

U. S. DEPARTMENT OF THE INTERIOR

GEOLOGICAL SURVEY

4TH ANNUAL

**SOUTHERN LAKE MICHIGAN COASTAL EROSION
STUDY WORKSHOP**

February 4-6, 1992

USGS Center for Coastal Geology

St. Petersburg, FL

Edited by

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Open File Report 92-324

This report is preliminary and has not been reviewed for conformity with U. S. Geological Survey editorial standards and stratigraphic nomenclature. Any use of trade names is for descriptive purposes only and does not imply endorsement by the USGS.

April 1992

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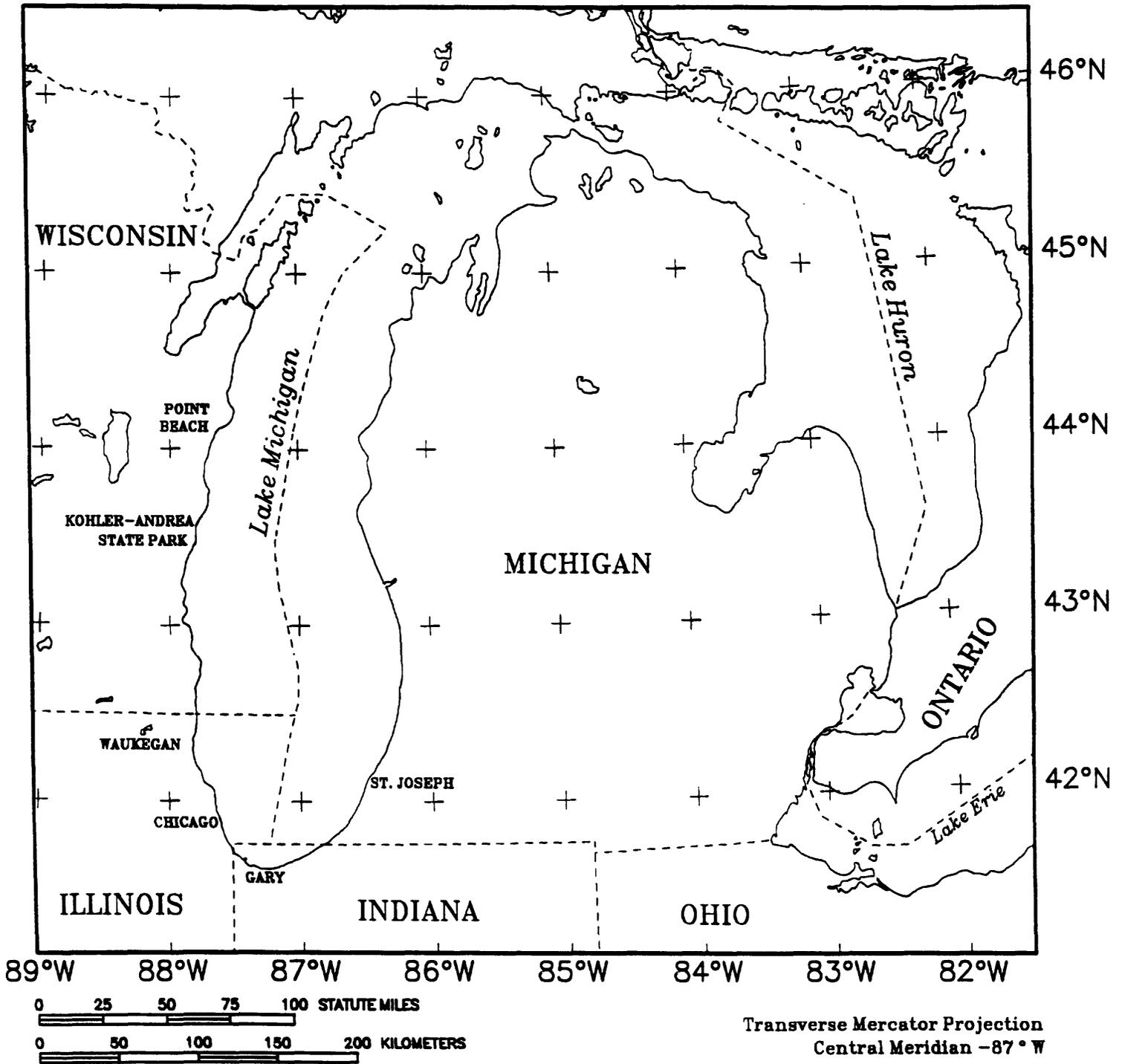


Figure 1a

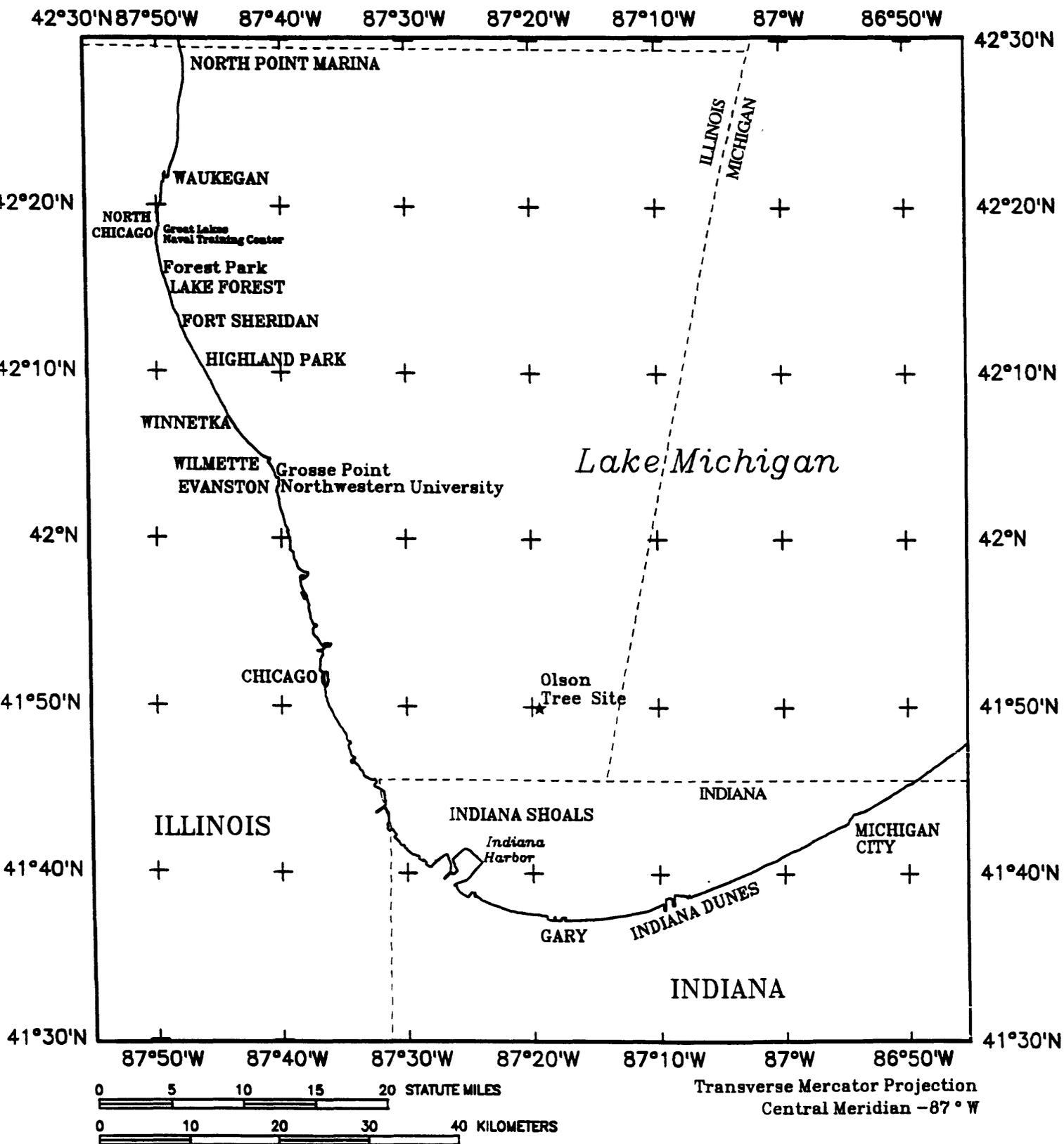


Figure 1b

INTRODUCTION

The Southern Lake Michigan Coastal Erosion Study was initiated in 1988 to provide better understanding of the timing, causes, and effects of the high lake levels of 1985-86 that resulted in extensive damage to the shoreline.

The field work for the three parts of the study is 95% complete; the remaining work will be carried out during the summer of 1992. All data will be reduced, compiled, and synthesized for submission in October, 1992 to the International Association of Great Lakes Research for publication as a Summary Volume.

The Summary Volume will comprise 17 papers. The first three in the Framework section include: Evolution of the southern Lake Michigan coast (Chrzastowski, Thompson, Trask), Nearshore stratigraphy and bottom sediment distribution (Folger, Foster), and Nearshore sand thickness (Shabica, Pranschke, Chrzastowski, Foster, Folger). Five papers in the Lake Level section include: Holocene beach ridge complexes, Illinois and Indiana (Thompson), Isostatic uplift history and Holocene landforms (Larsen), Lake level history (Colman, Foster, Reynolds, King, Goldhaber, Forester), Paleoclimatic and paleolimnologic record (Forester, Colman, Jones, Keigwin), and Overview of the history of lake level--implications for the future (Colman, Hansel, Larsen, Thompson). Nine papers in the Processes section include: Bluff recession (Jibson), Beaches and nearshore (Wood, Chrzastowski, Shabica, Haines, Holman), Beach response (Hunter), Nearshore response (Booth, Winter), Models (Wood, Haines), Eolian processes (Olyphant, Thompson, Wood), Ice processes (Kempema, Barnes, Holman), Sediment budget: sources and sinks (Colman, Foster), Sediment budget: pathways and rates (Barnes, Jibson, Olyphant, Kempema, Wood, Chrzastowski, Shabica, Haines)

SUMMARY OF PAPERS PRESENTED AT THE WORKSHOP

Folger, D. W., Colman, S.M., Barnes, P. W.

FRAMEWORK

The geomorphology of the Illinois-Indiana coastline developed in response to glacial processes that formed the lake margin and, subsequently, to coastal processes that modified the margin by erosion and accretion. The 156-km coast can be divided into three provinces. The northernmost is the Zion beach-ridge plain that extends from the Wisconsin border southward into Illinois as far as the city of North Chicago. This province is 19 km long, has a maximum width of 1 km and, stratigraphically, contains sediments as thick as 11 m. The second province, the Lake Border morainal-bluff coast, extends for 25 km from North Chicago to Winnetka. The shoreline has eroded into end moraines of the Lake Border Morainic Complex, which are as high as 30 m. The bluffs decrease in height southward in the third province, the Chicago/Calumet lacustrine plain, which rims the southern margin of the lake. This stretch of coastline extends 112 km from Winnetka, IL to the Indiana-Michigan state line. The relief extends from low lying areas near lake level to the Indiana Dunes which are as much as 50 m higher. Fifty-eight percent of all uplands along the Illinois-Indiana coast range from 0-10 m in height. All of the Zion beach-ridge plain and most of the Chicago/Calumet lacustrine plain are no more than 5 m above the mean lake level.

Compiled and interpreted maps of lake bottom sediment texture and stratigraphy show that most of the Illinois and Indiana nearshore area is a dynamic environment; currents, induced by storm waves, transport fine sand and silt, resulting in a patchy, continually changing distribution of lacustrine sediment overlying a till-gravel pavement. Only north of Waukegan and Michigan City does silty sand completely cover Wadsworth Till. The nearshore sand wedge is thickest north of Waukegan and thins southward to Chicago. Large volumes of sand offshore are limited to complex northeast-trending

ridges formed at the outer margin of the sand wedge between Waukegan and Lake Forest. South of Lake Forest, the nearshore sand wedge is limited to within 300 m of the shoreline. Though several meters of sand are present in some areas of the bottom in Indiana Shoals, net erosion of the lake floor has taken place there over the last 20 years. West of Michigan City, the nearshore sand wedge is thin or absent. Thus, over much of the survey area, erosion or non-deposition has been taking place exposing the 10-40 m thick Wadsworth till or gravel-boulder lag deposits, and in some places the underlying Devonian shale or Silurian and Devonian carbonates.

Sand has been diverted and entrapped by harbors and lakefills along the Illinois shore depleting the supply of littoral sands for longshore drift. Over 10,000,000 m³ of sand are present in the Waukegan Harbor sand fillet but much less is present in all the remaining lakefills surveyed as far south as Northwestern University. Comparisons of sand thickness in several areas south of Waukegan reveal that from 1975 to 1991 sand has been greatly depleted, exposing the underlying clay-rich till to erosion.

LAKE LEVEL

Analyses of the stratigraphy of the late Quaternary sediments deposited in Lake Michigan provide a good record of the last major glacial advance and retreat, of at least two incursions of flood waters from glacial Lake Agassiz, and of drastically lowered lake levels when ice retreat opened the North Bay outlet draining the Lake Michigan to the Chippewa low, at least 80 m below its present level. The subsequent rise in water level from the Chippewa low to the Nipissing high is well documented by the distinctive, planar, transgressive Chippewa unconformity that left little evidence of intermediate lake-level positions. A dramatic change in conditions in the lake occurred after about 5 ka; ostracodes and mollusks are poorly preserved, eliminating many tools for reconstructing paleolimnologic conditions. However, short-term variations in grain size and magnetic properties of the sediments, over time periods of 200 to 500 years, may be due to lake level changes.

Before 5 ka, the complex response of lake level to isostatic changes in the elevation of the lake outlets and to climatic changes has been deciphered by analysis of various species of ostracodes, whose abundance and occurrence are related to lake volume and chemistry. Stable-isotope compositions of ostracodes and mollusks also reflect changes in lake volume, temperature, and chemistry. Five periods have been identified. Data for the oldest suggest a cold, dilute lake; then they indicate falling lake level probably coincident with the opening of North Bay but also a drier climate which may have been driving the ice retreat; the third period appears to be a cold, dilute, and transgressing lake probably in response to isostatic rebound; the fourth event appears to be a time of lake regression controlled mainly by drier climate; and the fifth event indicates an increase in solute concentration by climatic control and possible closure of the outlet as water inflow dropped below outflow. As already noted, the most recent changes in lake level cannot be determined with this technique because of the poor preservation of ostracodes after 5 ka.

Variations in paleomagnetic declination and inclination are largely coherent among core sites in southern Lake Michigan and with secular-variation curves from other North American sites. Tentative age assignments and correlations of strata can be achieved. Long-term (1,000-2,000 yr) variations in the character and concentration of magnetic minerals correspond with long-term lake-level changes that have been reconstructed from the effects of isostatic rebound, from the changes in drainage, and from shoreline features. Short-term variations (200-500 yr) in the concentrations and character of magnetic minerals may record short-term fluctuations in lake levels at a high degree of resolution not easily obtained by other methods.

Beach ridges have been mapped to provide a record of former water level positions through time. Where shorelines prograde extensive beachridge complexes may develop. The highest altitude of upper shoreface deposits in each beach ridge marks the position of maximum wave runup on the beach. Although differential isostatic uplift complicates the interpretation of beach ridge complexes in Lake Michigan and Lake Huron, this technique shows great promise of providing a reliable lake level curve when dating is complete and

records for different complexes are correlated.

PROCESSES

Between 1872 and 1987, rates of bluff retreat between Wilmette and Waukegan vary from 10 to 75 cm/yr between discrete segments of bluffs. The average rate of retreat for the entire area, however, does not vary significantly between 1872-1937 and 1937-1987 and ranges from 20-25 cm/yr. No obvious correlation appears to exist between lake levels, rainfall, abundance of groins, and retreat rate. Local variations in retreat rate do, however, correlate closely with lithologic variations. Bluffs that contain lake-plain sand and silt have higher retreat rates than clay-till bluffs. However, the bluffs have little curvature across these boundaries indicating that the variations average out over time, producing long-term parallel bluff retreat. New data from cone penetrometer tests are being combined with the recession data to generate a model that will predict the annual sediment contribution to the lake along the bluff.

The construction of a marina north of Waukegan has been carefully monitored because it interrupted the natural high (3 m/yr) erosion rate by initially extending the shoreline lakeward about 200 m in a fan delta containing 1.2 million m³ of dredged gravelly sand. After the marina area was fully excavated and surrounded by protective boulders, sediment supply to the fan delta ceased and rapid erosion ensued despite attempts to protect it. This eroded material is now the prime sediment supply for the Illinois coastal sand wedge. Because the marina area is now defended, reducing the former high erosion rate, once the fan delta is depleted nearshore erosion and shoreline recession to the south will increase dramatically.

A video documenting the formation of ice ridges and various processes of sediment transport by ice, lake bed erosion by standing waves, and ice volcano formation, concludes that ice alters coastal erosion patterns and does not protect the coast from erosion during winter.

The Nearshore Ice Complex (NIC) influences the effect of winter

storm waves by forcing them to expend their energy further lakeward. An erosional trough as much as 50 cm deep and 2-3 m wide often develops near the lakeward wall of the NIC. The re-directed wave energy results in lakebed scour and mobilization of sediments and may be related to the winter displacement of bars.

The importance of ice rafting in sediment transport away from the coast was evaluated along 33 km of shoreline from Chicago to Wilmette. Nine samples, recovered between 5-10 km offshore, contained an average of 1.13 gm/l of sediment, mainly sand. During another survey along a 34 km transect between Chicago and Burns Harbor, samples contained an average of only 0.05 g/l. Extrapolating the figures off Chicago suggests that 30 kg of sediment were carried offshore by ice for each meter of coastline during the study period. Along the 33 km stretch of coastline about 1000 tons of sediment were being rafted.

Another mechanism that appears to entrain significant quantities of sediment is anchor ice. During 15 of 30 observations days in January, 1991, anchor ice was being formed. Anchor ice consists of randomly-oriented ice "plates" that were from 1-40 cm in diameter and a few mm thick and covered up to 50% of the bottom. Twenty-five samples of this floating anchor ice contained an average of 27 g/l of sediment and entrained pebbles up to 7 mm in diameter. On one occasion divers observed a layer of anchor ice 10-50 cm thick that had floated up from the bottom and accumulated under surface ice. An estimate of the amount of sediment entrained on one day was 280 kg/m of shoreline.

Efforts to track ice transport with Woodhead Seabed Drifters suggested that two drift pathways were most common. One is alongshore to the south; the second is taken by ice that escapes the nearshore zone, is incorporated in the counterclockwise current pattern that dominates the southern part of the lake, and which may deposit material on the Michigan shore.

Most eolian sand movement in Indiana Dunes occurs in late fall and spring when wind speeds are still high but marram grass and snowcover are not abundant. One dune in this area has grown by 75 cm since studies began in the fall of 1990. Storm winds from the

north transport sand most effectively and produce blow-out areas. Moisture is the second most important factor relative to wind speed in controlling the volume of sand moved. Highest transport rate (>126 g/cm/hr) were observed at wind speeds of 7 m/s from the north under dry conditions. In contrast, transport was low (26 g/cm/hr) during almost equally strong southerly winds (6 m/s) because the sand surface was damp from precipitation during the storm which inhibited grain movement.

The equilibrium beach concept has been tested and refined by many workers for the case of rising water level which allows breaking waves to influence more of the upslope beach profile. The effect is to erode material from the backbeach and deposit it offshore. How the beach profile adjusts to falling water level, however, has not been well established. Agreement does exist that beach and nearshore profiles respond on a much longer time scale than that of mean annual lake level fluctuations and that the equilibrium beach concept may not be applicable for predicting nearshore response to short-term water-level changes, particularly those associated with falling water level. Current research efforts are directed at the generation of models of beach response to synthetic quasi-random lake-level predictions.

Considering the uncertainties, initial efforts to quantify the sediment budget for southern Lake Michigan have been remarkably successful. Sediment sources are bluffs, rivers, aerosols, and basin import/export; sediment sinks include the lake basin, nearshore sand, beaches, and dunes. During the last 100 years, when best data are available, the primary source of sediment is bluff erosion and the primary sink is deposition in the deep basin. The budget nearly balances at 3×10^6 MT/yr. About half the sand derived from bluff erosion is deposited in the modern lake sediments. The other half appears to be deposited nearshore, and on beaches and dunes. For periods farther back in time the sediment sinks can be estimated fairly well but the sources are more difficult to evaluate.

All raw data and as much interpreted data as possible will be assembled in a Geographic Information System (GIS) and subsequently distributed in a CD-ROM to the Great Lakes user

community. All available raw data are to be submitted to the GIS team by mid-May for release as a USGS Open File Report in July. Interpreted data and the remaining raw data are to be submitted to the GIS team by mid-September for input to the CD-ROM in mid-November for release in December.

AGENDA

4th ANNUAL WORKSHOP

**SOUTHERN LAKE MICHIGAN COASTAL EROSION
STUDY**

USGS CENTER FOR COASTAL GEOLOGY

St. Petersburg, FL

February 4-6, 1992

Purpose: To review and integrate all aspects of the study for
presentation in a symposium volume.

TUESDAY

February 4, 1992

Introductory Comments

0830 Status of USGS coastal studies Abby Sallenger
0845 Agenda for the workshop Dave Folger

Review of Work Accomplished

GEOLOGIC FRAMEWORK

0900 Coastal Geomorphology of the Illinois
and Indiana shore of Lake Michigan Mike Chrzastowski
0930 The stratigraphic framework and bottom
sediment texture of the southern Lake
Michigan nearshore area Dave Foster
1000 Coffee Break
1015 Beach and nearshore sand thickness
and volume, Illinois and
Indiana shorelines Charlie Shabica
1045 Southern Lake Michigan GIS and
CD ROM demonstration Chris Polloni
Carol Brown
1145 Discussion
1200 Lunch

TUESDAY

February 4, 1992 (Con't)

LAKE LEVEL CHANGE

- | | |
|--|---------------|
| 1300 Introduction | Steve Colman |
| 1315 Deep lake sediments: stratigraphy,
chronology, relation to lake levels | Steve Colman |
| 1345 Sediment magnetism and
paleomagnetism as indicators of
lake-level and environmental change | Rich Reynolds |
| 1415 Paleolimnologic and paleoclimatic
record in the sediments of
the deep part of the lake | Rick Forester |
| 1445 Isostatic uplift and its constraints
on the timing and correlation of high
relative lake levels | Curt Larsen |
| 1515 Coffee | |

1530 Discussion of unresolved lake-level problems

Mike Chrzastowski
Steve Colman
Todd Thompson
Rick Forester
Curt Larsen

- A. The Algonquin stage in southern Lake Michigan
- B. The level of the Chippewa low stage
- C. The influence of Lake Agassiz flood influx
- D. Identification of Nipissing and Algoma levels throughout the basin
- E. The timing of post-Nipissing beach-ridge development

1700 Adjourn

WEDNESDAY

February 5, 1992

PROCESSES

0830 Introduction

Peter Barnes

0845 Rates and processes of bluff retreat along the Lake Michigan shoreline in Illinois

Randy Jibson

0915 Coastal processes at North Point Marina and littoral drift observations

Mike Chrzastowski

0945 Discussion

1000 Coffee

1015 Nearshore wave dynamics in the presence of ice	John Haines
1045 Discussion	
1100 Coastal ice regime and related erosion and sediment transport, southern Lake Michigan: a video	Peter Barnes
1130 Anchor ice formation and sediment transport by ice rafting	Ed Kempema
1200 Lunch	
1300 Contemporary eolian sand transport in the backshore-foredune area of south shore, Lake Michigan	Greg Olyphant
1330 Modeling coastal response to lake level change	Bill Wood
1400 Sediment budget: sources, pathways, and sinks	Steve Colman Dave Foster
1430 Discussion	
1500 Coffee	

COASTAL WETLANDS RESEARCH PROGRAM

1515 Introduction	Jeff Williams
1530 Crustal rebound	Curt Larsen
1550 Ridge-swale framework	Todd Thompson
1610 Lake Michigan assessment	Jerry Shideler
1630 Lake Erie evolution	Norrie Robbins
1650 Discussion	
1715 Adjourn	

THURSDAY

February 6, 1991

Data Integration, Synthesis, and Presentation

0830 Options for publication, length, and character of the symposium volume	Dave Folger
0900 Design and schedule for final product assembly and presentation	Dave Folger
0930 Plan for integration of papers	Steve Colman Peter Barnes Mike Chrzastowski
1000 Coffee	

1015 Discussion-Resolution of remaining
scientific inconsistencies or unresolved
problems

Steve Colman
Peter Barnes

1200 Lunch

1300 Group discussions

Framework

Dave Folger

Lake Level

Steve Colman

Processes

Peter Barnes

1500 Adjourn

LIST OF ATTENDEES

USGS

Barnes

Brown

Colman

Folger

Forester

Foster

Jibson

Haines

Larsen

Polloni

Reynolds

Robbins

Sallenger

Shideler

Williams

ILLINOIS

Chrzastowski

Pranschke

Shabica

INDIANA

Baedke

Bennett

Olyphant

Thompson

Wood

WASHINGTON

Kempema

ABSTRACTS

COASTAL GEOMORPHIC CHARACTERISTICS OF THE ILLINOIS-INDIANA COAST OF SOUTHERN LAKE MICHIGAN

Michael J. Chrzastowski

Illinois State Geological Survey, Champaign IL

The geomorphology of the Illinois-Indiana coast represents both glacial processes that formed the lake margin and coastal processes that have modified the lake margin by erosion and accretion. The 156 km coast is divisible into three coastal-geomorphic settings (Fig. 1).

The northernmost setting is the Zion beach-ridge plain which extends from the Illinois-Wisconsin line southward for 19 km to the city of North Chicago. This accretionary plain consists of beach ridges with low-lying dunes and inter-ridge coastal wetlands. Maximum width of this gravelly sand body is 1 km. Maximum thickness is 11 m along the present shore; thickness diminishes both landward and lakeward. The plain is a migratory body moving southward by littoral transport processes. Erosion along the northern (updrift) reach of the plain and accretion along the southern (downdrift) reach has resulted in a southward migration in a "tank-tread" fashion. Radiocarbon dating of inter-ridge basal peats shows that this plain first advanced across the Illinois-Wisconsin state line about 3700 BP.

South of the beach-ridge plain, extending 25 km from North Chicago to Winnetka, IL is the Lake Border morainal-bluff coast along which the coast intercepts end moraines of the Lake Border Morainic Complex. Bluffs of decreasing height continue south of Winnetka for an additional 8 km to Evanston, IL. This reach of low bluffs is the northernmost extent of the Chicago/Calumet lacustrine plain that rims the southern margin of the lake. This plain is the largest of the three coastal settings along this coast, extending 112 km from Winnetka, IL to the Indiana-Michigan state line. This is a glacially formed plain that was submerged to varying degrees and for varied intervals during high lake phases since late Wisconsinan time.

Within 1 km of the coast, upland relief varies from low-lying coastal reaches no more than 3 or 4 m above mean lake level such as

along the Zion beach-ridge plain, to localized occurrence along the Indiana coast of uplands as much as 50 m above mean lake level. All upland more than 10 m above mean lake level on the Illinois coast occurs as morainal bluffs, whereas all upland above this range on the Indiana coast occurs as coastal dunes. Fifty-eight percent of all uplands along the Illinois-Indiana coast range from 0 to 10 m in height. Nearly all of the Zion beach-ridge plain and most of the Chicago/Calumet lacustrine plain are no more than 5 m above mean lake level (Fig. 1).

A coastal classification scheme particularly applicable to the Illinois-Indiana coast is that of Shephard (1937, 1963) which focuses on the form and stage of coastal development. This is a genetic classification, distinguishing coasts according to whether they have been shaped mainly by terrestrial processes (primary or youthful coasts), or by coastal processes (secondary or mature coasts).

Based on the Shepard classification, the Illinois-Indiana coast can be divided into three zones, two of which lie entirely in Illinois (Fig. 2). Secondary coasts occur along the Zion beach-ridge plain and all of the Chicago/Calumet lacustrine plain except for its northern reach of low bluffs from Winnetka to northern Evanston. Between North Chicago and northern Evanston is a primary coast. Although wave erosion has modified this coast and substantial shore and bluff erosion has occurred, the overall shoreline configuration mimics the axes of the Lake Border moraines, and thus the coastal form is primarily influenced by the glacial-depositional history.

An alternate coastal classification scheme proposed by Valentin (1952, 1969) distinguishes advancing coasts (due to emergence or accretion) from retreating coasts (due to submergence or erosion). Considering the natural (i.e., pre-development) coastal setting, the Illinois-Indiana coast is divisible into two accretionary and two erosional zones (Fig. 3). The Zion beach-ridge plain is an erosional coast in its northern reach, and an accretionary coast in its southern reach. An erosional coast persisted along the remainder of the Illinois coast and across the state line into Indiana. The erosional

character of the coast along Chicago and into northwestern Indiana is documented on historical surficial geology maps showing the truncation of relict beach ridges by the modern shoreline. The transition to an accretionary coast occurred in western Gary at about the location of Buffington Harbor. The remainder of the Indiana coast is accretionary. This accretionary reach includes the pre-development zone of net convergence for littoral transport from the western and eastern shore of southern Lake Michigan. This convergence zone is documented on historical maps by the eastern deflection of the mouth of the Grand Calumet River at eastern Gary, IN, and the westward deflection of the mouth of Trail Creek at Michigan City, IN.

REFERENCES

Shepard, F. P., 1937, Revised classification of marine shorelines: *J. Geology*, v. 45, p. 602-624.

Shepard, F. P., 1963, *Submarine Geology*, 2nd edition: Harper Row, New York, N. Y., 557 p.

Valentin, H. 1952, *Die Kusten der Erde: Petermans Geog. Mitt. Erg.* 246, Gotha, Justus Perthes, 118 p.

Valentin, H. 1969, Principles of a handbook on regional coastal geomorphology of the world: *Zeitschr. Geomorphologie*, N. F., 13, 124-129.

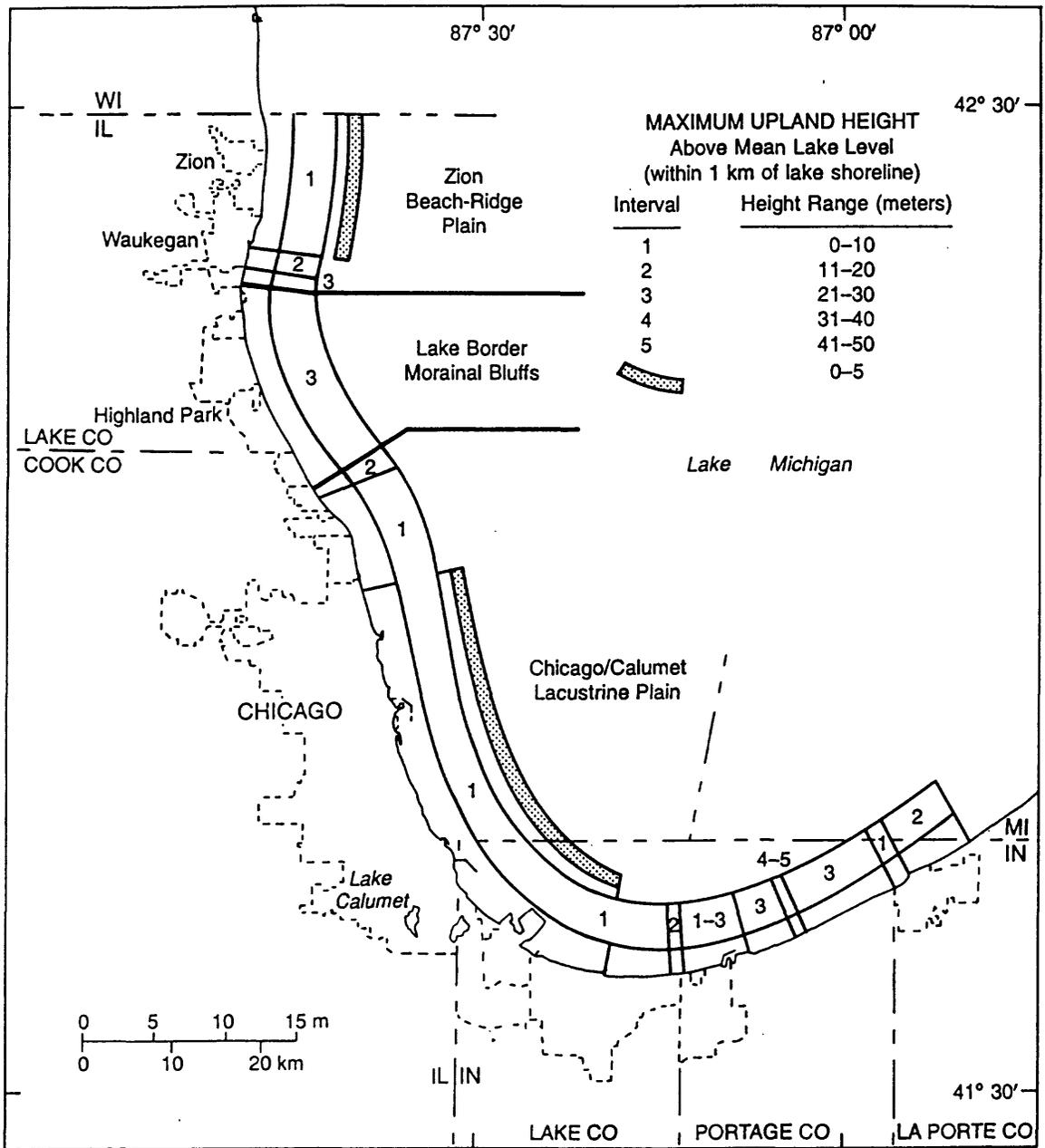


Figure 1. Division of coastal geomorphic settings along the Illinois-Indiana coast and generalized relief along the coastal margin.

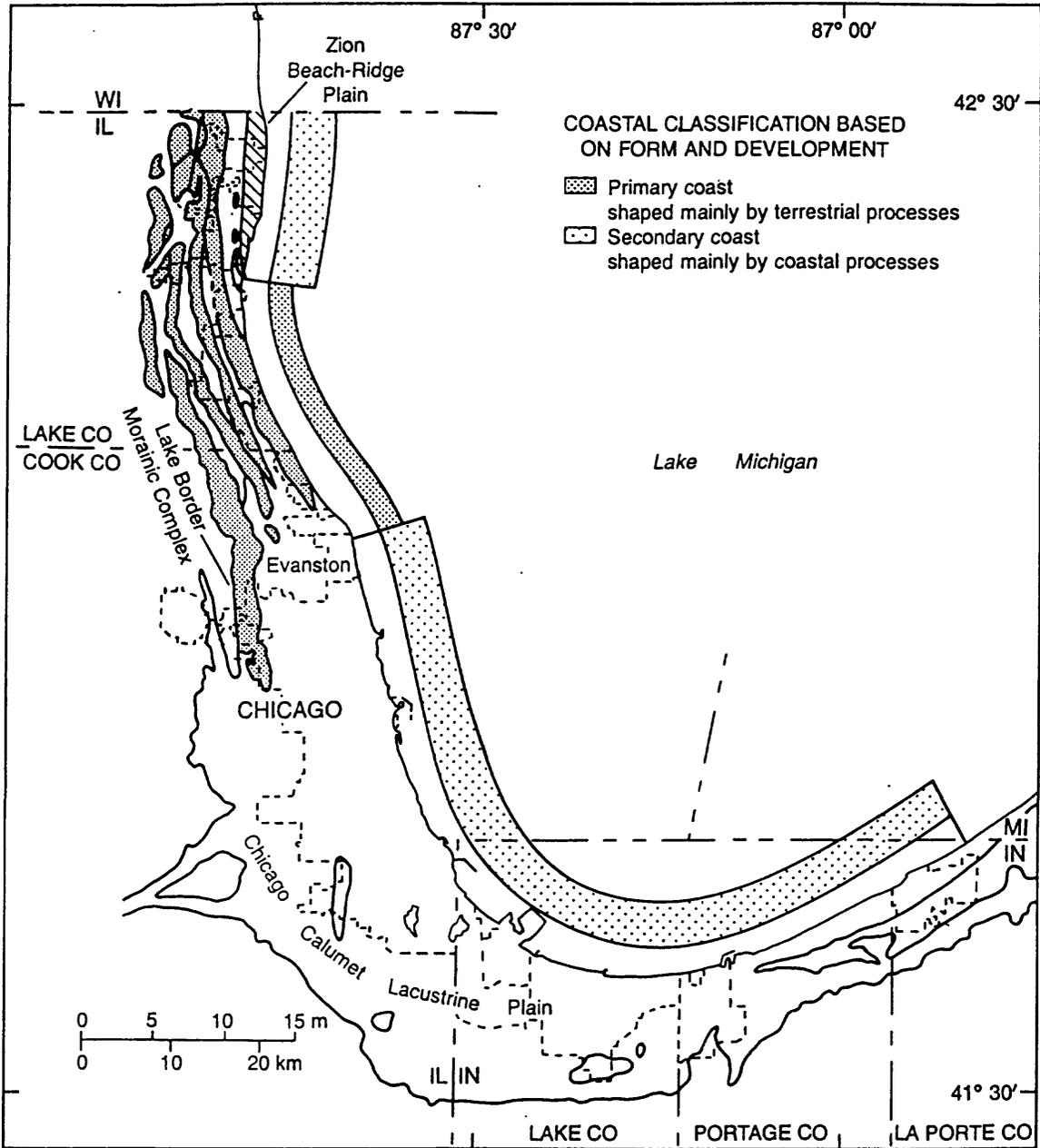


Figure 2. Coastal classification of the Illinois-Indiana coast based on coastal form and development according to the classification scheme of Shepard (1937, 1963).

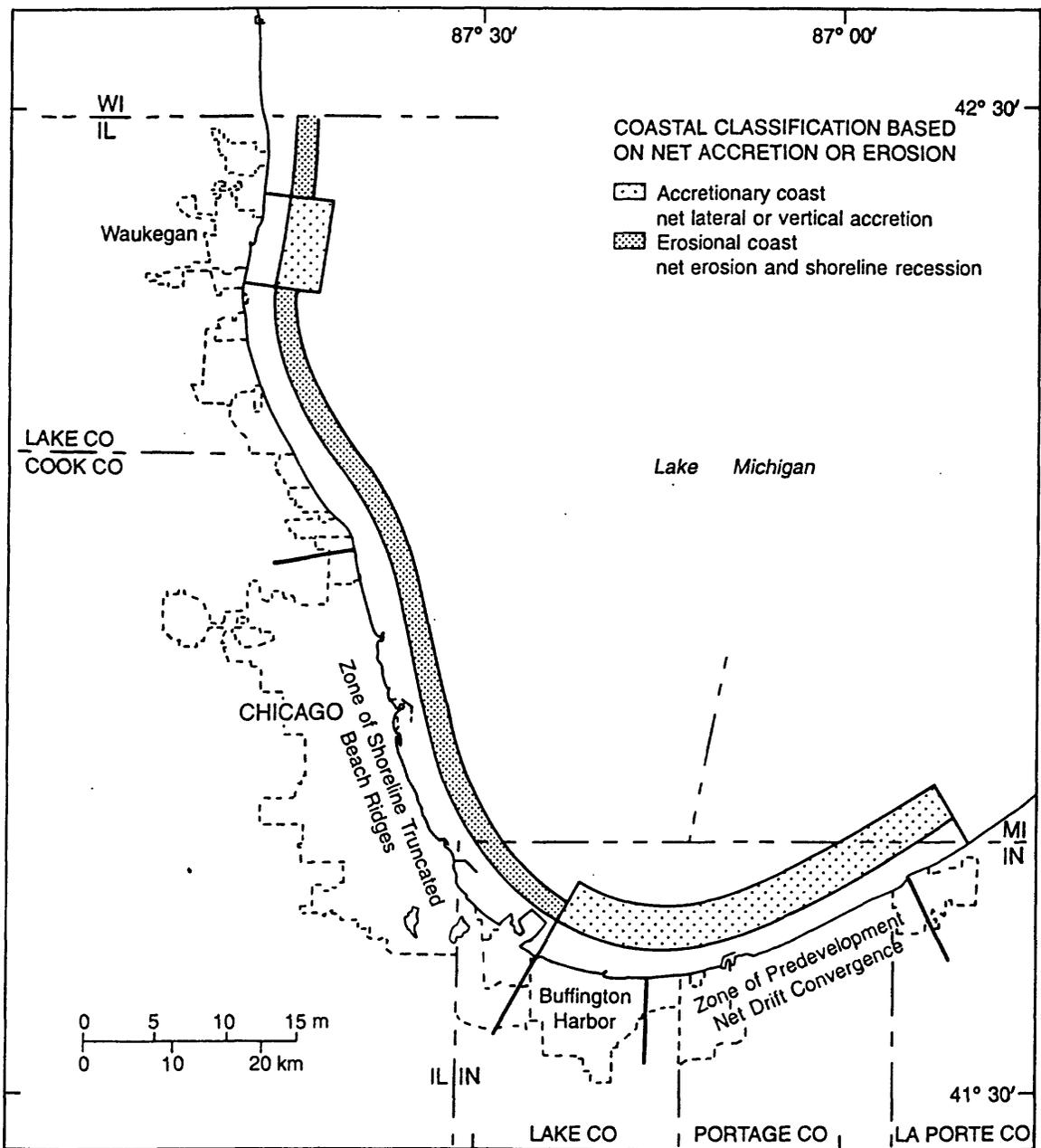


Figure 3. Coastal classification of the Illinois-Indiana coast based on shoreline accretion or erosion according to the classification scheme of Valentin (1952, 1969).

THE STRATIGRAPHIC FRAMEWORK AND DISTRIBUTION OF BOTTOM SEDIMENT TEXTURE--SOUTHERN LAKE MICHIGAN

Foster, D. S., Folger, D. W., Polloni, C. F., Brown, C. L.
U. S. Geological Survey, Woods Hole, MA 02543

To define the geologic framework of the southern Lake Michigan area we conducted acoustic surveys along 25 tracklines normal to the shoreline that are 18 km long and two shore-parallel tie lines as long as 150 km. To map the bedrock surface and Quaternary sediment thickness we ran boomer seismic reflection profiles; and to map bottom sediment distribution and shallow stratigraphy we ran 3.5 kHz seismic reflection, sidescan sonar, and echosounding profiles and collected bottom sediment samples. Detailed surveys with line spacing as close as 50 m were carried out at Indiana Shoals and the Olson tree site, and off Fort Sheridan, Grosse Point, Wilmette, and Michigan City (Fig. 1).

Bathymetric profiles show that south of Waukegan as far as the Indiana border, the lake floor of nearshore Lake Michigan forms a broad, gently dipping (1:770) slope that attains a maximum depth of about 24 m at the lakeward end of our profiles (18.5 km offshore). In the Indiana Shoals area, bathymetric ridges are as much as 3 m high, spaced 100-300 m apart, trend north-northeast. The ridges are common between Indiana Shoals out as far as 15 km east of Chicago. In contrast to the gently dipping shelf, north of Waukegan an abrupt break in slope occurs about 4.5 km offshore, increasing the gradient to about 1:240. Water is as much as 77 m deep 18.5 km offshore. East of Gary, Indiana, a steep ramp has developed nearshore; water increases in depth from 0 to 15 m within a distance of 1 km from shore producing a slope of 1:67. The slope is more gentle offshore and water is only 25 m deep 18.5 km offshore (slope 1:740); however, to the east, off Michigan City, the water is 47 m deep 18.5 km offshore (slope 1:400).

Glacial till overlies bedrock beneath the entire offshore area of Illinois and Indiana. The till fills bedrock valleys and buries bedrock highs resulting in the relatively smooth lake floor. Bedrock crops

out only in a few small areas of the lake floor between Waukegan and Chicago where the till is commonly less than 10 m thick. To the east, off Michigan City, the till thickens to 40 m.

Beneath the till and postglacial lacustrine deposits, strong seismic reflections are interpreted as the upper surface of Silurian and Devonian carbonates or Devonian shale. The shale overlies the carbonates beneath most of the Indiana nearshore area. It correlates with shale that is exposed on the bottom of eastern Lake Michigan north of Michigan City. West of Indiana Shoals, the shale is patchy occurring most often in broad valleys in the carbonate surface.

The regional survey shows that most of the lake floor in the area studied is characterized by non-deposition or erosion except north of Waukegan and Michigan City. South of Waukegan to Indiana Harbor, bottom sediment consists mainly of Wadsworth till with patches of sand, lag gravel, cobbles, and occasional boulders. Non-deposition or erosion is widespread. North of Waukegan a continuous layer of sand, at least 2 m thick, covers the till. East of Indiana Harbor, a thin (<30 cm) layer of silty sand and sandy silt more completely covers the Wadsworth till. The sand does not thicken shoreward and till crops out even nearshore.

A wedge of sand covers the bottom within 1-2 km of the shore between Waukegan and Lake Forest; it thins lakeward to a patchy veneer. The outer margin of the sand wedge is complex. Two northeasterly-trending sand ridges that are about 4 km long and 0.5 to 1 km wide overlie cobble pavement. The ridges are asymmetric in profile and reveal the direction of sand movement at the time our surveys were conducted. Their geometry suggests that these sand bodies are large, flat, southward-moving dunes. They thicken from a feather edge on the northwestern edge to a maximum of about 2 m on the southeastern steeply dipping edge. South of Lake Forest, the sand wedge is closer to shore and less sand is present offshore.

Sidescan mosaics show that the variability of bottom sediment texture is far more complex than can be interpreted from the regional, widely spaced survey lines. Off Fort Sheridan, Wilmette, and Grosse Pointe, in 0.7 by 5 km areas, a cobble till pavement is

covered with a few patches of thin sand; the nearshore sand wedge apparently feathers out lakeward within 300-400 m of shore. However, at Indiana Shoals in a 3 by 4.5 km area, coarse sand, gravel, and cobbles cover about half of the bottom. North-trending ridges are covered by coarse sand and gravel that is sometimes overlain by fine to medium sand. The thickness of sand deposited on the ridges varies from thick to thin; thus the ridges are, at least in part, of relict origin. To the east, off Michigan City, a detailed survey of a 0.7 by 10 km area revealed a complex distribution of postglacial lacustrine silty sand and sandy silt overlying Wadsworth till.

The southern feather edge of the Lake Michigan Formation can be traced across the survey area. It thickens to a maximum of 16 m about 40 km to the northeast. In contrast, to the west, postglacial deposits are thin and patchy exposing pebbly-silty clays of Wadsworth till and coarser lag deposits. Nearshore the sand wedge is less than 1 m thick and exposed till forms a surface of complex ridges and pinnacles.

In summary, stratigraphic and bottom sediment texture maps show that most of the Illinois and Indiana nearshore area is a dynamic environment; storm wave-induced currents transport fine sand and silt resulting in a patchy, continually changing, distribution of lacustrine sediment overlying a till-gravel pavement. Only north of Waukegan and Michigan City does silty sand completely cover Wadsworth till. The nearshore sand wedge is thickest north of Waukegan and becomes thinner southward to Chicago. Large volumes of sand offshore are limited to complex northeast-trending ridges formed at the outer margin of the sand wedge between Waukegan and Lake Forest. South of Lake Forest the nearshore sand wedge is limited to within 300 m of the shoreline. Though several meters of sand are present in some areas of the bottom in Indiana Shoals, net erosion of the lake floor has taken place there over the last 20 years. West of Michigan City, the nearshore sand wedge is thin or absent. Thus erosion or non-deposition has been taking place over much of the survey area, exposing the 10-40 m thick Wadsworth till or gravel-boulder lag deposits, and, in a few places, the underlying Devonian shale or Silurian and Devonian carbonates.

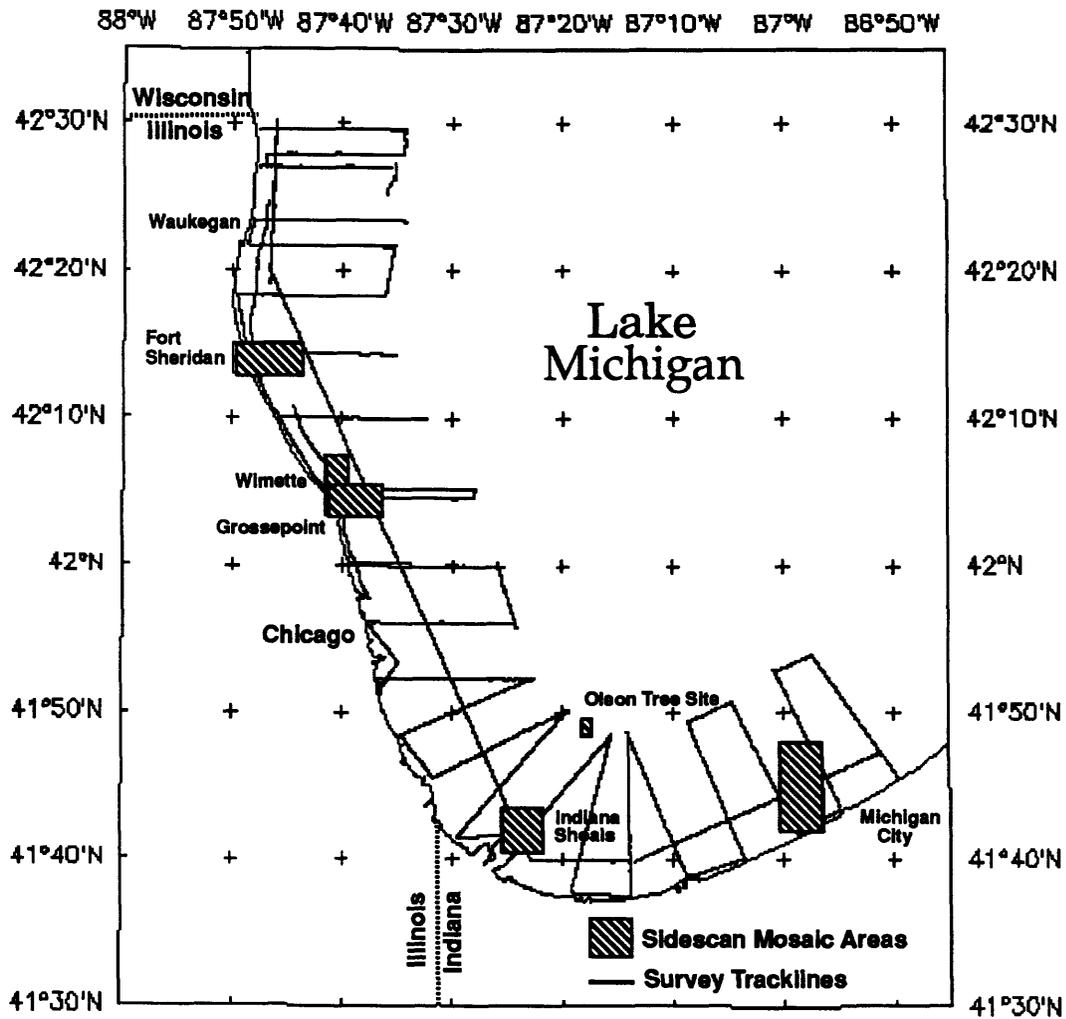


Figure 1. Map showing acoustic survey tracklines and detailed survey areas (sidescan mosaic areas).

SURVEY OF LITTORAL DRIFT SAND DEPOSITS ALONG THE ILLINOIS SHORE OF LAKE MICHIGAN

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Forty profiles of beach and lake bottom sand deposits were measured in 1989, 1990, and 1991 using a hydraulic probe at 400 locations on the Illinois shore of Lake Michigan from Winthrop Harbor to Evanston. Ten new profiles will be surveyed along the Indiana lake shore during the spring of 1992. Profiles were run from shore to the lakeward edge of the sand. These profiles extended typically 1750 ft or 535 m offshore south of the Great Lakes Training Center, or to a point where sand plus water depth exceeded the probe depth limit of about 38 ft or 11.6 m. These data were compared to data collected by the Illinois State Geological Survey in 1975 and by the Chicago Park District in 1989 (Table 1). Results show that thick deposits of sand are present north of Waukegan Harbor (Fig. 1), and that greatly depleted deposits of very fine sand covering glacial clay tills to the south (Fig. 2). In many areas south of Waukegan Harbor the sand veneer has been lost entirely, exposing the underlying clay to the erosive forces of storm waves. On almost all profiles sand deposits are thin near the shoreline. Table 2 lists some of the profile locations. Sand quantities calculated for each profile are averaged over the length of shoreline between adjacent profiles. Results are tabulated as "sand volume per shore length". Note the high quantities of sand north of Waukegan Harbor. Profiles immediately to the south show offshore sands diverted by Waukegan Harbor (Fig. 3). Trends of sand volume along the Illinois shore from Winthrop Harbor south to Wilmette are shown in Figure 4. An isopach will be constructed to display the sand volume distribution.

Sites resurveyed after one year (Fig. 2) show similar sand profiles, but in some areas anomalous variations in sand thickness exist. We think that lakebed erosion does not account for these observations. They may be artifacts due small offsets in the position of the profiles along the highly variable lakebed topography below the sand blanket.

In the spring of 1992, we intend to place steel rods in the lakebed along ten transects where the sand veneer is thin or non-existent. These transects will be monitored annually for evidence of lakebed erosion.

Lake Bluff - Arden Shore 08/27/91 Date:08/27/91 Time:

Enter lake surface 578.58 elevation for time of survey

Enter Graph: DATA A DATA B DATA C

Enter Dist. From Shore	Enter Water Depth	Enter Sand Thickness	Top of Sand Elev. 1991	Bottom of Sand Elev. 1991	Enter Sand Thick. 1975	Top of sand 1975	Enter Hard-pan Type	Sand Volume Cu.Yd. 1975	Per ft. 1991	
-25.0	0.0	0.0	578.6	578.6		578.6	Riprap	0.0	0.0	
0.0	0.0	0.0	578.6	578.6	NOT ENTERED AS YET	578.6	Riprap	0.0	0.0	
25.0	2.0	0.0	576.6	576.6		576.6	Rock&Sand	0.0	0.0	
50.0	4.0	2.0	574.6	572.6		572.6	Rock&Clay	0.0	2.8	
100.0	8.0	3.0	570.6	567.6		567.6	Rock&Clay	0.0	5.6	
150.0	9.0	0.0	569.6	569.6		569.6	Rock&Clay	0.0	0.0	
248.0	10.0	0.0	568.6	568.6		568.6	Rock&Clay	0.0	0.0	
495.0	12.0	0.0	566.6	566.6		566.6	Rock&Clay	0.0	0.0	
735.0	14.0	0.0	564.6	564.6		564.6	Rock&Clay	0.0	0.0	
1019.0	16.0	0.0	562.6	562.6		562.6	Rock&Clay	0.0	0.0	
1260.0	18.0	0.0	560.6	560.6		560.6	Rock&Clay	0.0	0.0	
1501.0	18.0	0.0	560.6	560.6		560.6	Rock&Clay	0.0	0.0	
1748.0	18.0	3.0	560.6	557.6		557.6	Rock&Clay	0.0	27.7	
2000.0	19.0	6.0	559.6	553.6		553.6	Rock&Clay	0.0	55.8	
2250.0			578.6	578.6		578.6	Rock&Clay	0.0	0.0	
0.0			578.6	578.6		578.6		0.0	0.0	
0.0										
TOTAL								0.0	91.8	
Note all measurements in feet								CuYd/ft 1975	CuYd/ft 1991	

Table 1. Data sheet

Lake Michigan Nearshore Sand Deposits
Zion - Shiloh Blvd. 8/15/91
(Cross-section Sand Volume: 898 CuYd/Ft)

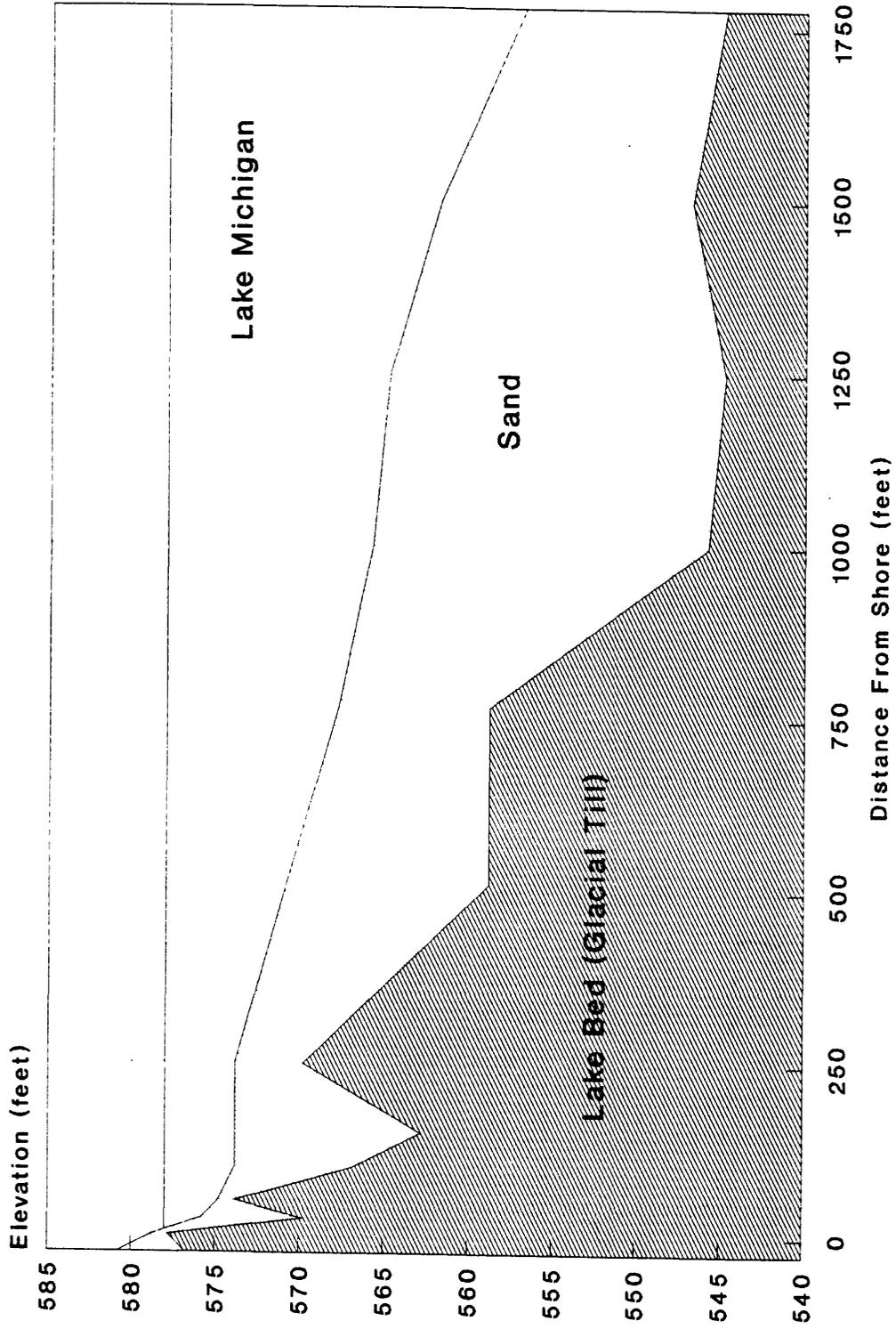


Figure 1. One of 40 cross-sections

Highland Park Ravine Avenue 6/27/89 And 8/29/91

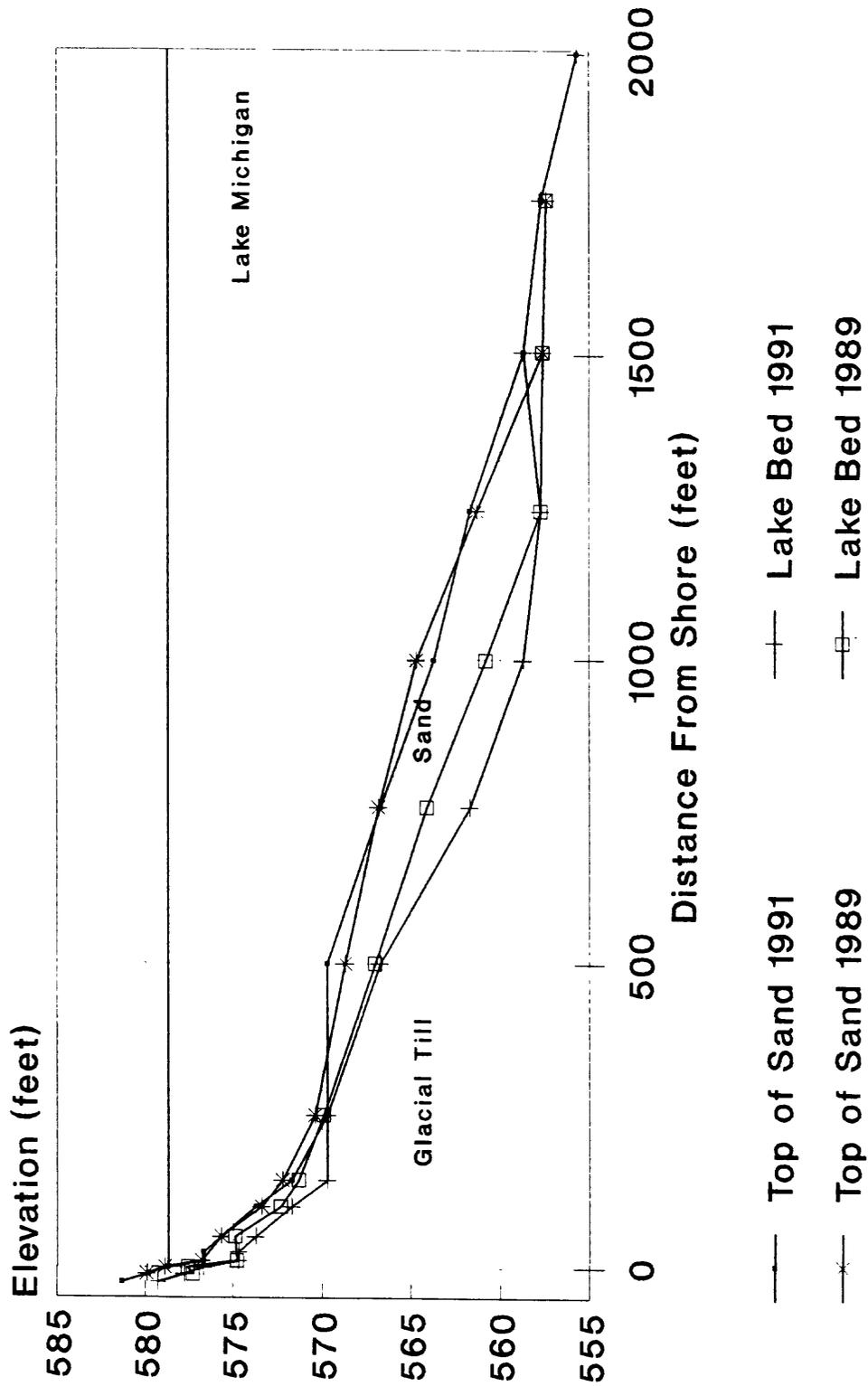


Figure 2. Same profile; 2 year interval

Lake Michigan Nearshore Sand Deposits
Lake Bluff Arden Shore 08/27/91

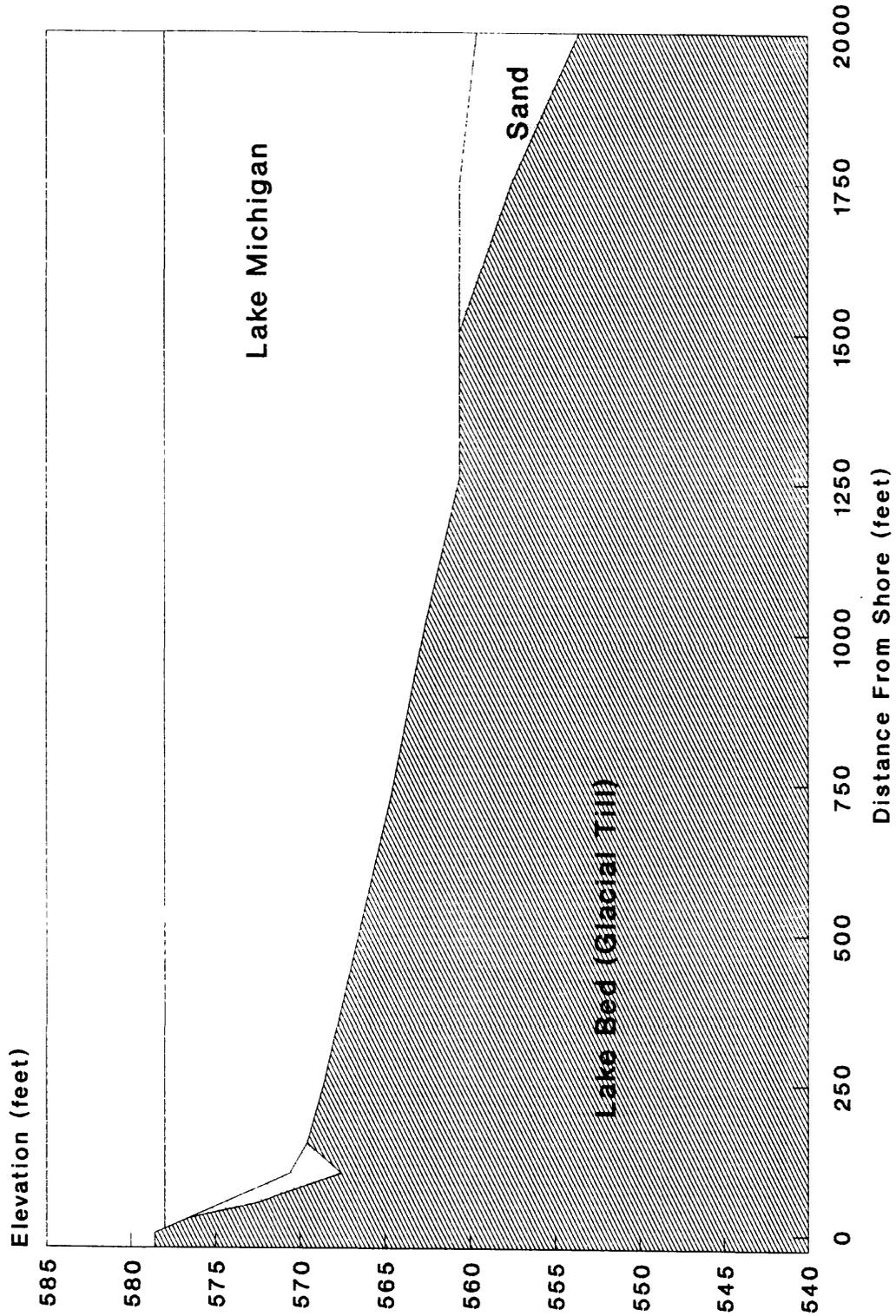


Figure 3. Cross-Section Sand Volume 91.8 CuYd/Ft

Profile Location	Enter Offshore Limit of Transect	Enter Profile Date	Enter State Plane Coord North	Enter State Plane Coord East	Shore Length Feet	Enter Sand Volume CuYd/ft	Sand Vol. per shore of Length	Sand Thick. (Ft.) at end of pro- file
State Line Rock	No Data		2122526	642757				
1 Winthrop Hbr. N. Beach	2000'	08/13/91	2122000	642763	1,064	837	890,150	2
2 Winthrop Hbr. N. Breakwater	1750'	08/13/91	2120925	644252	2,050	454	930,495	7
3 Winthrop Hbr. Sta 47	1750'	08/14/91	2117900	644078	3,056	374	1,142,638	5
4 Camp Logan Bulkhead	1750'	08/14/91	2114813	644486	4,195	657	2,755,367	9
5 Zion 21st. Street	1500'	08/15/91	2109511	644011	3,951	720	2,846,300	13
1 6 Zion Shiloh Blvd. Approx	1750'	08/15/91	2106911		4,415	898	3,965,104	12
7 Zion IL Beach Bath House	2000'	08/16/91	2100682	642890	4,578	937	4,290,959	12
8 Zion IL Beach Lodge	2000'	08/16/91	2097755	642906	4,017	857	3,440,534	12
9 Zion Dead River	2000'	08/16/91	2092649	642832	7,329	987	7,232,257	17
10 Waukegan Greenwood Ave. Appr	2000'	09/02/91	2083097		7,267	1495	10,862,691	20
10A Waukegan Hbr. Seahorse Dr.	2500'	07/22/90	2078116	640315	6,798	1759	11,953,404	16
10B Waukegan S. Cummings Ave.	3750'	07/25/90	2069502	636958	7,958	593	4,715,911	6
11 North Chicago FBI Range	2000'	08/27/91	2062200		6,226	206	1,281,311	5
11C GLTC North	2000'	07/23/90	2057050	636151	4,613	654	3,014,730	0
11D Lake Bluff Shore Acres	3000'	07/23/90	2052975	635005	3,425	462	1,582,008	4
3 12 Lake Bluff Arden Shore	2000'	08/27/91	2050200		4,467	92	410,025	6
12E Lake Bluff Sunrise Park	2000'	07/24/90	2044042	636587	9,250	15	135,975	0
13 Lake Forest Mayflower Ave.	2000'	08/27/91	2031700		9,971	25	245,287	0
13F Fort Sheridan Boat Launch	2000'	07/24/90	2024100		7,250	29	210,250	0
13G Highwood Waterworks	1750'	06/26/89	2017200		6,200	197	1,223,260	0
14 Highland Park Waterworks 2	2000'	08/28/91	2011700		4,350	292	1,271,940	2
2 15 Highland Park Ravine 2	2000'	08/28/91	2008500		3,850	173	665,280	0
16 Highland Park Rosewood	2000'	08/28/91	2004000		5,000	100	498,000	0
17 Glencoe Harbor Ave.	2000'	08/29/91	1998500		5,250	326	1,709,925	0
17J Glencoe Beach	2000'	08/14/90	1993500		6,400	107	685,440	0
17K Winnetka Tower Rd.	2000'	08/15/90	1985700		5,750		0	1
18 Winnetka Elm St.	2000'	09/13/91	1982000		3,250	200	650,000	0
18N Winnetka Elder Lane	1750'	06/27/89	1979200		2,350		0	2
18N Kenilworth Waterworks	2000'	06/26/89	1977300		2,350		0	4
19 Wilmette Langdon Park	2000'	09/15/91	1974500		2,200	295	648,340	1
19O Wilmette Gilson Park	1750'	08/15/90	1972900		1,400		0	0
19P Wilmette Gilson Pier	1750'	07/11/89	1971700		2,100		0	0
19Q Evanston North	3000'	06/27/89	1968700		3,250		0	0
19R Evanston Northwestern Beach	1750'	08/16/90	1965200		2,000		0	0
19S Evanston Northwestern Lakefill	1250'	06/27/89	1964700		2,000		0	0
19T Evanston Northwestern Beach S.	3000'	08/16/90	1961200		2,700		0	1
20U Evanston Lake St.	2000'	06/30/89	1959300		2,350		0	0
20 Evanston Lee Street	2000'	09/15/91	1956500		3,500	341	1,192,450	0
21 Evanston Calvary Cemetary Chicago Line	2000'	09/15/91	1952300 1951600		2,450		0	0
Total Volume of Sand (CuYd) North of Waukegan Harbor							50,309,899 ++	
Total Volume of Sand (CuYd) South of Waukegan Harbor							20,140,130	

OTHER PROFILES

14H Highland Park Waterworks 1	06/14/83	2011700	2,750	NO	0
15I Highland Park Ravine 1	06/27/89	2008500	1,600	NO	0

Table 2-Littoral drift sand deposits along the Illinois and Indiana shores of Lake Michigan DRAFT worksheet 1/14/92, Indiana data pending

SEDIMENT ENTRAPMENT BY COASTAL STRUCTURES ALONG THE ILLINOIS SHORE OF LAKE MICHIGAN

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Sand diversion and entrapment by harbors and lakefills are acknowledged to be important causes for depletion of the littoral sands along the Illinois shore of Lake Michigan north of Chicago. Until now, estimates of material trapped as sand fillets by structural barriers have been based mainly on maps and air photos. Little core or drill data, necessary for detailed estimates, are available.

In a preliminary survey, sponsored by Illinois/Indiana Sea Grant, Northeastern Illinois University and the U. S. Geological Survey, thicknesses of beach and lake bottom sands adjacent to structural barriers were measured using a hydraulic probe. Locations include Waukegan Harbor, Great Lakes Naval Training Center, Forest Park Beach in Lake Forest, Highland Park Waterworks, Winnetka Waterworks, Wilmette Harbor, and Northwestern University lakefill.

Results show that the Waukegan Harbor sand fillet contains more than 12,000,000 cubic yards of sand. Substantially lesser amounts were found at the remaining barriers, all of which are downdrift from Waukegan Harbor.

THE SOUTHERN LAKE MICHIGAN COASTAL EROSION STUDY CD-ROM

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The Geographic Information System (GIS) Laboratory in Woods Hole has generated maps for the Southern Lake Michigan Coastal Erosion Study. The GIS combines photo imagery, sidescan-sonar, bathymetry, geophysical profiles, sampling data, and interpretative maps and graphs, all of which can be displayed as graphic overlays. Because the requirements to compile a GIS are similar to those for the development of a useful CD-ROM, we shall be able to produce the CD-ROM for the Southern Lake Michigan Study soon after we receive input in the GIS format from all the participants.

All data for inclusion on the CD-ROM will be accepted as either an Arc/Info export file or an ASCII flat file. ASCII flat files must be placed in the first two fields as longitude (must have a negative sign) and latitude; all other data are in the remaining fields. All fields must be delimited by a blank space. All position data, regardless of format, must be in decimal degrees. Data can be shipped to AMG on DOS or Macintosh-compatible floppy disks or 8 mm or 9-track tape. Non-digital graphics and photographs can be scanned at AMG if a clean, positive copy is provided.

We have focussed on the manipulation and display of data with DOS-compatible software because about 80% of all CD-ROMS are DOS-based. The ISO-9660 CD-ROM file structure is also readable by MAC, UNIX, VMS, and most other systems. All files can be accessed and copied from the CD-ROM for use on any of these systems. The software provided in the CD-ROM gives the user great flexibility for analysis and display.

We anticipate that the ability to read CD-ROMS will spread quickly throughout the user community. If that turns out to be the case, we shall be able to reach a broad and diverse community of researchers and planners throughout the Great Lakes area.

STRATIGRAPHY OF LAKE MICHIGAN SEDIMENTS: CHRONOLOGY AND CONSTRAINTS ON LAKE-LEVEL HISTORY

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Synthesis of a large quantity of stratigraphic data for the late Quaternary sediments deposited in Lake Michigan provides new information on the occurrence and ages of events that affected the level of the lake. These data include seismic-reflection profiles, core stratigraphy and sedimentology, radiocarbon ages, biostratigraphy of ostracode assemblages, isotopic compositions of mollusks, remnant magnetization and magnetic properties. The results of these studies are detailed in other reports for this or previous Southern Lake Michigan workshops. This multidisciplinary approach has led to a detailed reconstruction of the sedimentation and paleoenvironmental history of Lake Michigan.

Till of the last major glacial advance into the Lake Michigan basin, the Two Rivers advance, is well imaged in our seismic-reflection profiles. The high-level Calumet phase (ca. 11.5 ka) of the lake and red glaciolacustrine deposits are associated with this advance. Ice began to retreat from its maximum position about 11.2 ka, while red glaciolacustrine clays continued to be deposited in the lake. As the ice uncovered the Indian River Lowlands and the Straits of Mackinac, lake level fell by an amount that is controversial. At about this time, a horizon that produces a prominent seismic reflection was formed within the red glaciolacustrine sediments. We infer that this major reflection represents a conformable horizon continuous with an unconformity, since removed by erosion at higher altitudes, in much the same way as the later Chippewa low stage is represented by an unconformity that grades into a conformable reflective horizon. Thus, the reflection within the red glaciolacustrine clays appears to represent a major lowering of lake level ca. 11 ka, probably correlative with the low Main Algonquin of Michigan level of Larsen (1987).

bove the Algonquin(?) horizon, red glaciolacustrine sedimentation was interrupted by deposition of the Wilmette Bed, a distinctive gray marker bed within the red sediments. This bed is so different from the overlying and underlying red clays that it certainly represents a major, but short-lived, change in sedimentation in Lake Michigan. Its age is bracketed between the beginning of the retreat of the Two Rivers glacier at 11.2 ka and the opening of the North Bay outlet at 10.3 ka, which caused lake level to fall to the Chippewa Low. The Chippewa unconformity truncates the Wilmette Bed. Based on its stratigraphic position and consideration of sedimentation rates, the most likely age for the Wilmette Bed is between 10.6 and 11.0 ka, in which case it correlates with the first major episode of eastward flooding of Lake Agassiz into the Great Lakes, during the Moorhead phase of Lake Agassiz (Teller, 1985). In addition to its inferred temporal association with eastward Lake Agassiz discharge, the Wilmette bed shares many characteristics with the sediments deposited during a later episode of Lake Agassiz influx, discussed below. The Wilmette Bed and the later sedimentary interval inferred to represent Lake Agassiz influx are nearly identical, consisting of moderately dark gray, moderately calcareous, silty clay containing streaks of black iron monosulfides. Both are nearly barren of organic remains, and both contain few or no ostracodes, in contrast to the

sediments above and below them. On the basis of these sedimentologic and biologic similarities, and the inferred correlation in age with Lake Agassiz discharge, we infer that the Wilmette Bed was deposited during a major, but short-lived incursion of Lake Agassiz water into the Lake Michigan basin sometime between 11 and 10.6 ka.

As the Laurentide ice sheet retreated, it uncovered a series of isostatically depressed northern outlets for the upper Great Lakes, culminating with the opening of the North Bay outlet at about 10.3 ka. This event resulted in a period of extreme low levels in the lakes, referred to as the Chippewa low phase in Lake Michigan. During this lake-level fall and subsequent transgression, a sandy zone that commonly contains small mollusk shells formed; this zone marks the unconformity associated with the low phase. Hough (1955) estimated that this sandy zone extended to a depth of 107 m below present lake level, and suggested lake level fell to this altitude, forming two separate lakes in the Lake Michigan basin, separated by the mid-lake bathymetric high. Our studies confirm that the sandy zone extends to depths greater than 100 m in the southern basin, but our seismic-reflection profiles show no evidence of a river draining across the mid-lake high. The present sill depth on the mid-lake high is about 100 m, so we conclude that the southern basin of the lake was always confluent with the northern basin, and that lake level fell to no lower than 100 m below present during the Chippewa low phase.

Wickham et al. (1978) noted that the red glaciolacustrine clays are truncated at a depth of about 82 m throughout the southern basin of Lake Michigan. From this relation and an assumed wave base of 20 m, they inferred that lake level fell only to a depth of about 62 m during the Chippewa low phase. This estimate agrees with Buckley's (1974) estimate of 61 m, based on the distribution of ostracodes in the lake sediments. However, the truncation of the red clays is a minimum estimate of the depth to which effective erosion occurred during the Chippewa low stage. In addition, the widespread existence of a sandy zone to depths of more than 100 m suggests that wave base extended at least this deep, at least 40 m below the lake level postulated by Wickham et al. (1978).

The stratigraphy of cores from our sites 9 and 12 on the west side of the southern basin provides additional information concerning the level of the Chippewa low. Core site 12, at a depth of 90 m, contains the sandy, shelly zone that marks the Chippewa unconformity, but appears to contain a nearly complete sedimentary sequence both above and below the unconformity. The Wilmette Bed, overlain by red clays, is present below the unconformity at this site, so that we infer that erosion of the red clays during the low stage was minor. In addition, the biostratigraphy of ostracode assemblages above the unconformity, with abundant nearshore species, is as complete as in any core that we have examined, so we infer that little or no time is missing due to non-deposition. In contrast, at core site 9 at 79 m depth, significant erosion of the red clay and non-deposition at the unconformity is indicated. Just below the sandy zone at the unconformity at core site 9, a radiocarbon analysis of ostracodes indicated an age of 12.4 ka; in addition, the Wilmette Bed is missing, presumably due to erosion, at this site. Above the unconformity, several ostracode events present in core 12 are missing. From these observations, we infer that the Chippewa shoreline was very close to core site 9, resulting in erosion of preexisting red clays and a period of non-deposition. At the same time, water was sufficiently deep at core site 12 that, although a sandy layer was deposited, little erosion

occurred and sedimentation was continuous or nearly so. Our best estimate is that the minimum level of the Chippewa low was at about 80 m. This provides for a wave base of 20 to 30 m, as indicated by the extent of the sandy, shelly layer to depths of 100 to 110 m. Core site 4, at 80 m depth on the eastern side of the basin, contains a complete ostracode sequence, no sandy zone, and little or no evidence of erosion. These observations suggest differential uplift of core site 4 of at least 10 m compared to core sites 9 and 12.

A second interval of eastward discharge of water from Lake Agassiz into the upper Great Lakes, at times catastrophic, occurred between 9.5 and 8.5 ka during the Nipigon phase of Lake Agassiz (Teller, 1985). Although the effects of this discharge have been documented in Lakes Superior and Huron (Lewis and Anderson, 1989), no effects have previously been known in Lake Michigan. However, our data, including sedimentology, stable isotopes, ostracode assemblages, and magnetic properties, clearly show a short-lived event that can only be reasonably ascribed to influx of water from Lake Agassiz. The age of this event is directly estimated by radiocarbon analyses of mollusk shells at 9.1 ka. The influx of water from Lake Agassiz surely raised the level of Lake Michigan, but the extent of the rise is unknown. Previous work has suggested that Lake Michigan lay above the level of Lake Huron at this time. The influx of Lake Agassiz water into Lake Michigan could be due to (1) hydraulic damming at North Bay that raised the level of Lake Huron, (2) completion of enough isostatic rebound to make the two lakes confluent by 9.1 ka, and(or) (3) overflow of Lake Superior directly to Lake Michigan through the Au-Train-Whitefish channels.

The rise of the lake from the Chippewa low to the Nipissing high level is documented in our seismic-reflection profiles by a distinctive, planar, transgressive unconformity. Erosion associated with this unconformity, coupled with a rapidly rising lake level, has left little evidence of intermediate lake-level positions, and little in the way of coarse-grained deposits.

A dramatic change in conditions in the lake occurred at about 5 ka, possibly associated with the Nipissing high phase. This change is clearly reflected in a sudden decrease in the preservation of ostracodes, a major change in the magnetic properties of the sediments, and in the sediment grain size at some sites. This change may be due in part to changes in the circulation and energy of the lake as the mid-lake high was completed submerged and the lake approached its present size, and in part due to paleoclimatic changes. After 5 ka, ostracodes and mollusks are poorly preserved, eliminating many of our tools for reconstructing paleolimnologic conditions, but grain size and magnetic properties of the sediments show short-term variations over intervals of on the order of 200 to 500 years, possibly due to lake-level changes on the same timescale.

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PALEOMAGNETISM AND SEDIMENT MAGNETISM OF HOLOCENE
SEDIMENTS IN SOUTHERN LAKE MICHIGAN--CONTRIBUTIONS TO
STUDIES OF LAKE-LEVEL AND PALEOENVIRONMENTAL CHANGE

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Paleomagnetic and sediment magnetic records of Holocene sediment from Lake Michigan contribute to intra- and inter-basin correlations, constrain sedimentation rates, describe variations in the concentration, grain size, and type of detrital magnetic particles that reflect changes in depositional environments and source area. The success of magnetic methods for these applications requires that the magnetizations in the sediments are caused by detrital iron oxide minerals which have remained unaffected by chemical alteration after deposition.

Geochemical (sulfur species, phosphate, and organic carbon) and petrologic results show that detrital iron oxide minerals are indeed responsible for the magnetic properties.

Paleomagnetic records reflect the secular variation of the ancient geomagnetic field. Curves of paleomagnetic declination and inclination are largely coherent among core sites in the lake and among secular variation curves from other North American sites, such as Lake St. Croix, Minnesota, thereby permitting tentative age assignments and correlations. The paleomagnetic interpretations are complicated in parts of the cores by the effects of sediment deformation (twisting and compaction) and by incomplete recovery.

Variations in the type, amount, and grain size of detrital magnetic minerals were determined from measurements of magnetic susceptibility, anhysteritic remanent magnetization, saturation

isothermal remanent magnetization, and backfield isothermal remanent magnetization. Long-term features (~1000-2000 yr) in the concentration and character of magnetic minerals correspond directly with long-term lake-level changes that have been reconstructed from the effects of isostatic rebound, from the changes in drainage, and from shoreline features. Short-term variations (~200-500 yr) in the concentration and character of magnetic minerals may record short-term fluctuations in lake levels at a high degree of resolution not easily obtained by other methods.

Our most detailed results (88 specimens) come from gravity core 4 recovered from a water depth of 80 m. From 240 to 160 cm, representing about ~8.1 to 5.8 ka, the content and grain size of magnetite decreases. Such decreases may result from diminishing depositional energy as the lake level rose from the Chippewa low stage. From 160 to 130 cm (~4.7 ka), magnetite decreases systematically in particle size as it increases dramatically in amount, both in an absolute sense and relative to ferric oxide. These changes apparently correspond to the growth of the lake as it approached high levels during the Nipissing lake phase. The abrupt increase in magnetite, the causes for which are not known with certainty, may reflect rapid changes in climate and related conditions, such as changes in erosion rates, and in the size of the catchment basin. The sediments from 160 to 15 cm (~5.8 ka to 150 yr B. P.) are characterized by short-term variations in magnetite abundance and grain size. Sediment having coarse-grained magnetite may have been deposited in a higher energy environment related to a lower lake level, relative to sediment having sparser, finer grained magnetite.

Long-term features of the magnetic-property profiles from the Holocene record in gravity core 6 (center of the southern basin at a water depth of 168 m) bear striking resemblances to those in core 4, 27 km away. Magnetite abundance diminishes gradually from the base of the Holocene at ~210 cm to 110 cm, above which it increases abruptly. A sharp decrease in overall magnetite grain size, as well as a sharp increase in magnetite content relative to hematite, accompany the increase in absolute magnetite abundance. We attribute these mineralogic changes in core 6, as in core 4, to

the rise in the level of the lake as it approached its current size between ~6 and 4.5 ka.

Correlations between gravity cores 4 and 6 based on the magnetic-property features constrain sedimentation rates for core 6 which has limited AMS ^{14}C age control. We find essentially no difference in sedimentation rate over the interval 150 to 110 cm (8130 to 5820 yr; $17\text{ cm}/10^3\text{ yr}$) compared to the interval 110 cm to the 10 cm (5820 to ~190 yr; $18\text{ cm}/10^3\text{ yr}$). In core 4, however, the sedimentation rates over these intervals are somewhat different-- $35\text{ cm}/10^3\text{ yr}$ and $25\text{ cm}/10^3\text{ yr}$, respectively.

Detailed measurements of the sediment magnetic properties of core 6 were not made except for the interval between 180 and 140 cm. At depths of ~161-166 cm, mollusks have very light $\delta^{18}\text{O}$ values, ostracode valves are absent, and two distinct horizons of pebbles are visible in X-ray images. These features have been ascribed to the influx of cold, dilute waters from ancient Lake Agassiz into the Lake Michigan basin caused by a catastrophic change of discharge into the Great Lakes. The magnetic properties reveal that the interval lacking ostracodes is enriched in coarse-grained magnetite relative to beds above and below. This characteristic may reflect higher depositional energies during a flood or ice-rafted detritus. The results thus support the idea that periodic influx from lake Agassiz before 8 ka contributed to changes in lake level in Lake Michigan.

LAKE MICHIGAN SEDIMENTS

RECORDS OF PAST LIMNOLOGY AND CLIMATE

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Lakes, whether large or small, are coupled to climate on some time scale. Dilute lakes exist in areas where precipitation is high compared to evaporation, while saline lakes exist in areas where evaporation is high compared to precipitation. Covariant changes in the dissolved ion (solute) composition also occur along climate gradients. Lake chemistry is thereby coupled to effective moisture (Forester, 1987, 1991). Similarly, air temperature is variously coupled to water temperature (Forester, 1987). Ostracode and stable isotope records provide physical and chemical information about the water mass and thus about climate and limnology.

The level and volume of Lake Michigan are not just a product of climate. Those parameters are also a function of isostatic changes in the elevation of the outlet(s). Isostatic change causes little or no change in the lake's chemical budget. Ostracode and isotope hydrochemical records identify climate change, while ostracode biofacies identify isostatic change.

The ostracodes Candona subtriangulata, C. crogmaniana, C. rawsoni, Limnocythere friabilis, and Cytherissa lacustris are the principal lake taxa. Other species lived in bays and smaller lakes on the lake's margin. These species are incorporated into the Lake Michigan record when the main lake transgresses. The complex ecology of these lacustrine species may be simplified to a few environmental parameters that can describe the lake's history. Candona subtriangulata and C. crogmaniana are cryophilic taxa. Candona crogmaniana is tolerant of salinity as high as 1000 mg/l. Candona

rawsoni is a eurythermic and euryhaline taxon that commonly lives in prairie lakes today. Cytherissa lacustris is a cryophilic and halophobic taxon found in Boreal Forest lakes. The ecology of Limnocythere friabilis is poorly known, although in the fossil record it is often found on lake margins, linked in some way to ground water and stream discharge. These general environmental responses provide the basis for reconstructing Lake Michigan's environmental history.

Ostracode stratigraphic profiles have been constructed for Lake Michigan core sites 4, 6, 9, and 12. Stable isotope profiles have also been generated from biogenic carbonate in many of these cores and additional material is being assembled for isotopic analysis. These data show that change in lake level during the late Pleistocene and Holocene is a complex response to both climate and isostatic uplift. Environmental changes caused by climate are recorded in all cores. Conversely, those due to isostatic uplift are primarily recorded in cores from the lake margin. Those two factors operate together throughout the lake's history, although isostasy tends to dominate during the late Pleistocene and early Holocene, while climate is more important during the middle and late Holocene.

The oldest event in core 4 (Fig. 1) is defined by the presence of only C. subtriangulata, indicating a cold, dilute lake. The second event is defined by the appearance of L. friabilis. Because that taxon is most abundant near the shoreline, its appearance implies that the shoreline is approaching the core site, so lake level is falling in response to ice retreat opening North Bay. The presence of C. rawsoni during the second event also suggests solute concentration driven by climate change to a drier state. The climate change may have contributed to the ice retreat.

The appearance of Cytherissa lacustris and other ostracode species with the decline in L. friabilis defines the third event (Fig. 1). That assemblage implies a cold, dilute, and transgressing lake in response to isostatic uplift and a wet climate. The fourth event (Fig. 1) is poorly defined in core 4, due to the sample interval. That event is characterized by an increase in the abundance of L. friabilis, C. rawsoni, C. crogmaniana indicating regression with limited

concentration and thus climate control. The ostracode record is interrupted by an episode of carbonate solution caused by an influx of meltwater from lake Agassiz (Colman, this volume).

During the last (fifth) ostracode event (Fig. 1) the abundance of L. friabilis, C. rawsoni, C. crogmaniana increases while that of C. subtriangulata declines. That assemblage indicates an increase in solute concentration. Lake level is therefore under climate control. Limited age control indicates that sediment accumulation during event five was slower than in the older events, yet ostracode abundance is greater. Shell preservation during this interval indicates that bottom waters were calcite saturated implying that the solute concentration is above 250 mg/l, which is supported by ostracode ecology. That concentration indicates lake level is not remaining in phase with outlet isostatic uplift resulting in topographic closure of the lake.

The ostracode record stops after the fifth event due to calcite understaturated bottom waters and slow sediment accumulation. These factors indicate a large increase in lake level, probably to the Nipissing high level.

The data from cores 12 (Fig. 2) and 4 (Fig. 1) are similar indicating that the same events occurred on the western side of the lake. The fifth event is not shown in core 12, because that section of the core was not sampled.

Limnocythere friabilis is absent at the basin center, but otherwise data from core 6 (Fig. 3) are similar to those from cores 4 and 12. The absence of L. friabilis is to be expected if, indeed, it defines the shoreline and the shoreline never regresses beyond cores 4 and 12. Finally, the data from core 9 (Fig. 4) show that the second ostracode event is absent, but is present in core 12 from deeper water. That geometry indicates erosion at the core 9 site. Because cores 4 and 9 are from the same water depth, erosion at the core 9 site implies that core 4 was in deeper water than it is today. Thus, the eastern Lake Michigan margin has undergone isostatic uplift compared to the western margin (see Colman, this volume).

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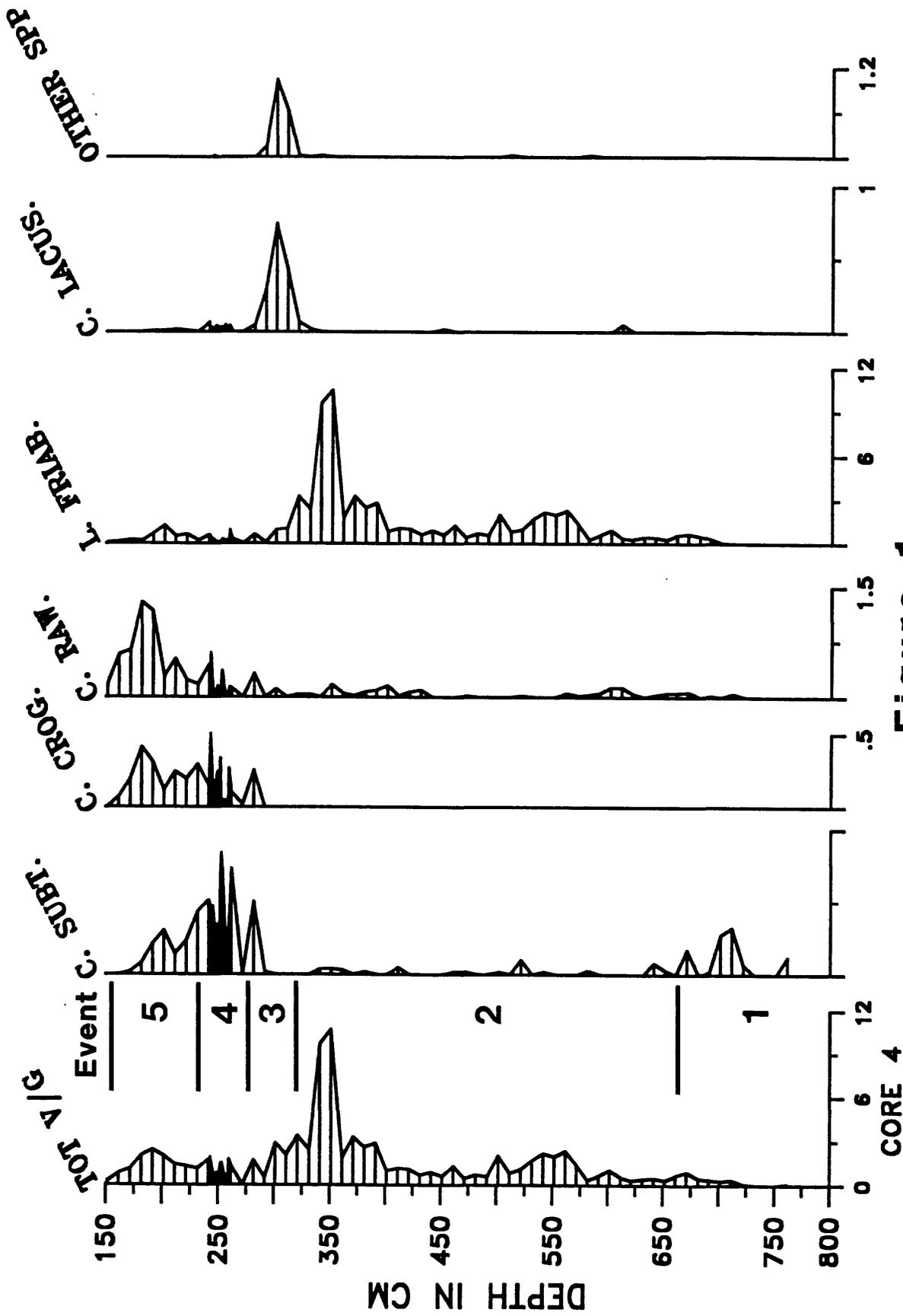


Figure 1

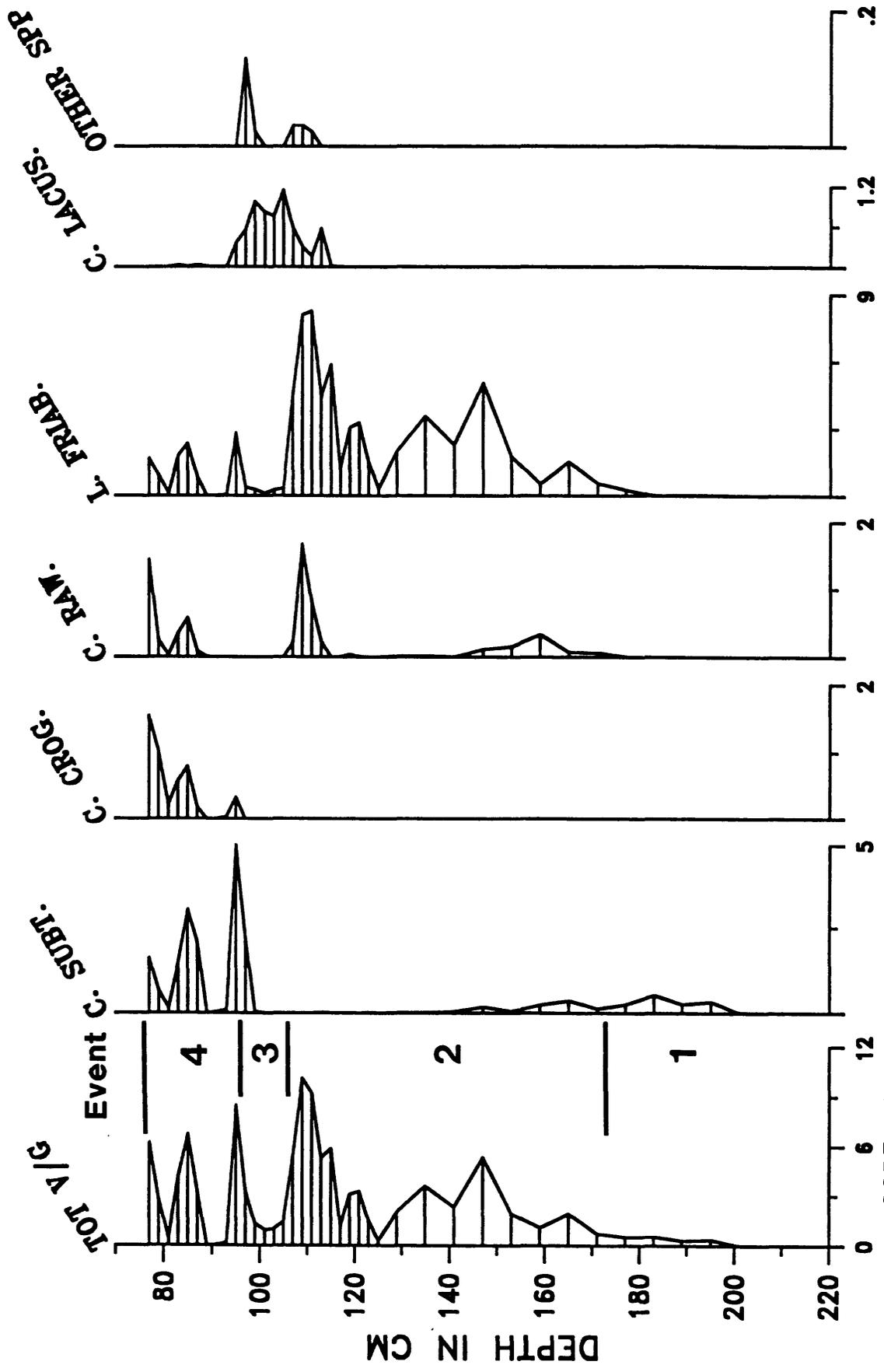


Figure 2

CORE 12

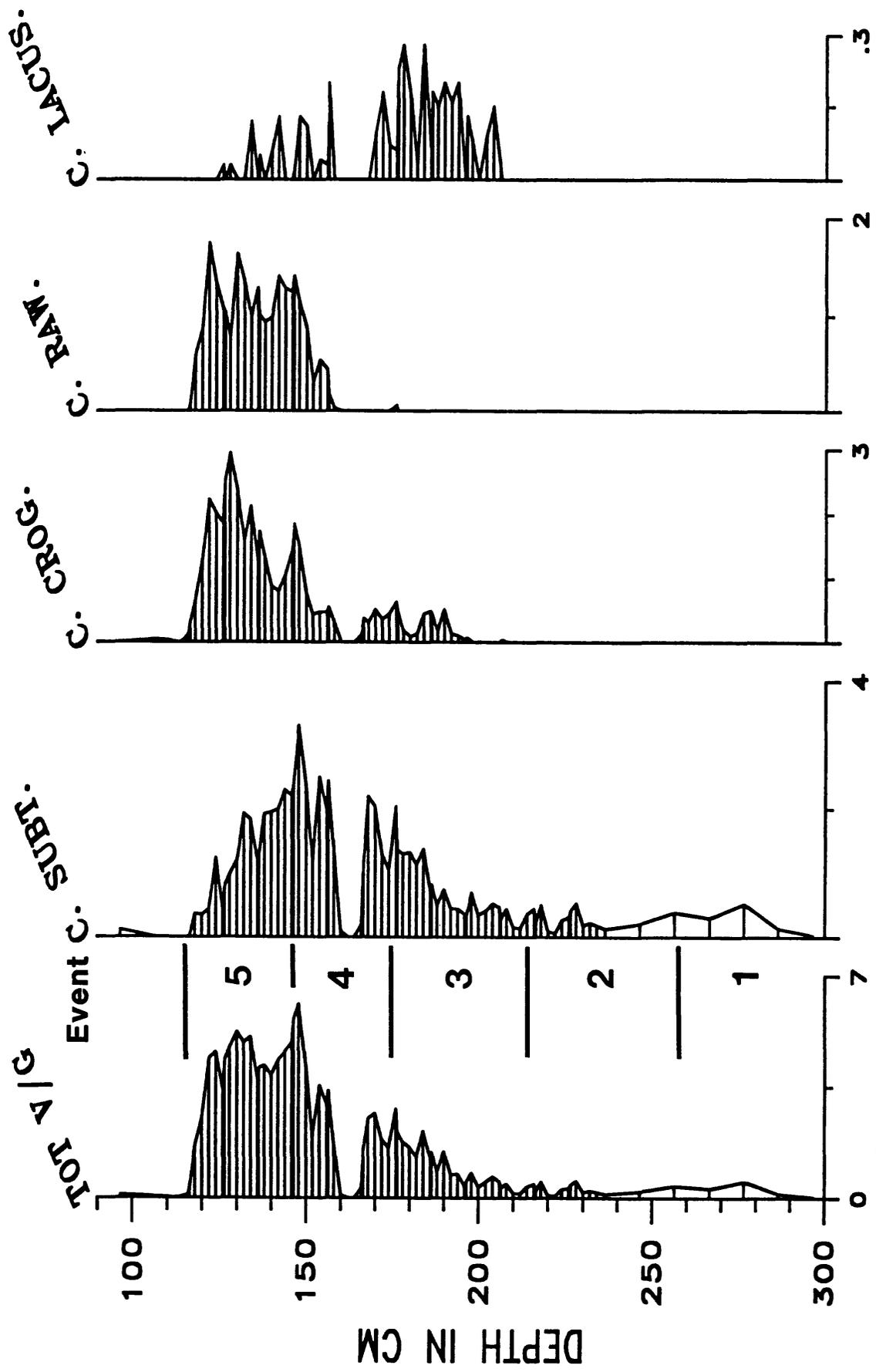


Figure 3

CORE 6

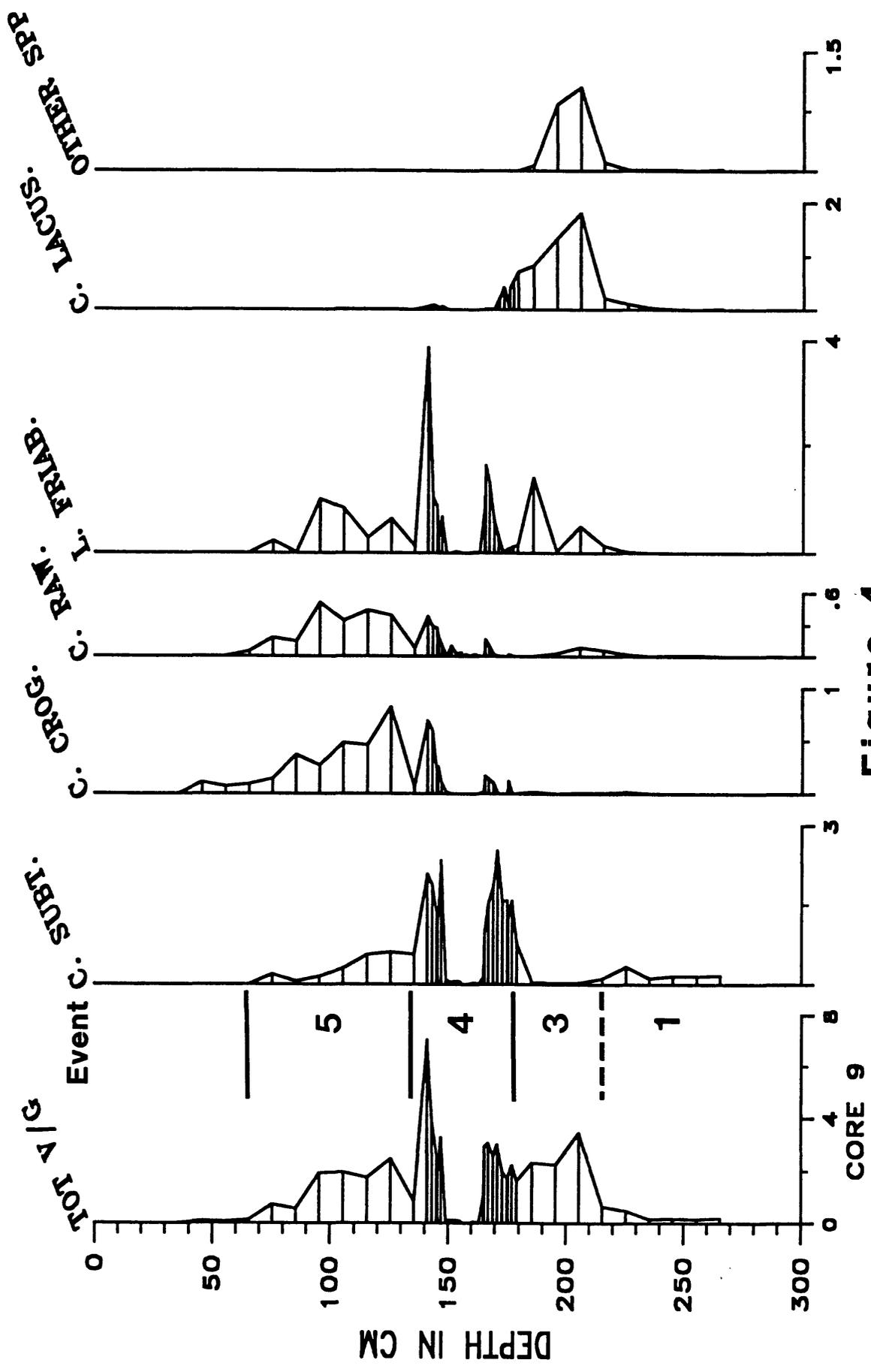


Figure 4

BEACH RIDGES AS MONITORS OF ISOSTATIC UPLIFT IN THE UPPER GREAT LAKES BASIN

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Beach ridges are geomorphic expressions of former active beaches that have been preserved and protected by the deposition of younger beach sediment lakeward of the former beach position. Where progradation of the shoreline is dominant, extensive beach ridge complexes may develop. Each ridge is underlain by sedimentary facies representing the backbeach, foreshore, and nearshore environments of a contemporaneous water level. Progradation of beach ridges may indicate abundant sediment supply, a falling water level, or a combination of both. Detailed sedimentologic and geomorphic analyses of beach ridge complexes can provide a record of former water level positions through time. The interface between for eshore and nearshore deposits is marked by a change in grain size from fine to medium sand of the swash-backwash zone (upper foreshore) to medium to coarse sand nearshore where wave energy is greater. The interface (lower foreshore) marks the transition between subaqueous and subaerial facies and is the approximate position of the contemporaneous water level. Although often masked by eolian sand, the highest portion of each beach ridge marks the position of maximum wave runup on the beach.

In the upper Great Lakes basin, differential isostatic uplift complicates the formation of beach ridges in each lake. In Lake Michigan and Lake Huron the record shows uplift to dominate north of an isobase of equal movement passing through the outlet to the lakes at Port Huron, MI. Uplift relative to the outlet in the north resulted in a progressive fall in lake level. At the outlet which controls the level of the two lakes, the record suggests incision of the channel at the same rate as the local uplift. The result was an overall falling level of the lakes during the past 5000 years due to a progressively lowered spillway. Thus, while relative levels were falling relative to the rising land surface in the north, the rate of regression was compounded by the rate that the outlet channel

eroded. Both were governed by isostatic uplift. South of the Port Huron isobase in the southern Lake Michigan basin, the record is more complex. There, uplift is minor in comparison to the northern shore of the basin, but the overall record of falling levels due to deepening of the outlet by erosion is pronounced. In addition, as the erosion rate of the outlet channel slowed in keeping with a decreasing rate of uplift, uplift at the outlet relative to the southern shore of Lake Michigan became dominant. As a consequence, water levels in southern Lake Michigan rose at the same rate as the uplift of the outlet. Two patterns of overall lake level change are present in Lake Michigan and Lake Huron: 1) falling levels north of the Port Huron isobase, and, 2) falling levels followed by slightly rising levels south of the isobase in Lake Michigan.

Beach ridge complexes monitor ongoing changes in relative lake level position. As an example, the current isostatic uplift model for the upper Great Lakes shows cumulative uplift of the region to follow an exponential decrease in the rate of uplift with time (Larsen, 1990). Concomitantly, the rate of uplift increases as a function of distance to the north. Coastal landforms follow a similar progression. As relative lake level falls in response to uplift and outlet incision, beach ridges are formed at successively lower altitudes, but as a function of the uplift at any specific location. To illustrate, if cumulative uplift follows an exponential function, then the altitudes of beach ridges should decrease toward the modern shoreline in a related manner and display a concave-upward profile. Topographic profiles plotted normal to beachridges on semi-logarithmic graph paper will therefore show the exponentially distributed landforms as linear profiles.

Figure 1 plots beach ridges formed on a relatively steep slope in a protected wave environment on Washington Island, Door County, Wisconsin, a few miles north of the Port Huron isobase. This area shows continual uplift relative to the outlet. Linear regression analysis on the altitude of beach ridges and troughs versus distance shows an exponential decrease in altitude with distance toward the modern shoreline. The slope of the regression line is similar to lines joining the highest ridges of the sequence, or the deepest

inter-ridge troughs. Thus, the slope can be approximated graphically as well.

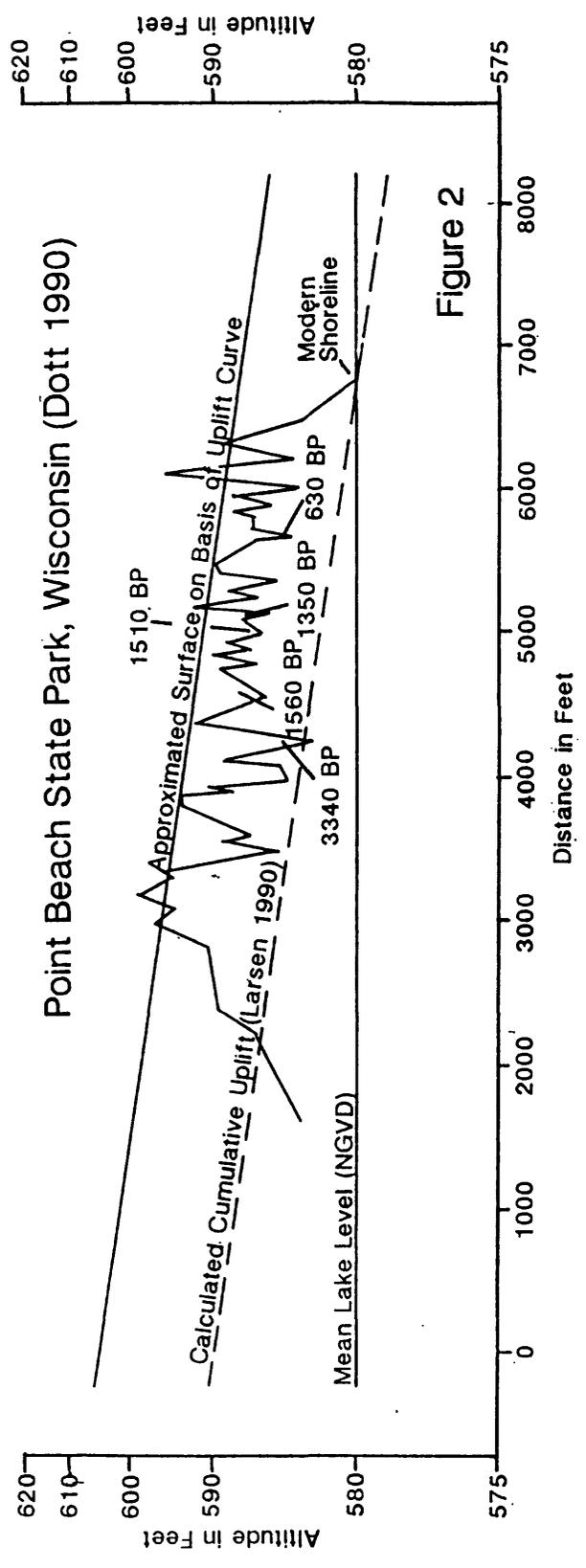
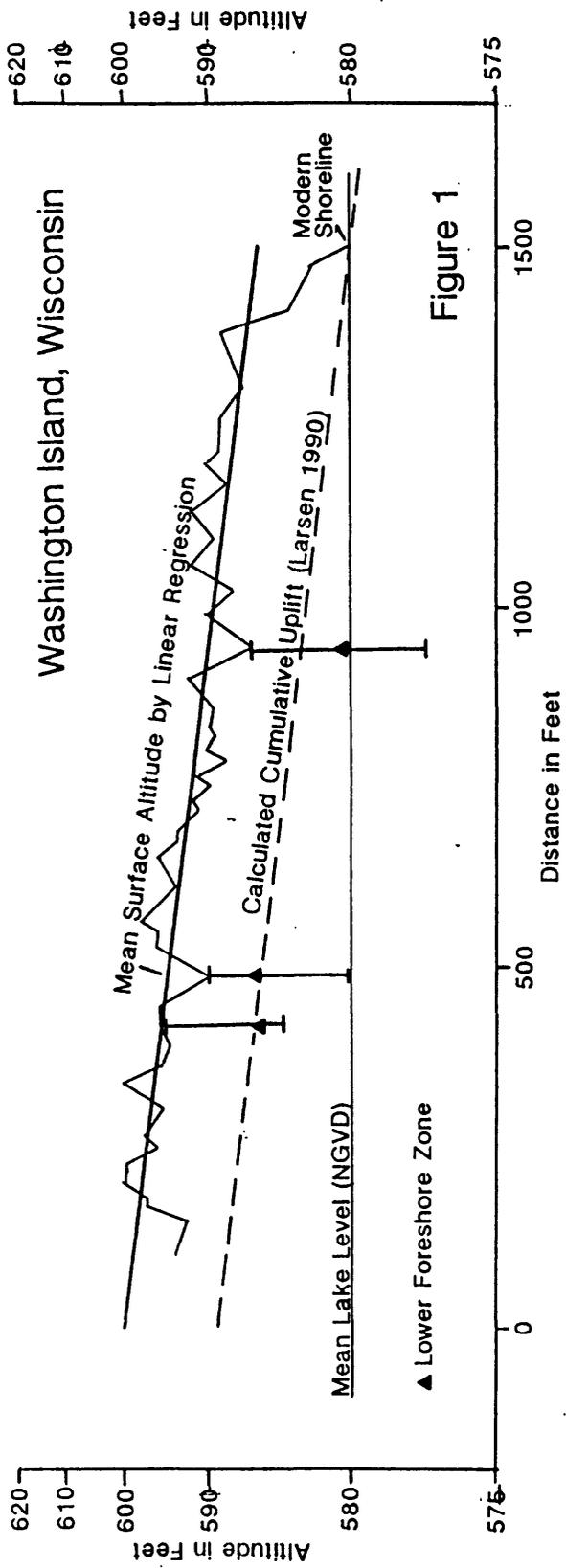
Figure 2 plots a dated beach ridge complex at Point Beach State Park, Kewaunee County, Wisconsin (Dott, 1990). This site lies near the Port Huron isobase and responds to the uplift rate at the outlet. Here, however, relative ages of landforms are known so that the relationship with isostatic uplift can be tested. The altitude of the earliest beach ridge in the sequence together with a limiting date of 3340 BP (calibrated) suggests that it corresponds to the Algoma level of the lake at Port Huron. Assuming a 3600 BP age for the ridge, the cumulative uplift for the Port Huron/Sturgeon Bay isobase was calculated (Larsen, 1990). This curve parallels the crests of beachridges in the sequence pointing to similarity between modelled uplift and an exponential decrease in the altitude of ridges as a function of uplift.

The altitudes of beach ridges in the Lake Michigan basin record the position of the a former water plane controlled by the spillway of the outlet at Port Huron but relative to isostatic uplift of the crust. When the ages of key beachridges can be determined with suitable accuracy, they can be used to monitor cumulative uplift at various parts of the lake basins.

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RATES AND PROCESSES OF BLUFF RETREAT ALONG THE LAKE MICHIGAN SHORELINE IN ILLINOIS

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Research on the behavior of the shoreline bluffs along the Lake Michigan shoreline in Illinois has focused on three fundamental issues: the temporal and spatial variation in rates of retreat, the relative significance of various mechanisms of retreat, and the character of the sediment that is added to the littoral sediment transport system by bluff retreat.

Rates of bluff retreat were calculated from measurements of bluff-top retreat at 300 locations spaced at 100-m intervals along the 30 km of shoreline from Wilmette to Waukegan, Illinois. We used historical airphotos and maps to measure amounts of retreat for two time periods, 1872-1937 and 1937-1987. Calculated rates of retreat vary from 10 to 75 cm/yr between discrete segments of bluffs (defined by lithology) and between time periods for a given bluff segment. The average retreat rates for the entire area, however, do not vary significantly between the two time periods and are approximately 20-25 cm/yr. Mean and maximum lake levels and rainfall, as measured between the two periods, do not vary significantly, and thus local temporal variations in retreat rates cannot be attributed to variation in these factors. The density of groins constructed does vary between time periods but shows no effect on regional retreat rates, although groin construction may effect the distribution of retreat rates throughout the area. Local rate variations do correlate closely with lithologic variations of the glacial materials exposed in the upper part of the bluff: bluffs that contain lake-plain sand and silt generally have higher retreat rates than clay till bluffs. These differences in retreat rates cannot have persisted through time, however, because the coastline is fairly linear and shows no abrupt change in character across these lithologic boundaries. The temporally constant regional retreat rates and the regular shape of the local shoreline indicate that a uniform rate of retreat prevails and that local variations in rates balance out through time to produce long-

term parallel (in map view) bluff retreat in the area. This parallel retreat probably is controlled by a uniform rate of retreat of the lithologically homogeneous clay till shoreface in front of the bluff.

Bluff retreat results from many different processes, which occur at different rates and respond to different triggering mechanisms. For example, wave erosion is a primary cause of bluff retreat, and brief, intense storms that generate large wave surges can trigger very large amounts of bluff retreat in a matter of a few hours or days. Longer term basin-wide increases in water level also can increase long-term rates of bluff erosion and recession. Surface erosion from precipitation runoff also can contribute to bluff recession; runoff from normal rainfall produces what might be considered a background rate of surface erosion, and less common major rainstorms may trigger brief episodes of surface erosion that far exceed the background rate. Landslides along the bluffs likewise contribute to bluff retreat, and such slides can be triggered by long-term changes in ground-water conditions, brief periods of intense rainfall, rapid snowmelt, and wave erosion at the base of the bluff. Along the Illinois shoreline, landsliding, probably triggered both by precipitation and by wave erosion, appears to be the most important mechanism of bluff retreat. Landslides generally activate during spring rains; they commonly form in areas lacking wide fronting beaches where wave attack has oversteepened the toe. The clay till bluffs generally form fairly deep (5-20 m) slump/earth flows that may move only every several decades. Benched topography even on apparently stable segments of the bluff indicates intermittent periods of landslide activity. Some clay till becomes plastic when saturated, which results in the slump blocks disaggregating and transforming into earth flows. The bluffs that contain lake-plain sands and silts tend to form shallow (1-5 m) slumps or earth slides that transform into earth flows when saturated.

Failed material from bluff recession is incorporated directly into the littoral sediment transport system by wave action attacking the base of the bluff; therefore, characterizing the grain-size characteristics of the bluff material provides useful information on a primary source of sediment along the shoreline. We conducted

cone-penetration testing (CPT) along the Illinois shoreline to characterize the distribution of sediment sizes along the bluffs; each CPT sounding produces a continuous record of grain-size characteristics from the top of the bluff to lake level. We are combining the CPT data with the recession data to generate a model that will predict the annual sediment contribution (by grain size-sand, silt, and clay) along each of the 300 bluff segments (each 100 m long) defined for the recession study.

SUMMARY OF 1987 TO 1991 MONITORING OF COASTAL EROSION IN THE VICINITY OF NORTH POINT MARINA, WINTHROP HARBOR, ILLINOIS

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Beach and nearshore geomorphic changes in the vicinity of the state-owned North Point Marina have been monitored since the start of construction of this 1500-slip marina in 1987. The survey area extends from the Illinois-Wisconsin state line for a distance 2.3 km south, and as far as 1 km offshore. The purpose of this study has been to document the rate and extent of shore and nearshore changes and the coastal sedimentary impacts related to construction of the facility.

Construction of the marina basin involved building shore-attached, rubble-mound breakwaters and excavating into the beach and backshore up to 370 m landward of the pre-construction shoreline. Approximately 1.2 million m³ of gravelly sand were excavated and discharged by slurry pipe to the south (downdrift) side of the marina basin. This material formed a fan delta which ultimately shifted the shoreline 200 m lakeward from its pre-construction position.

Comparison of 1987 and 1988 annual bathymetric surveys indicates lake-bottom erosion of 40,000 m³ and lake-bottom accretion of 240,000 m³, or net accretion of 200,000 m³. This net gain represents the shoreface progradation at the fan delta as well as the dispersion of sediments across the nearshore. Net accretion remained the dominant lake-bottom change between the 1988 and 1989 annual surveys. Erosion totaled 80,000 m³ and accretion totaled 180,000 m³, or net accretion of 100,000 m³. Although major erosion was occurring by early 1989, the net gain relates to sediment discharge continuing at the fan delta into late 1988.

Comparison of 1989 and 1990 surveys documents the reversal in lake-bottom change after the influx of excavated sediment ended. The transport deficiency from updrift (northward) due to the

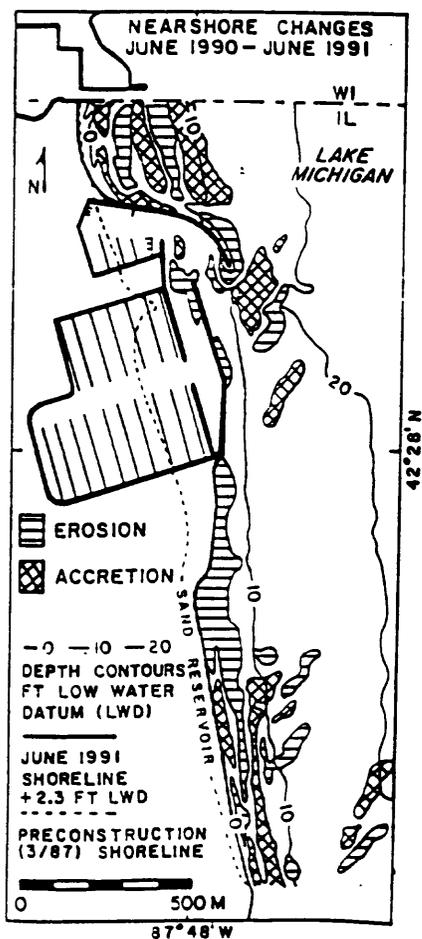
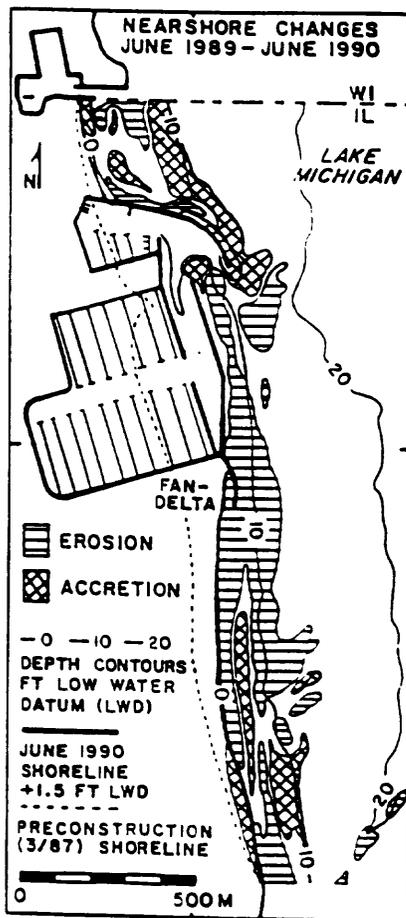
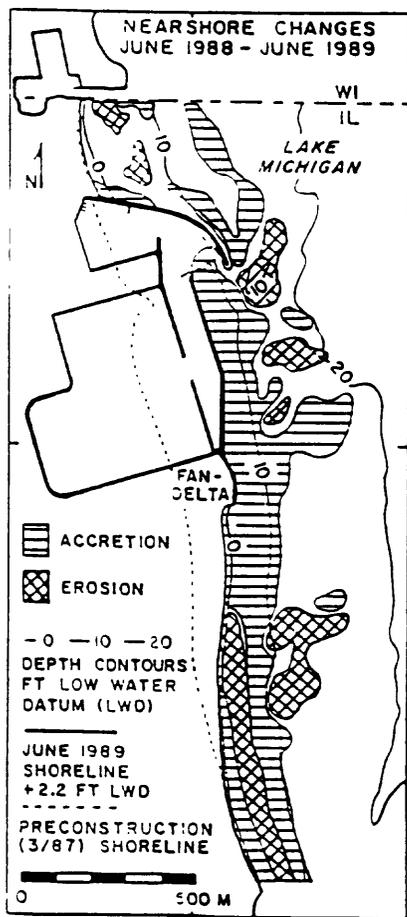
breakwaters, combined with the loss of discharged sediment to cause the nearshore to experience severe erosion to establish a new equilibrium configuration. Lake-bottom change in this one-year interval was erosion of 185,000 m³ and accretion of 85,000 m³, or net erosion of 100,000 m³. The greatest erosion was across the shoreface at the fan delta as well as along the nearshore of the south breakwater and downdrift from the fan delta. Shoreline recession at the fan delta in 1989 totaled 61 m before being halted by shore defense.

The 1990 and 1991 surveys document 96,000 m³ of erosion and 80,000 m³ of accretion, or net erosion of 16,000 m³. This significant decline in net erosion from the 100,000 m³ in 1989-1990 relates to shore defense at the fan delta and influx of littoral sediment from a sand reservoir placed south of the fan delta in September 1990. Erosion of this reservoir was intended to feed the downdrift littoral stream. By August 1991 approximately 40,000 m³ had eroded from this 100,000 m³ reservoir.

The four-year record of beach and nearshore changes in the marina vicinity documents the rapid rate at which the nearshore zone was able to adjust to a disruption of equilibrium caused by a major coastal engineering project. The amount of net erosion recorded between 1989 and 1990 further indicates that wave energy along this coastal reach is sufficient to transport as much as 100,000 m³ of sediment per year if the supply is abundant and readily available. The sediment transport and lake-bottom changes during the four-year study occurred in a narrow band extending from the shoreline to no more than 350 m offshore. The maximum depth in this zone of sediment mobility was about 4.5 m below low water datum.

The projection for future changes in the marina vicinity is for continued beach and nearshore erosion south of the marina. This erosion will be enhanced by the deficit of littoral sediment supply from updrift. Although a small volume of sediment is moving south across the state line, the sand reservoir along the beach south of the

marina is now the prime sediment supply for the Illinois coast. Once this reservoir is depleted, nearshore erosion and shoreline recession will increase due to littoral sediment starvation.



COASTAL ICE REGIME AND RELATED EROSION AND SEDIMENT TRANSPORT, SOUTHERN LAKE MICHIGAN; A VIDEO

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Part of the goal of science is to communicate the results to other scientists and to the general public. As part of our effort to communicate we assembled a video that addresses the question raised by the presence of lake ice along the coast. Is coastal ice protective or erosional? The video is assembled using scenes from field work in 1989, 1990, and 1991 and includes observations from aerial, surface, and submarine camera opportunities. Drawings, maps, and graphic displays are also incorporated.

After posing the question of ice effects amid scenes of man's encroachment on the coast, subsequent sections of the video cover our approach used in answering this question, our results from field work, and their implications for coastal processes and coastal stability. Scenes that show longshore drift, wave overwash, ice volcano eruption, and lake bed morphology are especially well communicated in this medium. The final sections of the video stress the importance of ice and conclude that ice alters coastal erosion patterns and does not effectively protect the coast from erosion in winter, but also cautions that in many areas our knowledge is rudimentary and uncertain.

COASTAL PROFILE MODIFICATIONS IN WINTER RELATED TO LAKE ICE; SOUTHERN LAKE MICHIGAN

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The growth of a Nearshore Ice Complex (NIC) in southern Lake Michigan influences the effect of winter storm waves by forcing them to expend their energy further lakeward, where ice ridges act as ephemeral seawalls. Beach and nearshore profiles show several ice and lakebed features that can be related to the NIC. Comparisons of shore-normal profiles indicate that ice ridges are associated with an underlying bar as noted by earlier workers. However, the association is not rigorous; commonly there are more ice ridges than bars.

A small but persistent feature of our ice-influenced coastal profiles is an erosional trough, commonly 10 to 15 cm deep, but as much as 50 cm deep and 2 to 3 m wide at the lakeward edge of the grounded ice ridges. At Point Beach, WI a shore-normal profile was repeated three times in a 4-day period and showed rapid formation and infilling of this trough (Figure 1). At Kohler-Andrea State park, WI, a spread of profiles show an uneven lakebed associated with the NIC and a trough inconsistently developed adjacent to the offshore ice ridge (Figure 2). In addition, a second trough is present under the NIC along the lakeward edge of the icefoot ridge at Kohler-Andrea.

Underwater video observations along the outer margin of the ice ridges also suggest that depressions lakeward of ice ridges are ubiquitous and are associated with the underwater shape of the ice ridges adjacent to the trough. At one site, a new ice ridge intersected the lakebed at the deepest part of the trough as a nearly vertical wall, and an older ice ridge at St. Joseph, MI sloped inshore as much as 3 m toward the trough axis.

Our observations support those of Bajorunas and Duane (1967), that re-directed wave energy results in lakebed scour and mobilization of sediments. A systematic offshore development of successive ice

ridges and associated lakeward displacement of wave energy and resulting sediment mobilization could explain the winter offshore displacement of bars noted by Wood and Weishar (1984).

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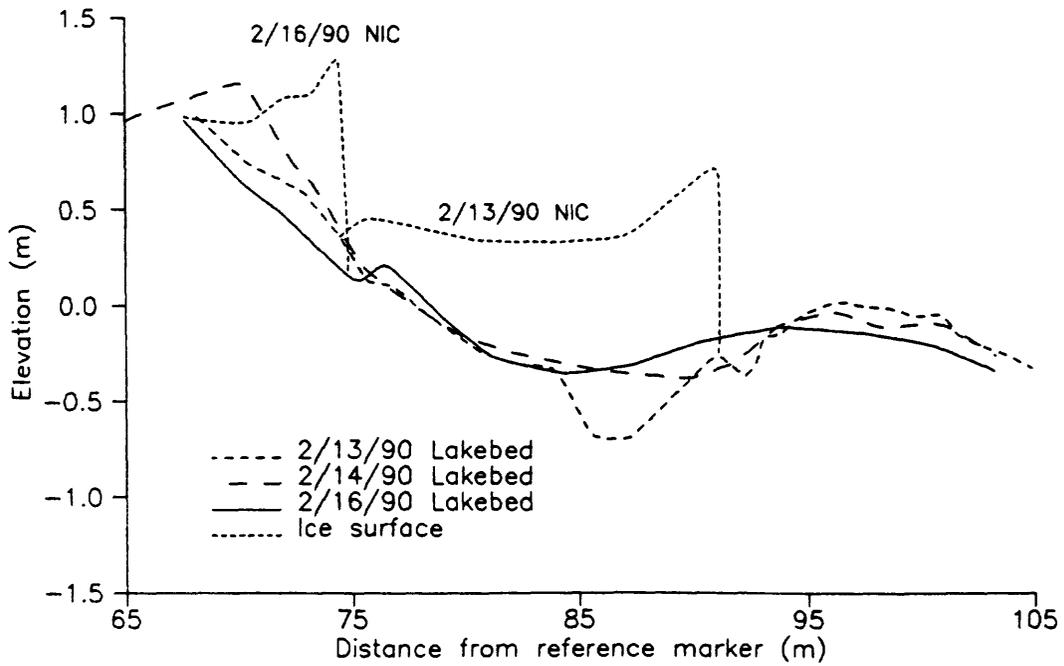
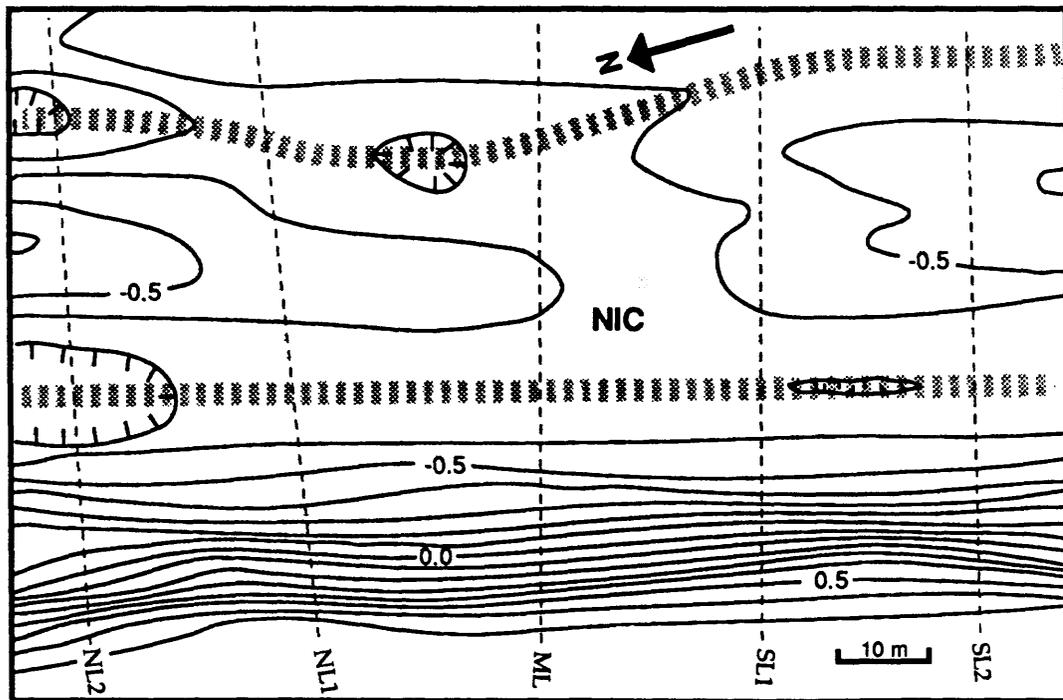


Figure 1. Repetitive coastal profiles at Point Beach State Forest, WI showing the demise and redevelopment of an erosional trough adjacent to an ice ridge. Local water level was 0 for our arbitrary datum on the 13th and about 0.3 m higher on the 16th.

Figure 2. Nearshore morphology at Kohler-Andrae State Park, WI, February 20, 1990. Map shows location of profiles and major bars and troughs (dashed bands). Contour interval is 0.1 m.



a

SEDIMENT CONTENT OF OFFSHORE ICE IN SOUTHERN LAKE MICHIGAN,
1991

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Understanding the influence of ice on coastal erosion requires a knowledge of the quantities, trajectories, and fate of coastal sediments rafted offshore by ice. During a one day cruise (January 19, 1991) along 33 km of shoreline from Chicago to Wilmette, IL, about 5-10 km offshore, 9 representative samples were taken of the floating lake ice. "Representative" samples were obtained from the nearest ice along the transect after a certain transit time had elapsed. The sediment content of these samples ranged from 0.01 to 7.13 g/l of melt water with an average of 1.13 g/l and a mode of 0.30 g/l. The dominant sediment was sand. One atypical sample contained as much as 112 g/l suggesting that our estimates of ice-rafted sediment load may be low.

During a helicopter flight 4 days later, 7 additional representative samples were scooped from a 2 to 7 km-wide area of wave-driven brash ice and slush constituting nearly 100% ice cover along a 34 km transect between Chicago, IL, and Burns Harbor, IN. These samples contained an average of only 0.05 g/l (0.02-0.06 g/l range). The low values may be typical of ice formed offshore, away from coastal sediment entrainment sources.

Using these few samples to extrapolate the sediment load carried in the offshore ice requires assumptions about ice concentration and thickness and how they vary. Based on field estimations, the ice cover varied from less than 1% to 30%, and it increased northward along the transect. Ice thickness varied from a few cm to 50 cm. We assume the samples from the transect represent the sediment load carried in the ice and further assume a 10 cm thick ice cover over 2% of the transect. We also assume that the observed ice volume is composed of 27% ice and 73% water (Kempema and others this volume). This means that each square meter along the transect contained 6 g of sediment $\{0.02 \times [(100 \times 100 \times 10)/100] \times 1.13 \times 0.27=6 \text{ g}\}$. By extrapolating to include the area of ice within 5 km to

the coast we suggest that 30 kg of sediment were carried in the offshore ice per m of coastline. If conditions were similar along the 33 km stretch of coast during these observations, 1000 tons of sediment were being rafted.

From these observations, however, it appears that most of the sediment is carried in widely distributed patches of high concentration. A representative analysis will require both large sample sizes and larger sample numbers along with synoptic information on the ice cover extent and thickness to assess the magnitude and character of offshore ice-borne sediment in the lake.

ANCHOR ICE FORMATION AND SEDIMENT TRANSPORT IN SOUTHERN LAKE MICHIGAN

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During January, 1991, observations were made at Gillson Beach, Wilmette, Illinois, to determine the effects of lake ice development on coastal erosion and sediment transport. During that month, evidence of anchor ice (ice attached or anchored to the lake bed) was observed on 15 days. These observations, along with observations made in 1988 and 1989, show that anchor ice is a common phenomenon in shallow coastal waters.

Conditions for anchor ice formation in the lake are similar to conditions described for its formation in rivers. Anchor ice usually formed on cold, clear nights when air temperatures fell below -6°C. Wind directions were usually obliquely offshore, resulting in relatively calm coastal waters. Significant wave heights (H_S), calculated from short time-series data records collected on mornings following formation events were 0.08 to 0.26 m.

Anchor ice was observed on the lake bed on many morning diving traverses that covered water depths of 0.7 to 4 m. This anchor ice consisted of randomly oriented ice "plates" that were from 1 to 40 cm in diameter and a few millimeters thick. These plates were either individually attached to the bottom or formed interfingering mats that covered up to several square meters of the lakebed. Anchor ice covered up to 50 percent of the bottom on any given traverse, and was attached to sand, pebble, and boulder substrates. The concentration of anchor ice was highest in 0.7 to 1.5 m water depth and decreased as water depth increased offshore.

Anchor ice formed predominantly at night (evidence for daytime anchor ice formation was only seen once). On mornings following formation, anchor ice was sporadically released from the bottom

over a period of three to five hours. This released anchor ice, commonly with entrained sediment, would float to the surface, where it was advected along or offshore. Twenty-five samples of this floating anchor ice were collected to determine the entrained sediment concentration and composition. Sediment concentrations ranged from 1.3 to 96 g l⁻¹ (mean concentration: 26.3 g l⁻¹, standard deviation: 26.6 g l⁻¹). The entrained sediment consisted of sand and pebbles up to 7 mm in diameter.

Anchor ice is released from the bottom sporadically during the morning. As anchor ice rises to the surface, it drifts off, making it difficult to determine the total volume of anchor ice formed during a night. However, the morning of January 27, 1991 presented an opportunity to estimate the total amount of anchor ice formed, and by extension the amount of sediment carried to the surface by that anchor ice. In the early morning, a thin sheet of solid ice covered the lake surface to the horizon, trapping anchor ice as it was released from the bed. By mid morning, all but 40 m of this solid ice attached to the outer edge of the nearshore ice complex had drifted offshore. Diving observations revealed that the remnant solid ice was underlain by a layer of released anchor ice that was from 10 to 50 cm thick. Observations made on other dives indicated that anchor ice formed to at least 4 m depth, at a distance of 200 to 300 m from shore. To estimate the amount of sediment carried in the released anchor ice, we assumed that it averaged 20 cm thick for a distance of 200 m beyond the outer edge of the nearshore ice complex. The average measured sediment concentration in collected samples (26 g l⁻¹) was used for the sediment concentration in the ice on this day. Only one bulk sample of floating anchor ice and water was collected. This sample contained 27 percent ice; this value was used to calculate the total volume of ice in the floating ice layer. Based on these values, the amount of sediment entrained into the water column by anchor ice on this day was 280 kg m⁻¹ of shoreline. The surface drift direction was offshore, so this sediment was carried away from the nearshore zone. The calculated amount of sediment in the anchor ice is similar to the average amount of sediment contained in the nearshore ice complex at a given time. The relatively high value represented by this single event, combined with observations

of the high frequency of events over the course of a winter, suggests that anchor ice can transport a significant amount of sediment from the coast each winter.

ICE DRIFT IN SOUTHERN LAKE MICHIGAN BASED ON SURFACE DRIFTER TRAJECTORIES

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Reimnitz et al. (1991) speculate that sediment-laden ice formed in Lake Michigan coastal zones “. . . has good potential to reach and feed (sediment to) beaches on the opposite side of the lake.” In an attempt to document this across-lake transport, we buried 102 Woodhead Seabed Drifters in an ice ridge at Gillson Beach, Wilmette, Illinois during January, 1991. Wave-induced decay of coastal ice ridges can result in large, sediment rich blocks of the ice ridge eroding into the mobile brash/slush ice zone. We reasoned that bottom drifters would be transported with this mobile ice as long as they remained trapped in larger blocks. Any drifters found on the east side of the lake would be evidence of across-lake transport of sediment-laden ice.

The ice ridge containing the drifters was destroyed between 2/3/91 and 2/10/91. Between 3/10/91 and 7/28/91, 14 drifters were recovered and returned. Unfortunately, 13 of these drifters had lost the weights that had made them negatively buoyant, so they acted as surface drifters for at least part of their deployment.

In spite of the weight losses, the distribution of returned drifters gives an indication of the fate of the ice that entrained them. This is because even after the drifters lost their weights, they should have followed the same trajectories as the surrounding ice. The major difference is that the ice could melt anywhere along the drift trajectory, and entrained sediment would be lost.

The pattern of drifter returns (Figure 1) suggests two separate drift pathways. The first pathway, shown by the eight drifters found in Illinois and Indiana, is associated with longshore drift to the south, as was often observed along the western shoreline of the lake. The second pathway, shown by the six drifters found in Michigan, is the path taken by ice that escapes from the nearshore zone. This ice probably travels some distance along the coast

before being advected offshore at promontories. Once the ice is offshore, it is incorporated into the counterclockwise current pattern that dominates the southern part of the lake (Allender, 1977). There is a core of warmer water in the center of the lake during the winter, and it is probable that most ice advected offshore melts while traversing this core. Any sediment entrained in the ice is then deposited in deep water.

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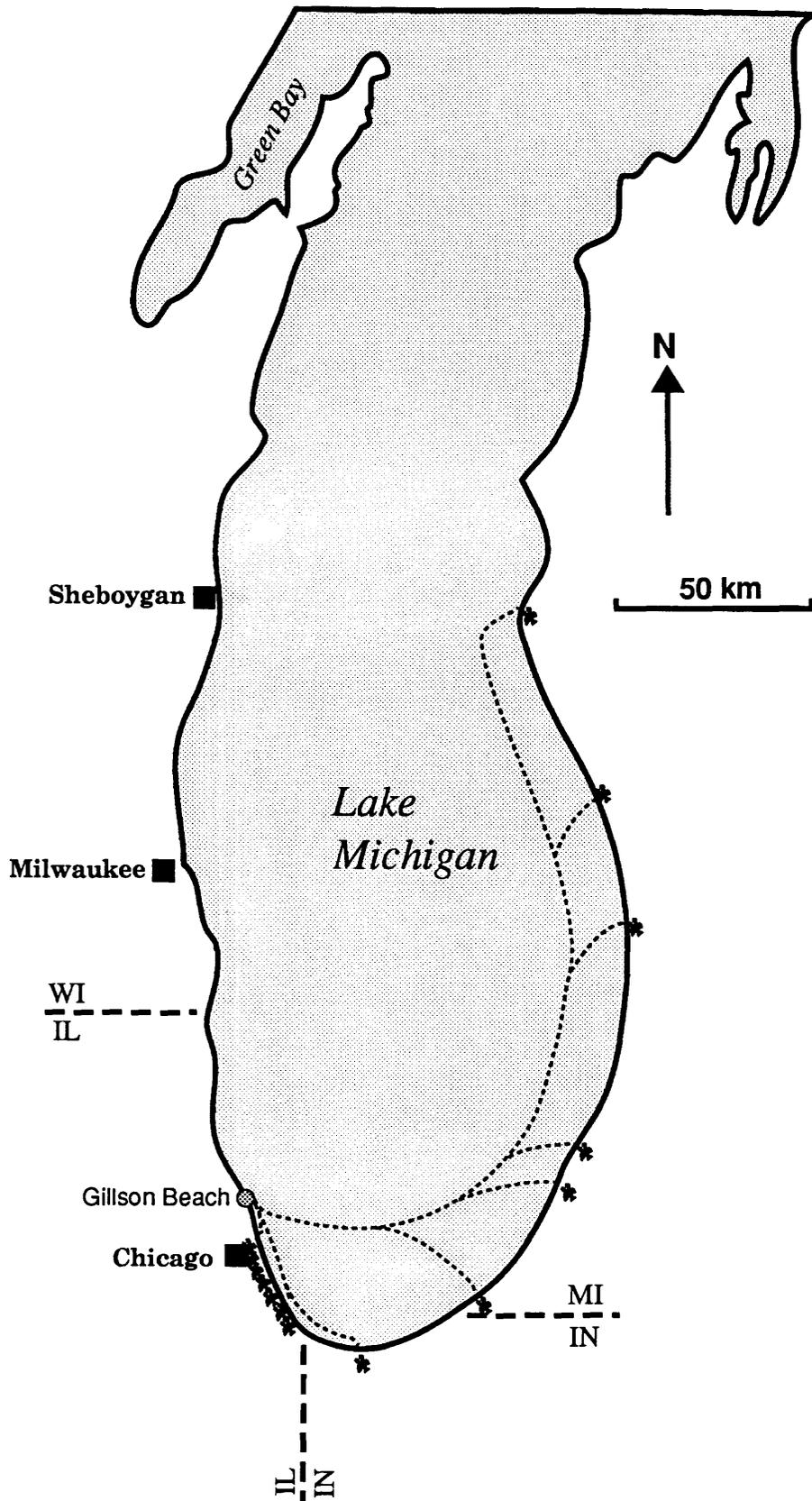


Figure 1. Asterisks show locations of 1991 drifter returns. All drifters were buried in an ice ridge at Gillson Beach. Dotted lines show possible drift paths.

CONTEMPORARY EOLIAN SAND TRANSPORT IN THE BACKSHORE- FOREDUNE AREA OF SOUTHSHORE, LAKE MICHIGAN

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Ongoing studies of wind and sand transport across a vegetated foredune and through an adjacent blowout area provide a basis to evaluate quantities and pathways of eolian sand transport in the Indiana Dunes area, south shore, Lake Michigan. These data will be used to compare contemporary conditions with those determined for the late-Holocene by Todd Thompson.

Repeated transit surveys and data collected from vertical trap transects indicate that most of the sand movement occurs in late-fall and spring when wind speeds are relatively high and the stabilizing effects of marram grass cover (warm season) and snowcover (mid-winter) are minimized. Autumn and early-spring storm winds tend to come from the north so most of the observed changes in the dune profile occurred on its windward (north-facing) slope where a wedge of eolian sand accumulates each season. We have observed virtually no changes in the topography of the dune on its landward side where a dense cover of marram grass exists. Large amounts of sand have been captured by our vertical traps in the blowout during every major wind storm; our transit surveys indicate that the topography of the blowout changes frequently as it is subjected to repeated cut-and-fill episodes. The main feature of the blowout site is an isolated dune at its landward outlet that has grown 75 cm in thickness since our study began in the fall of 1990.

Data collected in the blowout by an Automated Sand Trap indicate that the relationship between wind speed and sand transport depends on storm wind direction and antecedent moisture conditions. The

largest sand transport rates that we have measured ($>126 \text{ g cm}^{-1} \text{ hr}^{-1}$) occurred when storm winds averaging $>7 \text{ m s}^{-1}$ came directly out of the north and through the blowout. It is under these conditions of maximum sand fetch and spatially accelerating wind (due to the funneling effect of the blowout) that the loss of sediment from the backshore (by wind) is maximized. Southerly storm winds averaged ca. 6 m s^{-1} two days earlier, but the average rate of sand transport remained low ($< 26 \text{ g cm}^{-1} \text{ hr}^{-1}$) because the sand surface was damp from precipitation that accompanied the storm.

Our preliminary analyses of the relationship between wind speed and rates of sand transport indicate that the threshold wind speed for sand movement at the dune crest site is very high ($> 9 \text{ m s}^{-1}$), especially in summer and early autumn, due to the stabilizing effect of the marram grass, but the threshold wind speed in the blowout is equal to, or less than, the average value of ca. 4 m s^{-1} reported in the literature (we have measured values as low as 2 m s^{-1}). Measured values of Bagnold's dimensionless proportionality coefficient are also variable; typically ranging between 0.2 and 2.0, but much higher values have occurred on days when the wind was out of the south and the vertical profile of wind speed was inverted. The best-fit parameters for Bagnold's sand transport equation will be used in conjunction with a seven year record of hourly wind speed and direction to estimate the average contemporary rate of eolian sand transport in the backshore-foredune area of the Indiana Dunes region.

MODELING BEACH AND NEARSHORE PROFILE RESPONSE TO LAKE LEVEL CHANGE AND STORM WAVE FORCING

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INTRODUCTION

Design of beach and nearshore change models entails a thorough understanding of physical processes involved and the proper application of appropriate model concepts. However, the complexities of the coastal environment make the modeling tedious and computationally intensive. Even with the advent of supercomputers, time restrictions demand that simplifications of the environmental processes be made. A simplification common to many coastal models is application of the equilibrium beach concept.

Bruun (1954) analyzed the equilibrium profile concept and derived the equation $y^{3/2}=px$, where y is the water depth, x is the distance offshore, and p is a constant dependent on the system in which the equation is applied. Dean (1977) expressed the profile shape in the slightly different form $h(x)=Ax^m$, where $h(x)$ is the offshore water depth, x is the distance offshore, A is an arbitrary coefficient, and m is an arbitrary exponent. After testing this form on 502 beach profiles, Dean's results (1977) proved to be similar to Bruun's (1954) with the exponent m falling in a range of 0.6 to 0.7. Stockberger (1989) and Stockberger and Wood (1990) showed a range of m from 0.3 to 1.1 with an average value of 0.63 for southern Lake Michigan profiles. Therefore, a value of 0.67 is chosen to concur with theory (see Moore, 1982).

Moore (1982) concluded that for uniform wave action on a profile, a state of equilibrium energy may exist above which a grain of relevant hydrodynamic characteristics may be picked up and transported. He used this concept to suggest that a relation exists between grain size and wave energy dissipation and thus between

grain size and the A parameter. This relation was verified with field and lab data, resulting in what is referred to as Moore's curve.

Stockberger (1989), however, found disagreement with Moore's curve when tested against data from southern Lake Michigan. He found no correlation with Moore's curve and questioned the usefulness of fixing the value of m at 0.67. No significant dependence could be shown between the A value and sediment size for outer sections of analyzed profiles and only a slight trend was found for inner sections (Stockberger, 1989).

The equilibrium beach concept has been tested, and refined by many researchers for the case of rising water level on both ocean and Great Lakes coasts (Bruun, 1962; Edelman, 1972; Swart, 1976; Dean, 1977, 1991; Le Mahaute and Soldate, 1980; Kriebel and Dean, 1985; Hands, 1979, 1980, 1984; Stockberger, 1989; Stockberger and Wood, 1990; and many others). The driving force behind changes to the beach and nearshore, in the rising water level case of the equilibrium beach, is the breaking waves which have moved shoreward on the profile. This allows for breaking waves to influence a length of profile that was previously free from such large forces. The effect is to erode material from the backbeach and deposit it offshore until the equilibrium profile is attained.

The original equilibrium concept as presented by Bruun (1962) did not address the question of applicability of this model to falling water level. However, Hands (1980, 1984) has suggested that the equilibrium beach concept is applicable to this case for Great Lakes coasts. Conversely, Weggel (1979) states, referring to erosion and Bruun's equilibrium concept, that "a decline in water level will not reverse the process". Therefore, if the concept of an equilibrium beach profile existing for a given water level and wave climate is correct, the question arises as to how the profile adjusts to equilibrium under conditions of falling water level.

DATA ACQUISITION AND ANALYSIS

In an effort to study the effect of lake level variation on beach and nearshore response, an extensive 15 year data set from the southern shore of Lake Michigan was analyzed. The data set included 104 long

(to closure depth) hydrographic surveys, 117 dune/beach topographic surveys, 700 sediment samples, 10 sets of aerial photographs, and approximately 600 documentary photographs.

This extensive data set was used to evaluate the relationship between lake-level variation and beach profile response. Four topics were initially investigated. First, the equilibrium profile concept was also tested to determine its validity for rising and falling lake levels. Second, the appropriate value for the exponent m was evaluated. Third, the reliability of Moore's curve (1982) was tested on beach sediment samples. Fourth, "A" value variation with time was compared to lake level change for inner profiles and for profiles to closure depth.

RESULTS

The equilibrium beach concept is based on two primary assumptions. The first is that the form or shape of the nearshore profile is known, the second is that the nearshore profile responds on a time scale similar to that of water level change. Results of this study have shown that the nearshore profile form found by Dean (1977), $h(x)=Ax^{2/3}$, is appropriate for use in describing the "average" or characteristic nearshore profile found in southern Lake Michigan. However, the results have also shown that beach and nearshore profiles respond on a much longer time scale than that of mean annual water level change and that the equilibrium beach concept may not be applicable for predicting nearshore response to short term water level changes. There may be a "phase-lag" between beach profile response and lake level rise, but the magnitude of that lag is not discernible. Hands (1980) suggested a lag period on the order of "a few years" for Lake Michigan profile response, but was unable to quantify the relationship.

The effect of falling water level on the nearshore profiles could not be determined due to the slower than expected response of the profiles to water level change. Since questions still exist as to the applicability of the equilibrium beach concept to falling water level, it is strongly suggested that this concept not be applied under conditions of falling water level.

Stockberger (1989) investigated this concept for falling lake levels and showed no support for the expectation that the effect of a falling water level was simply to reverse the effect of rising water level. While it is reasonable to assume that a beach may widen with falling water level due to emergence, "rebuilding" of the still water level is not explained by the Bruun concept. Some material may eventually be redeposited on the beach due to wave action during periods of setup; however, the majority of the material can not be replaced on the upper beach, due to the lack of a sufficient driving force. Since all sediment within a littoral cell remains within that cell, excess sediment may add to the profile in the form of additional offshore bars or it may increase the amount of sediment being transported longshore within the cell.

Current research efforts are directed at the generation of synthetic quasi-random lake-level predictions. The purpose of this work is to develop a method for generating data for input to the beach and nearshore profile response model. Results to date have produced synthetic lake records for periods of 120, 500, and 1000 years. A recent modification to the generating program incorporated precipitation as a modulating function imposed on the quasi-random generator.

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SEDIMENT BUDGETS FOR SOUTHERN LAKE MICHIGAN: A PROGRESS REPORT

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We have attempted to produce a sediment budget for southern Lake Michigan by comparing sources and sinks of sediment for three different time periods: (1) modern, or the last 100 yr; (2) the last 5 ka, or post-Nipissing phase; and (3) the last 10 ka, or Holocene time. Sediment is measured as mass, and the following sources and sinks are defined:

SOURCES

M_{BI} - Bluff erosion
 M_{RI} - River input
 M_{AI} - Aerosol input
 M_{IE} - Basin import/export (\pm)

SINKS

M_{LS} - Lake basin
 M_{NS} - Nearshore sand
 M_{BS} - Beaches
 M_{DS} - Dunes

The sediment budget equation is thus:

$$M_{BI} + M_{RI} + M_{AI} \pm M_{IE} = M_{LS} + M_{NS} + M_{BS} + M_{DS}$$

Because the mass of sand stored in the nearshore zone, in beaches, and in dunes is poorly known, we have further separated the budget into a sand budget and a mud budget. The mud budget is simpler, because the only sinks for mud are the export of suspended sediment from the basin and deposition in the deep part of the lake. For mud, the equation is thus:

$$M_{BI} + M_{RI} + M_{AI} = M_{LS} + M_{IE}$$

For the modern budget, each of the terms can be independently estimated from published values for modern processes and sediment compositions. Doing so results in a budget that nearly balances at about 3×10^6 MT/yr. Two terms dominate the equation: (1) bluff erosion, which is an order of magnitude larger than either rivers or aerosols as a source; and (2) deposition in the deep basin, which is more than two orders of magnitude greater than suspended sediment transport out of the basin as a sink.

Because bluff erosion is the only significant source of sand, the modern rate of sand contribution to the lake can be estimated in the same way it was for the mud budget, as the complement of the mud component of the bluffs. The result is about 2.4×10^6 MT/yr. The amount of sand deposited in the deep lake can also be calculated from modern grain size and mass flux data. These calculations indicate that about half of the sand derived from bluff erosion is deposited in the deep lake; the other half must be deposited in nearshore sand bodies, beaches, and dunes.

The primary sink for mud for the 5 ka and 10 ka periods is the deep lake basin, as it is for the modern budget. We can estimate this sink reasonably well from our core and seismic-reflection data. In contrast, the sources of mud for past intervals are difficult to estimate. Extrapolations of river and eolian inputs are problematic because both are dramatically influenced by climate and human activity. However, if bluff erosion was the dominant source of mud in the past, as it is at present, then the contribution of mud from bluff erosion can be solved for by equating it to the amount deposited in the deep lake basin. The related contribution of sand from the bluffs is then readily calculable, assuming the composition of the bluffs has not changed with time. Although we can calculate the mass contribution from bluff erosion for past time periods, we cannot calculate bluff recession rates for the past because the configuration of the bluffs has changed with time in a way that is difficult to reconstruct.

Despite the uncertainties in many of our estimates of sediment sources and sinks, the attempt to reconstruct sediment budgets for different time periods leads to important insights about erosion and sedimentation processes in Lake Michigan. Bluff erosion appears to be the dominant source of both sand and mud in the basin. The deep lake floor appears to be the primary sink for mud, whereas both the deep lake and nearshore areas are important sinks for sand.

PRODUCTS

Scientific

Summary Volume (Journal of
Great Lakes Research)

Papers and maps in USGS, ISGS, IGS
publications and outside professional
journals

Compilations on CD ROMS

Non-technical

USGS Circular (Public Issues in
Earth Science)

Newspaper and magazine articles

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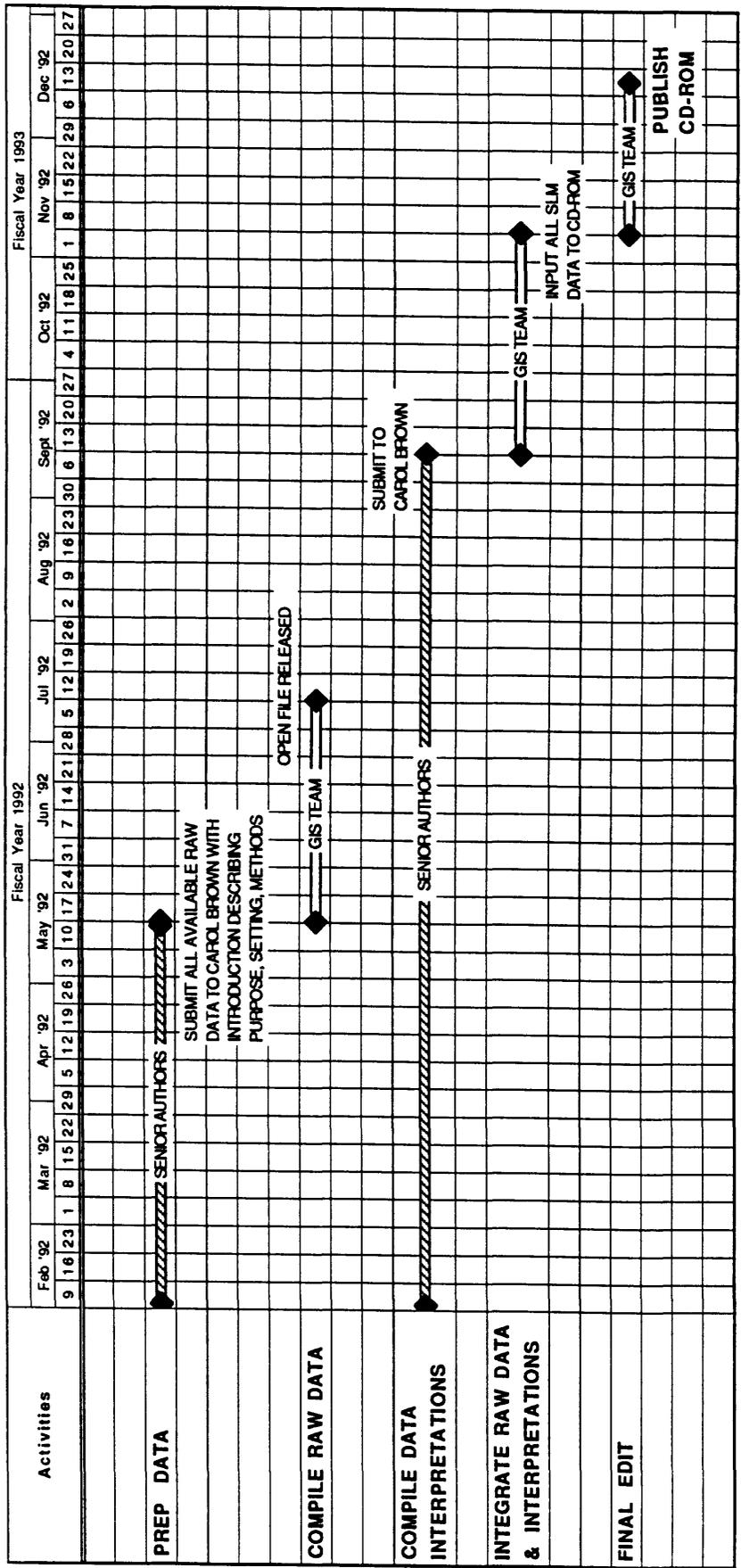
APPENDIX A

Schedule for Summary Volume preparation

APPENDIX B

Schedule for CD-ROM preparation

SLM CD-ROM PREP SCHEDULE



APPENDIX C

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