcuate, shore-attached, rubble-mound breakwaters forming the lakeward side of the basin. During 1988, an estimated 1.2 million m^3 of gravelly sand was dredged from the marina basin and discharged on the south (downdrift) side of the marina, creating a fan-delta extending as much as 200 m lakeward of the preconstruction shoreline. In June 1988 the shoreface slope at the delta was as steep as 1:10.

In the marina design phase, the dredge discharge was intended to be a sand reservoir and feeder beach for long-term nourishment to the downdrift, state-park beaches (Moffat and Nichol Engineers, 1986). However, site development required a land-use design change, resulting in the crest of the dredge spoil being graded 3.6 to 5 m above mean lake level so that parking facilities, access roads and a restroom/shower could be built atop the landward half of this sand body.

In January 1989, excess stone from the breakwater construction and on-site rock debris were placed as riprap along the northern half of the fan-delta shoreline. This stone was placed at water line with filter cloth beneath but not behind it. No stone was placed as toe protection. The riprap terminated opposite the midpoint of the proposed parking facility. Construction of the parking lot and associated facilities began in spring 1989.

Erosion Monitoring

Shoreline recession began adjacent to the south end of the riprap soon after the January stone emplacement. Observations by the ISGS on February 22 and May 1 indicated that the shoreline and a 1- to 2-m scarp were already being modified into a logarithmic-spiral plan form as a response to the prevailing and predominant waves from the northeast quadrant and wave refraction around the riprap terminus. On June 27 detailed monitoring began and continued once a week on average until October 19 when shore defense was first added. For a distance of 150 m south of the riprap terminus, east-west measurements were made at 15 m (50 ft) intervals from a north-south baseline to the edge of the receding scarp. Recession into higher elevations of the fan-delta eventually resulted in a scarp up to 4.5 m high.

Figure 1 shows a partial record of 1989 scarp positions. Figure 2 is an aerial view of scarp position on August 25. Measurements between June 27 and October 19 indicate that mean scarp recession rates ranged from 2 m/mo near the riprap terminus to 17 m/mo 150 m south. During extreme high wave events (wave height 2 to 3 m) maximum scarp recession was 40 cm/hr. Between late January and October 19 the maximum recession was approximately 61 m. Estimated above-water erosion in the monitoring area was 34,000 m^3. Some eroded sediment moved offshore to adjust the lower shoreface profile, while most was transported southward to form a prominent nearshore bar.

In letters dated July 27 and August 1, the ISGS notified the appropriate state officials and engineers of the rates of change and the potential short-term implications. It was suggested that the projection of an equilibrium logarithmic-spiral shoreline (Yasso, 1965) could reach into the eastern half of the parking lot (Fig. 1), and that the recession rates suggested that the more lakeward access road could be intercepted by year's end.

Monitoring the position of twelve riprap boulders during the period August through October shifting and settling of these stones as they were undermined by shoreface erosion. Four of the twelve boulders were lost. Of the eight remaining boulders, the maximum measured elevation change was -1.3 m. Comparison of ground photographs shows that many boulders settled more than those that were monitored. Beginning in late October enough shifting and settling of stone had occurred to allow wave overtopping and erosion landward of the riprap.

Remedial Action

On August 15 an emergency meeting at the site was attended by state officials and engineering consultants to consider options for defending the parking lot and the shore segment with shifting and settling riprap. The project engineers agreed on a line 21.3 m (70 ft) lakeward of the access roads along which a concrete-cube revetment would be built (Fig. 3). Erosion was allowed to continue to this line to provide sand for downdrift nourishment as well as to remove much of the fill which would otherwise need to be excavated to build the revetment. The ISGS monitored this erosion. On October 10, ISGS notified the project engineers that the scarp had receded to within 23 m of the access road drainage ditch. A storm on October 19 required emergency dumping of riprap to halt extreme erosion opposite the access road turn-around. Construction of the cube revetment began on November 1 and was completed by November 12. The available funds of $250,000 were sufficient to build a revetment from the south side of the parking facility to within 125 m of the south breakwater. Construction to the south breakwater will be finished in 1990; the riprap will then be removed, and fill between the riprap shoreline and cube revetment will be allowed to erode for downdrift nourishment.

Continued Monitoring

Monitoring of beach and nearshore changes at the marina will continue through 1990. The principal concern is the anticipated erosion south of the cube revetment, and changes to the shoreface profile lakeward of the revetment that may affect stability of the toe stone.

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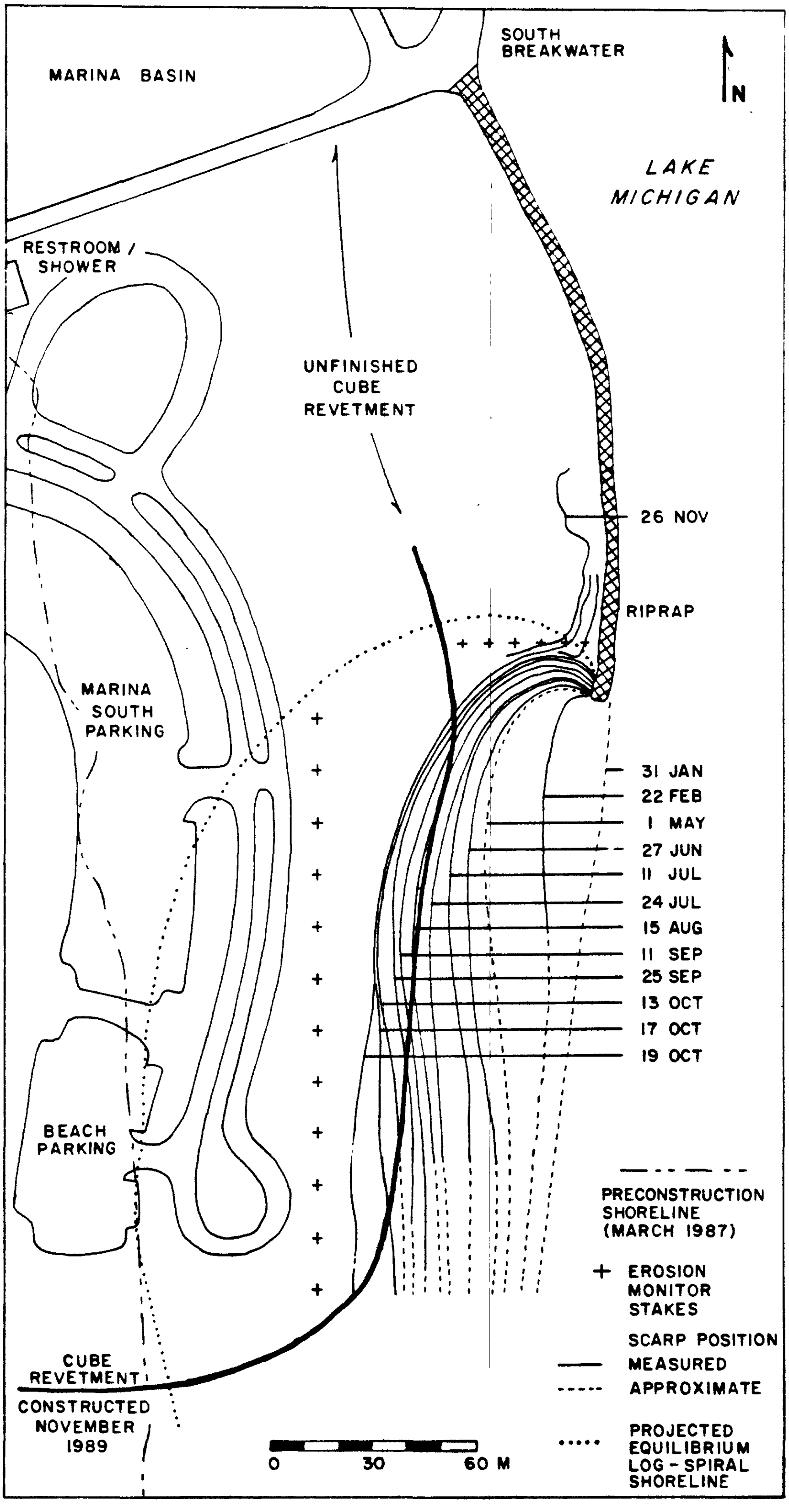

Figure 1. Partial record of 1989 scarp positions.

Figure 2. Aerial photograph of the North Point Marina south beach area on August 25, 1989. Paving is complete for the parking lots and access roads. Minimum distance from the scarp edge to the east edge of the access road is 33 m. The scarp edge is as close as 11.7 m from the line of proposed shore defense. (Daily mean lake level +1.96 ft LWD; NOAA Station 908-7044, Calumet Harbor, Illinois.)

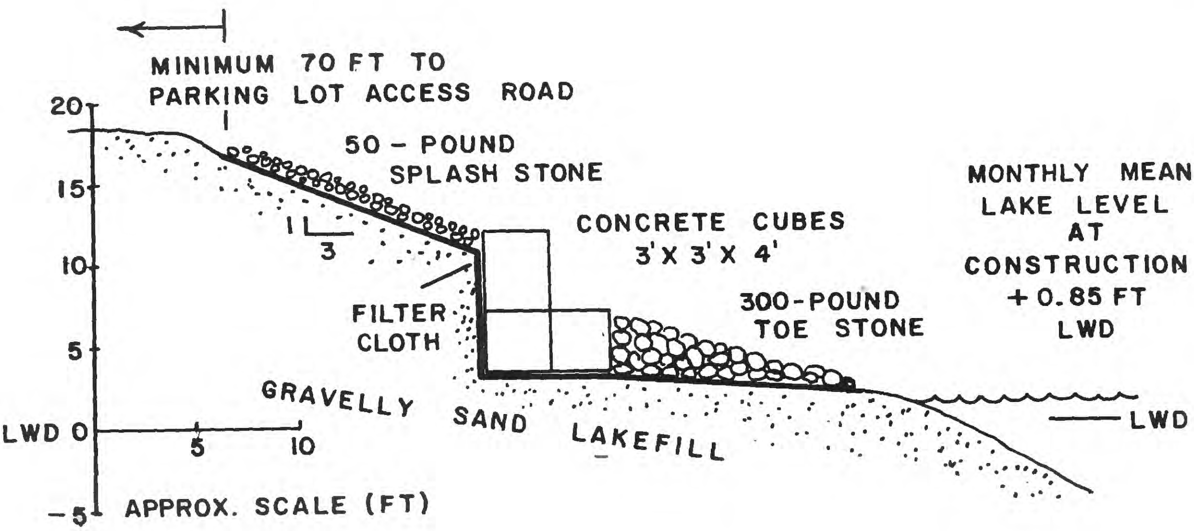

Figure 3. Schematic cross section of concrete-cube revetment.

COASTAL BLUFF RETREAT ALONG THE LAKE MICHIGAN SHORELINE IN ILLINOIS AND SOUTHERN WISCONSIN

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Introduction

The Lake Michigan shoreline between Wilmette and North Chicago, Illinois, is defined by Quaternary till bluffs averaging 20 m high. Coastal erosion in this area is a complex process involving landsliding and erosion of the bluff face and littoral transport of displaced bluff material and beach sediment at the base of the bluff. This summary discusses the procedures and preliminary results of studies related to bluff retreat along the Illinois shoreline. Activities to date have involved an airphoto documentation of bluff retreat, a subsurface cone-penetration investigation to determine the regional distribution of material types and properties, and preliminary stratigraphic mapping of the coastal bluffs between Racine and Port Washington, Wisconsin, for comparison with the Illinois bluffs. Figure 1 shows locations of bluffs referred to in this report.

Airphoto Study of Bluff Retreat

A fundamental objective of this study is to determine the spatial and temporal variability in the rates at which coastal bluffs are receding along the Lake Michigan shoreline. We developed a 50-yr record of bluff retreat by comparing locations of features on the oldest available airphotos, taken in 1937 (scale 1:14,400), with those from airphotos taken in 1987 (scale 1:14,400).

We determined the amount of bluff retreat by using a zoom-transfer scope to trace the position of the shoreline, base of the bluff, and top of the bluff directly from the airphotos onto a 1:12,000-scale base map enlarged from 1:24,000 scale. The lines were then digitized from the base map using GSMAP (Selner and Taylor, 1989). Bluff lines for different years were plotted on top of one another and distances between them measured. The bluff was projected onto a north-northwest trending line and divided into 100-m segments to facilitate analysis of individual cells. The average distance between the top of the 1987 and 1937 bluffs was measured in each 100-m cell. The widths of the bluffs in 1937 and 1987 were determined by measuring the average distance between the top and base of the bluff over each cell. The average height of the bluff in each cell was estimated from existing 1:24,000 topographic maps having a contour interval of 5 ft (1.5 m).

Using the measurements described above, we calculated the amount of retreat of the top of the bluff between 1937 and 1987 and the volume of sediment lost from each bluff segment over that period. The primary sources of error in the method described are the inherent distortion

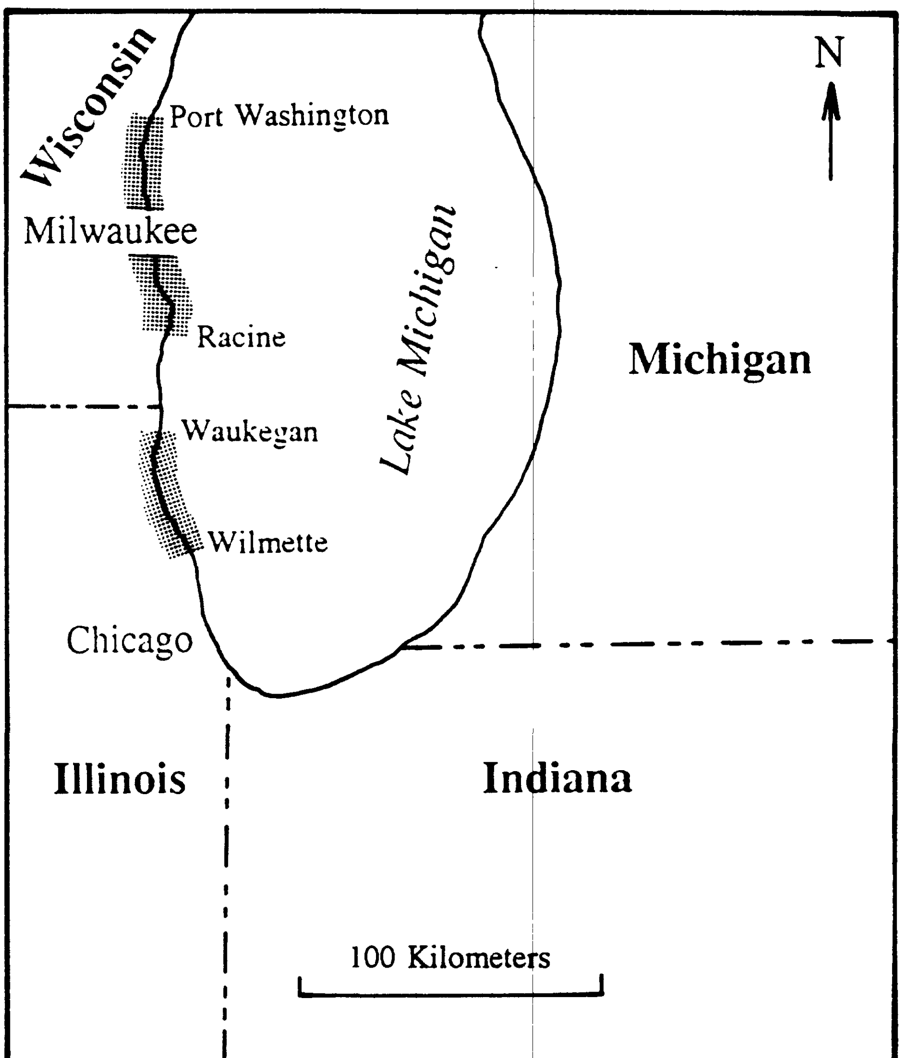

Figure 1.–Location map showing bluffs being studied (shaded) in Illinois and Wisconsin.

in the airphoto, registering the photo and base map on the zoom-transfer scope, and visually locating the base of the bluff on the airphoto. We estimate that the combined location error from all sources is about ± 3 m for any single feature and thus is ± 6 m for the distance between any two features.

Figure 2 shows the 50-yr bluff retreat and the mean annual bluff retreat in the study area. The data were filtered to smooth some of the spikes by averaging the value of each cell and its two adjacent cells. Amounts of bluff retreat vary considerably from cell to cell, and significant amounts of bluff retreat occur throughout the entire area and are not limited to a single portion of the bluffs. The maximum 50-yr retreat in a single cell from the unfiltered data is 39 m, which corresponds to 0.8 m/yr of retreat. The filtered data in figure 2 indicate that maximum 50-yr amounts of retreat range from 20 to 30 m, which corresponds to a 0.4- to 0.6-m/yr retreat rate. The calculated mean 50-yr retreat for all bluff segments for which data are available is 10.9 m, which corresponds to a mean rate of 0.22 m/yr.

Figure 3 shows 50-yr sediment volumes involved in bluff retreat and corresponding annualized rates. Data were filtered as described above. Volumes generally increase northward to a maximum of about 70,000 to 80,000 m^3, which corresponds to a mean rate of 1,400 to 1,600 m^3/yr. The calculated 50-yr total sediment volume from the bluffs is about 6,500,000 m^3; the annualized rate is thus about 130,000 m^3/yr. The mean annual rate for each 100-m cell is about 420 m^3/yr.

Landslide localities and types were mapped from airphotos taken in several years between 1937 and 1987. Comparing numbers and types of landslides and periods of activity throughout the 50-yr period will allow analysis of the recurrence histories of landslide movement along different parts of the bluffs and the effects of lake level, climate changes, and human development on bluff stability in the area.

Figure 4 shows a sampling of the data from six different years spanning the 50-yr period for which airphotos are available. Many landslide areas appear on each successive generation of airphotos, which suggests continuing activity throughout the 50-yr period. Other areas contain landslides in one or more years but not all, which suggests intermittent activity that could be controlled by lake level, human development, or other factors. Detailed analysis of these data is not yet complete.

Cone-Penetration Investigation

In August 1989, we contracted Stratigraphics, Inc.[1] to conduct cone-penetration testing (CPT) along the bluffs at 14 locations between Winnetka and North Chicago, Illinois. The CPT investigation used a truck-mounted hydraulic ram to push a 4.3-cm-diameter instrumented probe

[1]Use of company name does not imply USGS endorsement but is for information purposes only.

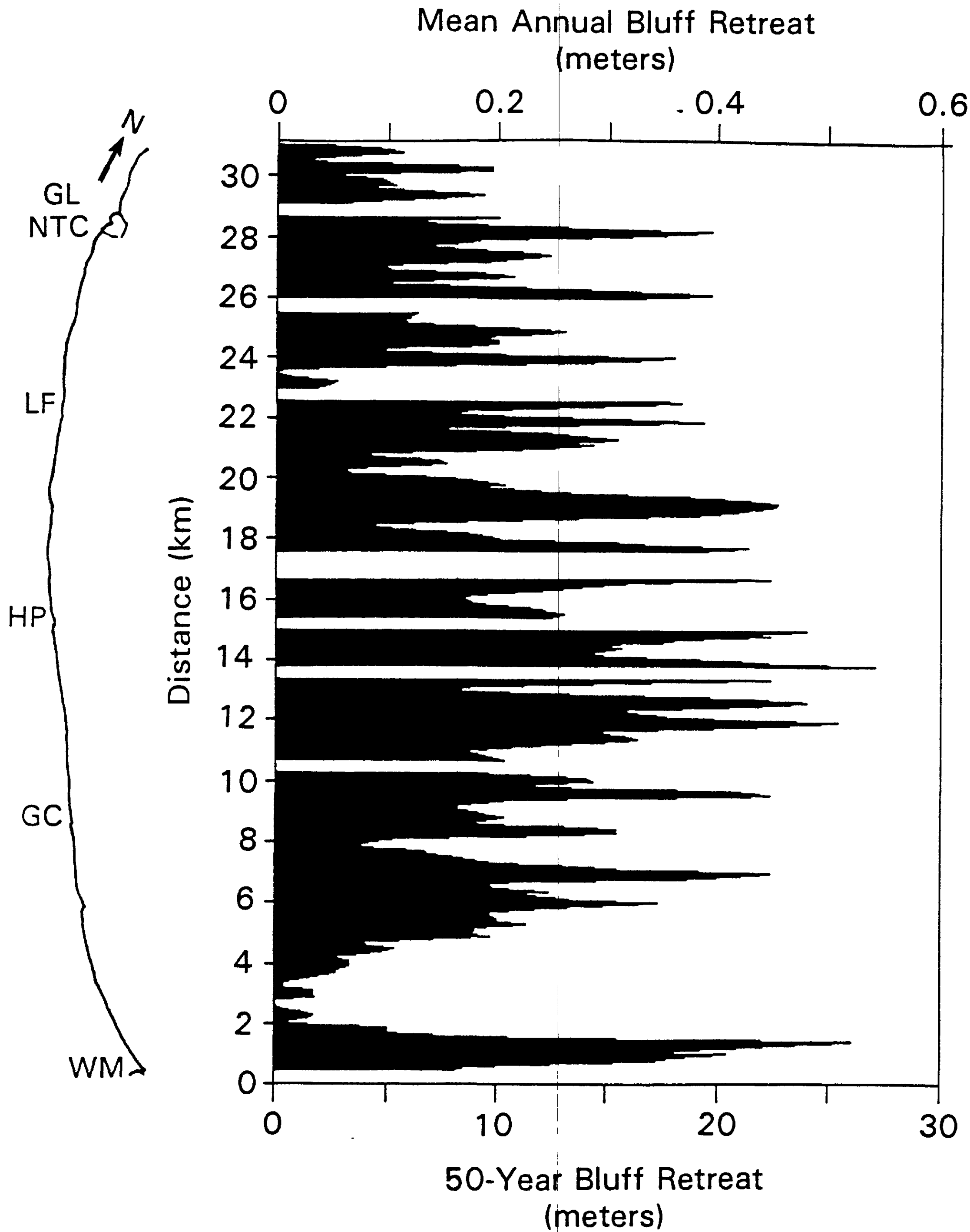

Figure 2.–Mean annual and 50-yr amounts of bluff retreat along the Lake Michigan shoreline in Illinois. Data were filtered by averaging the value of each cell with its adjacent cells. Distances are from Wilmette harbor, the southern terminus of the study area. On the shoreline map on the left, WM is Wilmette harbor, GC is Glencoe, HP is Highland Park, LF is Lake Forest, and GLNTC is Great Lakes Naval Training Center.

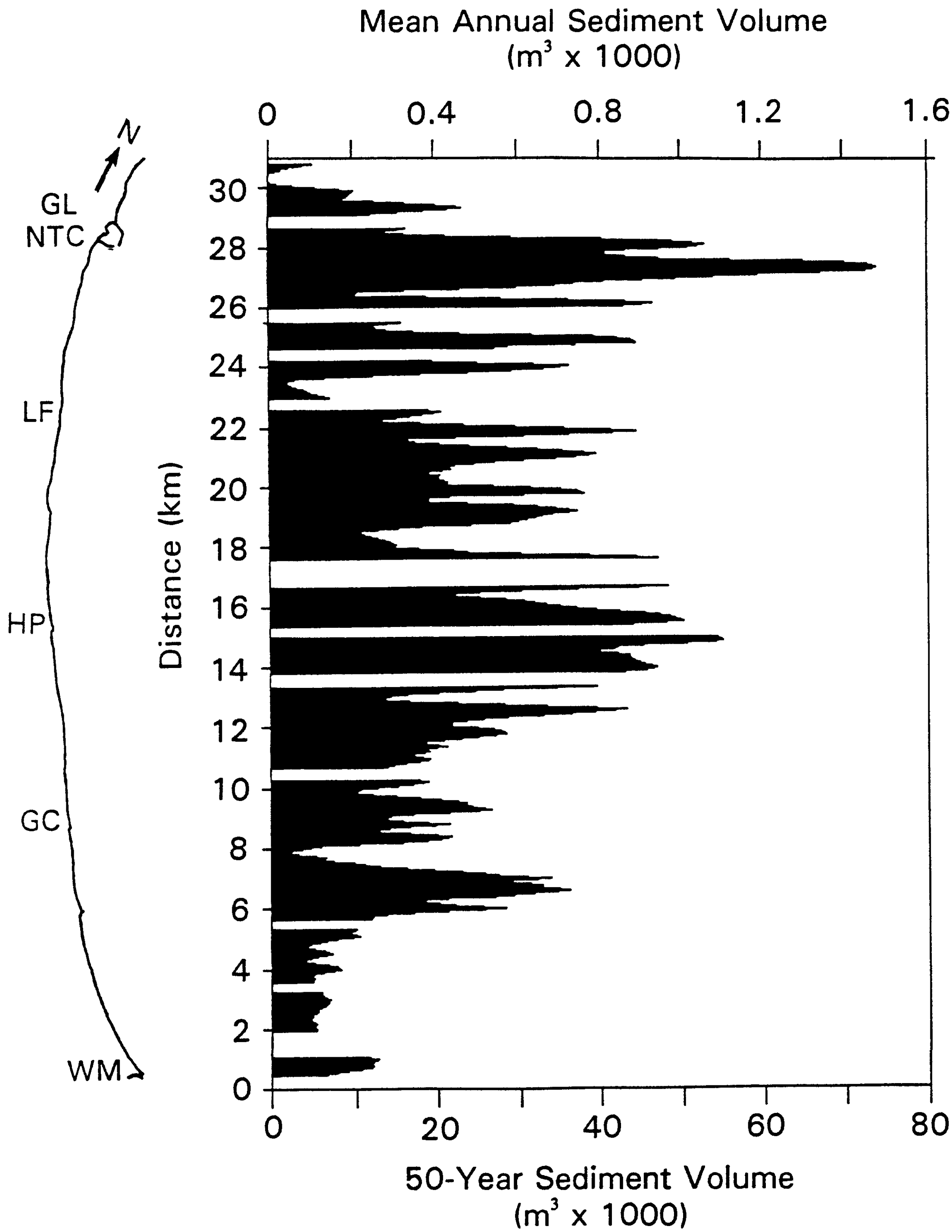

Figure 3.–Mean annual and 50-yr sediment volumes from bluff retreat along the Lake Michigan shoreline in Illinois. Data were filtered by averaging the value of each cell with its adjacent cells. Distances are from Wilmette harbor, the southern terminus of the study area. On the shoreline map on the left, WM is Wilmette harbor, GC is Glencoe, HP is Highland Park, LF is Lake Forest, and GLNTC is Great Lakes Naval Training Center.

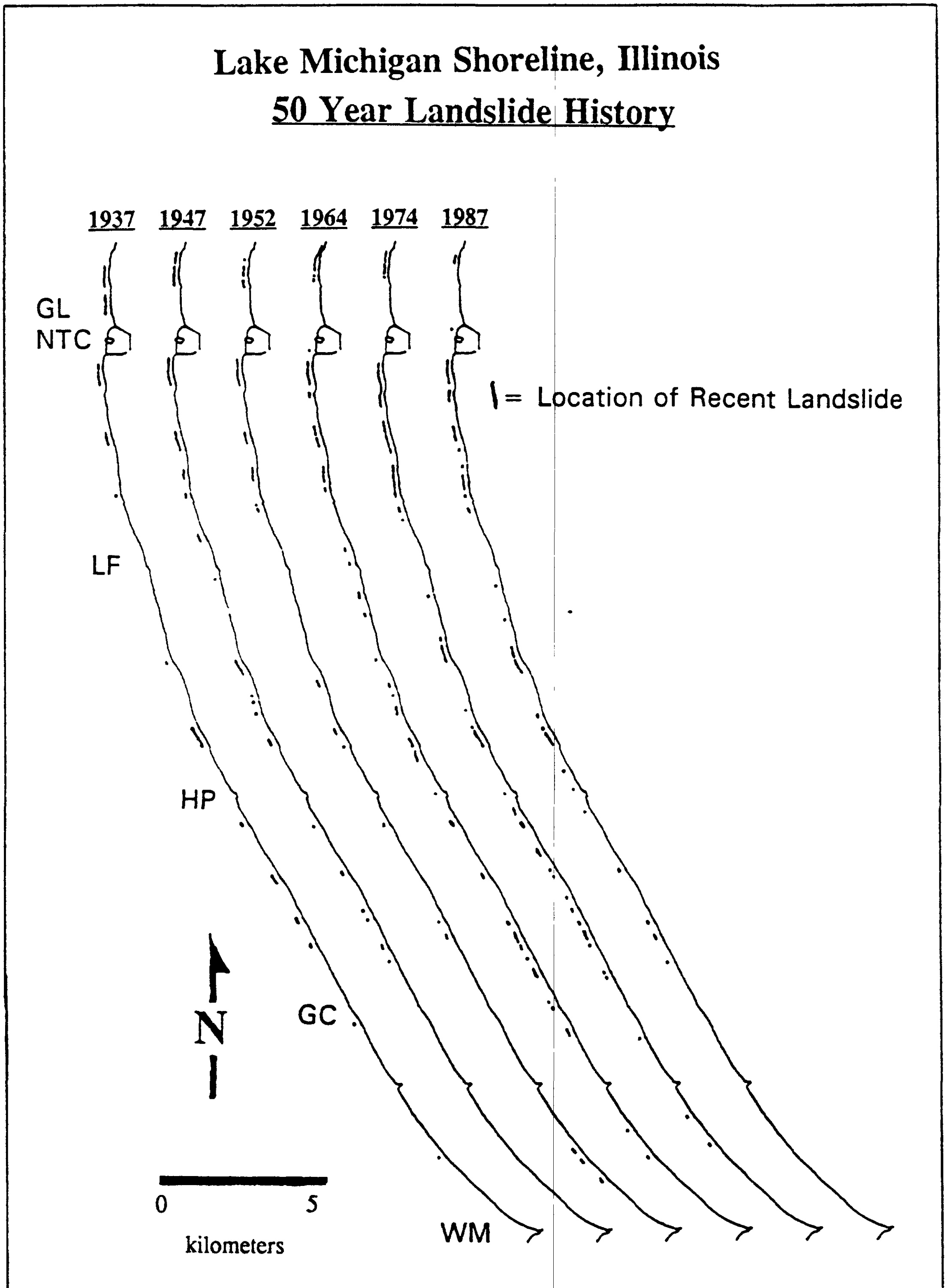

Figure 4.–Landslide locations along the Lake Michigan shoreline bluffs in Illinois for six years between 1937 and 1987. WM is Wilmette harbor, GC is Glencoe, HP is Highland Park, LF is Lake Forest, GLNTC is Great Lakes Naval Training Center.

having a conical tip into the ground to depths between 17 and 28 m. CPT data is used to determine the grain-size, plasticity, shear strength, permeability, and pore-water pressure of sediments. Layers as thin as a few centimeters can be detected, so very detailed stratigraphic profiles can be derived.

At Fort Sheridan, we placed four pairs of CPT soundings along 3 km of bluffs to determine the extent of local variation of material types and properties and the geometry of the water table near the edge of the bluff. Each pair consisted of one sounding within 7 m of the edge of the bluff and a second sounding 15 to 30 m inland from the first. To determine regional variations in material types and properties, six additional soundings were placed between Winnetka and Lake Bluff. CPT data will be combined with existing Standard-Penetration test (SPT) data and outcrop mapping to construct a cross section showing the distribution of types and properties of bluff materials.

Figure 5 shows the part of the CPT cross section between Highland Park and Lake Forest. Vertical logs of the cone tip resistance and the friction ratio (the ratio of sleeve to tip resistance of the penetrometer) are plotted; tentative correlation lines connect sediment layers that are texturally similar, and piezometric levels are indicated where they could be measured.

For each sounding, tabular data on soil type, shear strength (drained or undrained), and equivalent SPT blow counts are compiled at 0.3-m intervals. Throughout most of the area, man-made fills or organic soils extend from the ground surface to about 0.2 to 1.5 m depth. Below this surface layer, a stiff, desiccated, silty to sandy clay crust extends to depths of 2.4 to 5.5 m. Below this crust are two silty clay till units, separated by thinner silty sand layers. The upper till is uniformly stiff; the lower till is somewhat weaker. The CPT data will be analyzed in detail to evaluate the effects of material type and properties on bluff retreat.

Stratigraphic Mapping in Wisconsin

In August 1989 we conducted field work to develop a stratigraphic framework for examining bluff-recession processes along the southern Wisconsin shoreline between Racine and Port Washington. Bluffs in this area are primarily undeveloped and are freely eroding, and the till is very stiff and well exposed; processes here provide a valuable comparison to the Illinois bluffs, which are heavily developed and consist of somewhat softer till covered by colluvium and residuum. Field work (conducted primarily by Reinhardt) involved measuring and describing several late Quaternary stratigraphic sections between Racine and Port Washington.

Figure 6 shows columnar sections of the sites investigated. Preliminary results indicate that the deposits examined in the bluffs correlate with previously dated deposits ranging in age from 11,800 to more than 15,500 years old (Reinhardt, 1990). The nature and distribution of these deposits appear to influence the pattern of landsliding and consequently the recession of the bluffs. Sedimentary features in the glacial deposits record intervals of rapid deposition associated with glacial outwash sedimentation alternating with lake sedimentation. Synsedimentary

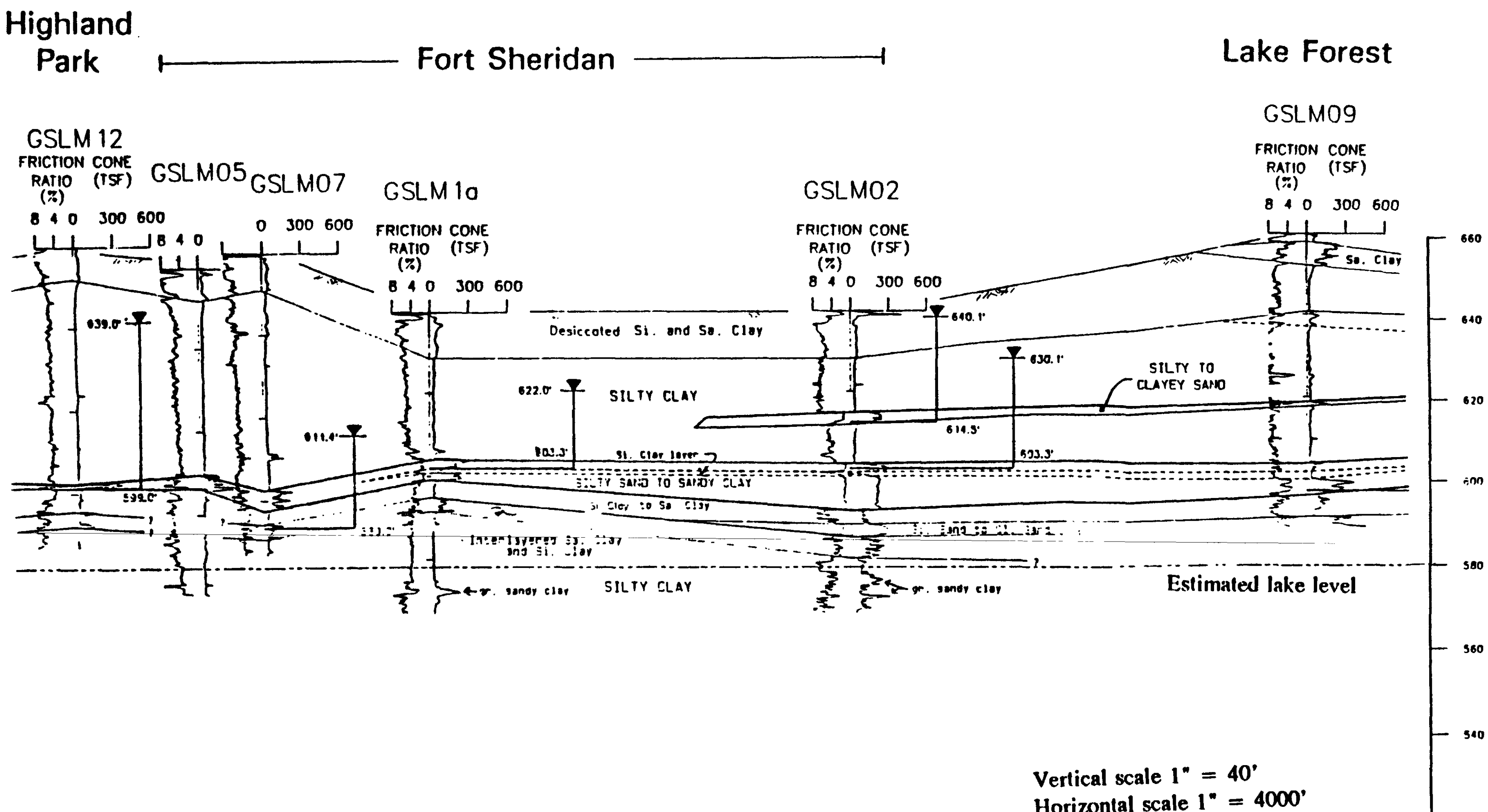

Figure 5.–Portion of the cross-section between Highland Park and Lake Forest, Ill., developed from cone-penetration testing. Inverted triangles show ground-water piezometric levels. Conversion of units is as follows: 1 TSF (ton/ft^2) = 9,765 kg/m^2; 1 ft = 0.305 m; 1 in = 2.54 cm.

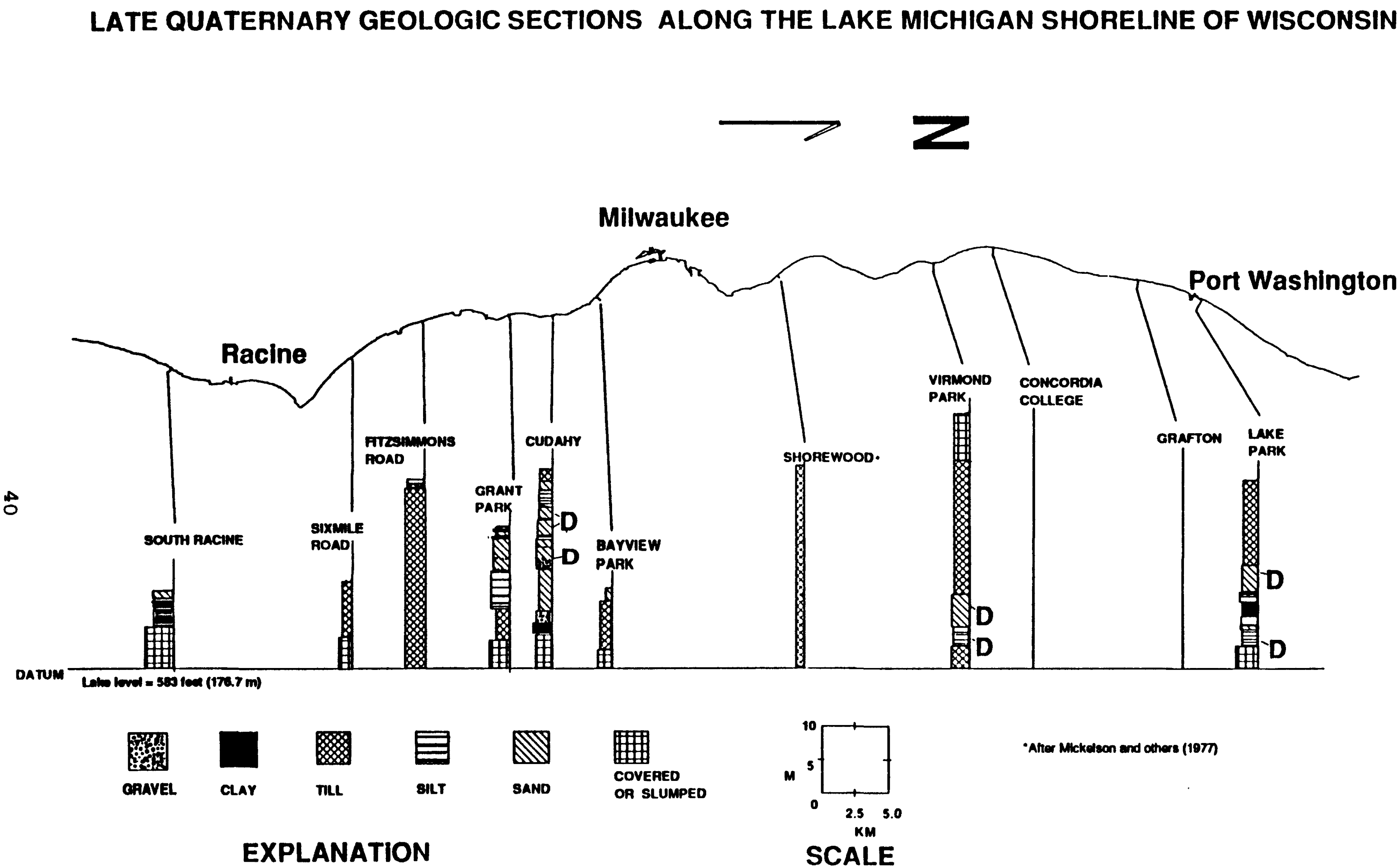

Figure 6.—Cross section showing late Quaternary geologic sections along the Lake Michigan Shoreline in Wisconsin (from Reinhardt, 1990).

deformational features occur most commonly in fine-grained deposits and probably result from loading and differential compaction. Locally, however, some large-scale injection structures are present that could have resulted from paleoseismic activity in the region.

Conclusion

Airphoto interpretation, cone-penetration testing, and stratigraphic mapping provide new information that enhances our understanding and quantification of bluff erosion along the southern Lake Michigan shoreline. Continuing analyses of data from these studies will lead to development of refined models of bluff retreat and coastal erosion in this area.

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GROUNDED ICE RIDGES AS SEAWALLS: A SHORT REVIEW

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Shorefast ice complexes in the Great Lakes have cross-shore dimensions of several hundred meters and may extend along shore for many kilometers. These ice complexes consist of one or more grounded ridges separated by zones of low-relief ice (fig. 1). Formation of shorefast ice complexes requires: (1) subfreezing air temperatures, (2) large water bodies that remain unfrozen well into the winter season, (3) onshore winds and storm waves, and (4) a supply of ice fragments and slush ice (Bryan and Marcus, 1972; Marsh et al, 1973). All of these conditions are met in the Great Lakes; as a result shorefast ice complexes are ubiquitous. Ridges form when breaking waves deposit freezing spray and slush on the outer edge of the floating ice. This spray and slush thickens the ice until it becomes grounded and builds a vertical escarpment above the water line (Seibel et al, 1976). Often this escarpment is marked by "ice cones" or "ice volcanoes" that may rise more than eight meters above water level (O'Hara and Ayers, 1972; Bryan and Marcus, 1972; Fahnestock et al, 1973; Marsh et al, 1973).

Most studies of shorefast ice complexes in the Great Lakes have concluded that grounded ice ridges act as natural seawalls. Although this comparison is commonly made, no one has taken the results of seawall research and applied them to grounded ice ridges. In this paper, we review some aspects of nearshore ice ridges in the Great Lakes and discuss how some of the results of seawall research might apply to grounded ice ridges.

Shorefast ice complexes in the Great Lakes commonly grow lakeward as a cold spell progresses. Ice ridges that form as the winter progresses are commonly larger, further from shore, in deeper water, and more regular than the ridges that form near the shoreline in early winter. Often ridges in deep water extend for several kilometers alongshore without a break. As shorefast ice complexes grow, the surf zone is displaced progressively lakeward and the beach is protected from erosion. Evanson and Cohn (1973), in a study on Lake Ontario, calculated that more than 60% of all incoming wave energy occurs during the winter months when the beach is protected by grounded ice ridges. They concluded that beach retreat rates are significantly reduced because of the ice. Marsh et al (1973) compared calculated longshore sediment transport rates at Point Barrow, Alaska, Lake Superior, and typical ice-free mid-latitude coasts. They found that the estimated 130,000 $m^3\ yr^{-1}$ littoral transport rate in southern Lake Superior is about midway between arctic beaches (~10,000 $m^3\ yr^{-1}$) and ice-free beaches (200,000-300,000 $m^3\ yr^{-1}$). Marsh et al conclude that this intermediate transport rate results from an intermediate-length ice season relative to arctic and temperate coasts, because the presence of a nearshore ice complex protects the beach from wave-induced erosion. This conclusion must be viewed skeptically because Marsh et al failed to consider differences in factors such as fetch, storm severity, and wave climate when comparing the different coastal regions.

While it is generally acknowledged that nearshore ice ridges protect the beach from erosion, there is some question about the effects of ice ridge/wave interactions in the nearshore zone. As the ice complex grows outward during the winter, the surf zone is progressively shortened, so wave energy is transmitted to a shorter section of the bottom (Marsh et al., 1973). Bajorunas and Duane (1967) state that nearshore ice ridges direct some of the forces of impinging waves downward, resulting in lake bottom scour and suspension of bed sediment. Once the sediment is in suspension, it can be advected along shore by longshore currents or can be thrown onto the growing ice ridge by succeeding waves. Bajorunas and Duane state that scouring at the base of grounded ice ridges will result in over steepening of the bottom. When the ice ridges melt, the bottom will be unstable and subject to wave modification. O'Hara and Ayers (1972) report that wave action will scour sand from beneath ice ridges, leading to the collapse of ridge sections. Seibel et al (1976) state that scouring at the base of ice ridges may destroy offshore bars. This destruction may lead to increased shoreline and bluff erosion after the ice complex melts in the spring because the bars are no longer there to dissipate wave energy.

Although all of these authors conclude that interactions between ice ridges and waves lead to scour development, none of them have conclusively shown that scour depressions form lakeward of ice ridges. Marsh et al (1973) surveyed a beach in Lake Superior and concluded: "Although it is evident that part of the wave energy is concentrated downward at the ice front, profiles reveal negligible net erosion of the bottom in this zone." If no one has documented scour depressions forming lakeward of a grounded ice ridge, what evidence is there for scouring? The main evidence for scour is found in high concentrations of sediment that are incorporated into shorefast ice complexes. This sediment is entrained into the ice ridge when breaking waves wash spray and slush ice onto the growing ice ridge. The presence of sediment in the ridge indicates that sediment is in suspension in the water column near ice edge, and suggests that a scour depression might be forming.

Nielsen (1988) reports on a study conducted in Denmark where a section of beach was surveyed regularly over a two year period. Nielsen found that during the winter when an ice ridge was present there was a net loss of sediment between the 60 and 100 cm contours. Nielsen concluded that this loss resulted from a reflective wave environment caused by ice-ridge build up in the nearshore zone. Nielsen only carried the surveys out to 1 m depth, so the final disposition of the lost sediment is not known; it could have been deposited offshore in bars.

During February, 1989, we made observations near the ice edge at 4 points around southern Lake Michigan. These observations consisted of both wading surveys and ROV dives. Both of these techniques revealed the presence of a depression immediately lakeward (~0-2 m) lakeward of the ice edge. These depressions were 30-40 cm deeper than the zone 2 to 5 m lakeward of the ice edge, but it is not entirely clear whether the depression results from scour, from deposition further lakeward, or from some combination of these two processes.

Although many authors recognize the similarities between seawalls and grounded ice ridges, little or no literature on seawalls is discussed in ice ridge papers. It seems that this would be worthwhile, because of the prevalence of the analogy.

Kraus (1988) recently completed a comprehensive review of the effects of seawalls on the beach. Kraus states that ". . . A seawall introduces interactions between water and sediment not existing in the original beach and wave-current system." Seawall research is concerned with both longshore (up- and down-drift) and cross shore changes associated with seawall construction. Grounded ice ridges commonly extend for many kilometers in the longshore direction when fully developed, so the present discussion deals only with effects seen directly seaward of seawalls.

After reviewing the available laboratory, field, and theoretical studies, Kraus (1988) concludes that scour depressions can form seaward of a seawall. The depth of the scour depression can be approximated by the significant deep water wave height for the wave conditions that caused the scour. The amount of time necessary to reach this scour depth is not known. Kraus further states: "field studies indicate that the volume of material scoured at a seawall has similar magnitude and variation as the volume eroded from adjacent beaches not backed by walls." If this statement applies to grounded ice ridges, it would imply that the beach is maintained through the winter at the expense of the nearshore zone seaward of grounded ice ridges. However, the final distribution of sediment scoured from the base of a seawall or ice ridge is unknown.

Kraus (1988) reviews a wave tank study conducted by Chestnutt and Schiller (1971). In their study, Chestnutt and Schiller found that maximum local scour occurred when a seawall was placed in a "critical region" located between 1/2 and 2/3 of the way across the surf zone from the shoreline. This is a region where grounded ice ridges commonly form, and this observation suggests that formation of grounded ice ridges in the mid surf zone could result in maximum scour. However, when Chestnutt and Schiller moved the seawall to a position landward of the "critical region", the scour depression began to fill immediately with wave-transported sediment. If this observation applies to grounded ice ridges, as soon as the ice melts any scour depression would fill in, so it is impossible to document scour formation with post-melt surveys. In addition, if sediment scoured from the lakeward edge of grounded ice ridges is deposited offshore, this sediment would fill in the scour, and beach protection would occur at little or no expense to the nearshore region.

The formation of long stretches of grounded ice ridges throughout the Great Lakes protects the beach from wave erosion, but very little is known about what happens immediately lakeward of the grounded ice edge. Our preliminary observations show that a small scour depression forms within 2 m of the ice edge, or a bar forms at distances of 2 to 5 m from the ice edge. Results of seawall research suggest that scouring is dominate process. To better understand what happens in the winter we must: (1) confirm the size and formation mechanisms of scour depressions that form lakeward of grounded ice ridges. (2) Determine where sediment scoured from this region is deposited. (3) Determine the processes and rates of sediment transport in the zone immediately lakeward of grounded ice ridges. By addressing these 3 problems, we will gain new insights into how the nearshore ice complex affects sediment transport and coastal erosion.

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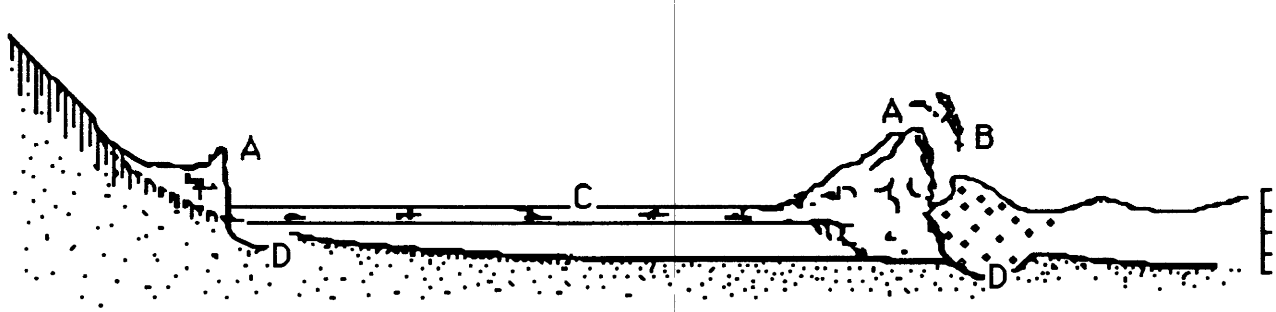

Figure 1. Cross shore profile of typical shorefast ice complex. Grounded ice ridges (A) are built up by wave splash and slush ice overwash (B). The low relief ice (C) between ridges forms during quite water periods. Scour depressions at foot of ice ridges (D) are inferred. 5X vertical exaggeration. (Modified from Nielsen, 1988).

GRAVEL TRANSPORT UNDER WAVES

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INTRODUCTION

Lake Michigan beaches often contain material eroded from glacial till; gravel beaches and oness composed of both sand and gravel are common. In recent years, the rapid changes in lake levels have lead to an interest in how to best predict shoreline changes and to protect beaches. Accurate predictions of shoreline changes and our ability to effectively use gravel to stabilize beaches requires an understanding of the movement of coarse gravel under oscillatory flow.

The purpose of this study is to investigate the mechanics of entrainment of gravel sediment under waves using theoretical and field techniques.

ENTRAINMENT EQUATION

Wiberg and Smith (1987) have recently developed an equation to determine the initiation of motion of gravel sediment from a bed of mixed grain sizes. They use a balance of forces approach that can be used for oscillatory flow as well as unidirectional flow if a few modifications are made. In oscillatory flow, acceleration forces can impart an additional force to the grains. The acceleration force will act on bed particles in a manner geometrically similar to the drag force. The balance of forces equation can be written to include acceleration forces:

$$(F'_g \cos\beta - F_L) \tan\phi = F_D + F_A + F'g \sin\beta \quad (1)$$

Where F'_g is the submerged weight of the grain, F_L is the lift force, F_D is the drage force, F_A is the acceleration force, β is the bed slope, and ϕ is the angle of internal friction of the sediment. Entrainment will occur when the weight of the grain is just balanced by the lift and drag forces acting about the angle of internal friction of the grain.

The acceleration force (Denny et al., 1985) can be written as:

$$F_A = \rho\, C_m\, V\, (dU/dt) \quad (2)$$

where ρ is the fluid density, C_m is the coefficient of inertia of the grain, V is the grain volume, and dU/dt is the acceleration of the fluid with respect to the grain.

Appropriate expressions for the acceleration and other forces can be substituted into the balance of forces equation. When evaluating conditions for grain entrainment, the force balance is commonly expressed as a dimensionless critical shear stress, τ_{*cr}, for a given grain size. τ_{*cr} is the ratio of fluid forces acting on the grain to those resisting grain motion. The resulting expression is in terms of the ratio of lift to drag forces (F_L/F_D), the velocity averaged over the area of the grain ($\langle f^2(z/z_0)\rangle$), the particle ange of internal friction, ϕ, and the acceleration force, defined above. The resulting expression (Brabeck, 1989; Brabeck and Prestegaard, in review) can be expressed as:

$$(\tau_*)_{cr} = \frac{2}{((C_D)_{cr}\langle f^2(z/z_0)\rangle + (C_m)_{cr}D[\frac{d(f(z/z_0))}{dt}])\alpha} \frac{(\tan\Phi_0\cos\beta - \sin\beta)}{[1+(F_L/(F_D+F_A))_{cr}\tan\Phi_0]} \quad (3)$$

This expression is similar to that derived by Wiberg and Smith (1987) for grain entrainment in unidirectional flows. The most important difference is the presence of the grain diameter in the denominator of the equation. This means that when acceleration forces are significant, the value of the critical dimensionless shear stress, τ_*, decreases directly with grain size. The equation predicts that large grains under high fluid accelerations may begin to move at lower shear stresses than smaller grains because of the volume-dependence character of the acceleration force. The equation also predicts a reduction in τ_* for large grains in sediment mixtures due to the reduction in values of the angle of internal friction for the larger grains (Wiberg and Smith, 1987).

The effects of acceleration forces can be shown on a Shields' diagram, a plot of the critical dimensionless shear stress, τ^*, against boundary Reynold's number (Re*). Wiberg and Smith (1987) showed that for grains in sediment mixtures, the Shields' curve is transformed into a family of curves with different ratios of grain size to bed roughness (D/k_s). A river or beach bed will have a mixture of grain sizes and therefore a mixture of D/Ks values. Figure 1 shows the effects of acceleration forces on grains in a typical gravel mixture. As acceleration forces increase, the lines are displaced towards lower values of Re*,illustrating the increased mobility of particles with increasing acceleration forces. Lines of equal acceleration also become increasingly curved with large sediment sizes (large values of D/ks), due to the volume dependency of acceleration forces which act most strongly on the largest grains.

FIELD TESTING OF THE ENTRAINMENT EQUATION

We tested the entrainment equation by collecting field data in the nearshore of Lake Michigan. The field site is in Illinois Beach State Park (fig. 2). We collected bedload transport rates and bedload size distributions along with nearbed velocity data in both offshore and onshore directions. Some of the data for one of the study days is shown in fig. 3.

One way of evaluating entrainment conditions is to examine the shear stress at which the largest grains in a sediment mixture begin to move. For heterogeneous mixtures, the relative grains size of the largest particle will influence its mobility. Therefore, entrainment can be evaluated by comparing dimensionless shear stress, τ_*, to relative grain size for the largest particle. τ^* evaluated from field data can be determined from:

$$\tau_* = \tau_0 / (\rho_s - \rho)\, gD \qquad (4)$$

where τ_0 is the fluid shear stress, $(\rho_s - \rho)$ is the immersed weight of the sediment, g is the acceleration due to gravity, and D is the grain size. Fluid shear stress is evaluated from measurements of nearbed velocity and bed roughness.

Figure 4 shows the field data from 8/26/88 plotted as τ^* vs. D_{max}/D_{50}, where D_{max} is the largest grain in the bedload sample and D_{50} is the average size of the sediment on the streambed. In such a diagram, if all particles in the mixture begin moving at the same fluid shear stress, then the data should follow a trend with a slope of -1. The offshore transport data approximate this trend, but the onshore data do not. As waves approach the shore, there is asymmetry in the duration and magnitude of the onshore and offshore flow. Our work, and that of Huntley and Bowen (1975) on gravel beaches, indicates that the offshore data have a nearly constant value of acceleration with given wave conditions whereas the onshore data show a large range of acceleration values. Clearly, acceleration plays an important role in onshore sediment transport. This suggests that sediment entrainment in the nearshore zone can not be properly evaluated without considering acceleration forces. This point is also made in fig. 5, which shows sediment entrainment under a range of wave conditions. The different wave climates produce a range of acceleration forces which incluences the shear stresses at which the particles move eventhough relative grain size remains constant.

To evaluate acceleration forces, we collected velocity time series data, an example of which is shown in fig. 5. Acceleration values (dU/dt) from the time series data were used to calculate acceleration forces using equation (2). Acceleration forces and other terms in equation (3) were evaluated using field data or existing relationships. Equation (4) was then rearranged to solve for maximum bedload particle size. Predicted values of maximum bedload particle size were then compared with the measured values from field data (fig. 6). The values for maximum grain size predicted from our equation are close to those measured in the field for both onshore and offshore measurements and a variety of wave climates. The strongest disagreement among the data occurred when the flow was capable of entraining larger particles than were available on the bed.

CONCLUSIONS

We have developed an entrainment equation to predict the initial motion of gravel under oscillatory flows. The equation was developed by introducing acceleration forces into the balance of forces acting on a grain at rest. Acceleration forces show a strong dependence on particle volume. The entrainment equation predicts that coarse material in the nearshore is mobile under lower shear stresses than the same material would be in a unidirectional flow. This suggests that coarse sediment on beaches can move during smaller waves and storms than we would have expected using earlier models of sediment entrainment.

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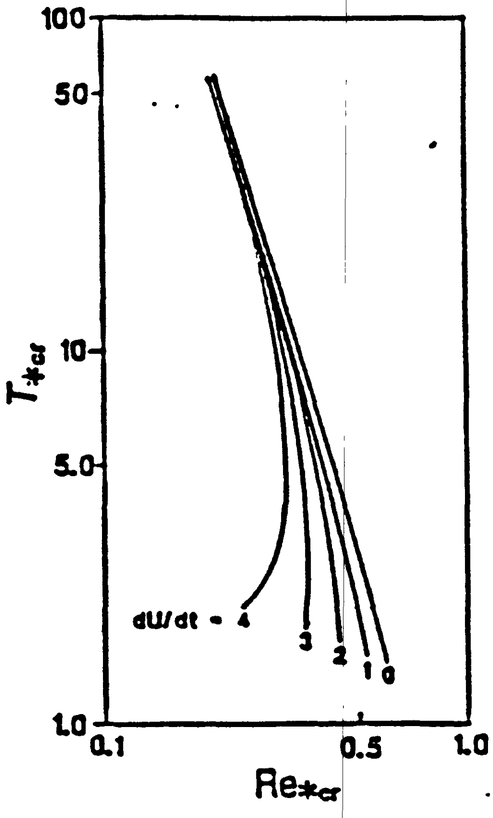

Fig. 1: Initiation of motion curves for a single mixed-sized sediment predicted from equation (3). A sediment mixture in unidirectional flow is illustrated by the curve with dU/dt = 0.

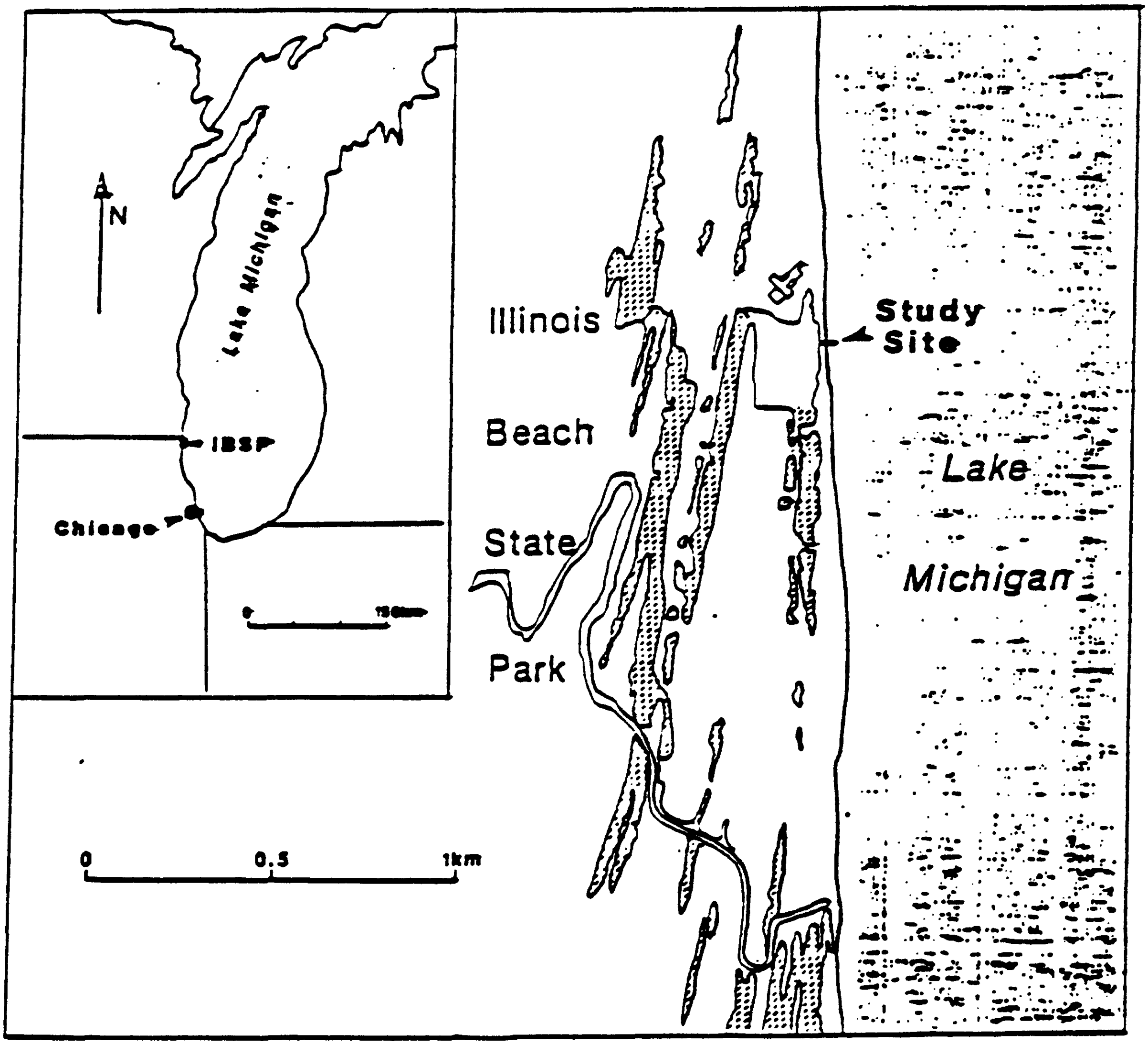

Fig. 2: Location Map of the study reach at Illinois Beach State Park.

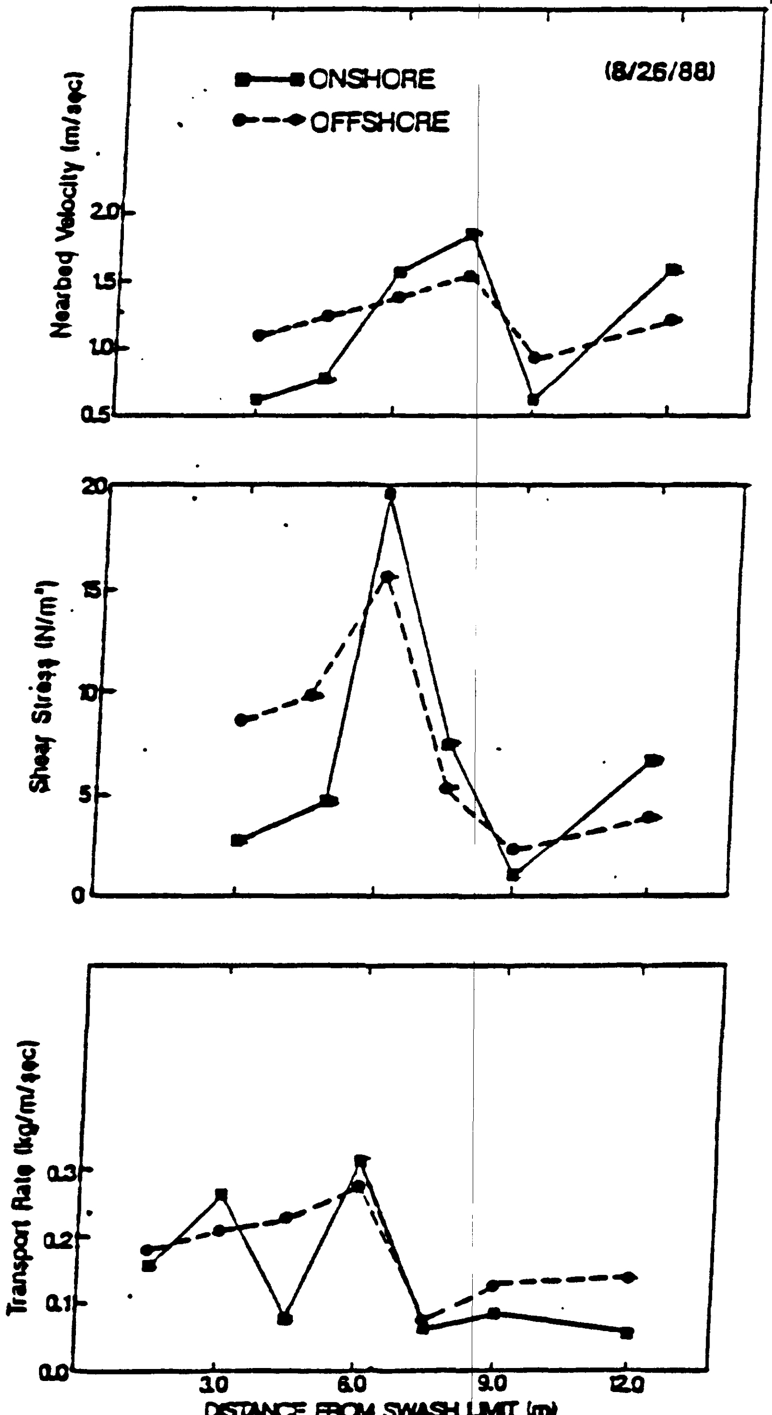

Fig. 3: Values of onshore and offshore velocity, shear stress, and bedload transport versus offshore distance for 8/26/88.

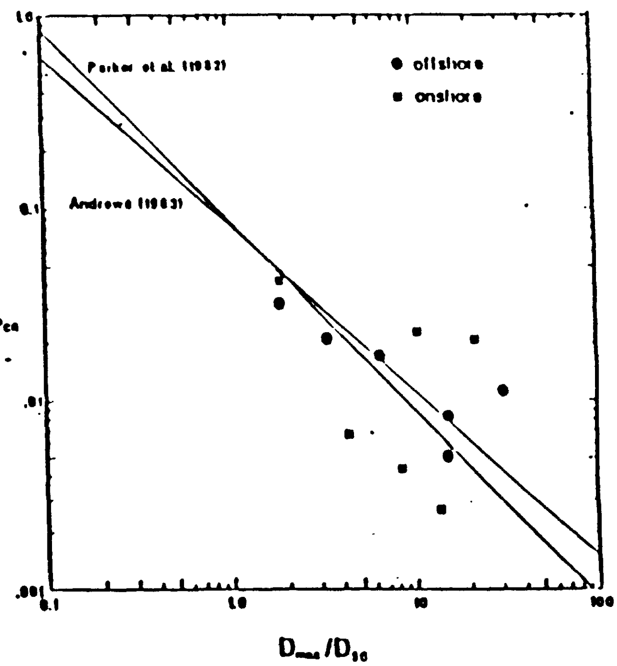

Fig. 4: Critical dimensionless shear stress vs. relative grain size for the 8/26/88 data. The two lines represent data from unidirectional flows.

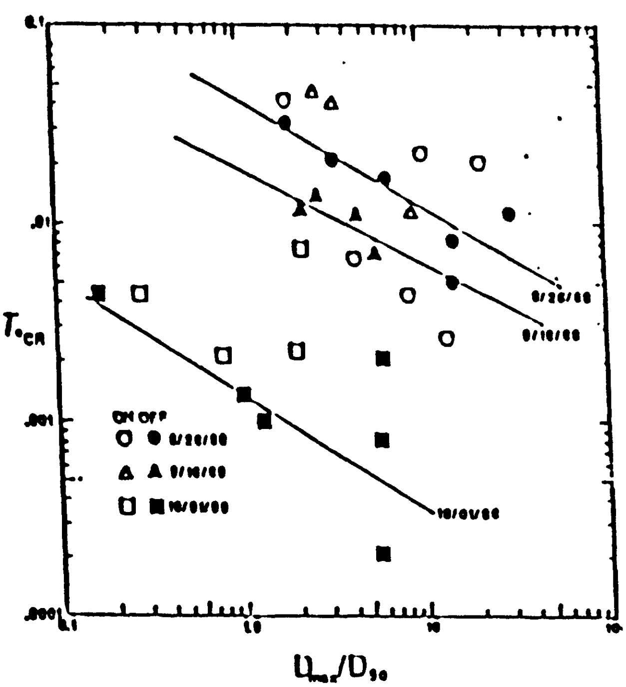

Fig. 5: Same as for fig. 4, but including data from days with lower wave heights.

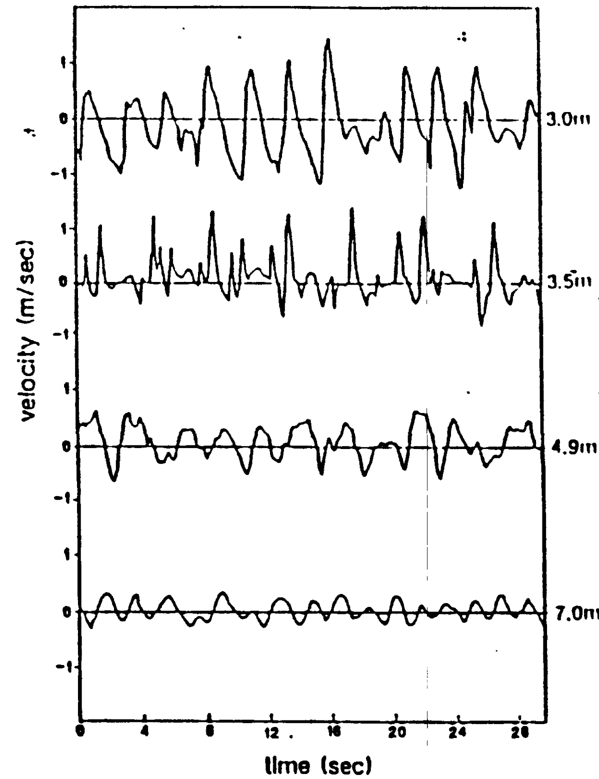

Fig. 6: Time series velocity data from a low wave height day plotted against distance from the swash zone.

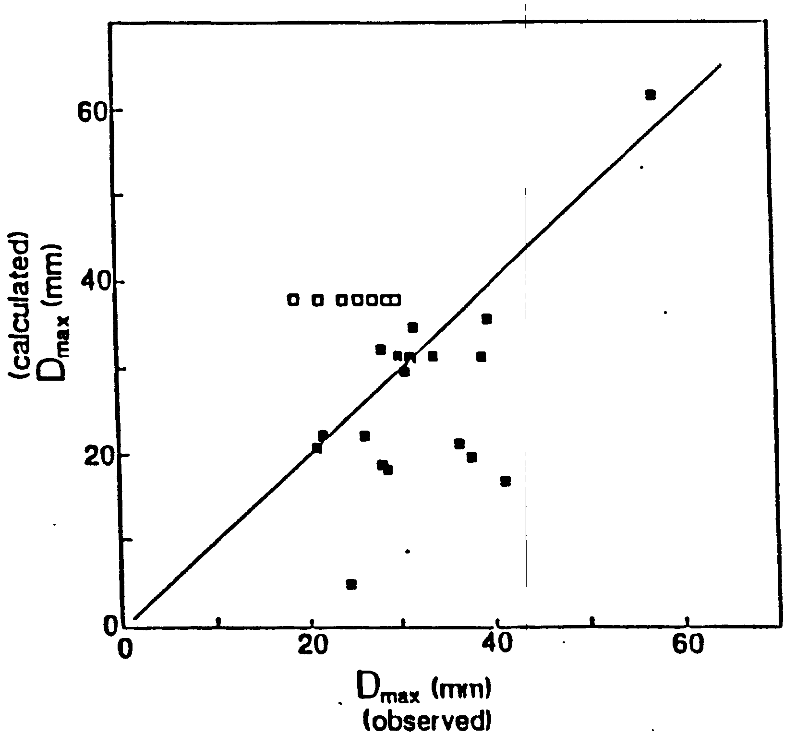

Fig. 7: Comparison among predicted values of maximum particle size using equation 3 and observed values.