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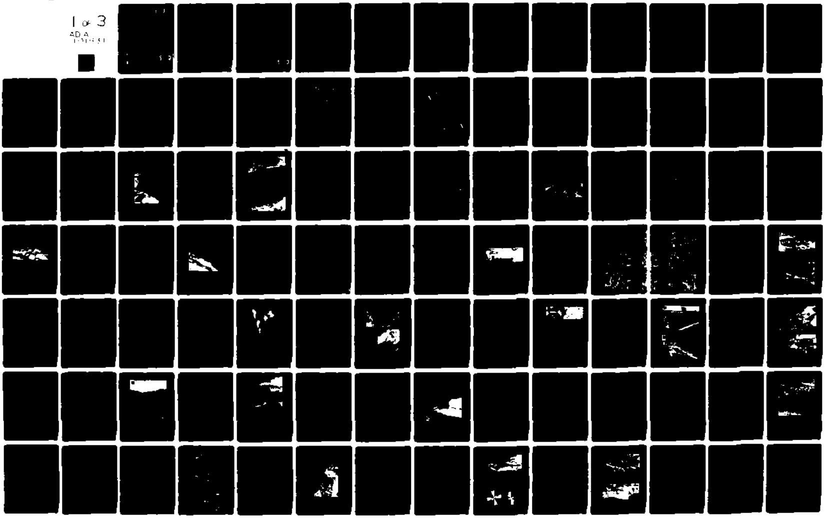

LEVEL II

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(6)

Coast of Lake Erie

Report

on

LITTORAL PROCESSES AND SEDIMENTATION

IN THE CATTARAUGUS EMBAYMENT, New York

(10) Robert F. Fahnestock
Donald Messinger
John Walton
Dag Nummedal
David Shearer

(9)

Final Report for Contract

(15) DACW49-74-C-0118 — SU of New York at Fredonia, Dept of Geology

(11) 1974 (12) 260

U. S. Army Engineer District, Buffalo

Corps of Engineers

Buffalo, N. Y. 14207

SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

REPORT DOCUMENTATION PAGE

READ INSTRUCTIONS BEFORE COMPLETING FORM

1. REPORT NUMBER	2. GOVT ACCESSION NO. AD-A101 831
3. RECIPIENT'S CATALOG NUMBER	
4. TITLE (and Subtitle) Coast of Lake Erie on Littoral Proceses and Sedimentation in the Cattaraugus Embayment, New York	5. TYPE OF REPORT & PERIOD COVERED Final
	6. PERFORMING ORG. REPORT NUMBER
7. AUTHOR(s)	8. CONTRACT OR GRANT NUMBER(s) DACW49-74-C-0118
9. PERFORMING ORGANIZATION NAME AND ADDRESS U.S. Army Engineer District, Buffalo 1776 Niagara Street Buffalo, New York 14207	10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS
11. CONTROLLING OFFICE NAME AND ADDRESS U.S. Army Engineer District, Buffalo 1776 Niagara Street Buffalo, New York 14207	12. REPORT DATE 1974
	13. NUMBER OF PAGES 195
14. MONITORING AGENCY NAME & ADDRESS(if different from Controlling Office)	15. SECURITY CLASS. (of this report) UNCLASSIFIED
	15a. DECLASSIFICATION/DOWNGRADING SCHEDULE

16. DISTRIBUTION STATEMENT (of this Report)

Distribution Unlimited

17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)

18. SUPPLEMENTARY NOTES

19. KEY WORDS (Continue on reverse side if necessary and identify by block number)

Littoral Processes
Shoreline Erosion
Wave Refraction
Breakwaters
Cattaraugus Embayment

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

It is the intent of this approach to determine in detail the littoral process pattern during any individual storm and to outline the consequent long-term sediment dispersal paths. Based on the developed process response model for the unmodified Cattaraugus Embayment, the report concludes with a prediction of possible sedimentation problems associated with five different breakwater configurations at the Creek mouth.

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Coast of Lake Erie

Report

on

LITTORAL PROCESSES AND SEDIMENTATION IN THE CATTARAUGUS EMBAYMENT, N. Y.

Final Report for Contract

DACW49-74-C-0118

U. S. Army Engineer District, Buffalo

Corps of Engineers

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ACKNOWLEDGEMENTS

This study was supported by the U. S. Army Engineer District, Buffalo, by contract No. DACW49-74-C-0118 to Robert K. Fahnestock. Thomas Wilkinson, Robert Johnson, John Koller, and James Karsten, all of the U. S. Army Engineer District, Buffalo, are acknowledged for guidance and active participation in various phases of this project.

The bulk of the field work was performed by Dag Nummedal, Miles Hayes, Robert Clemens, David Shearer, and Leita Hulmes, all of the Coastal Research Division, Department of Geology, University of South Carolina, and Robert Fahnestock, Donald Messinger, and John Walton of the Department of Geology, State University of New York at Fredonia.

Authors of the report were:

Dag Nummedal, David Shearer, and Robert Clemens - Sections 1, 2, 6, 7, 8, 9, 10.

Miles Hayes, Leita Hulmes, and Robert Clemens - Section 3.

Robert Fahnestock, Donald Messinger, and John Walton - Sections 4 and 5.

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SUBJECT: Cattaraugus Creek Harbor, New York

TO: U. S. Army Engineer District, Buffalo

1. AUTHORITY AND SCOPE

This study was undertaken in accordance with specifications set forth in contract No. DACW49-74-C-0118. The Scope of Work, Paragraph 1, specifies:

> (The) purpose of (the) work (is) to provide data on littoral currents and stream currents and the source and amount of sediment transported by each. The data provided is to be used by the Buffalo District Corps of Engineers in their study of the proposed breakwater structures for the Cattaraugus Harbor project and the effects of these structures on both the littoral and stream currents.

Based on the data collected according to the Scope of Work, Paragraph 3(b), we have analyzed five alternative breakwater configurations. The selection of a preferred structure was based on criteria specified in Scope of Work, Paragraph 2(4):

> Based on his findings (the contractor should) propose a breakwater configuration that will have the least detrimental effect on the regional environment.

2. REPORT OUTLINE

The problems specified above have been analyzed in this study of sediment distribution and process variability within the Cattaraugus Embayment. It is the intent of this approach to determine in detail the littoral process pattern during any individual storm and to outline the consequent long-term sediment dispersal paths. Based on the developed process-response model for the unmodified Cattaraugus Embayment, the report concludes with a prediction of possible sedimentation problems associated with five different breakwater configurations at the creek mouth.

3. RECONNAISSANCE OF THE MORPHOLOGY AND SEDIMENTS OF THE SOUTHEAST SHORELINE OF LAKE ERIE

3.1 Introduction.

Before the geomorphology and sedimentation of the Cattaraugus embayment can be properly assessed, it is necessary to determine how it relates to the rest of the southeastern shoreline of Lake Erie. In order to do this, a regional reconnaissance of the morphology and sediments of the shoreline between Fairport Harbor, Ohio and Wanakah, New York (Fig. 1) was carried out in May, 1974. The purpose of this study was to: (a) determine regional patterns of erosion and sedimentation; (b) briefly examine all major man-made structures in the area; and (c) to describe as succinctly as possible the morphology and sediments of specific sites thought to be representative of the region as a whole.

This regional reconnaissance was accomplished by application of the <u>zonal</u> <u>method</u> developed over the past few years by Hayes and associates of the Coastal Research Division. This method consists of the following steps:

1. A single large physiographic unit is chosen as the area of study, in this instance, the southeastern shoreline of Lake Erie.
2. Study of aerial photographs, maps and charts of the area chosen, as well as of the available literature, precedes the field work.
3. Field work begins by aerial reconnaissance of the entire area. The study area (Figs. 1 and 2) was flown twice, once in April and once in May. The area was photographed in detail during both flights.

Figure 1. Location map showing the area studied during the regional reconnaissance of the southeastern shoreline of Lake Erie. The study covered the area between Fairport Harbor, Ohio, and Wanakah, New York.

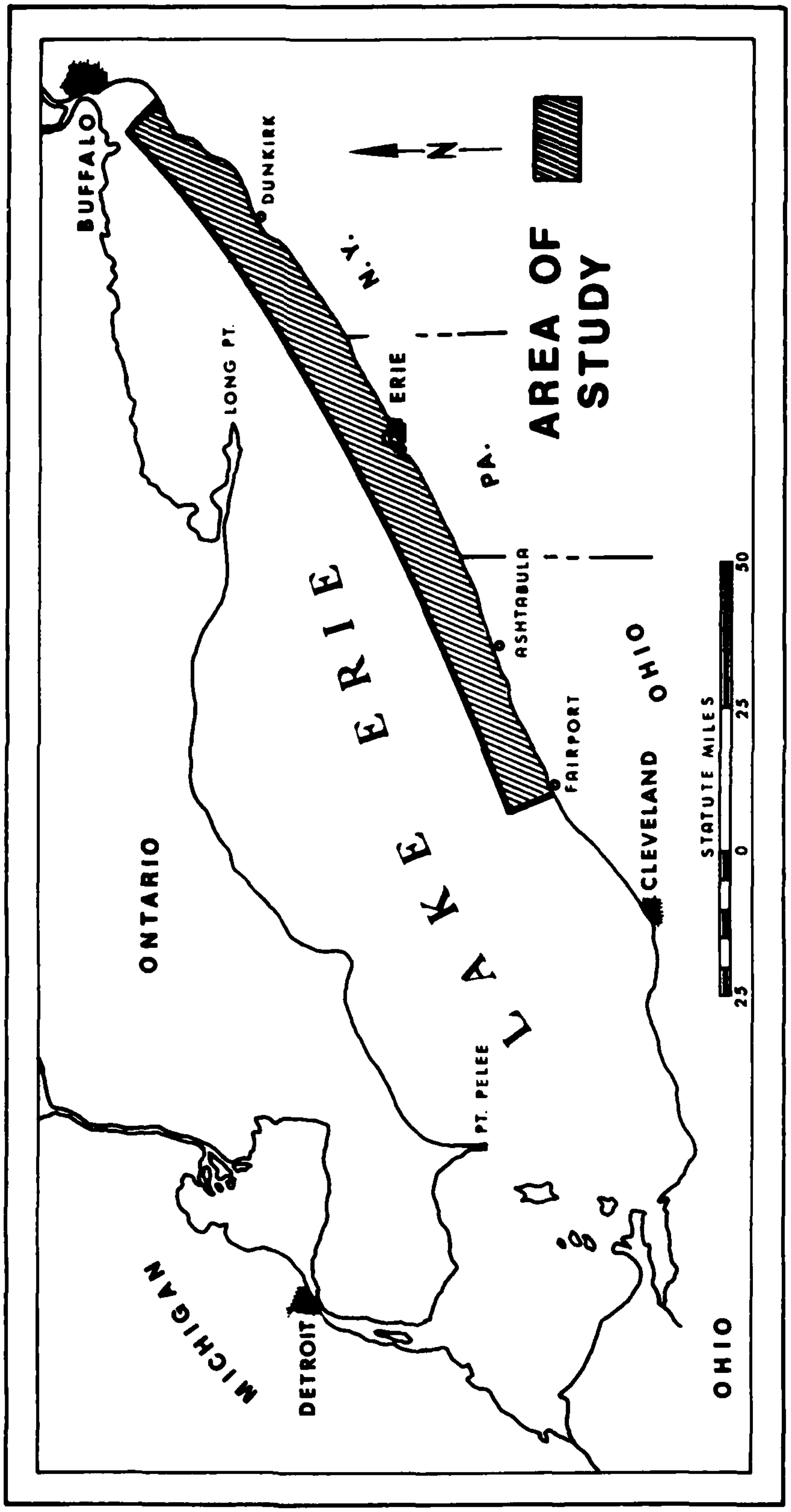
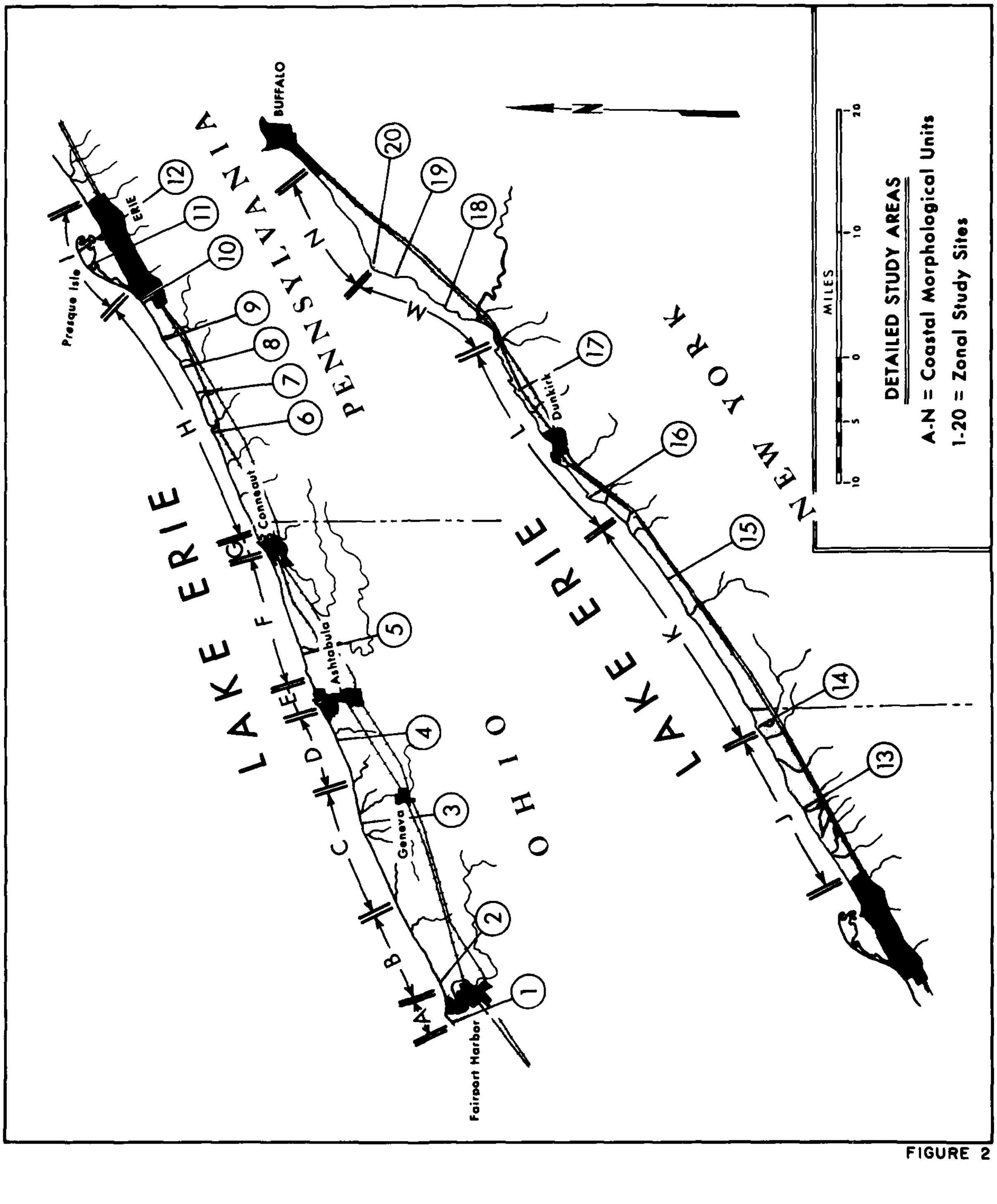

BUFFALO
DUNKIRK
N
N.Y.
AREA OF STUDY
LONG PT.
ERIE
PA.
ASHTABULA
LAKE ERIE
FAIRPORT
OHIO
CLEVELAND
STATUTE MILES
25
0
25
50
ONTARIO
PT. PELEE
MICHIGAN
DETROIT
OHIO

FIGURE 1

Figure 2. Location of shoreline morphological units (A-N) and zonal study sites (1-20) on the southeastern shoreline of Lake Erie. Descriptions of the morphological units are given in Table I.



LAKE ERIE
LAKE ERIE
OHIO
PENNSYLVANIA
NEW YORK
BUFFALO
Erie
Presque Isle
Conneaut
Ashtabula
Geneva
Fairport Harbor
Dunkirk
A
B
C
D
E
F
G
H
I
J
K
L
M
N
1
2
3
4
5
6
7
8
9
10
11
12
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15
16
17
18
19
20
N
MILES
10
5
0
10
20
DETAILED STUDY AREAS
A-N = Coastal Morphological Units
1-20 = Zonal Study Sites

FIGURE 2

4. If desired, a sediment sampling interval is then chosen. In this study, we did not sample the sediments in detail because of lack of time and resources necessary to work up the data in the laboratory.

5. Next, the study area is divided into physiographic subdivisions. These subdivisions are defined on the basis of a change in morphology or in one of the major process parameters. During the second flight, the study area was carefully described (with a tape recorder) and coastal physiographic units were chosen, as well as sites for detailed study, within each major unit. The study area was divided into 14 coastal units, which are located on Figure 2.

6. Within each of the subdivisions, specific sites thought to be representative of that particular type of coastal morphology are chosen for detailed study. There may be several of these sites within each subdivision, depending upon the complexity of the unit. In the study area, 20 of these detailed studies, called zonal studies, were carried out by a 3-man crew.

Each zonal study may include the following:

a. Construction ot a three-dimensional block diagram of the beach zone. In the study area, this was usually accomplished by combining beach profiles with pace-and-compass maps.

b. Grain-size estimates and photographs of the sediments are made at selected localities.

c. Detailed topographic surveys and statistical studies of features within the zone.

d. Detailed photographs to illustrate sediment characteristics and topographic features within the zone, both from the ground and from the air.

e. Detailed sketches are made of the zone. These are important because they force the observer to carefully inspect all aspects of the morphology and sediments within the zone.

The end product of a zonal study is a general summary and map of the morphology of a large coastal region, with some details on the local morphology and sediment dispersal trends. The location of the 14 coastal units and 20 zonal study sites for the study area are given in Figure 2.

3.2. Shoreline units.

3.2a. Introduction. The fourteen coastal units chosen are described in Table I. The boundaries between the units were chosen at points where significant changes in morphology occurred, such as at major harbor structures (e.g. at Ashtabula and Conneaut), or at significant topographic breaks (e.g. southwest border of Presque Isle).

3.2b. Unit A. The Fairport Harbor area, Unit A (Fig. 2), is an improvement project that was authorized in 1835 and has been modified several times since then. It consists of an outer harbor about 360 acres in area, a west breakwater 3878 ft. long, which is connected with the shore, and an east breakwater 6750 ft. long, which is separated from the shore by approximately 2700 ft. of open water. Figure 3A gives an outline map of the harbor area.

A brief ground study, or zonal study, was conducted on the beach west

Table I. Description of major shoreline morphological units (A-N; Fig. 2).

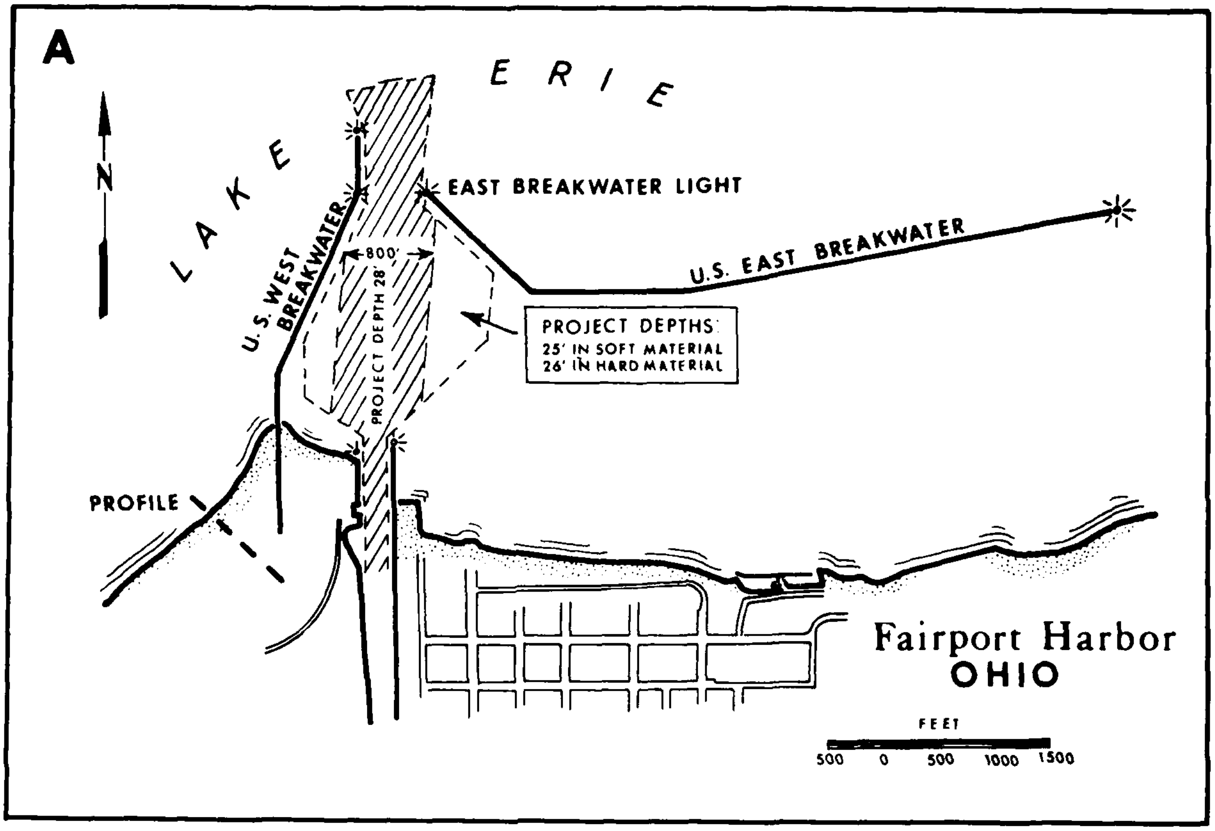
Unit	Location	Description
A	Fairport Harbor, Ohio, area	Major harbor structure consisting of two large breakwaters and dredged area.
B	Eight miles of shoreline northeast of Fairport Harbor, Ohio	Eroding cliffs of intermediate height (50-60 ft.) composed predominantly of fine-grained Pleistocene sediments.
C	Unit B to Indian Creek, Ohio (10.5 miles)	Lowland topography with numerous deltas separated by some cliffs; heterogeneous area; severe erosion.
D	Indian Creek, Ohio, to Ashtabula, Ohio, (6.5 miles)	High eroding cliff composed predominantly of glacial deposits; cliff relatively straight.
E	Ashtabula, Ohio, structure	Major harbor structure consisting of two long breakwaters and dredged area.
F	Ashtabula, Ohio, to Conneaut, Ohio (13 miles)	High eroding cliff composed predominantly of glacial deposits; cliff somewhat irregular.
G	Conneaut, Ohio, structure	Major harbor structure consisting of two long breakwaters and dredged area.
H	Conneaut, Ohio, to Erie, Pa. (21 miles)	Cliffs of variable heights with shale at base; several minor deltas; complex shoreline.
I	Presque Isle, Pa.	Large recurved spit system migrating northeastward.

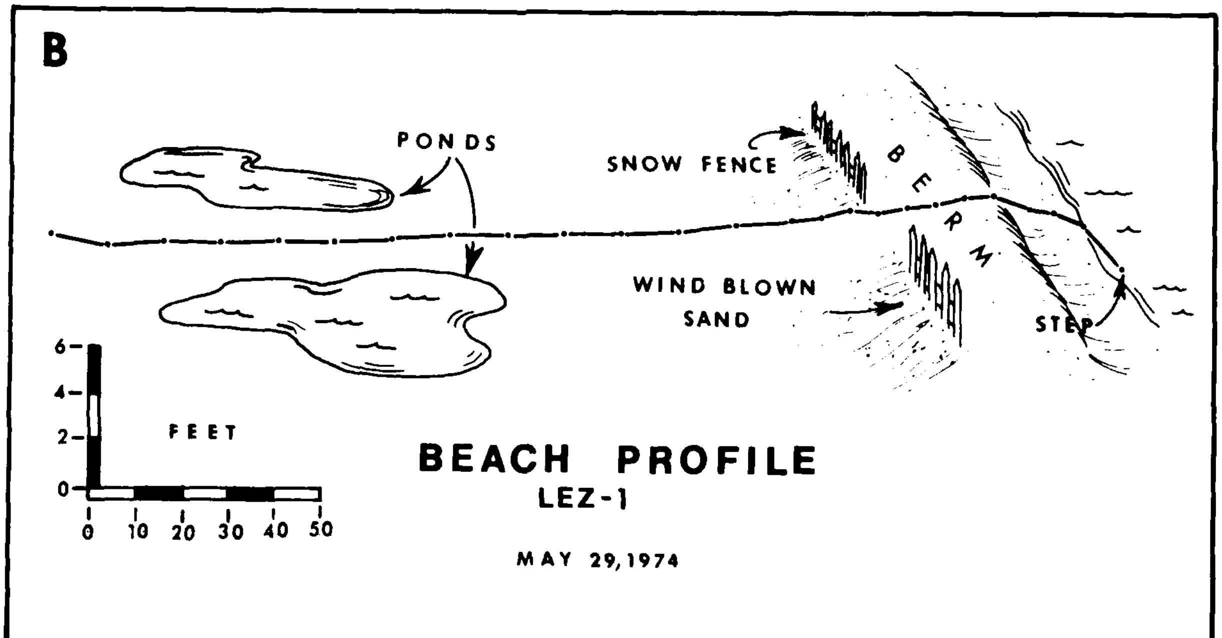
Table I. (cont'd.)

Unit	Location	Description
J	Erie, Pa., to Twentymile Creek, Pa., (16 miles)	Complex area with numerous deltas separated by cliffs of varying heights; amount of bedrock in cliffs increasing.
K	Twentymile Creek, Pa., to Lake Erie State Park, N.Y. (22 miles)	Cliffs of intermediate height composed predominantly of bedrock; many small river deltas; shoreline relatively straight.
L	Lake Erie State Park, N.Y., to Silver Creek, N.Y. (16 miles)	Cliffs of intermediate height composed entirely of bedrock (shale); shoreline very irregular with orientation of major headlands controlled by joint patterns in bedrock.
M	Silver Creek, N.Y. to Sturgeon Pt., N.Y. (16 miles)	Headlands of intermediate height separating wide, sandy embayments; large streams with heavy sediment input.
N	Sturgeon Pt., N.Y. to Wanakah, N.Y. (8.5 miles)	Cliffs of intermediate height composed of bedrock and glacial sediments; shoreline somewhat irregular.

Figure 3. A. Map of the structure at Fairport Harbor, Ohio. Note location of beach profile given in B.

B. Profile of beach just west of the west breakwater of the Fairport Harbor structure. Profile was measured on 29 May 1974. This wide, predominantly sandy beach has accumulated at this locality as a result of the Fairport Harbor structure trapping sediment in transport in the nearshore zone. The sediment transport direction is predominantly from southwest to northeast in this area.





FIGURES 3A AND B

of the west breakwater. The profile of the beach at that location is given in Figure 3B. The measured beach profile consists of a very wide, high, predominantly sandy berm. A large portion of the beach, principally that area behind the snow fence (shown in Fig. 4), has been manicured with bulldozers to maintain a flat profile. The measured width of the beach between the low dune scarp and the present water level was 357 ft., which makes this one of the widest, sandy beach areas on the southeast shore of Lake Erie. The beach is wide at this position as a result of the attenuation of longshore transport of sediments in a northeasterly direction by the exceptionally long west breakwater of the Fairport structure. It is evident from the aerial photograph in Figure 4 that a large bar occurs offshore (note waves breaking on bar). We also observed ridge-and-runnel systems and beach protuberances at different times at this locality; therefore, this is an area of active sediment transportation and deposition.

3.2c. Unit B. Unit B, an area of eroding cliffs of intermediate height, starts just east of the Fairport Harbor structure and continues eastward for about 8 miles (Fig. 2). The cliffs are composed of glacial material and are frequently scalloped by landslides and slumping, as at zonal site #2, where a road has recently been truncated by a large slump (Fig. 5A,B). The cliff is composed mainly of fine-grained gray clay. The measured height of the cliff at the zonal site is 57 ft.

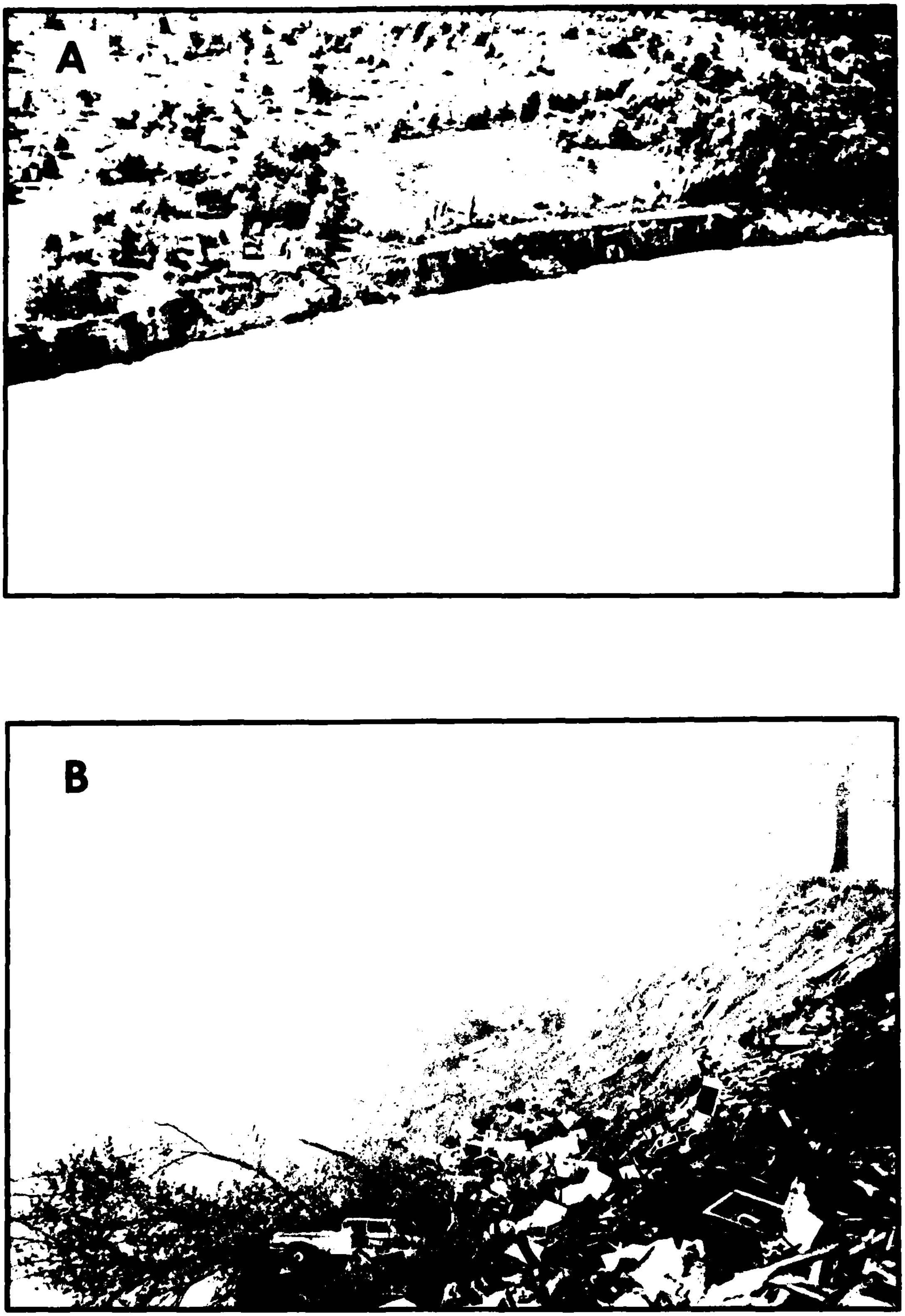
3.2d. Unit C. Unit C is approximately 10.5 miles in length (Fig. 2) and is dominated by lowland topography that contains numerous small river deltas separated by some erosional cliffs. In general, the area is intensely erosional and much property is being lost. Unit C offers a strong contrast

Figure 4. Wide sandy beach located southwest of Fairport Harbor structure (west breakwater is shown in foreground). Note location of beach profile given in Figure 3B.

FIGURE 4

Figure 5. A. Eroding cliff at zonal study site #2 (Fig. 2). This site is located approximately 3 miles east of Fairport Harbor, Ohio.

B. Cliff near area shown in aerial view (A). Note intensive slumping of the cliff.



FIGURES 5A AND B

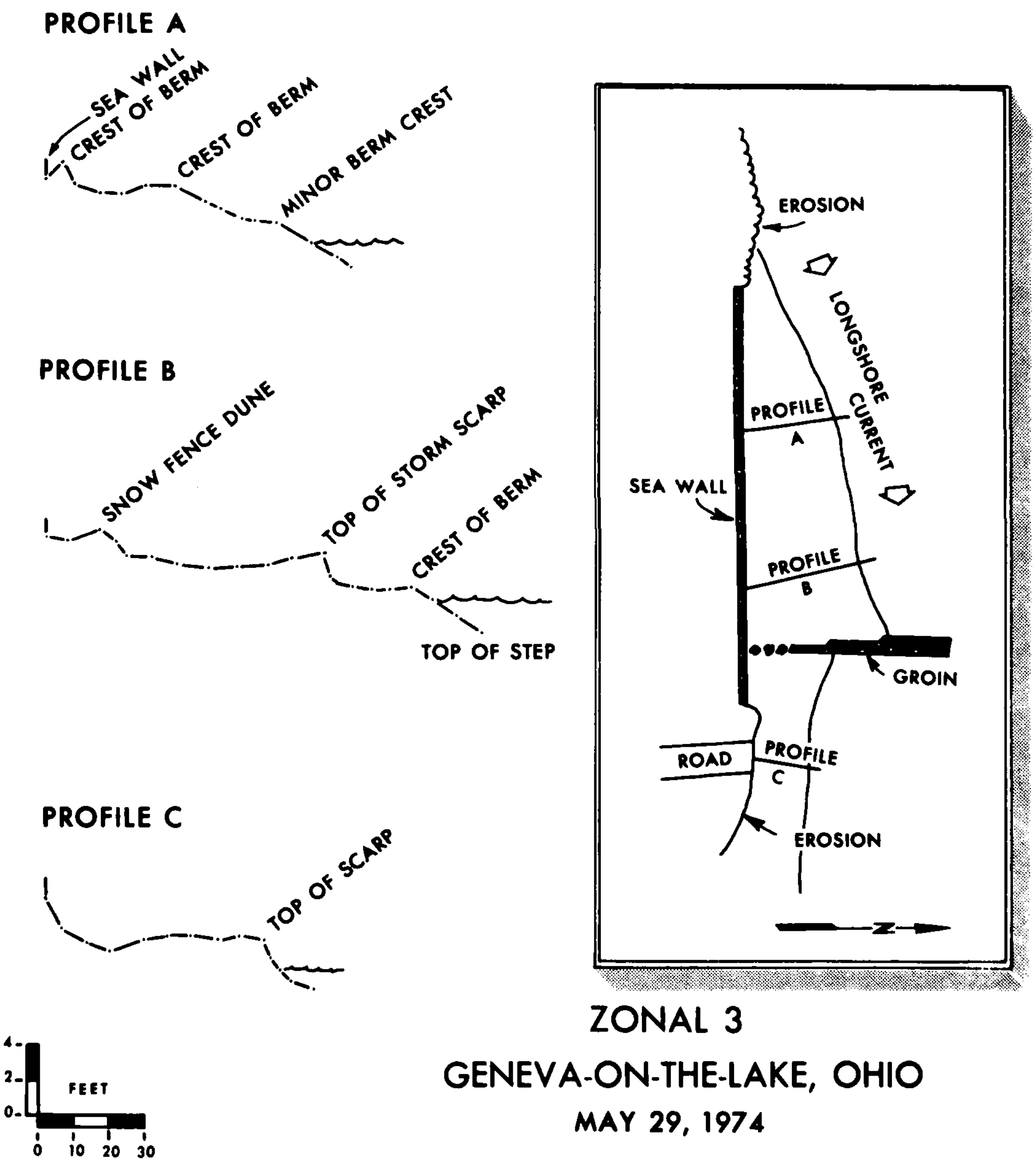
to Unit B, in that it is much more heterogeneous, contains more rivers, and is notably lacking in thick accumulations of glacial material.

Zonal site #3 is located at Geneva-on-the-Lake, Ohio. It is dominated by a single groin structure 139 ft. in length, which has a large accumulation of sediment on the west side (see sketch map in Fig. 6). The sediment accumulated updrift of the groin is 106 ft. wide at the groin and extends 330 ft. updrift. The accumulation amounts to approximately 4,200 cubic yards of sediment. To the west of this accumulation, a corrugated seawall has been built which has been only partially successful in retarding erosion in that area, and to the east of the structure, severe erosion is presently taking place. In fact, the general area represented by Zonal #3 is one of the most severely eroding portions of the southeastern shoreline of Lake Erie.

Three beach profiles were measured at the zonal site. Two profiles on the updrift side, A & B (Fig. 6), are made up of multiple berms that are composed of a mixture of fine gravel and sand. This area is illustrated by the photograph in Figure 7. The profile downdrift of the groin is narrow, also consists of multiple berms, but is finer-grained, being composed mostly of granule-sized material.

3.2e. Unit D. Unit D., which extends for 6.5 miles between Unit C and Ashtabula, Ohio (Fig. 2), is a high eroding cliff composed predominantly of glacial material. The cliff is relatively straight but shows some slumping and erosional features. The zonal site (#4; Fig. 8) is located at Red Brook, Ohio, which is a small stream cutting through the cliff. It contains small jetty structures, which are illustrated in the aerial

Figure 6. Sketch map (right) and three beach profiles measured at zonal site #3 (Geneva-on-the-lake, Ohio) on 29 May 1974. There is strong nearshore sediment transport from southwest to northeast in this area. Note heavy sediment accumulation on the updrift side of the groin.



ZONAL 3

GENEVA-ON-THE-LAKE, OHIO

MAY 29, 1974

FIGURE 6

Figure 7. Area updrift of the groin at zonal site #3. View looks east-northeast. Compare with profile B in Figure 6.

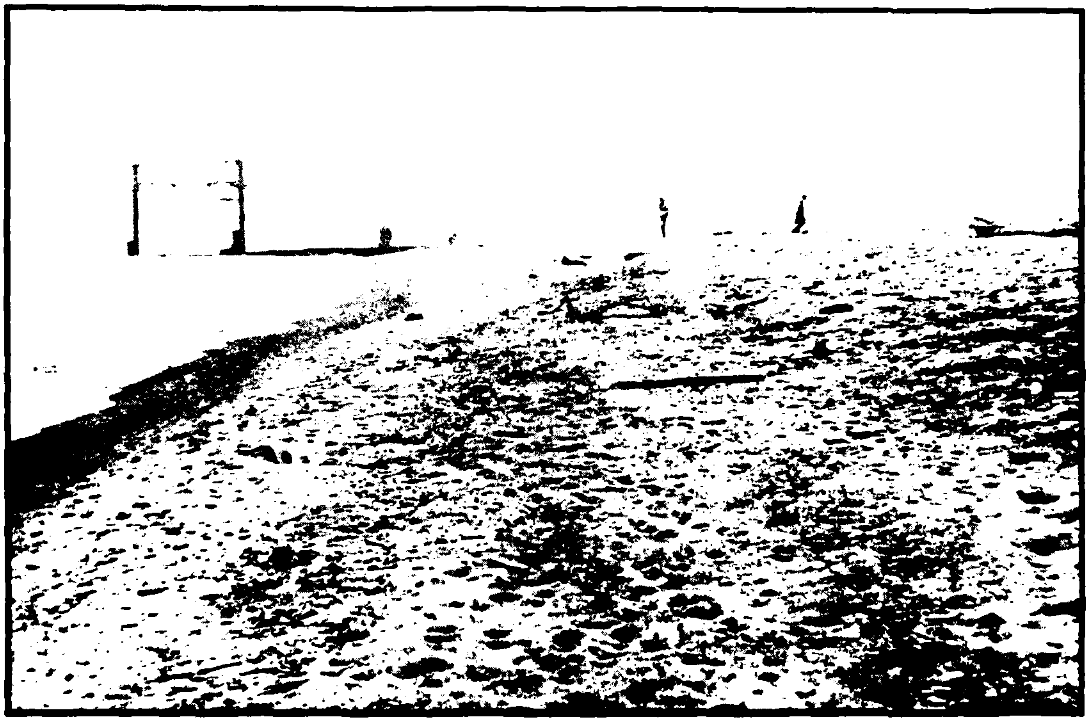
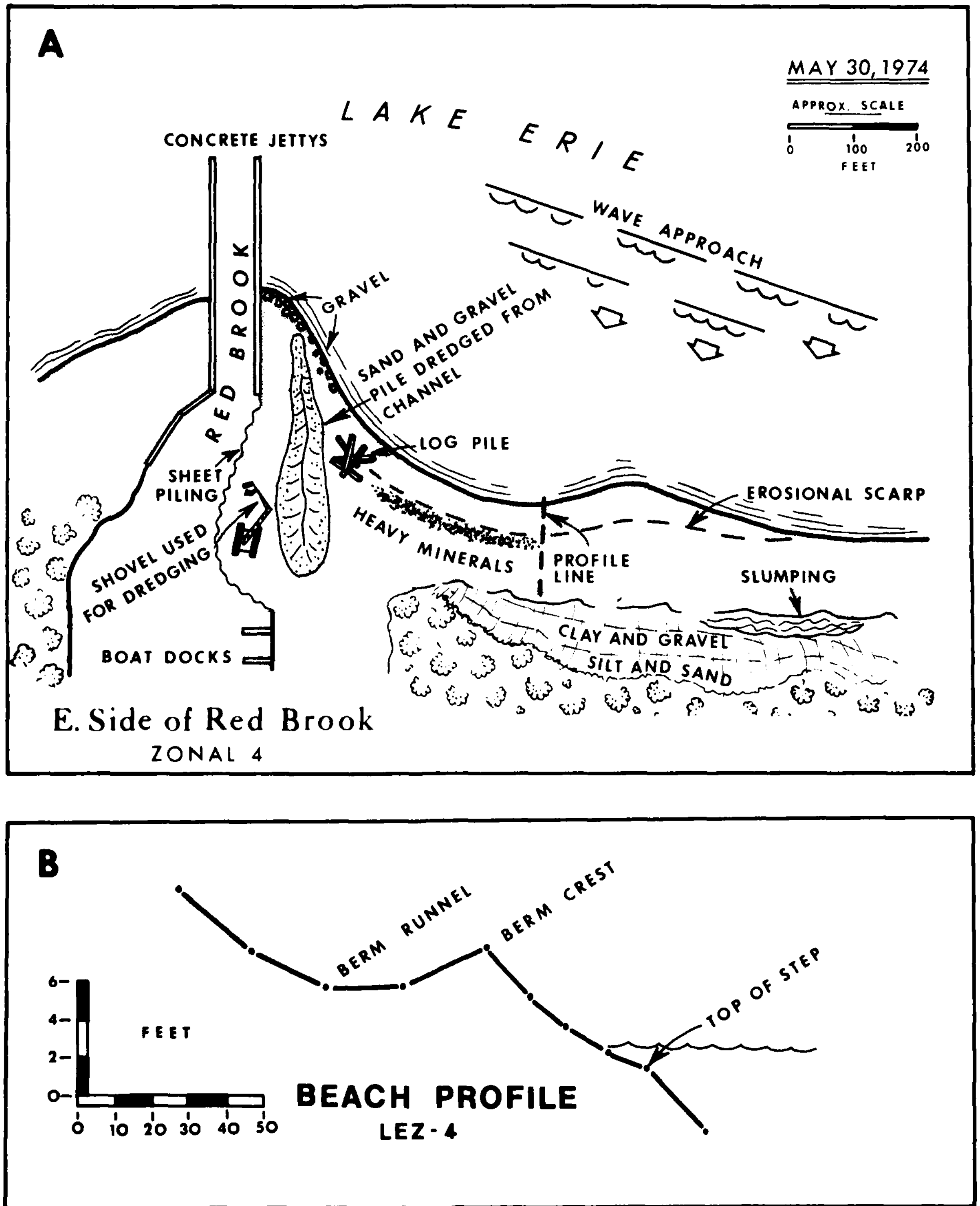


FIGURE 7

Figure 8. A. Sketch map of zonal site #4 at the mouth of Red Brook, Ohio. Sediment is accumulating on the updrift (southwest) side of the jetties and periodic erosion occurs on the downdrift (northeast) side. Note location of beach profile given in B.

B. Profile of beach approximately 400 feet northeast of the Red Brook jetties. Profile was measured on 30 May 1974.



FIGURES 8A AND B

photograph in Figure 9. The cliff is 20 ft. in height. It is composed primarily of fine clay with pebbles scattered throughout (presumably till). A 2.3 ft. layer of silty sand occurs at the top of the cliff. As indicated by the sketch map (Fig. 8A), the jetties show a wide updrift accumulation of sediment (also see aerial photograph in Fig. 9), and periodic erosion on the downdrift side, although there was a narrow beach in front of the cliff on the date we visited the site (30 May 1974). The profile of the beach in front of the cliff was measured (Fig. 8B). At this location, the profile consists of a single sandy berm with coarse gravel occurring at the step.

The jetties at Zonal #4, like other structures in this general area, strongly demonstrate the rapid rate of sediment transport from southwest to northeast. All structures of this nature show sediment accumulation on the west side and accelerated erosion on the east side.

3.2f. Unit E. The Ashtabula structure (Unit E; Fig. 2) was authorized in 1896 and has been subject to many modifications since that time. It consists of an outer harbor about 185 acres in area, and two long breakwaters, a west breakwater 7891 ft. long and an east breakwater 4342 ft. long. There is noticeable sediment accumulation to the southwest of the west breakwater. With reference to the regional geomorphology, the Ashtabula structure separates two like units, D and F, which both consist of high, eroding till cliffs.

3.2g. Unit F. Unit F extends from the Ashtabula, Ohio, structure to Conneaut, Ohio, a distance of 13 miles (Fig. 2). Unit F is a very homogenous morphological unit, consisting almost entirely of

Figure 9. Jetties at mouth of Red Brook, Ohio. Arrow indicates direction of predominant longshore sediment transport.

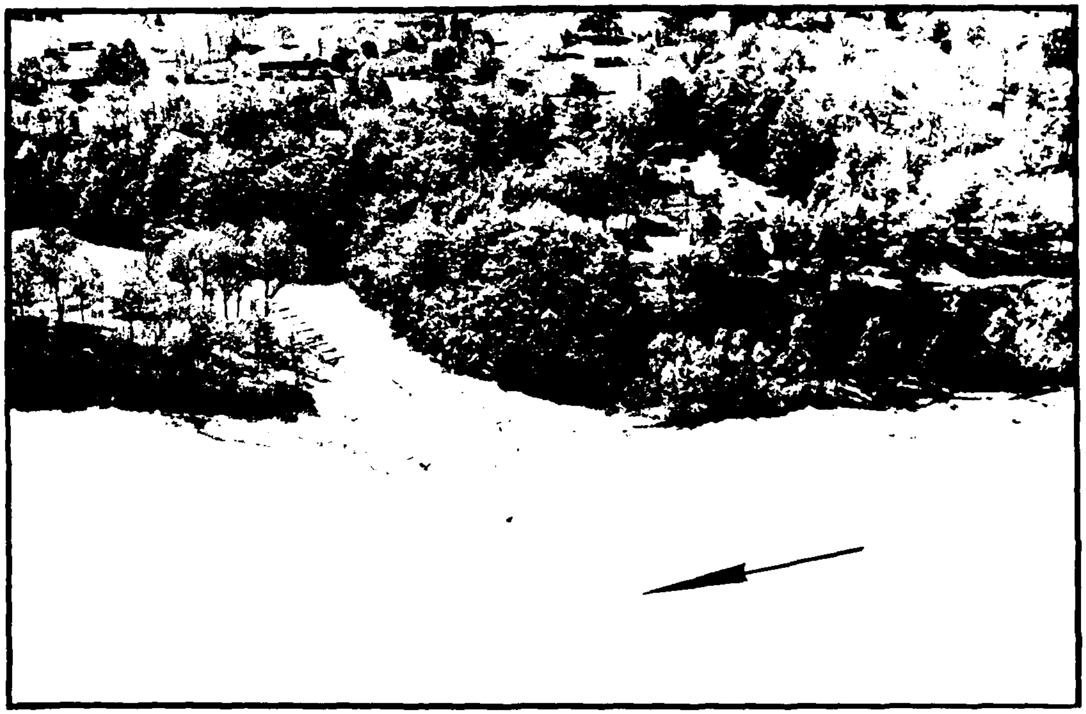


FIGURE 9

an irregular high till cliff which has intensive slumping at some places. At Zonal site #5, the cliff consists of clay that contains scattered pebbles of unknown origin. Figure 10 is a ground view of the cliff. Note the slumping and the occurrence of a gravel beach at the base of the cliff.

3.2h. Unit G. The Conneaut Harbor, Ohio, structure, which was authorized in 1910 and has been altered several times since then, consists of a double breakwater system with a large outer harbor occupying approximately 142 acres. The west breakwater is 5938 ft. long, and the east breakwater is 3675 ft. long. This structure, like the others in the area, shows excessive deposition on the west side. Figure 11 is a map showing the general configuration of the Conneaut Harbor structure.

3.2i. Unit H. This morphological unit extends from Conneaut Harbor, Ohio, to Erie, Pa., a distance of 21 miles (Fig. 2). This is such a variable area that we found it necessary to do five zonal studies (6-10) in order to properly describe it. The unit contains abundant cliffs of variable heights interspersed among several minor deltas. There is strong evidence of longshore sediment transport from southwest to northeast, as indicated by the accumulation of sediments on the southwest sides of the numerous jetties and groins that occur along this section of shoreline. Erosion is severe in many localities.

The first morphological type encountered east of Conneaut is an eroding, scalloped cliff of intermediate height. A number of small deltas occur further to the east. Zonal site #6, at Elk Creek, Pa., is representative of these deltas. The mouth of Elk Creek is flanked by a

Figure 10. Eroding and slumping cliff in Pleistocene sediments at zonal site #5, which is located 4 miles northeast of Ashtabula, Ohio. Photograph taken on 30 May 1974.

FIGURE 10

Figure 11. Structure at Conneaut Harbor, Ohio.

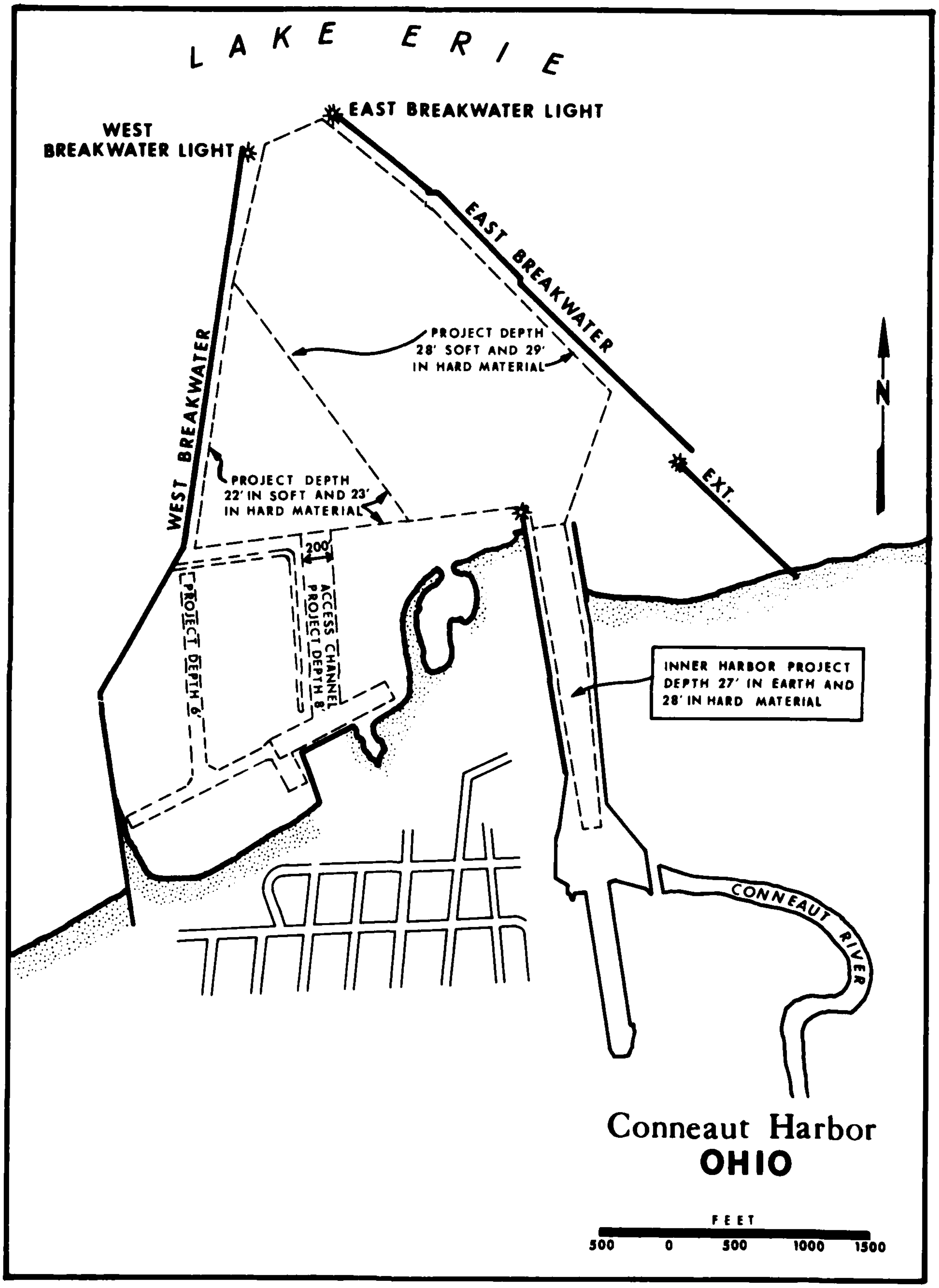

LAKE ERIE
EAST BREAKWATER LIGHT
WEST BREAKWATER LIGHT
EAST BREAKWATER
WEST BREAKWATER
PROJECT DEPTH 28' SOFT AND 29' IN HARD MATERIAL
PROJECT DEPTH 22' IN SOFT AND 23' IN HARD MATERIAL
200
PROJECT DEPTH 6'
ACCESS CHANNEL PROJECT DEPTH 8'
EXT.
N
INNER HARBOR PROJECT DEPTH 27' IN EARTH AND 28' IN HARD MATERIAL
CONNEAUT RIVER
Conneaut Harbor
OHIO
FEET
500 0 500 1000 1500

FIGURE 11

westerly projecting gravel spit composed of multiple berms and covered by abundant logs and tree limbs. The nature of this spit is illustrated by the aerial photograph in Figure 12. The multiple berms are composed of different grain sizes of gravel beginning with the coarsest material at the highest berm and gradually decreasing in size to the swash line. This grain-size decrease presumably indicates diminishing strength of waves from the peak of the storm, during which time the coarse material was deposited on the crest of the high berm, through the waning stages of the storm, during which time finer-grained material was deposited on the berms of diminishing height. This gradation in grain size is demonstrated by the photographs in Figure 13. At the present time, the main channel of Elk Creek is floored by coarse gravel and the stream itself is considered to be the source of most of the material now accumulating at its mouth. The gravel here, like the gravel in most parts of this section of the Lake Erie shoreline, is composed of sedimentary rock fragments that are flat and discoidal in shape. Many of the gravel particles are composed of relatively fine-grained siltstones.

Proceeding east from Elk Creek, the shoreline once again becomes an eroding cliff which at points exceeds 80 ft. in height. At zonal #7, which is illustrated by the two photographs in Figure 14, the cliff consists of shale at the water line, a unit of coarse-grained till overlying the shale, and a thick clay sequence, presumably lake-bed deposits, overlying that. The nature of the till is illustrated by the photograph in Figure 14B. The till is approximately 5 feet thick; the clay is silty and is blue in color. At this location a groin was emplaced in 1940 which has effectively protected the property just west of the groin. However, the cliffs have

Figure 12. Mouth of Elk Creek, Pa., the site of zonal #6. The line indicates the location of beach profile given in Figure 13.

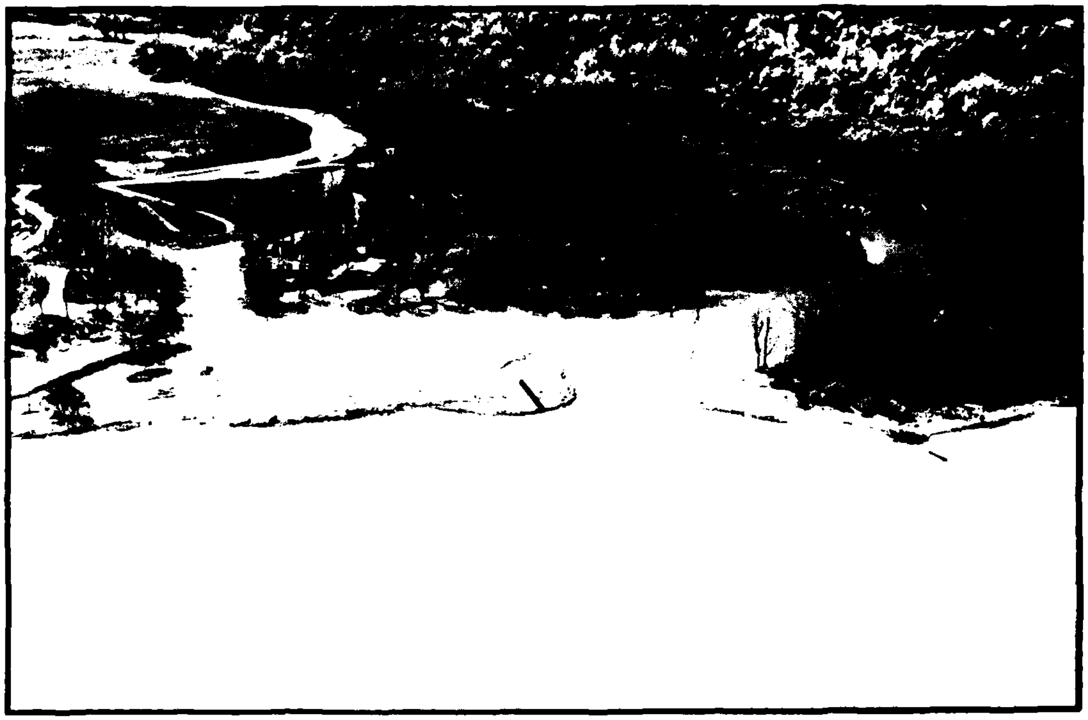
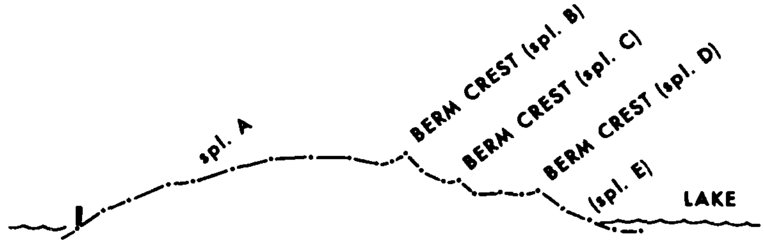
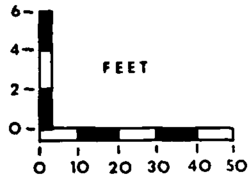


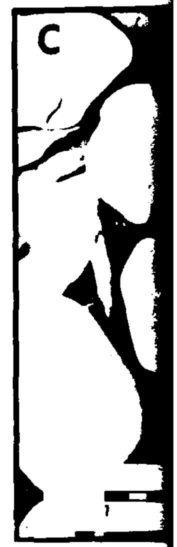
FIGURE 12

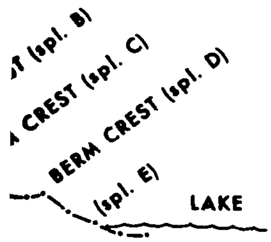
Figure 13. Beach profile and sample photographs at zonal site #6 (see location of profile on aerial photograph in Fig. 12). Coarsest material occurs on the highest berm and grain size diminishes gradually toward the swash line.

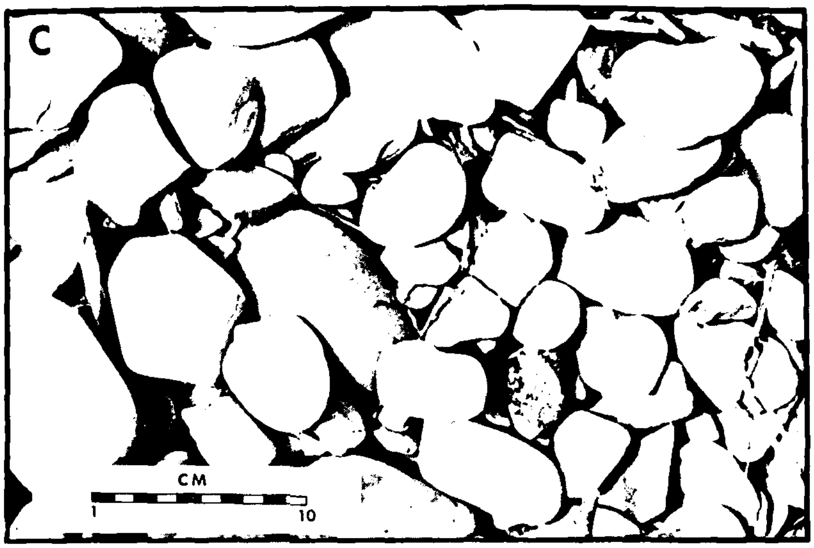




LEZ-6
MAY 30, 1974



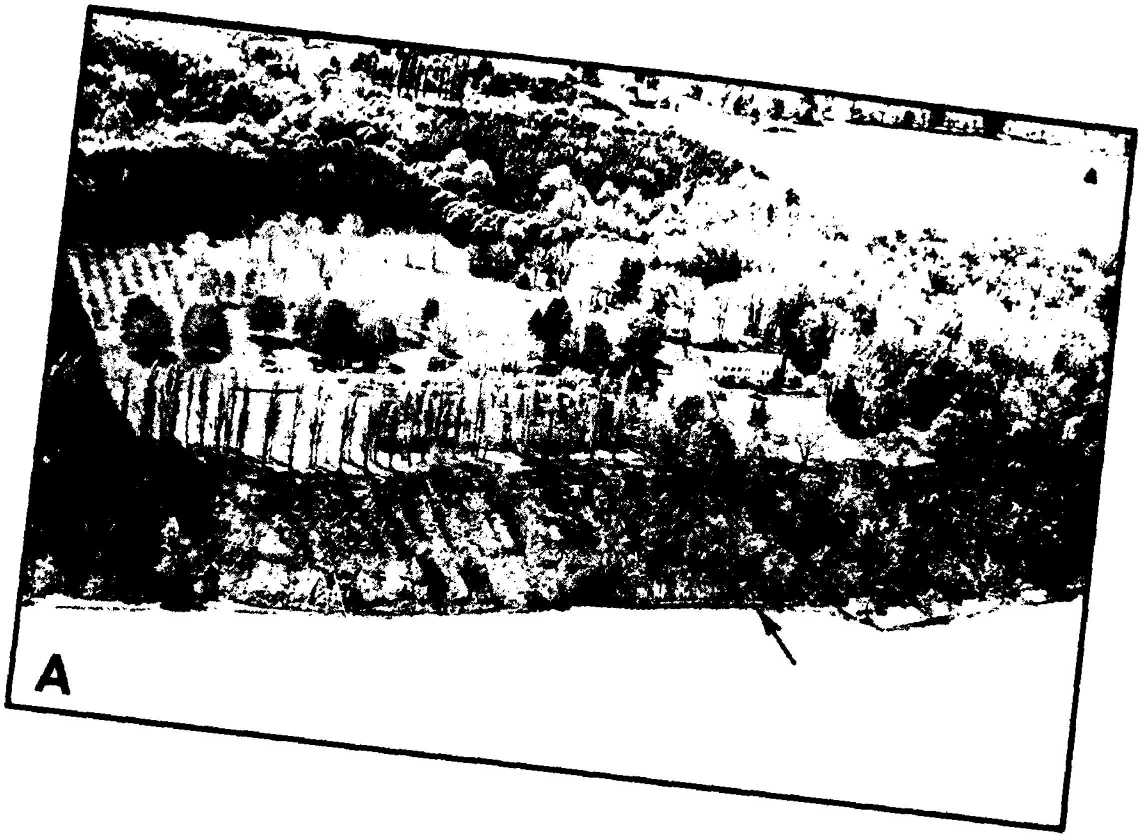




FIGURES 13, 13A, B, C, D AND E

Figure 14. A. Zonal site #7, near Fairplain, Pa. The cliff is 70-80 feet high at this location. Note the erosion downdrift of the small groin in the right foreground. Arrow points to locality shown in photograph B.

B. Base of cliff at zonal site #7. Coarse-grained till at base of cliff is approximately 5 ft. thick.



A

B

FIGURES 14A AND B

eroded severely on both sides of the groin since that time. Refer to aerial photograph in Figure 14A. This type of private protective structure is very common along this section of cliffs.

The interval between Zonal sites #7 and #8 continues to be a high eroding cliff. At Zonal #8, the cliff is 78 ft. in height. It consists from top to bottom of 30 ft. of light, yellow-brown coarse silt, which is laminated (possibly loess), overlying 46 ft. of till, which overlies 2 ft. of shale. The till is composed of blue clay with scattered pebble fragments. There is some question as to whether this should be called till; it could be lake deposits containing dropstones. The beach area is the site of several groin structures, which are shown in Figure 15. Two beach profiles were measured (Fig. 15), which show multi-level berms with an erosional scarp on the lakeward side of the high berm. A field sketch of profile B is given in Figure 16, and photographs in Figure 17 demonstrate the nature of both the cliff and the beach area. The beach material is composed of a mixture of sand and gravel with sand predominating. The sediments on the beach were definitely not derived from the cliff, because of great differences in the composition and the absence of coarse gravel in the cliff. A coarse gravel platform is present just lakeward of the step area.

The larger groin shown in the sketch in Figure 16 and the photograph in Figure 17A was extended 4 months before the field work was done on 30 May 1974. This structure has accreted a large volume of sediment on the west side of the groin within that short period of time, further substantiating the occurrence of strong drift from west to east in this area.

Zonal site #9 is located at Walnut Creek, Pa., which has a small jetty

Figure 15. Map of part of the groin field at zonal site #8, which is located near the mouth of Trout Run Creek, Pa. Note large sediment accumulation on west side of groins. Inset gives beach profiles at the two localities indicated on the map.

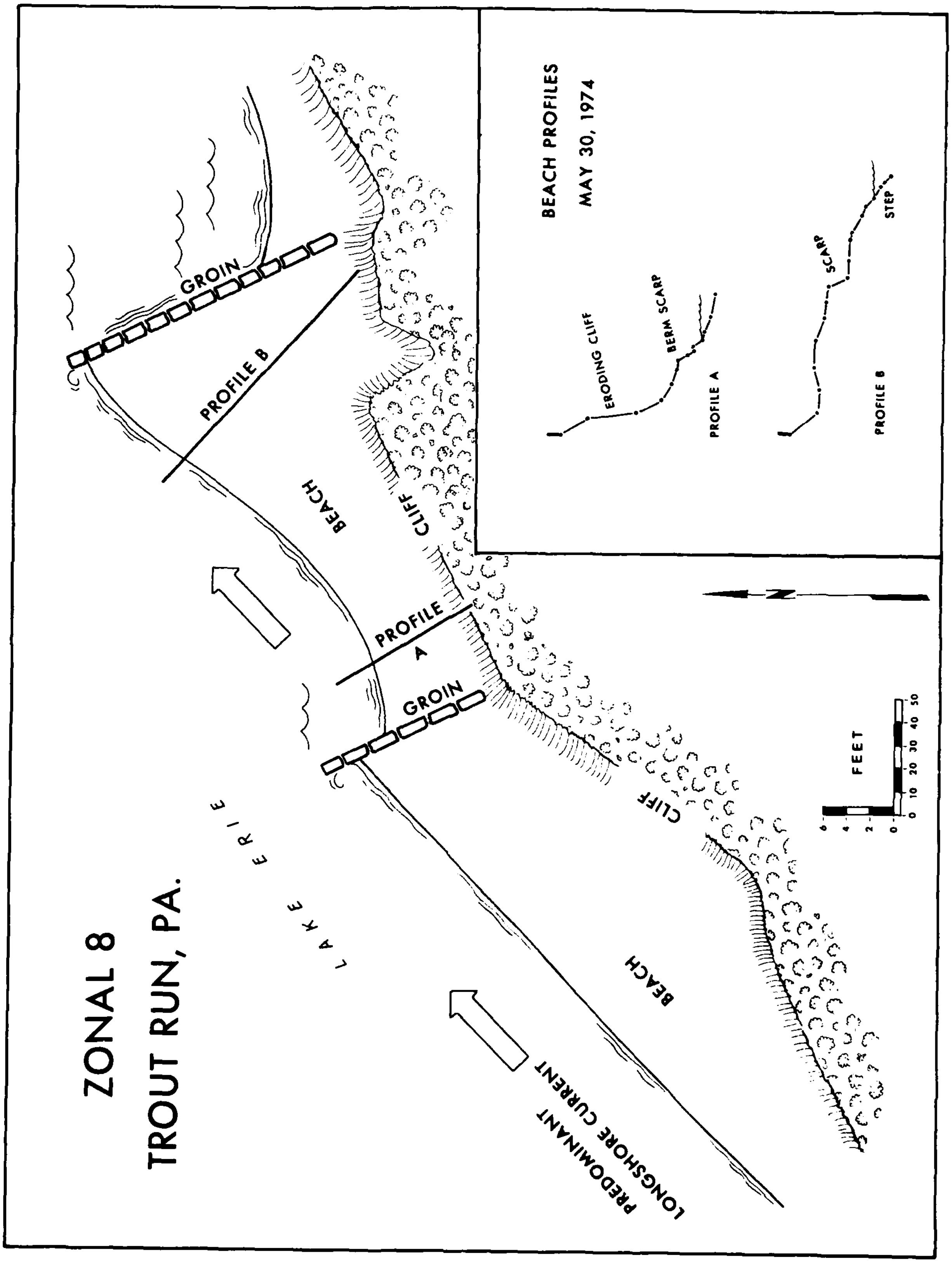

ZONAL 8
TROUT RUN, PA.
LAKE ERIE
PREDOMINANT LONGSHORE CURRENT
GROIN
GROIN
PROFILE B
PROFILE A
BEACH
BEACH
CLIFF
CLIFF
BEACH PROFILES
MAY 30, 1974
ERODING CLIFF
BERM SCARP
PROFILE A
SCARP
STEP
PROFILE B
FEET
N

FIGURE 15

Figure 16. Field sketch of profile B at zonal site #8. Heavy line indicates position of profile, which is plotted in Figure 15. Multi-level berms are formed when the lake is at different levels as a result of wind tides.

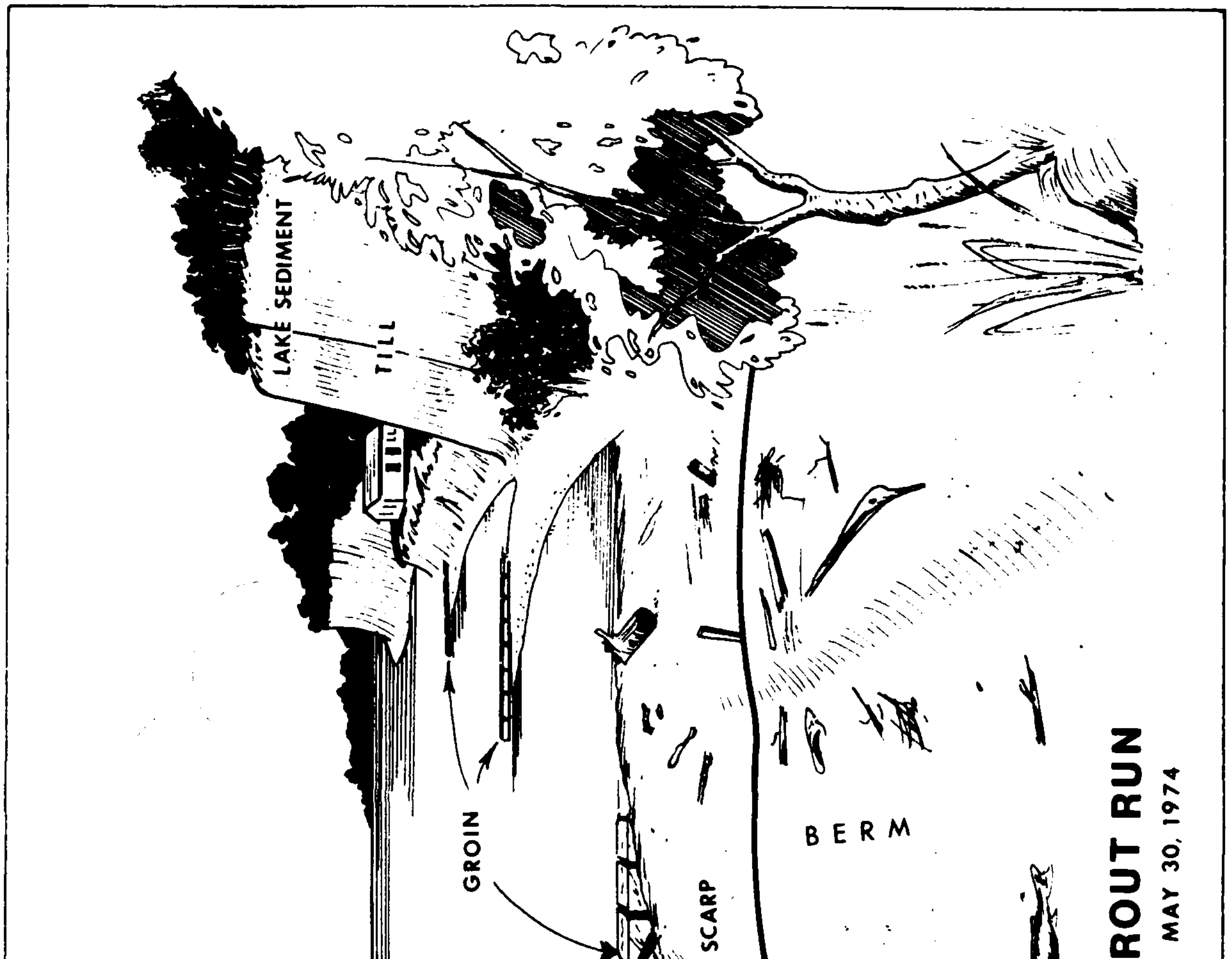

LAKE SEDIMENT
TILL
GROIN
SCARP
BERM
MOSTLY SAND
PURE SAND
STEP
TROUT RUN
MAY 30, 1974

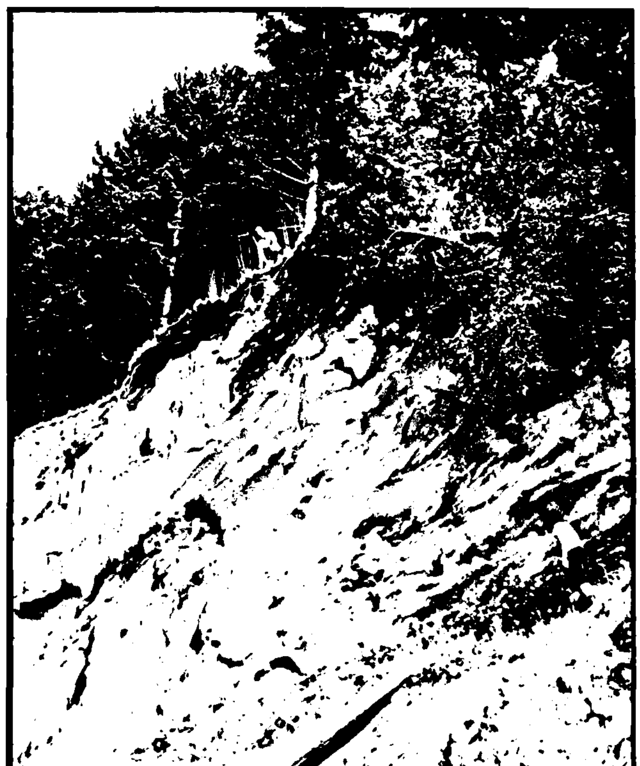
FIGURE 16

Figure 17. A. Cliff-top view of groin field at zonal site #8, Trout Run, Pa.

B. Eroding beach cliff at zonal site #8. Description of cliff sediments is given in text.

A

B



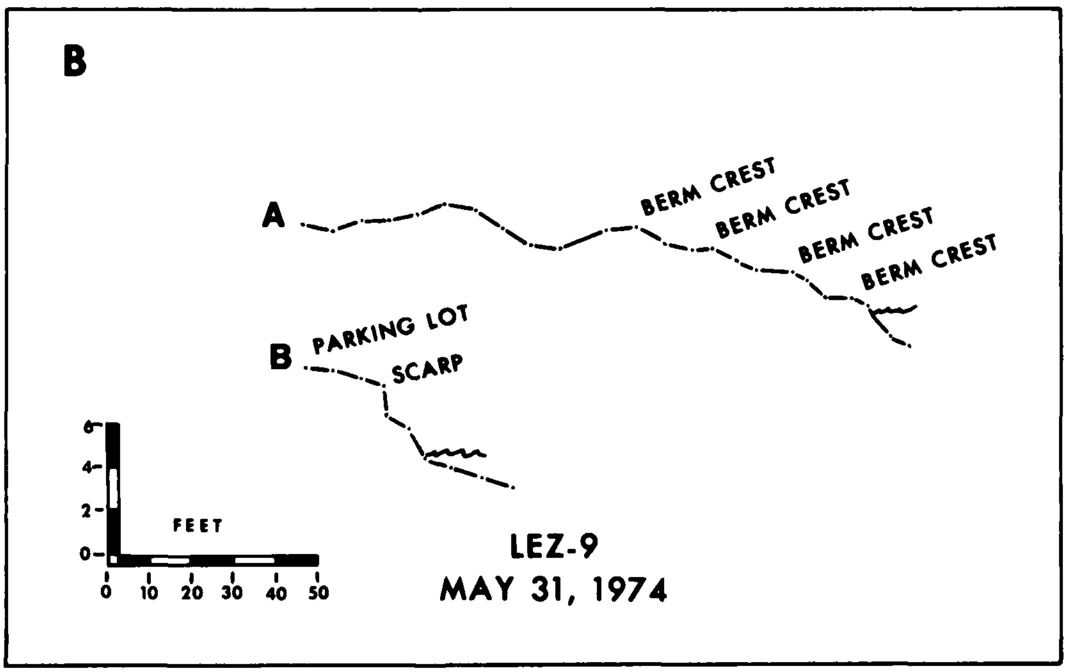
FIGURES 17A AND B

system at its mouth. These jetties produce a classic updrift deposition/ downdrift erosion system (see Fig. 18). The offset of the beaches on either side of the jetties was 70 ft. In general, the gravel is finer on the updrift side than on the downdrift side. There has been some manicuring of the beach on the updrift side by bulldozers. Updrift of the jetties, the gravel has been deposited in a series of multiple berms (Figs. 18B and 19A). Downdrift of the jetties, erosion has been intensive. Note the eroding parking lot in the photograph in Figure 19B. Observations of N. Shea, an employee of the Pennsylvania State Fisheries Commission, indicate that 5 acres of land have been lost on the downdrift side since 1960.

Zonal site #10 is the location of the most intensive destruction of property seen along this whole southeastern shore of Lake Erie. Many beach cottages have been totally destroyed during the recent lake-level rise. Evidence of this destruction can be seen in the photographs in Figure 20A,B. Note the large accumulation of trees and logs on the beach. These logs were used as battering tools by storm waves, bashing in the fronts of many of the cottages. Also, the logs have stacked up at some places and have served as natural groins, as shown by the photograph in Figure 20A. This is the only place we visited where the beach cottages had been built on the beach below the crest of the cliff, which is 83 feet high at this locality. This indicates to us that the beach must have been considerably wider at this location when the cottages were built than it is today, inasmuch as the present beach is not significantly different at this locality from most of the other localities visited. See, for example, the beaches at Zonal sites #7 and #8. Since the destruction of the cottages,

Figure 18. A. Jetties at mouth of Walnut Creek, Pa. (zonal site #9). Lines show locations of profiles given in B. Note accretion on the right (southwest) side of jetties and erosion on the left (northeast) side. Ground views of these areas are shown in Figure 19.

B. Beach profiels on updrift side (profile A) and downdrift side (profile B) of the Walnut Creek jetties. Note abundance of gravel berms in profile A.



FIGURES 18A AND B

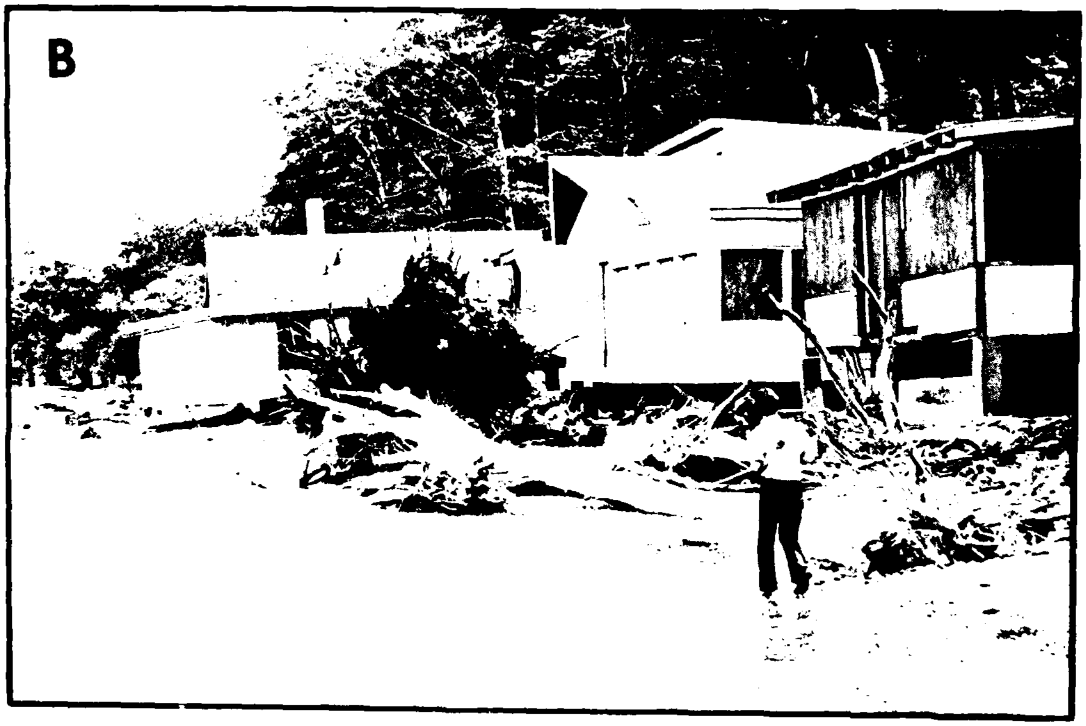
Figure 19. A. Beach zone just updrift of the Walnut Creek jetties. Note multi-level gravel berms. Compare with profile A in Figure 18B.

B. Beach zone just downdrift of the Walnut Creek jetties. Blocks of the parking lot pavement occur several feet offshore. Compare with profile B in Figure 18B.

FIGURES 19A AND B

Figure 20. A. Intense erosion zone one-half mile west of Presque Isle, Pa. (zonal site #10). The geologist is standing on a gravel berm built up onto the rooftop after the house collapsed. Note natural groin effect of the log jam in the middle distance.

B. Beach zone 200 feet west of the area shown in A.



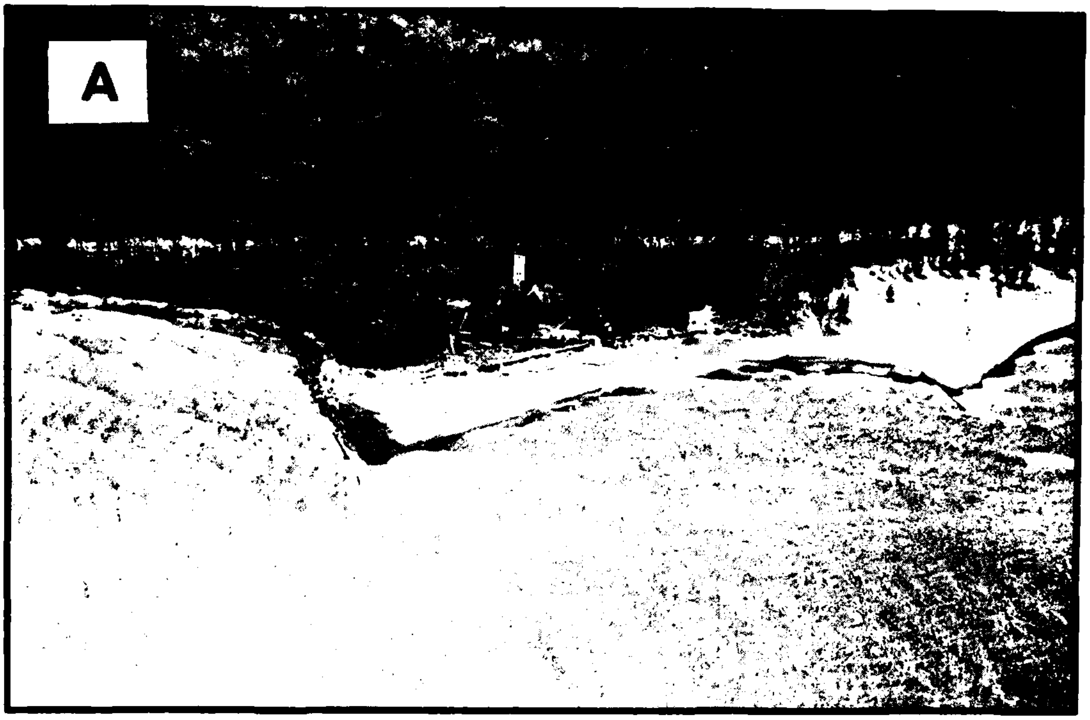
FIGURES 20 A AND B

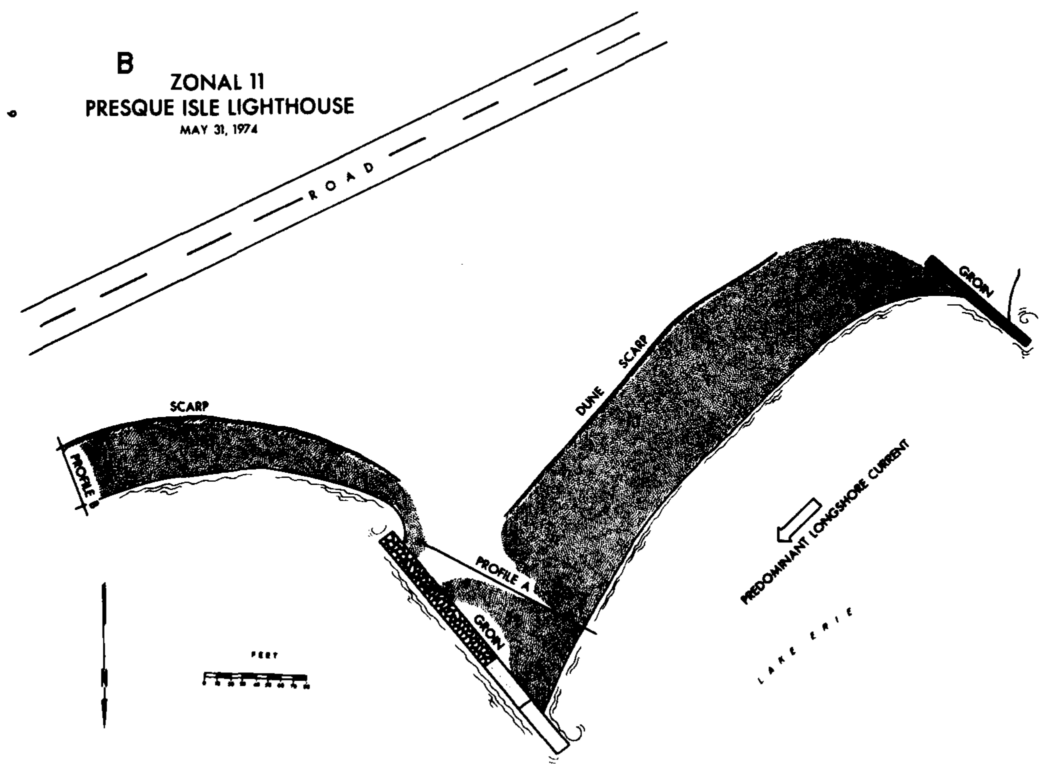
a storm berm of coarse gravel has been deposited in front of them. This berm can be seen in the photograph in Figure 20A. The gravel at this locality, as at most of the other localities along this stretch of shore, consists of discoidal siltstone.

3.2j. Unit I. Presque Isle, Unit I (Fig. 2), is a flying spit composed of a mixture of sand and gravel, which is building progressively northeastward as a series of recurved spits. On Presque Isle, we have chosen two sites as being representative of its general morphology. Zonal site #11 is on the western, or eroding, side of the isle, and zonal site #12 is located on the depositional, or recurve, portion of the isle. Zonal #11 is located in a groin field near the lighthouse on the northwest point of the spit. As shown by the aerial photograph (Fig. 21A), the planimetric map of the area (Fig. 21B), and the measured beach profiles (Fig. 22C), the groins have brought about remarkable changes in erosional and depositional conditions. The offset on the groin located just northeast of the lighthouse is approximately 400 ft. Erosion on the downdrift side has threatened the roadway behind the lighthouse. Notice the eroding scarp with abundant trees falling into the lake in the photograph in Figure 22A. Sediment on the updrift side of the groin is accumulating in a series of multi-level berms and is mostly sand except where gravel has been deposited in the berm runnels (Fig. 22B). This gravel is fine, averaging between .5 and 1.0 cm in diameter. This area has one of the most pronounced groin offsets witnessed in any location by the writers. All of the groins on the west side of Presque Isle show some degree of offset and indicate strong littoral transport of sediment along the spit from the southwest to the northeast.

Figure 21. A. Zonal site #11, Presque Isle, Pa., lighthouse.

B. Map view of zonal site #11. Note large sediment accumulation on up-drift (southwest) side of groins, and intensive erosion on the down-drift side. Beach profiles A and B are given in Figure 22C.



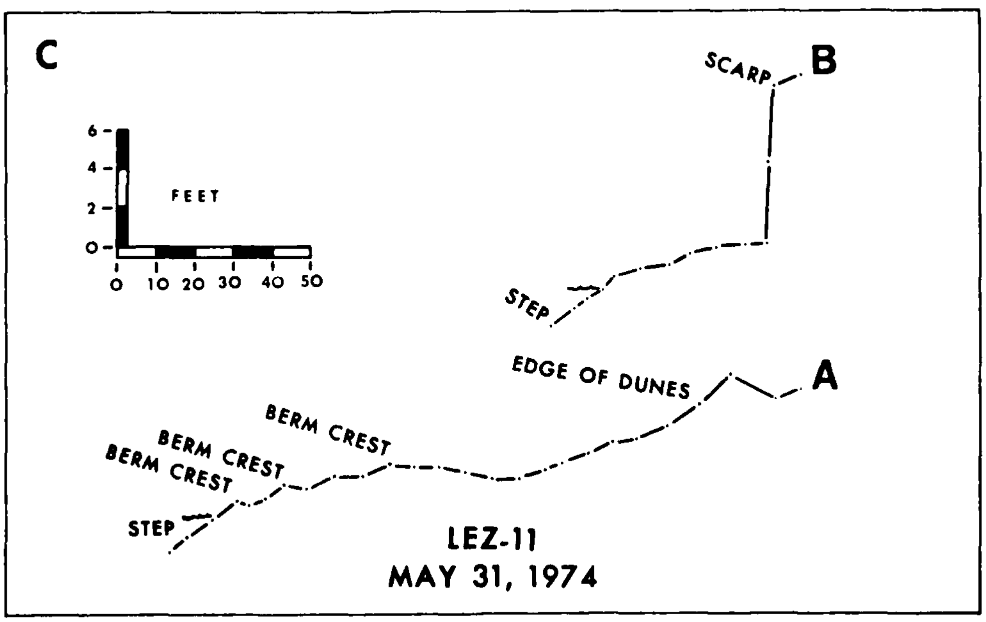


FIGURES 21A AND B

Figure 22. A. Area downdrift of lighthouse groin; zonal site #11. Profile B (see C) is located in foreground.

B. Area updrift of lighthouse groin. Profile A (see C) is located in middle of photograph.

C. Profiles A and B at zonal site #11. See map in Figure 21B for location.



FIGURES 22A, B AND C

Zonal site #12, located on the recurve spit portion of Presque Isle (Fig. 23), is the first natural depositional system between Fairport Harbor and Presque Isle that we studied. All the other depositional areas occurred updrift of man-built structures. The sediment making up the spit is mostly sand and what gravel is present is small and discoidal in shape. The major component of the spit at this location is basically an overwash terrace that is pushed landward during storms (see three-dimensional block diagram in Fig. 24). It is interesting to note that the beach face and nearshore zone on this spit is relatively steep. This is presumably a result of the fact that the spit is building out rapidly into a deeper poriton of the lake. Sediment is transported along the face of the spit in the form of a series of beach protuberances, which are illustrated in the aerial photograph in Figure 23.

3.2k. Unit J. Unit J extends for 16 miles from just northeast of Erie, Pa., to approximately 2.5 miles west of the New York border. It is a complex area, being composed of numerous deltas separated by cliffs of varying heights. The amount of bedrock in the cliffs, which is principally siltstone and shale, increases in a northeasterly direction. The cliffs contain chasms and sea caves in the places where the bedrock predominates, and the higher cliffs show considerable slumping and scalloping. Till predominates in the upper portions of the higher cliffs. The delta at Twelvemile Creek, Pa. (Zonal site #13), was visited on 20 May 1974, but no detailed data were collected. It is a small delta and the stream channel is flanked by several higher terraces. The stream itself is transporting gravel, and a coarse

Figure 23. Zonal site #12, the recurved spit area on Presque Isle, Pa. The approximate location of the specific area mapped (see block diagram in Fig. 24) is located between the two lines.

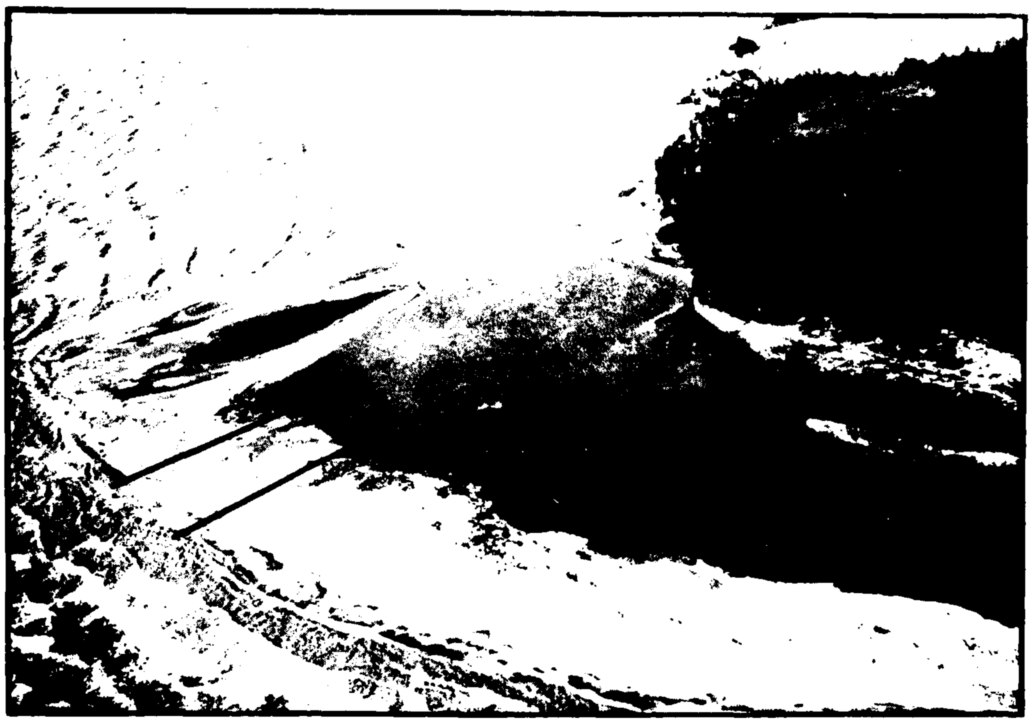
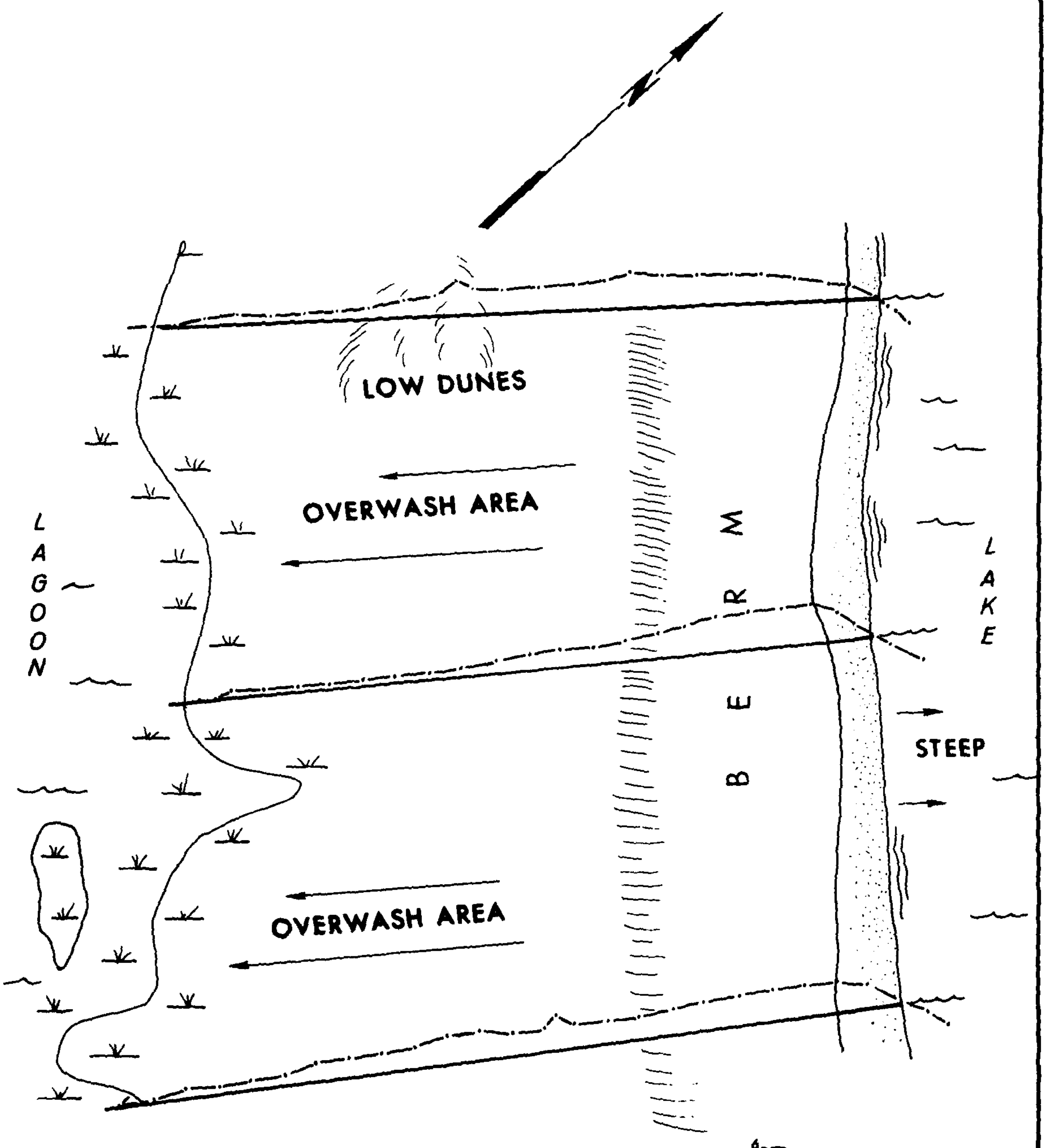


FIGURE 23

Figure 24. Block diagram of recurved spit area of Presque Isle (zonal #12). This feature is principally an overwash terrace that migrates lagoonward during storms.



ZONAL 12
PRESQUE ISLE, PA.
MAY 31, 1974

FIGURE 24

gravel bar and gravel beaches are deposited around the margin of the delta. At the time of the visit, a gravel bar was building to the west across the mouth of the stream under the influence of waves approaching from the northeast.

3.21. Unit K. Unit K, which extends 22 miles along the shore between Twentymile Creek, Pa., and Lake Erie State Park, N. Y. (Fig 2), is distinct from Unit J in that it is composed of cliffs of intermediate height that are predominantly bedrock. There are still many small river deltas that disect the cliff, but the cliff is the dominant feature. The cliff shows pronounced effects of rock jointing and erosion along the joints, although, in general, the shoreline is relatively striaght. In many places, waterfalls cascade down the face of the cliff. The two zonals studied were chosen to represent the two dominant morphologies in the area. Zonal site #14 is at the mouth of Twentymile Creek, Pa., whereas Zonal site #15 is in the bedrock cliffs at Blue Water Beach, Pa.

Zonal #14 is dominated by a long gravel spit that overlaps the mouth of Twentymile Creek. The spit projects toward the northeast a distance of 500 ft. According to local residents, the entire spit has been built since 1972. It has been deposited as a series of small recurves projecting in the northeasterly direction. The spit consists of multi-level berms with a high central berm composed of coarse gravel, which had a mean grain size of 33 mm on the date of observation (20 May 1974), and a lower level berm, which had a mean diameter of 21 mm (measurements made at profile B). The decreasing size of the gravel from the high berm to the low berm probably indicates diminishing wave energy following storms, with the high berm being built by major storm waves. The gravel consists primarily of flat, discoidal siltstone fragments. The nature of the spit is illustrated by the aerial and ground views in Figure 25A,B, by the three-dimensional diagram of Figure 26, and by the gravel photographs in Figure 27. On the night before the date of observation, 20 May 1974, the direction of wave approach shifted from west to east, and a gravel spit began to build in a westerly direction. This indicates that the gravel is very mobile and can be transported readily by Lake Erie waves and built into gravel spits within the matter of a few hours.

Zonal site #15 is located in a bedrock cliff area at Blue Water Beach. The most conspicuous feature in the cliff is the intensive jointing pattern which is illustrated in the photograph in Figure 28. Two primary joint directions were noted, N 60° E and N 10° W. These two joint directions control the orientation of the cliff faces on a local scale. The height of the cliff at this locality is 19.5 ft. The contact between the bedrock and the till occurs at 10.6 ft. above the water level. The bedrock consists of interlayered siltstones and mudrock. This has been an area of considerable erosion over the past few months. According to a local resident, a 75 ft. wide beach composed of sand and gravel was present as recently as the summer of 1973.

At Barcelona, which is near the midpoint of Unit K, a breakwater system was completed in June 1960. The east breakwater is 693 ft. long and is not connected with the shore. The west breakwater, which measures 790 ft., is connected with the shore, and a large amount of sediment has accumulated on the updrift side since it was built.

3.2m. Unit L. Unit L, which extends 16 miles from Lake Erie State

Figure 25. A. Zonal site #14, mouth of Twentymile Creek, Pa. Note long rivermouth spit projecting northeastward across the mouth of the stream. A three-dimensional block diagram of the spit is given in Figure 26.

B. View along rivermouth spit shown in A (looking southwest).

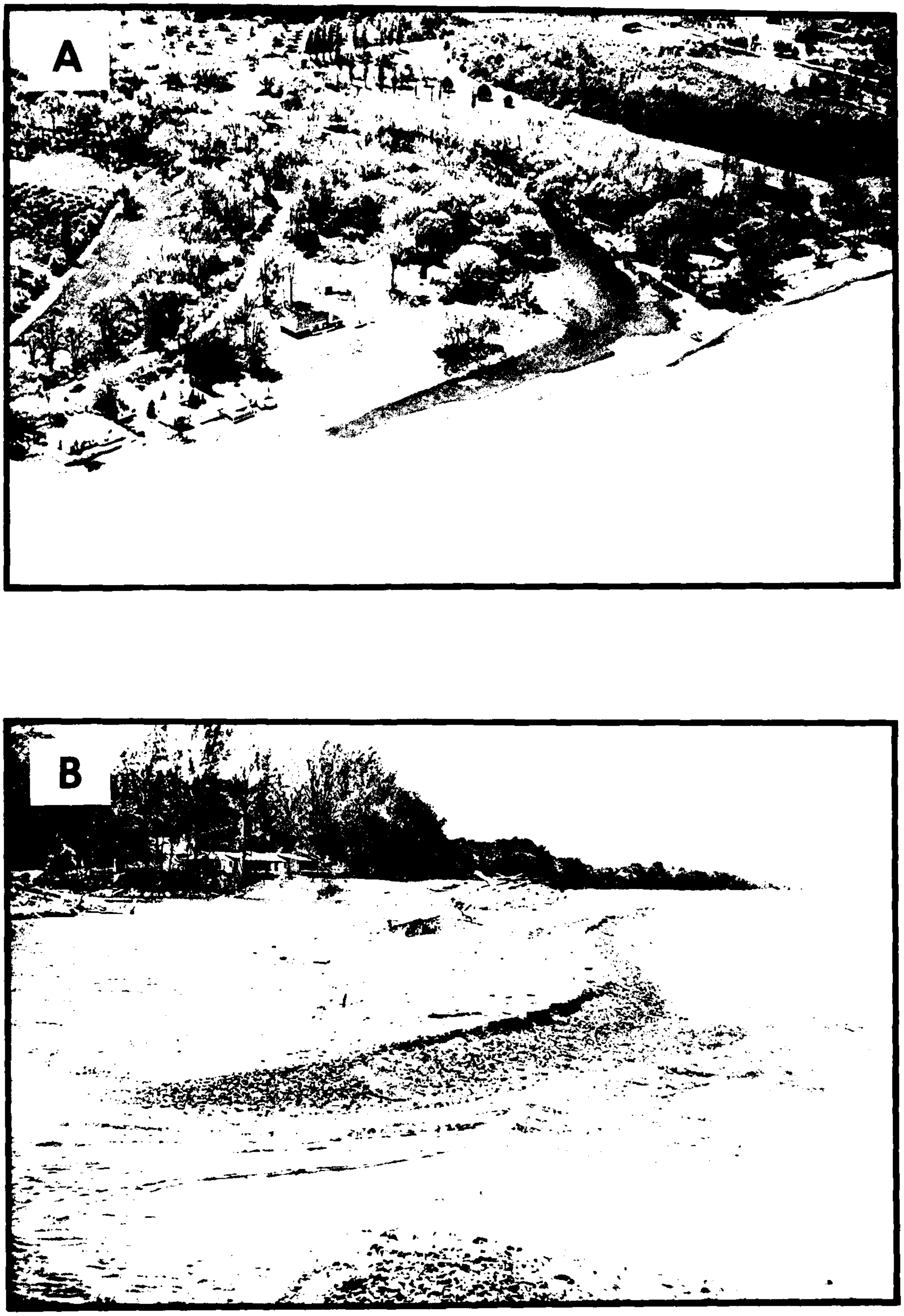


FIGURE 25

Figure 26. Three-dimensional diagram of zonal site #14. The spit is composed almost entirely of gravel, which accounts for the steep beach profiles. The spit grew in a northeastward direction as a series of smaller recurved gravel spits.

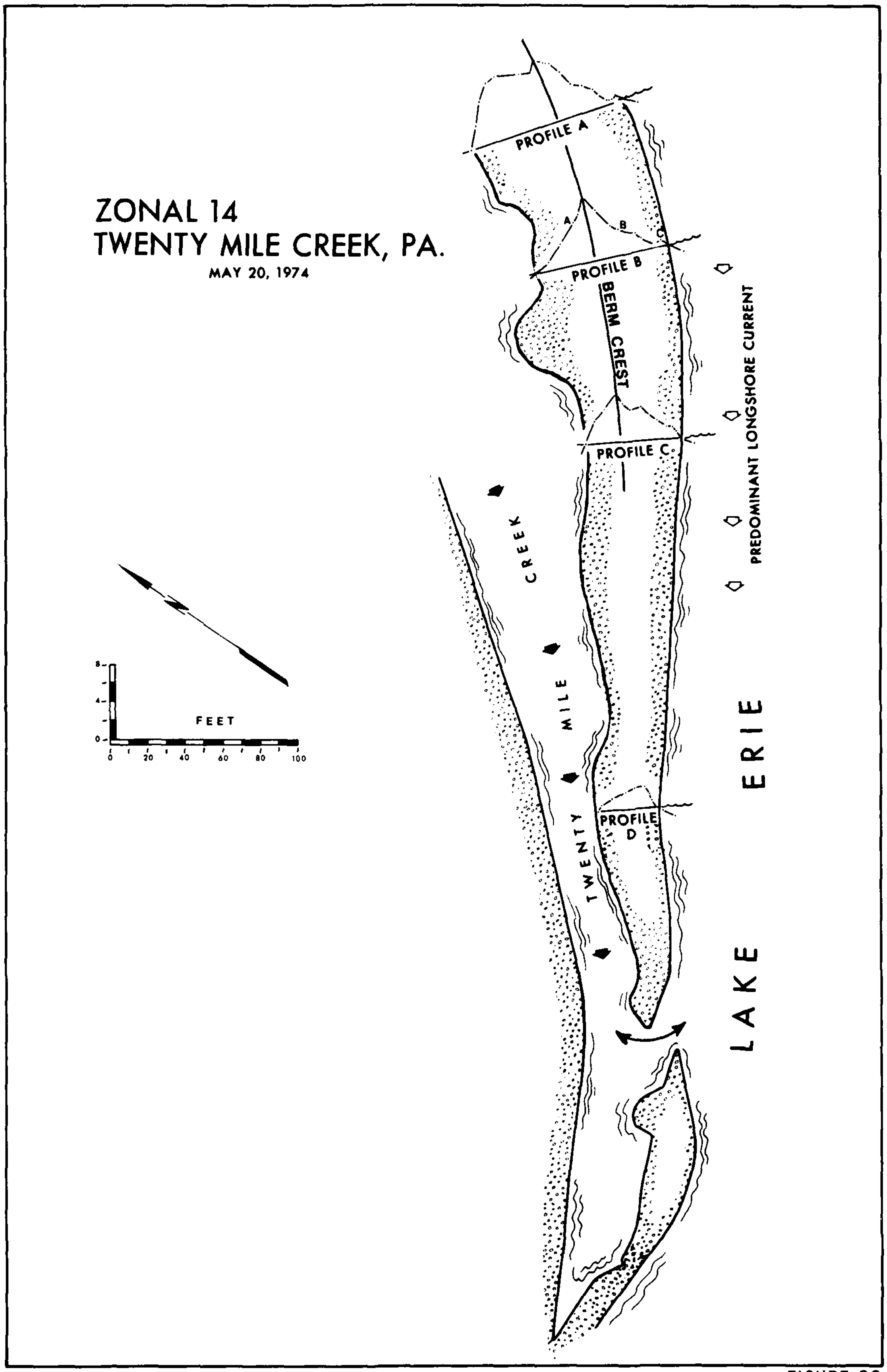
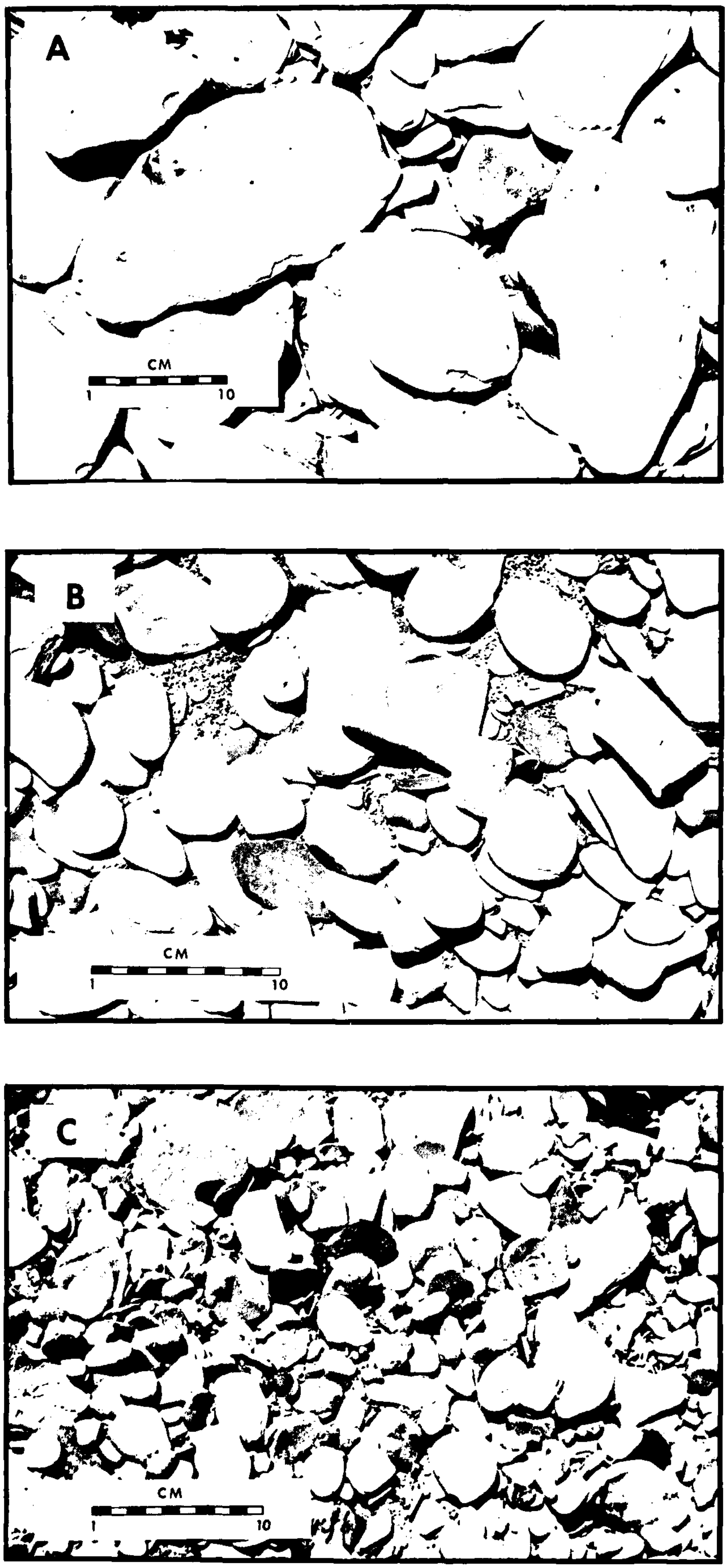

ZONAL 14
TWENTY MILE CREEK, PA.
MAY 20, 1974
PROFILE A
A
B
C
PROFILE B
BERM CREST
PROFILE C
PROFILE D
PREDOMINANT LONGSHORE CURRENT
N
FEET
0
4
8
0
20
40
60
80
100
TWENTY MILE CREEK
LAKE ERIE

FIGURE 26

Figure 27. Gravel samples A, B, and C on profile B at zonal site #14 (located in Fig. 26). Sample A is located on the high berm and samples B and C are located progressively closer to the swash line.



FIGURES 27A, B AND C

Figure 28. Rock cliff at zonal site #15, Blue Water Beach, N. Y. Note well developed joint pattern in the shale. Two joint trends predominate, N 60° E and N 10° W.

FIGURE 28

Park, N. Y., to Silver Creek, N. Y., is a very distinctive morphological unit composed of headlands that project in a northerly direction away from the general orientation of the shoreline. Ten headlands occur in this area, with the two largest being Van Buren Point and the headland just south of Dunkirk. The cliffs are generally of intermediate height and are composed almost entirely of bedrock. There is a remarkable joint pattern in these cliffs, which appears to control the general configuration of the shoreline. This joint control is illustrated by the photograph and measured joint patterns given in Figure 29A,B.

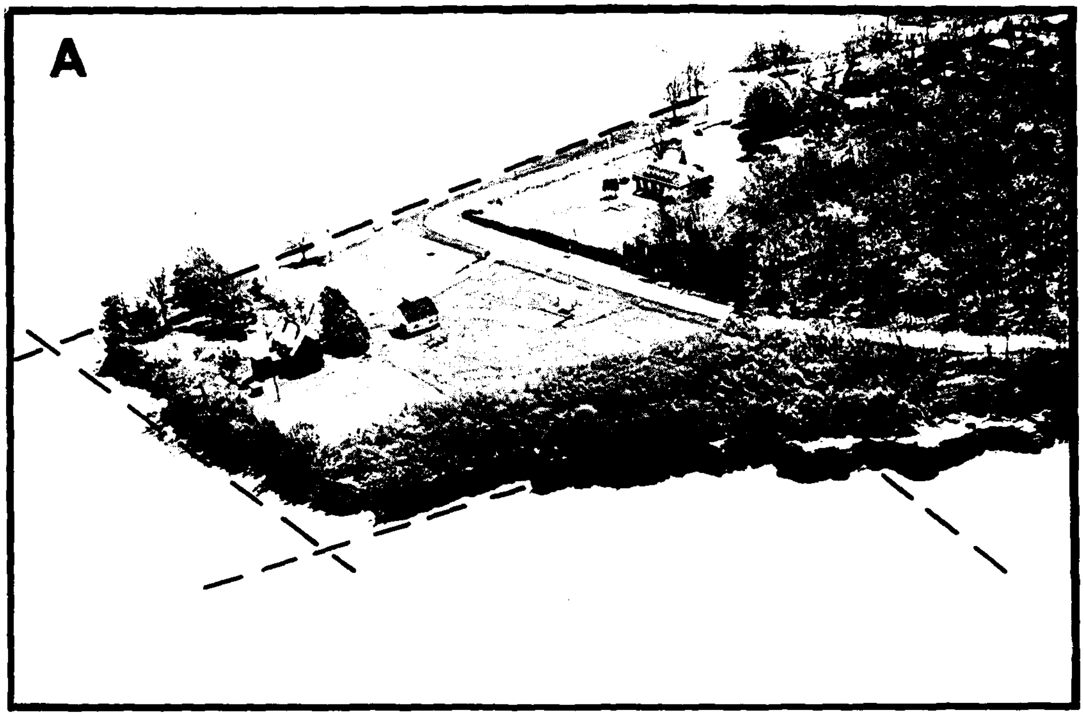
Zonal site #16 is located at Van Buren Point, N. Y. It is an eroding headland and has the classic features of bedrock headlands including a sea stack and sharply eroding cliffs with pocket gravel beaches. These features are illustrated by the two photographs in Figure 30A,B. The rocky headland at Van Buren Point is all shale and is representative of the general area between Van Buren Point and Cattaraugus Creek. Joint control is important with two trends prodominating, N 10° W and N 60° E (see Fig. 29). The beach pebbles are over 95% sedimentary rocks with shale and siltstone fragments being most abundant. The gravel particles, which average about 35 mm in mean diameter at this locality, are extremely discoidal. Our observations indicate that erosion is occurring at the rate of at least 3-4 ft. per decade along these cliffs. The two beach profiles measured at this locality consist of multiple berms of gravel which generally grades from coarsest material on the highest berm to finest material at the present water level. The cliff height at profile B is 18 ft.

Zonal site #17 (Fig. 2) is located along a straight stretch of high, inaccessible vertical cliff which measures approximately 75 ft. in height.

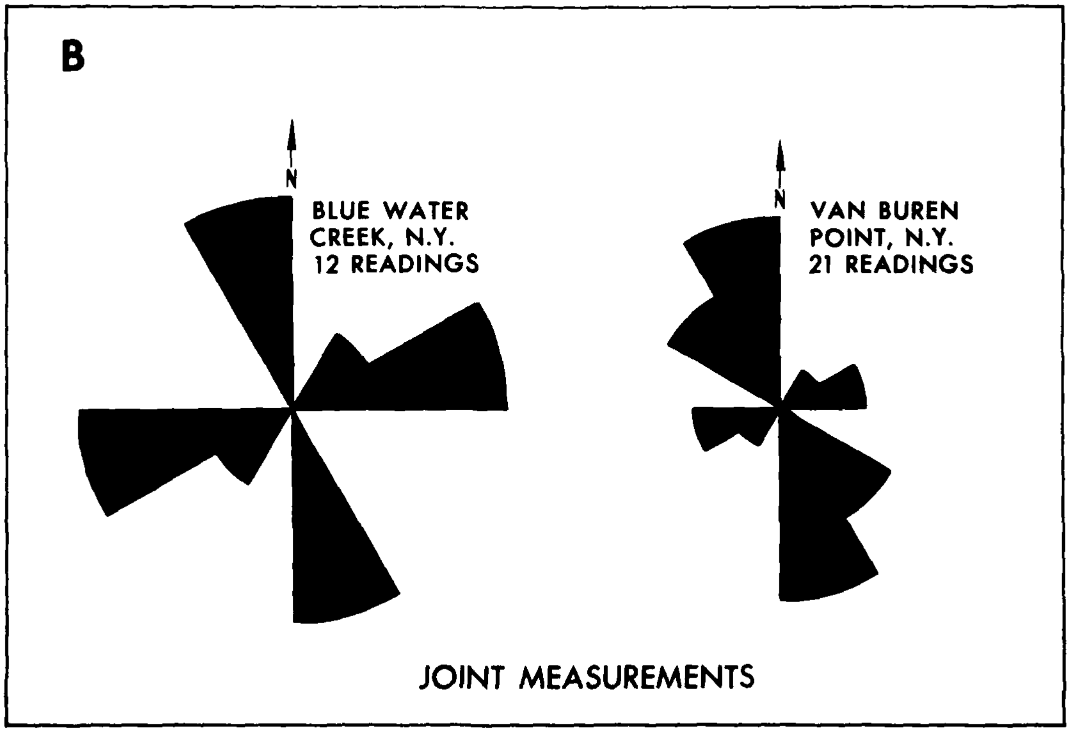
Figure 29. A. Joint-controlled topography on headland just south of Dunkirk, N. Y. (lighthouse is Dunkirk Light). The two shoreline trends, indicated by the dashed lines, conform with the two major joint patterns measured in the shale bedrock (N 10° W and N 60° E; see B).

B. Joint patterns measured at Bluewater Creek and Van Buren Point, N. Y.

A



B

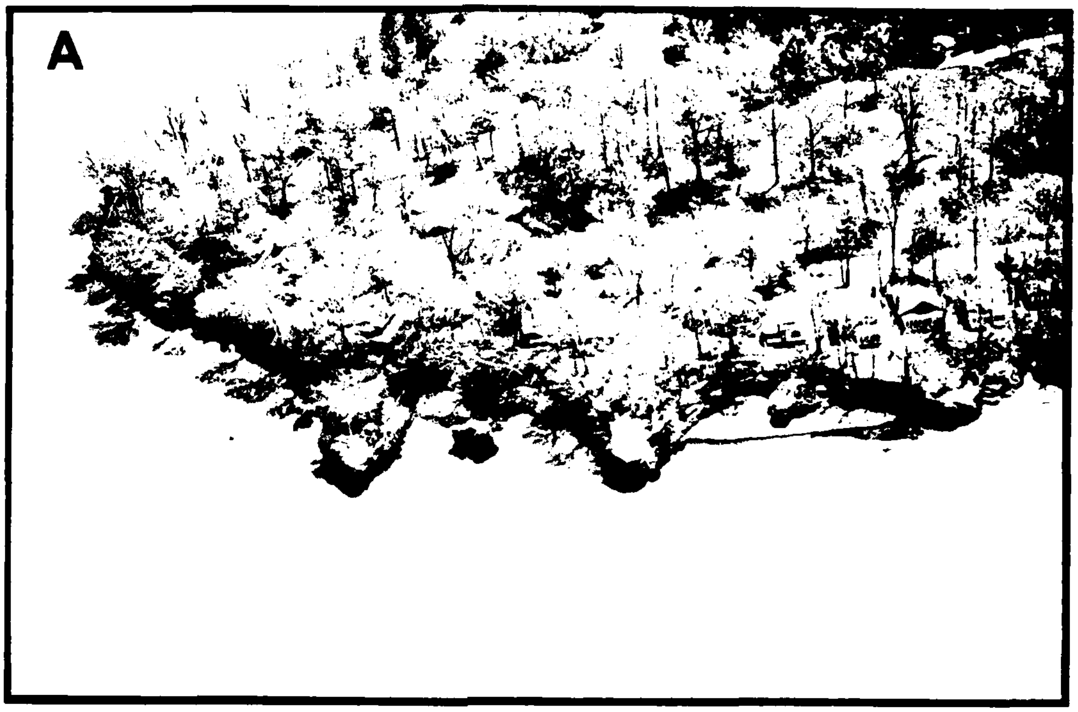


FIGURES 29A AND B

Figure 30. A. Zonal site #16, Van Buren Point, N. Y.

B. Ground view of the area shown in the right-central portion of the aerial photograph. Note joint-controlled patterns in the cliff.

A



B

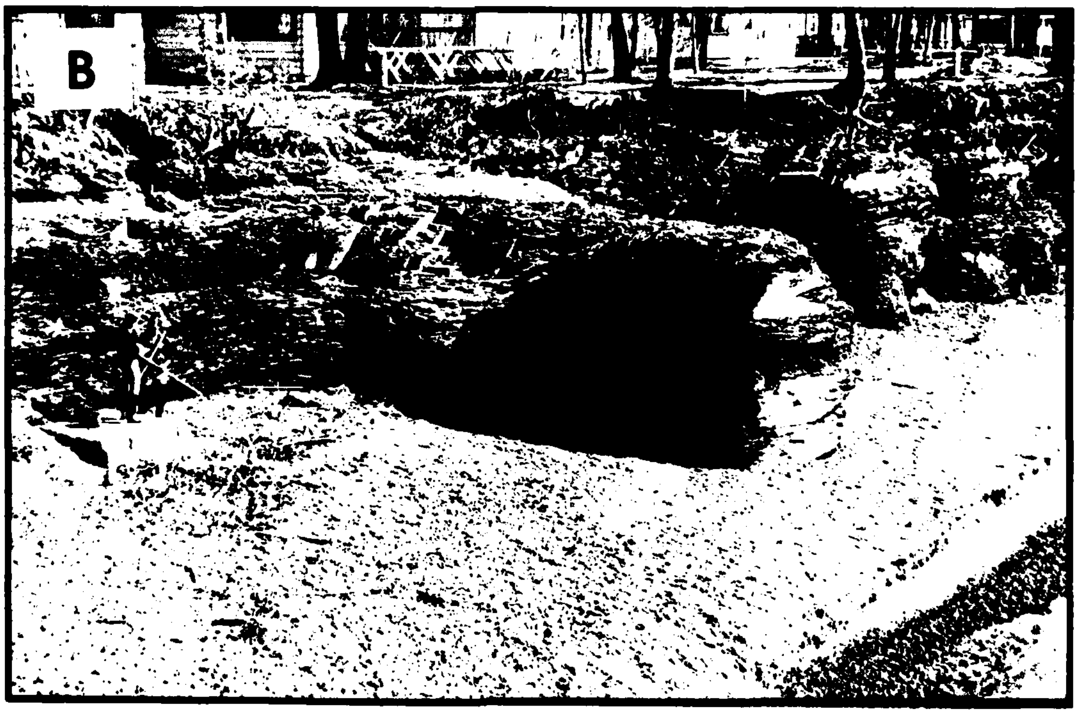


FIGURE 30

The upper half is mostly shale but the lower half contains abundant siltstone beds 1-2 ft. thick. There is no evidence of beach deposits at the base and the water depth appears to increase rapidly away from the cliff. No joint patterns were evident in the cliff face.

The major man-made structure at Dunkirk Harbor, N. Y., is located approximately 5 miles northeast of the southern border of Unit L. The harbor is a deep draft navigation project which was authorized in 1827 and has been modified many times over the past 150 years. There is a detached breakwater located seaward of the main channel. We did not do field observations here in detail and there is no evidence that this structure has a strong effect on the littoral drift system.

3.2n. Unit M. Unit M extends 16 miles from Silver Creek, N. Y., to Sturgeon Point, N. Y. This unit is distinctly different from Unit L in that it is made up of headlands of intermediate height separating wide embayments that have large streams with a heavy sediment input. Consequently, the area has abundant wide sandy beaches which show excellent spit growth toward the north, and, in places, the development of coastal sand dunes. The main reasons why sandy beaches are so well developed in this area are probably:

1. The occurrence of numerous streams carrying sediment into the area, including the largest stream on the northeast shoreline of Lake Erie, Cattaraugus Creek. The detailed study conducted along the entire stretch of the Cattaraugus Creek embayment makes up the bulk of this report, so it will not be discussed in this section.
2. The orientation of the shoreline, which is almost perpendicular to

the dominant wave approach direction (i.e., waves approaching from the west), which tends to slow down the rate at which sediment is transported out of the area.

Zonal site #18 is located at Evangola State Park, N. Y. The beach is sheltered between two projecting headlands of shale cliffs of intermediate height. The beach averages around 180-200 ft. in width, contains several berms as indicated by the sketch in Figure 31, and has been frequently manicured by the managers of the park. The sediment of the beach is very variable in size, being mostly sand but containing gravel as coarse as 8 in. in diameter. A unique aspect of the gravel at this locality is the occurrence of angular shale fragments created by frost heaving on the rock platform upon which the beach is situated. A small active dune area is located just in front of the seawall, at the back part of the beach. A large zone of driftwood accumulation occurs along the middle portion of the beach. The configuration of the beach is shown by the three-dimensional block diagram in Figure 32 and the general aspect of the beach on the ground is shown by the photograph in Figure 33. This beach is considered typical of the numerous wide sandy beaches that occur along the entire length of Unit M.

Zonal site #19 is the northward projecting spit that overlaps the mouth of Big Sister Creek, N. Y. Two sites were investigated in detail on the spit, which is shown by the aerial photograph in Figure 34A. The first area studied, the end of the spit, is shown in the block diagram in Figure 34B. The spit end is a growing recurve system which is formed basically as a sandy washover terrace. Gravel berms accumulate on the east end of the spit, indicating selective transport of the gravel toward

Figure 31. Field sketch of zonal site #18, the beach at Evangola State Park, N. Y. This wide beach, which is predominantly sand with an admixture of gravel, is sheltered between two bedrock headlands.

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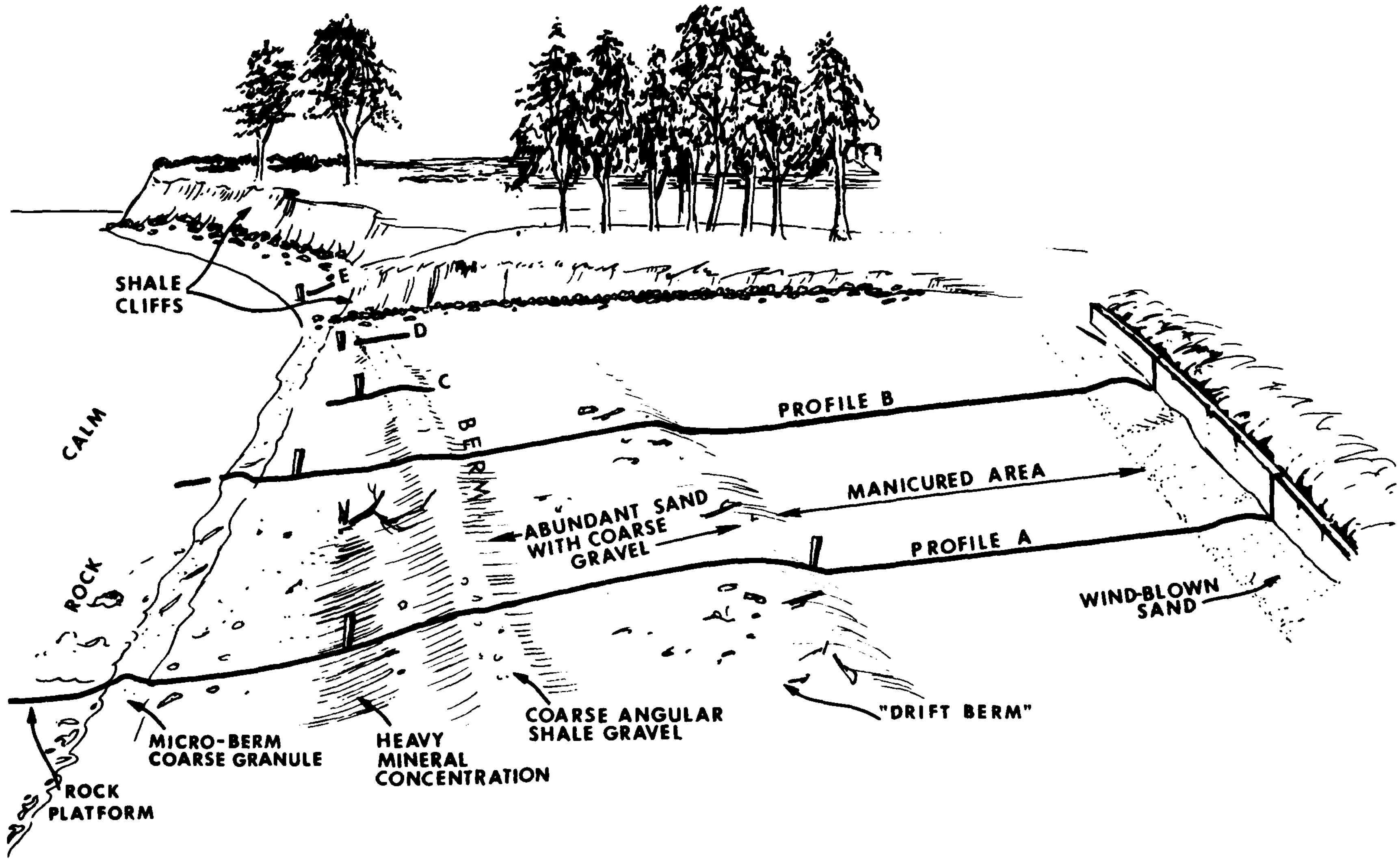


EVANGOLA STATE PARK

MAY 21, 1974

FIGURE 31

Figure 32. Three-dimensional diagram of the beach zone at Evangola State Park. This sandy beach sits on top of a rock platform cut by the waves.

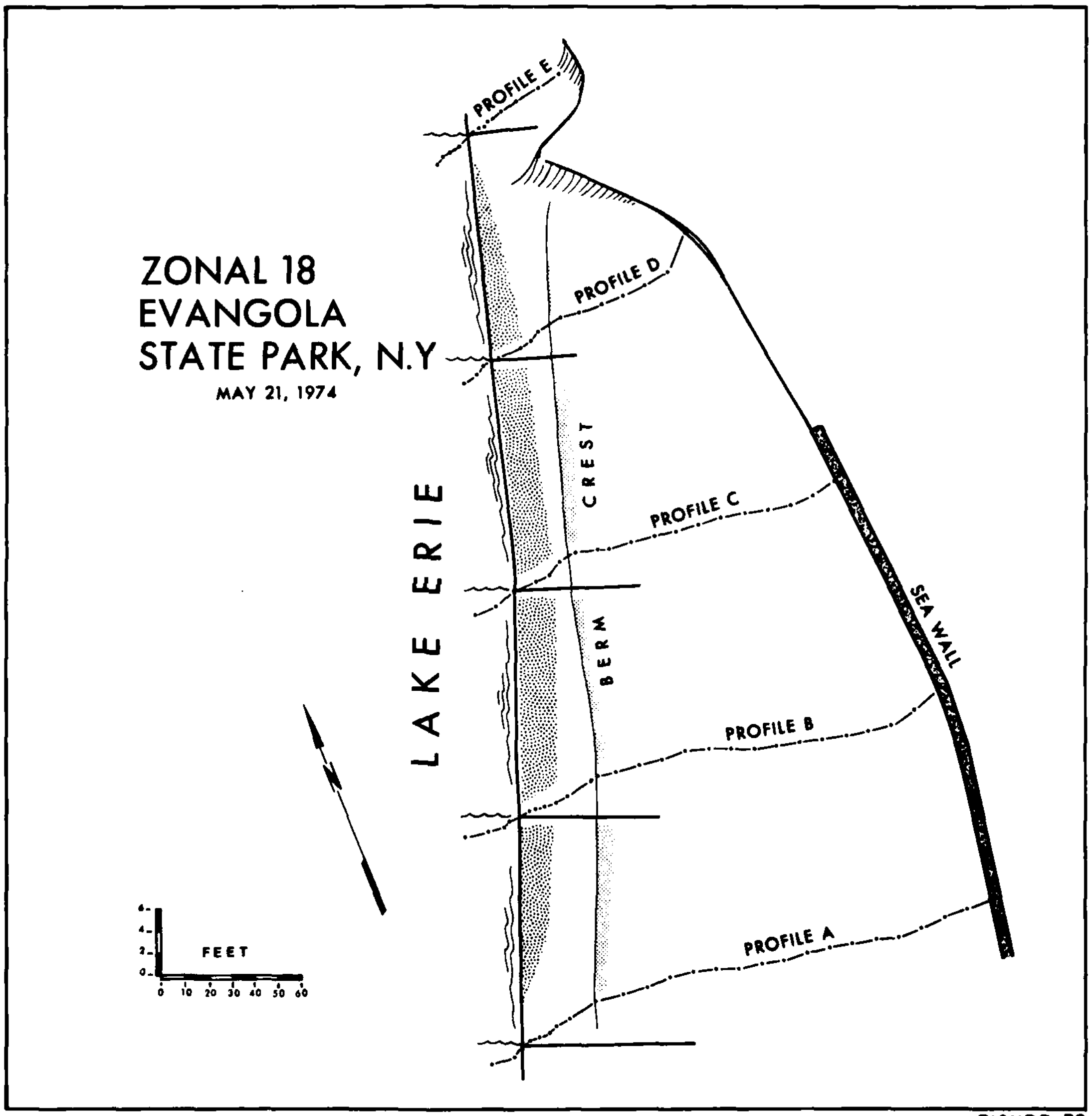

ZONAL 18
EVANGOLA
STATE PARK, N.Y
MAY 21, 1974
LAKE ERIE
PROFILE E
PROFILE D
PROFILE C
PROFILE B
PROFILE A
CREST
BERM
SEA WALL
FEET
0
2
4
6
0 10 20 30 40 50 60

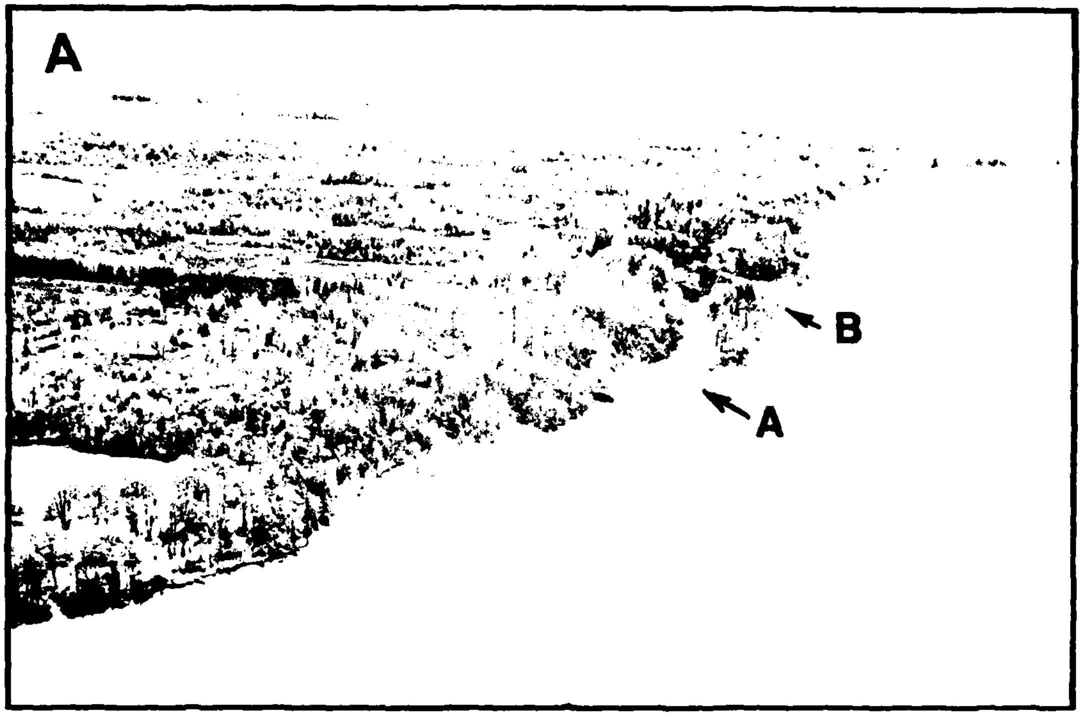
FIGURE 32

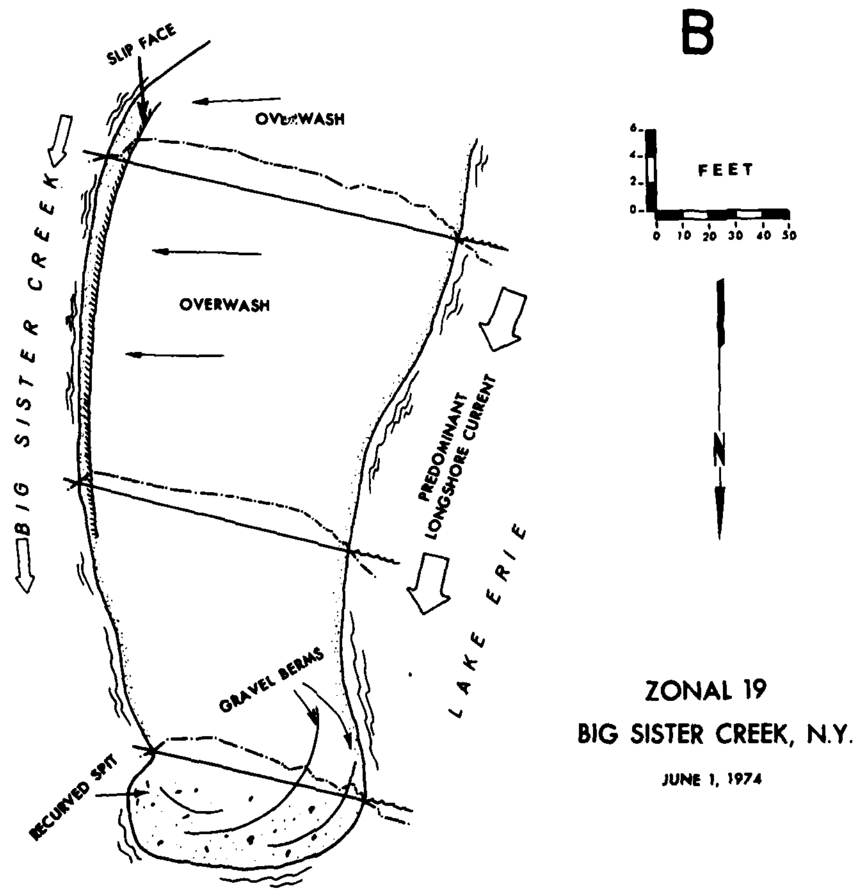
Figure 33. The beach at Evangola State Park. View looks southwest. Note cusps developing in new fine-grained gravel berm.

FIGURE 33

Figure 34. A. Zonal site #19, Big Sister Creek, N. Y. (second stream from left). View looks southwest. Note the northeastward projection of the spits, indicating longshore sediment transport in that direction. Arrow A points to spit area mapped and presented in B. Arrow B points to the profile presented in Figure 35A.

B. Spit at the mouth of Big Sister Creek. This entire spit, which is migrating in a northeasterly direction as a series of recurved gravel spits, is overwashed by waves during storms. Note actively accreting slip face on the west side of the spit.





FIGURES 34A AND B

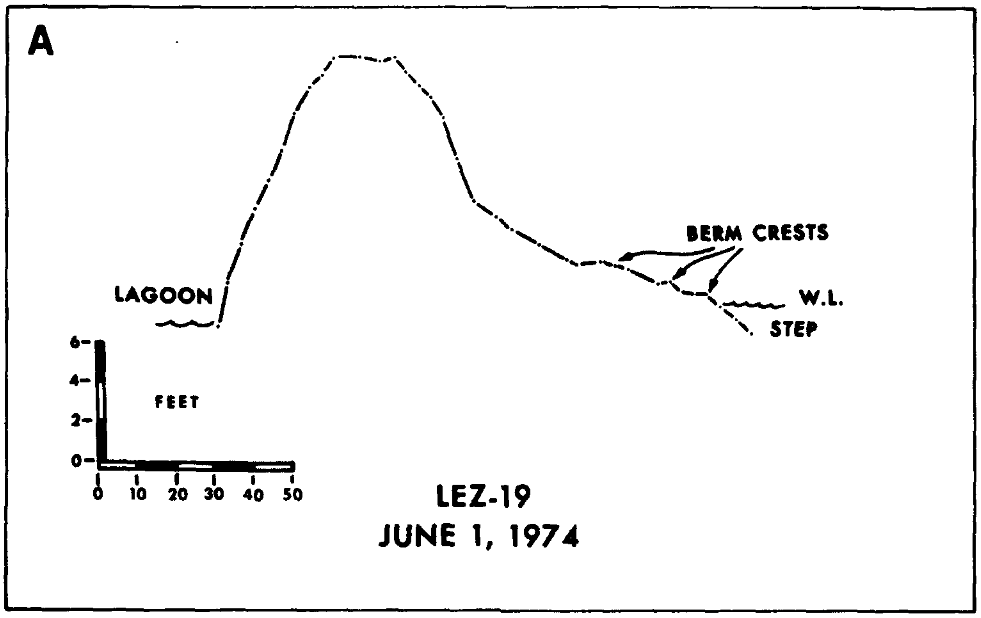
the end of the spit. The surface of the spit is flat and is obviously frequently overwashed by waves during periods of high wind tides. Thus, the spit is building both toward the northeast and landward into Big Sister Creek. The main portion of the spit is capped by high, vegetated eolian dunes. A profile of an active dune area is given in Figure 35A, and photographs illustrating the details of the profile are given in Figure 35B & C. These dunes at Big Sister Creek are the biggest that occur on the northeast shoreline of the lake and rival in size those occurring anywhere on the lake, with the possible exception of those found on Long Point, on the Canadian shore. At the present time, the dunes are eroding, with an erosional scarp occurring along much of the dune area. Heavy mineral layers accumulate in front of the scarp as it retreats during this period of high lake level. There are several other spits overlapping stream mouths in Section M.

Zonal site #20 is located at Sturgeon Point, N. Y. The dominant feature there is a breakwater, the shape and dimensions of which are shown in Figure 36. It is a very effective trap for sediment being transported from both the south and east, consequently the harbor has to be dredged repeatedly if it is to serve as an effective boat basin. To the southwest of the structure, the beach narrows, being composed of a number of berms made up of sedimentary rock fragments overlying a flat rock platform cut by the waves in black shale. At this locality, black shale has become a predominant component in the sediment fraction and it is commonly quite angular, as is illustrated in the photograph in Figure 37A. A general view of the beach along this area is given in Figure 37B. Black

Figure 35. A. Dune and beach profile extending from the lagoon of Big Sister Creek to the lake. The profile is located by arrow B on the aerial photograph of Figure 34A. The peaked central area is an eroding dune ridge.

B. Beach zone of profile shown in A. Note gravel accumulations on berms.

C. Slip face on dune at landward margin of profile given in A. Big Sister Creek can be seen on the right.



FIGURES 35A, B AND C

Figure 36. Structure at Sturgeon Point, N. Y. (zonal site #20). Note heavy sediment accumulation on both sides of the structure.

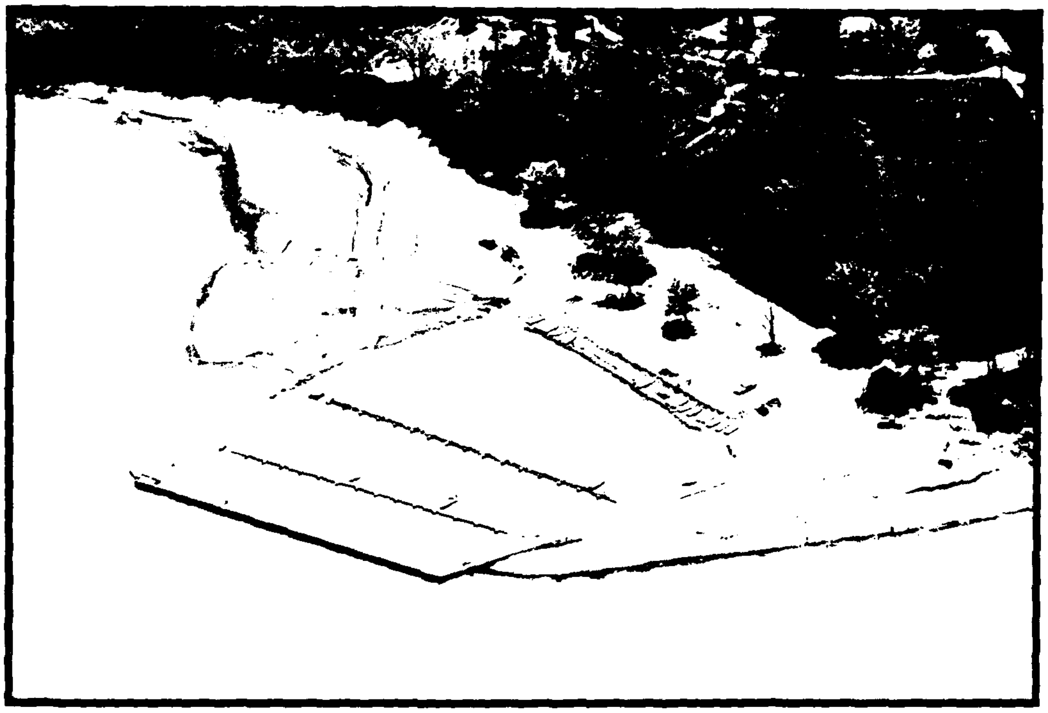


FIGURE 36

Figure 37. A. Gravel on beach a few hundred feet southwest of the structure at Sturgeon Point. Gravel is composed predominently of black shale, which crops out in the cliff at this locality.

B. View looking southwest at locality A (above). A rock platform in the black shale occurred just below water level at the time the photograph was taken (21 May 1974).

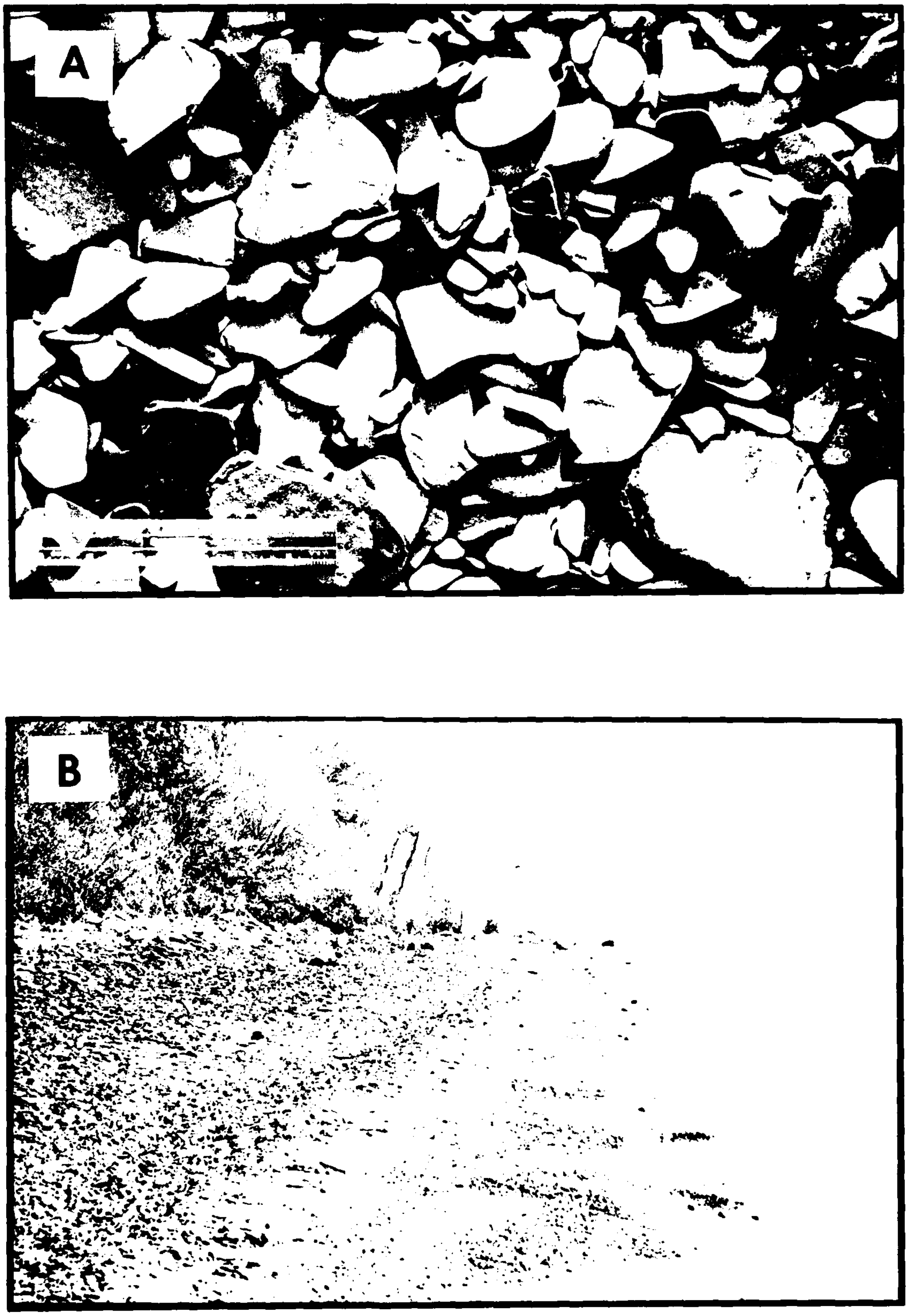


FIGURE 37

shale crops out at the base of the cliff, but the bulk of the cliff, which is approximately 60 ft. high, is made up of unstratified and stratified till.

Unit M is obviously a zone of intense sediment accumulation. It has more sandy beaches than any other part of the southeastern shoreline of Lake Erie. It is the only major sand accumulation zone, with the exception of Presque Isle, in the entire study area.

3.2o. Unit N. At Sturgeon Point there is a sharp break in the orientation of the shoreline, with the shore projecting in an east-northeasterly direction away from the point. Also, there is a corresponding strong change in the morphology of the coast at that point. The bedrock and till cliffs become considerably higher, and there is very little sand accumulation. The cliffs are somewhat irregular, being quite similar to the stretch of shoreline located between Dunkirk and Silver Creek (Unit L). The terminus of Unit N and the terminus of the study area is located at Wanakah, N.Y. Unit N is 8 1/2 miles in length. No zonal study was done in this area, inasmuch as it is so similar to Zonal #17 in Unit L, which was an inaccessible vertical cliff. Parts of Unit N and the rest of the shoreline between Wanakah and Buffalo, N.Y. have been so intensely modified by man that we could not determine details of the origin of the morphology of the coast, therefore we omitted those areas from the reconnaissance study.

3.3 Conclusions.

This reconnaissance study of the morphology and sediments of the southeastern shoreline of Lake Erie has led us to the following general conclusions:

1. The Cattaraugus embayment is somewhat unique in its morphology and sediments in that it occurs in an area that has an exceptionally large sediment supply and accumulation. Wide sandy beaches commonly occur between widely spaced bedrock headlands. This is thought to result from the facts that:

   a. Cattaraugus Creek and neighboring streams deliver a large amount of sediment to the Lake Erie littoral drift system (discussed in detail later in report); and

   b. The orientation of the shoreline in the Cattaraugus embayment area is into, or perpendicular to, the dominant wave approach direction (from west). This tends to slow down the rate at which sediments are transported out of the area.

2. The dominant longshore littoral transport in this area is from southwest to northeast. The morphological evidence for this trend is overwhelming, as is indicated by data collected at almost all of the 20 individual zonal study sites.

3. A severe erosion problem exists along most of the southeastern shoreline of Lake Erie. This is presumably the result of the present high stand of the lake. If the lake level does not recede soon, large losses of private and public property will continue.

4. Almost without exception, any man-made structure built in the beach area, such as jetties or groins, has a profound effect upon erosional and depositional conditions of the adjacent shoreline. The usual

pattern is widening of the beach on the southwest side and intensified erosion on the northeast side.

5. The role played by the cliffs in the erosional and depositional history of the shoreline is still uncertain. More detailed studies are needed on the relationship between cliff composition and local conditions.

6. A wide variety of morphological types are found in this area; it makes an excellent field laboratory for the study of coastal processes and geomorphology.

4. GEOMORPHIC HISTORY OF CATTARAUGUS HARBOR AND VICINITY

In the development of the Cattaraugus Embayment, shoreline, stream, and glacial processes acted on a relatively uniform shale bedrock. On a regional scale, glaciers advanced through the area for hundreds of miles to the west and more than forty miles south (Fig. 38). The topography over which the ice advanced controlled the ice flow. The most prominent of these topographic features was the lowland that is now the basin of Lake Erie and the 1000 foot escarpment that now borders it on the south in New York. Ice flow through the escarpment was controlled by pre-glacial stream valleys.

Predominant among these pre-glacial stream valleys in New York was the Ancient Allegheny Valley (Fig. 39). In many places this valley is filled with glacial deposits which have been compacted by thousands of feet of overriding ice. This valley is followed from Gowanda, New York, by the present Cattaraugus Creek. Records of wells drilled through the glacial deposits indicate that the elevation of bedrock is between 200 and 300 feet below sea level. A gravity survey along the beach places the bedrock at the present mouth of Cattaraugus Creek at about 275 feet below the lake (Wilson, 1973). Such deposits often provide reasonable foundation conditions, but the variability of the fill requires detailed on-site investigation. Detailed studies of the glaciation of western New York and extensive bibliographies are contained in Muller (1963, and in press).

The primary evidence of the earlier glaciations is the blockage of the northward course and the establishment of the southward flowing Allegheny-Ohio River system (Fig. 39). The last major continental ice in the area

Figure 38. Simplified glacial map of the eastern part of Lake Erie.

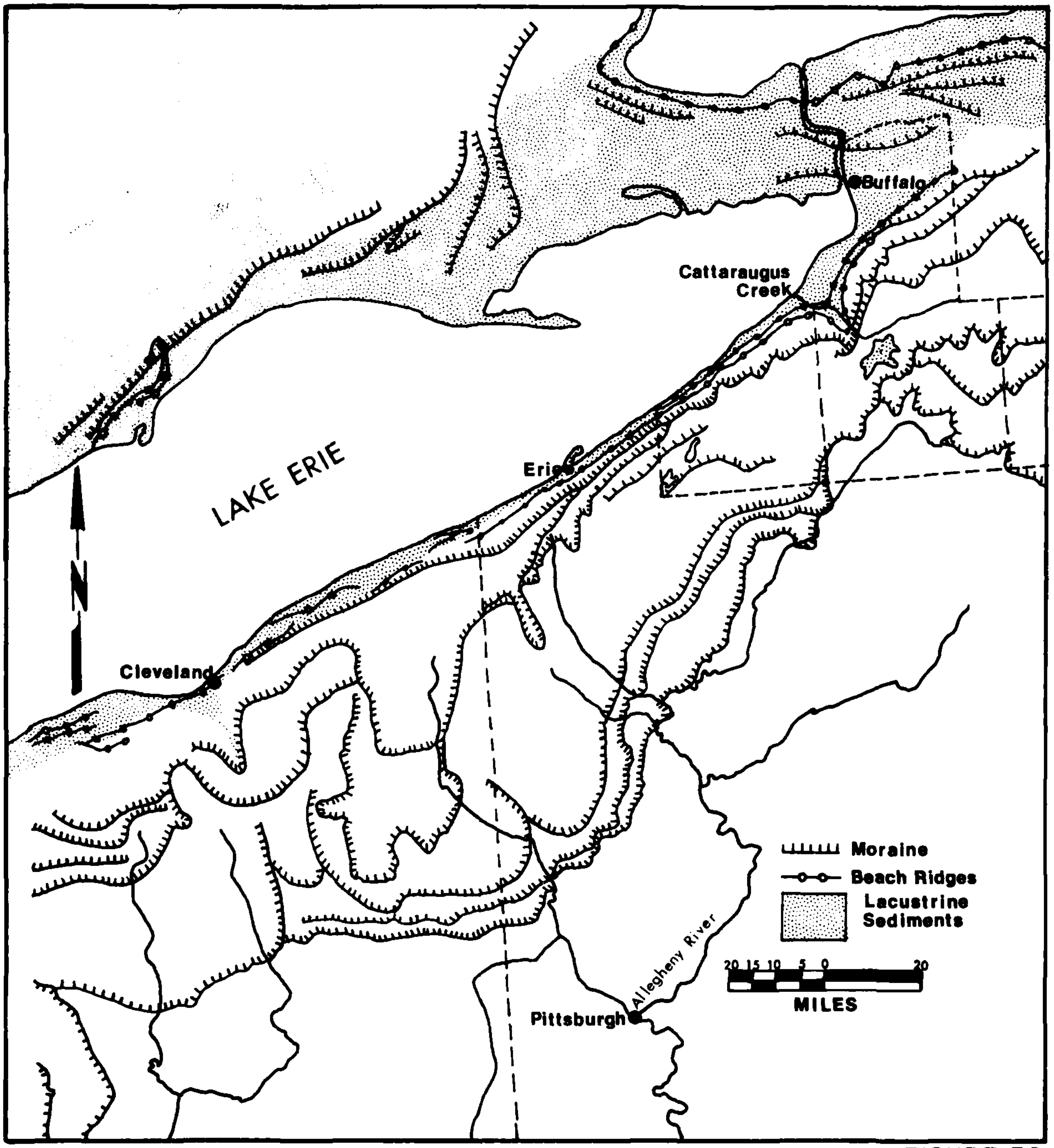

LAKE ERIE
Buffalo
Cattaraugus Creek
Erie
Cleveland
Pittsburgh
Allegheny River
N
Moraine
Beach Ridges
Lacustrine Sediments
20 15 10 5 0 20
MILES
FIGURE 38

Figure 39. Formation of the Allegheny River from preglacial drainage.

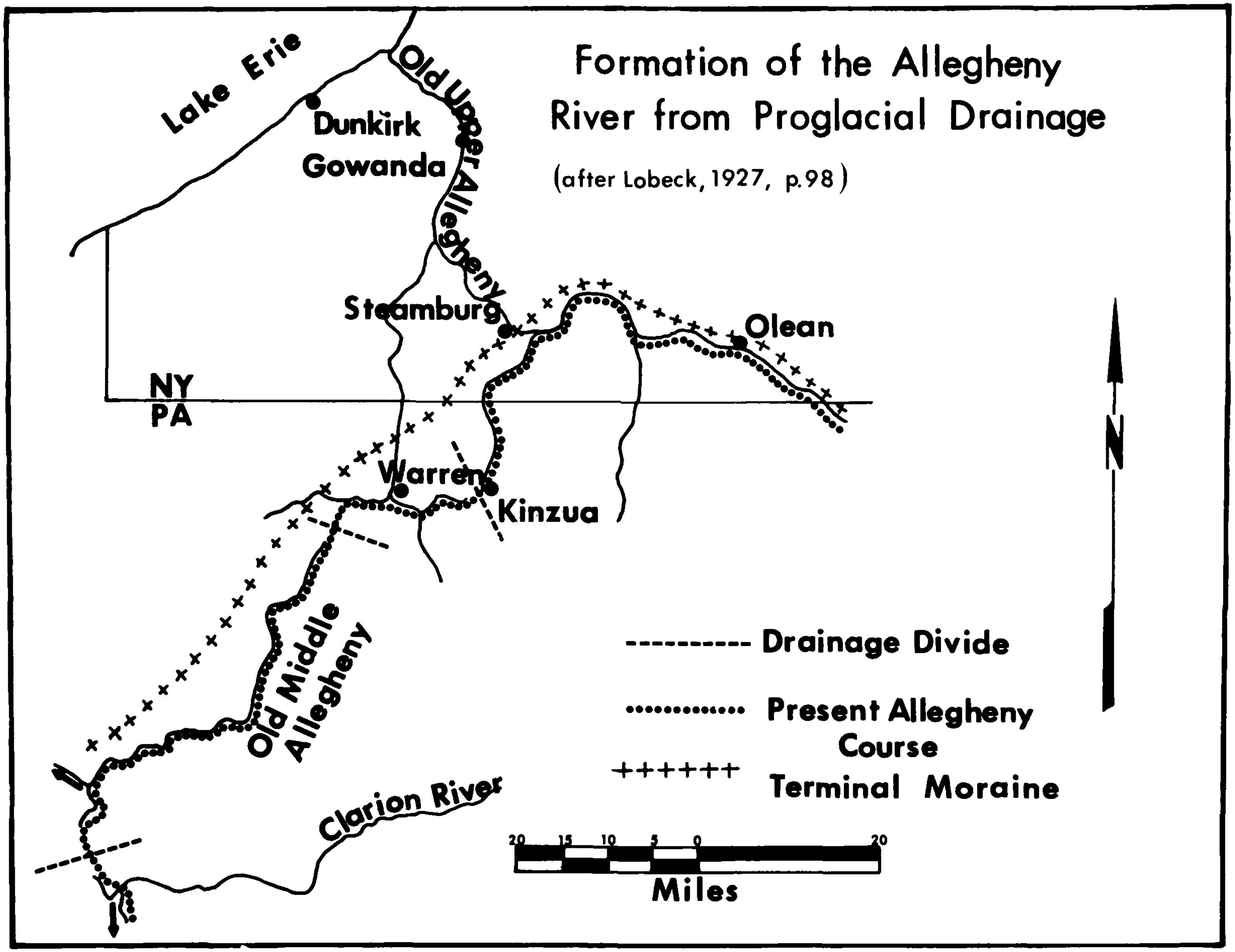

Formation of the Allegheny River from Proglacial Drainage
(after Lobeck, 1927, p.98)
Lake Erie
Dunkirk
Gowanda
Old Upper Allegheny
Steamburg
Olean
NY
PA
Warren
Kinzua
Old Middle Allegheny
Clarion River
Drainage Divide
Present Allegheny Course
Terminal Moraine
20 15 10 5 0 20
Miles
N

FIGURE 39

left behind a detailed record of its retreat in its moraine deposits (Figs. 38 and 40). A chronology of these events is given in Table II.

The moraines are ridges of unsorted sediment, formed during pauses in the glacier's retreat when the rate of melting was balanced by the rate of ice flow toward the margin. Under these equilibrium conditions the ice front may have remained at the same location for tens to hundreds of years, piling up the sediment that the glacier delivered as a sort of conveyor belt. The moraines in the vicinity of Cattaraugus Creek are shown in Figure 40, and ice positions and drainage development associated with these moraines in Figures 41, 42, and 43.

This glacial material provided the sediment source for beaches and deltas built during periods of high lake levels. These ancient lakes (Figs. 38 and 43) were formed when the outlet over the Niagara Escarpment was blocked and the flow of the Great Lakes basin, swollen by the meltwaters of Canadian glaciers, poured south through such rivers as the Wabash and the Illinois. Each time the retreat of the glacier allowed these ancient lakes to find a lower outlet, a new system of shoreline features was formed.

Unlike the shoreline of the present lake, these shorelines were primarily depositional features with only a few miles of wave-cut bedrock cliffs and many miles of beaches much wider than those of Lake Erie today. Detailed investigations and an extensive bibliography on these ancient lakes and beaches are contained in Calkin (1970). The beach features in the vicinity of Cattaraugus Creek are shown in Figure 40.

The relatively thick cover of unconsolidated glacial materials provides

Figure 40. High-level beaches and moraines of western New York.

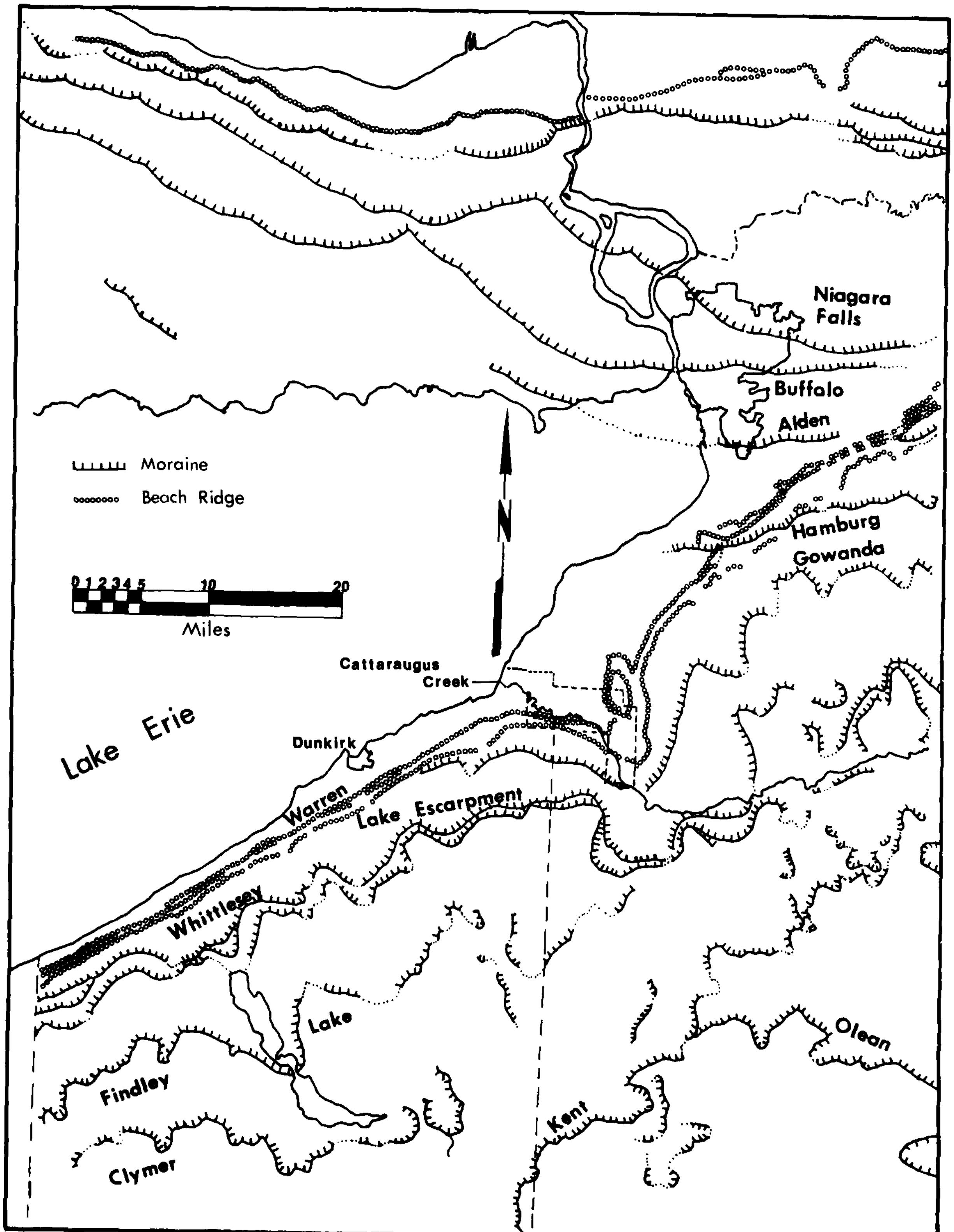
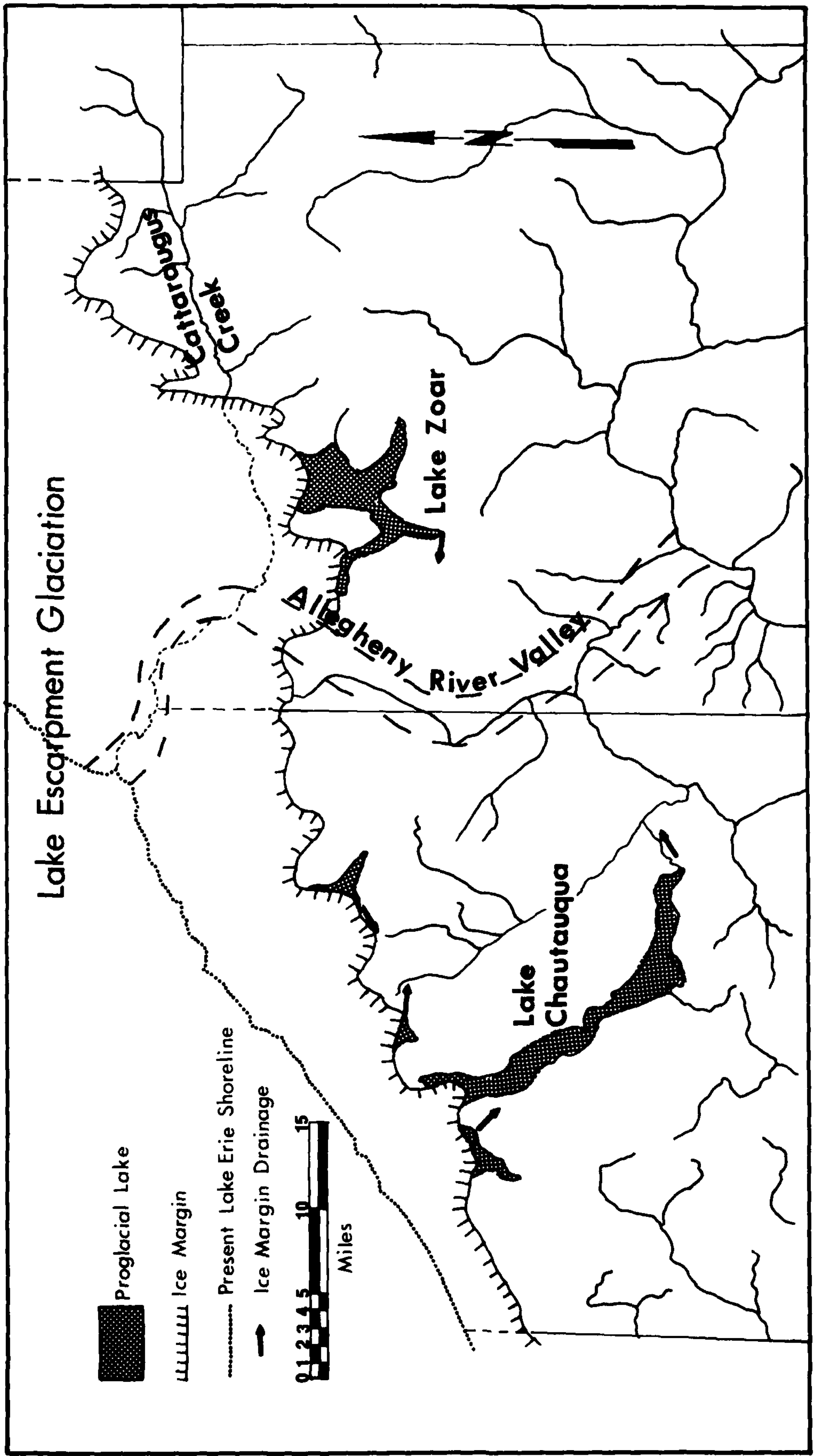

Niagara Falls
Buffalo
Alden
Hamburg
Gowanda
Moraine
Beach Ridge
0 1 2 3 4 5 10 20
Miles
N
Cattaraugus Creek
Dunkirk
Lake Erie
Warren
Lake Escarpment
Whittlesey
Lake
Findley
Clymer
Kent
Olean

FIGURE 40

Figure 41. Lake escarpment glaciation. Position of ice-margin and drainage patterns.



Lake Escarpment Glaciation
Cattaraugus Creek
Lake Zoar
Allegheny River Valley
Lake Chautauqua
Proglacial Lake
Ice Margin
Present Lake Erie Shoreline
Ice Margin Drainage
0 1 2 3 4 5 10 15
Miles
N

FIGURE 41

Figure 42. Gowanda glaciation. Position of ice-margin and drainage pattern.

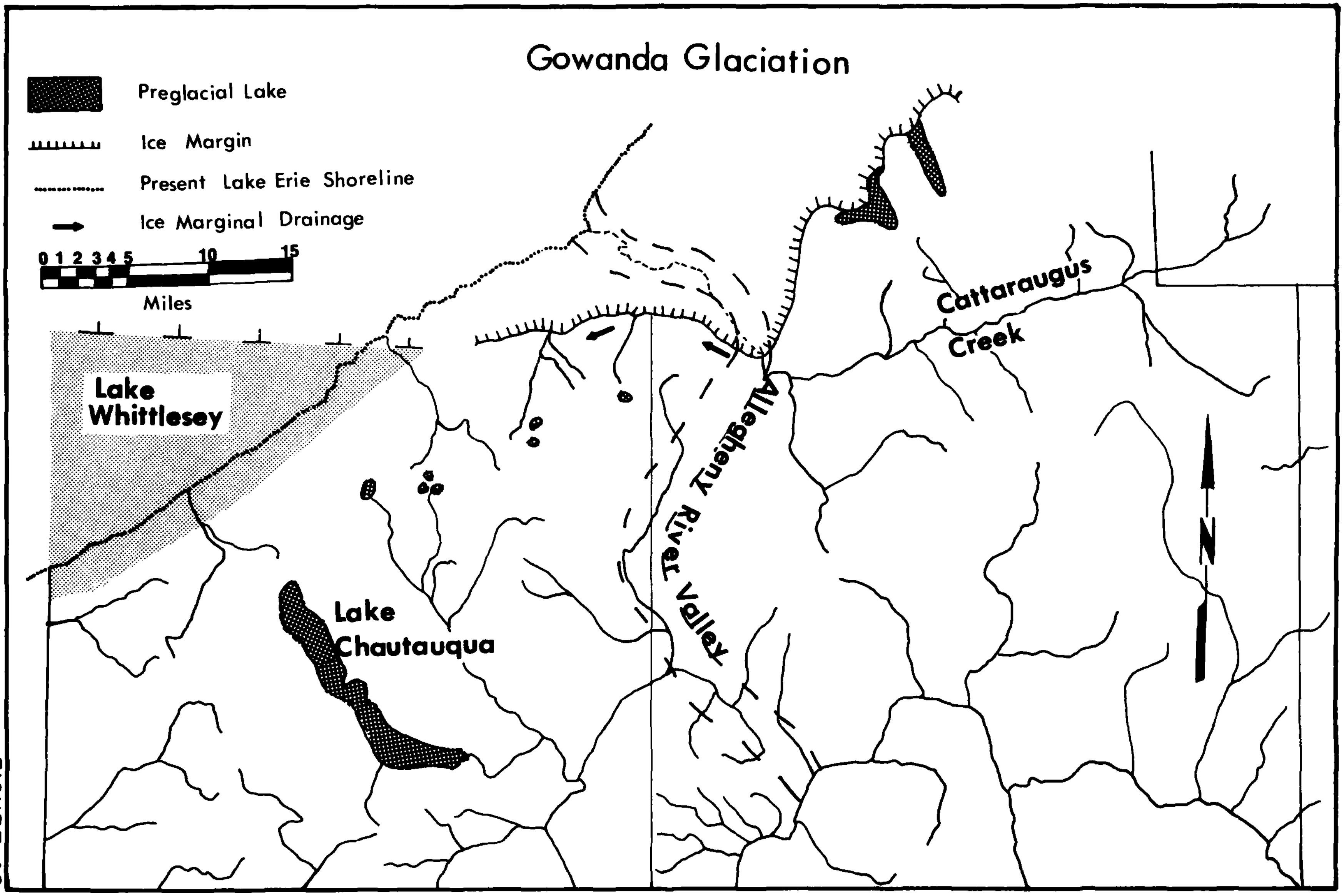
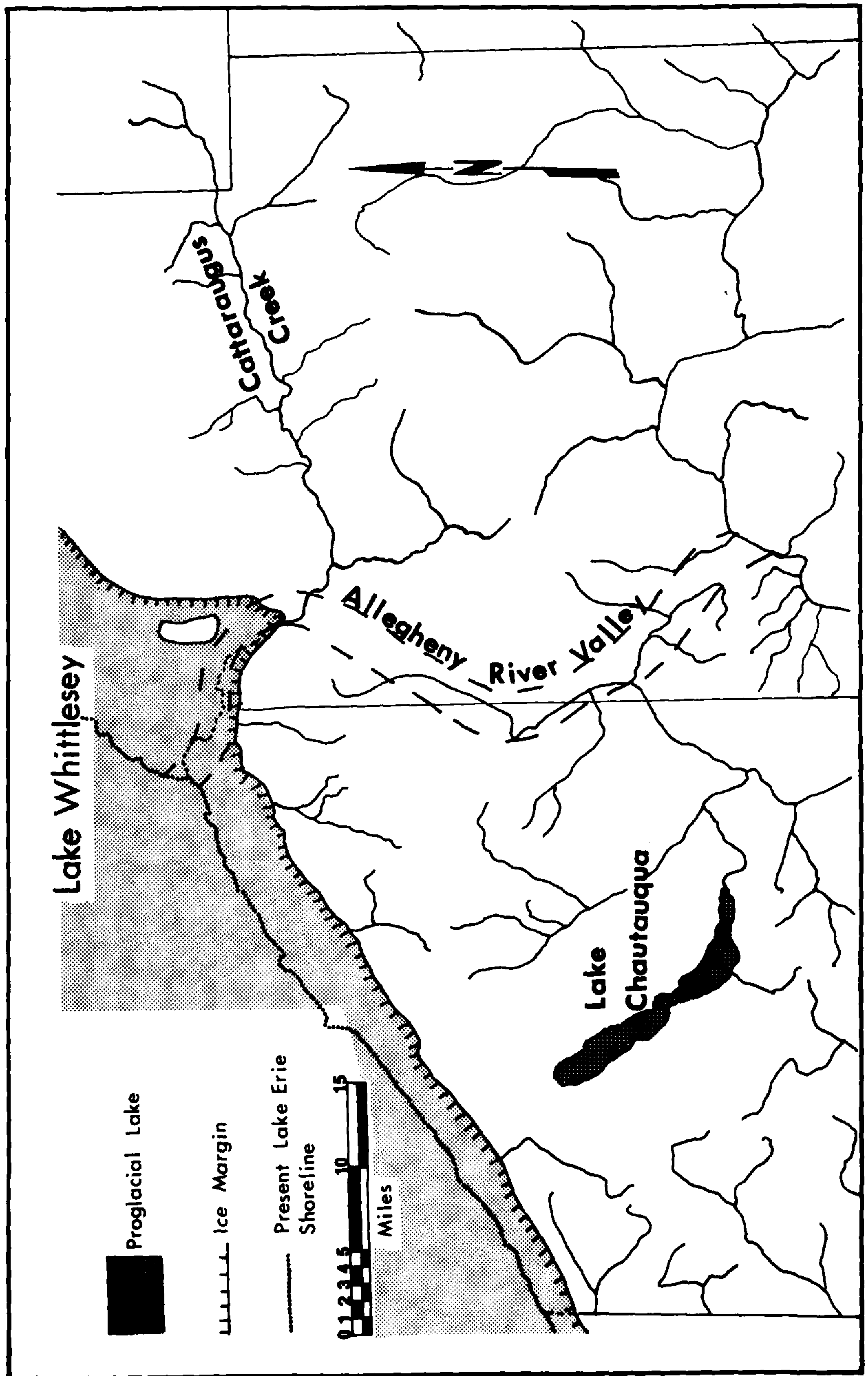

Gowanda Glaciation
Preglacial Lake
Ice Margin
Present Lake Erie Shoreline
Ice Marginal Drainage
0 1 2 3 4 5 10 15
Miles
Lake Whittlesey
Lake Chautauqua
Cattaraugus Creek
Allegheny River Valley
N

FIGURE 42

Figure 43. Lake Whittlesey and associated drainage.



Lake Whittlesey
Cattaraugus Creek
Allegheny River Valley
Lake Chautauqua
N
Proglacial Lake
Ice Margin
Present Lake Erie Shoreline
0 1 2 3 4 5 10 15
Miles

FIGURE 43

TABLE II

Correlation of Late Wisconsin Lakes† and Moraines,

Western New York, from Calkin (1970)

Years B.P.	Glacial Event	Lakes of Erie Basin (*evidenced in N.Y.)	Moraines in N.Y.
	St. Lawrence ice-free		
-11,000			
	Valders Advance		
	Two Creeks Interstade	Iroquois (Ontario basin)	
		*Early Erie (473?)	
-12,000	Rome, N.Y. ice-free	*Dana (570)	Albion M.
		*Early Algonquin (605)	Barre M.
		*Lundy (620)	
		*Grassmere (640)	Batavia M.
		*Warren III (675)	Niagara Falls M.
		*Wayne (660)	Buffalo M.
		*Warren II (680)	Alden M.
		*Warren I (690)	Marilla M.
			Hamburg M.
	Port Huron Advance	*Whittlesey (738)-?	Gowanda M.
			Lake Escarpment M.
-13,000	Cary/Port Huron	Ypsilanti? (543-373)	
		III (695)	
		II (700)	
		Arkona I (710)	
	Cary Advances		Moraines of SW New York (see Muller, 1963)
-14,000			

†Elevations of glacial lakes south of respective zero isobases, (after Wayne and Zumberge, 1965).

the present streams, such as Cattaraugus Creek, with a readily available source of both fine and coarse sediment which ultimately is delivered to the lake. Wave erosion of glacial materials exposed along the lake shore contributes a major amount of sediment to the lake, but not near the mouth of Cattaraugus Creek.

Table II indicates that, following the high-level lakes of the Lake Erie Basin, a level considerably lower than the present stage existed for an unknown length of time. In adjusting to the lower lake level, streams cut channels in bedrock or in glacial drift. As the lake level rose to the present level, some of these channels, like Cattaraugus, were backfilled while others remained as estuaries.

Wave erosion has caused the present shoreline of Lake Erie to retreat hundreds to thousands of feet in most places since the lake rose to its present level. Partly as a result of the sediment supplied by Cattaraugus Creek, this segment of the shoreline may be one of the few to have escaped severe wave erosion. Table II suggests that the present lake is no more than 11,000 years old and may be considerably younger than that.

5. HISTORIC CHANGES NEAR THE MOUTH OF CATTARAUGUS CREEK

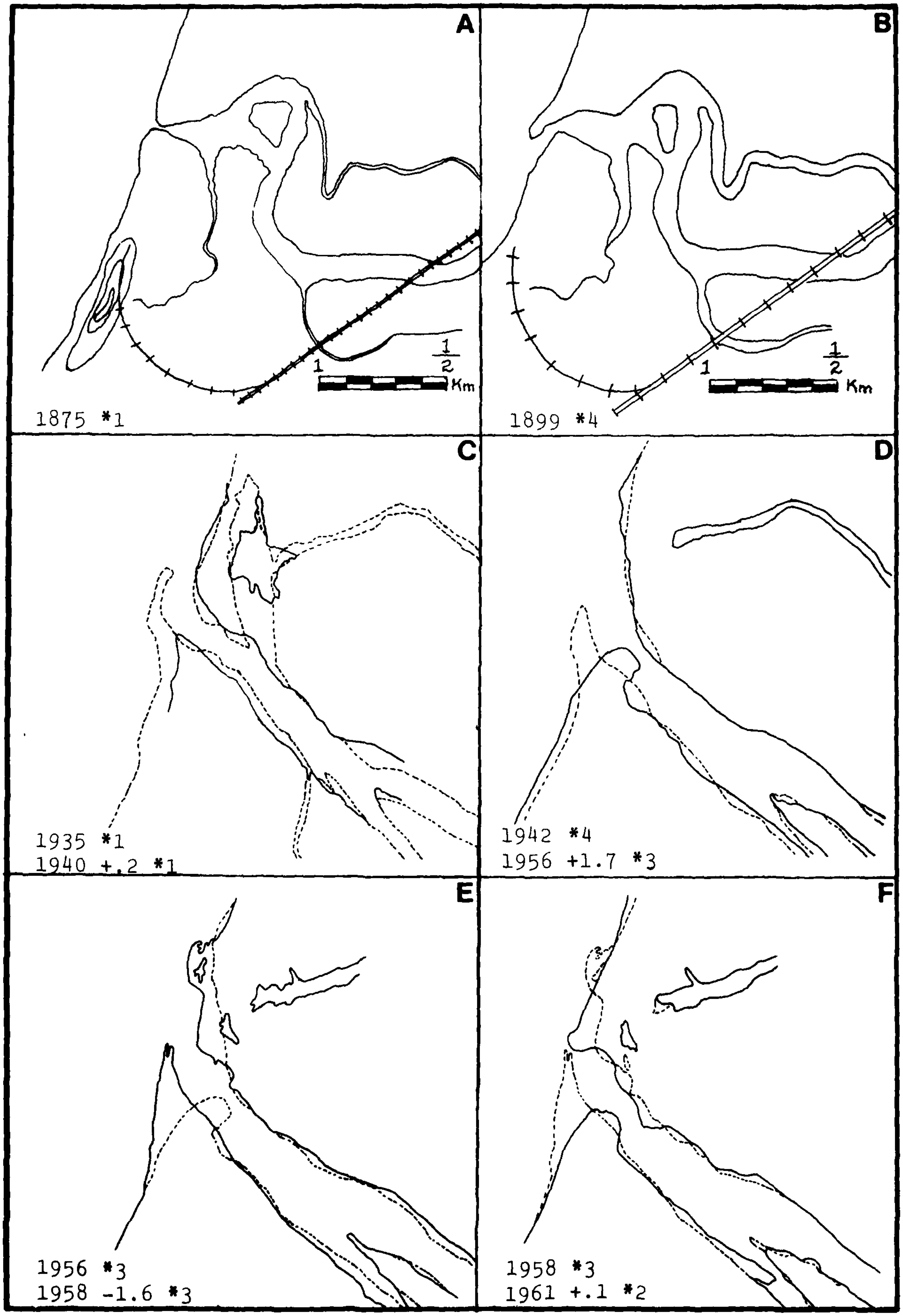
Air photos and maps provided the basis for a series of maps showing the changes in the configuration of the shoreline and the stream near the mouth of Cattaraugus Creek (Fig. 44,45). The role of stream and shoreline processes is evident on close inspection. Changes in lake level for the period between 1935 and 1969 on the average beach slopes of 1 in 10 (north side of Creek mouth) and 1 in 30 (south side) would result in little or no apparent change in position of the shorelines at the scale of the map.

In general, the interaction of littoral and fluvial currents appears to control the form and position of the deposits at the mouth of the creek. The maps of 1935, 1942, 1958, and 1966 show the south spit to be projecting northwest into the lake, a condition thought to reflect relatively strong fluvial currents in the period prior to the mapping. This contrasts to 1956, 1961, and 1971, when the south spit was found to recurve into the creek mouth, a condition probably caused by sustained wave-power dominance.

The changes between maps reflect the sum of all the changes in the intervening years. Floods may flush out sediments blocking the mouth of the creek only to have them replaced by high wave and current activity at lower stream flow. The seasonal fluctuations in spit morphology are discussed below.

The spit on the north side of the mouth is almost always recurved into the harbor, indicating its dominant control by wave power. The latest air photo, 1971, showed that the creek had broken through the north spit about 300 meters north of the present channel mouth. This breach has been closed

Figure 44. Maps of Cattaraugus Creek mouth and the adjacent shoreline. From 1875 to 1961. See Figure 45 for legend.



A
1
1/2
Km
1875 *1
B
1
1/2
Km
1899 *4
C
1935 *1
1940 +.2 *1
D
1942 *4
1956 +1.7 *3
E
1956 *3
1958 -1.6 *3
F
1958 *3
1961 +.1 *2

FIGURE 44

Figure 45. Maps of Cattaraugus Creek mouth and the adjacent shoreline. From 1961 to 1971.

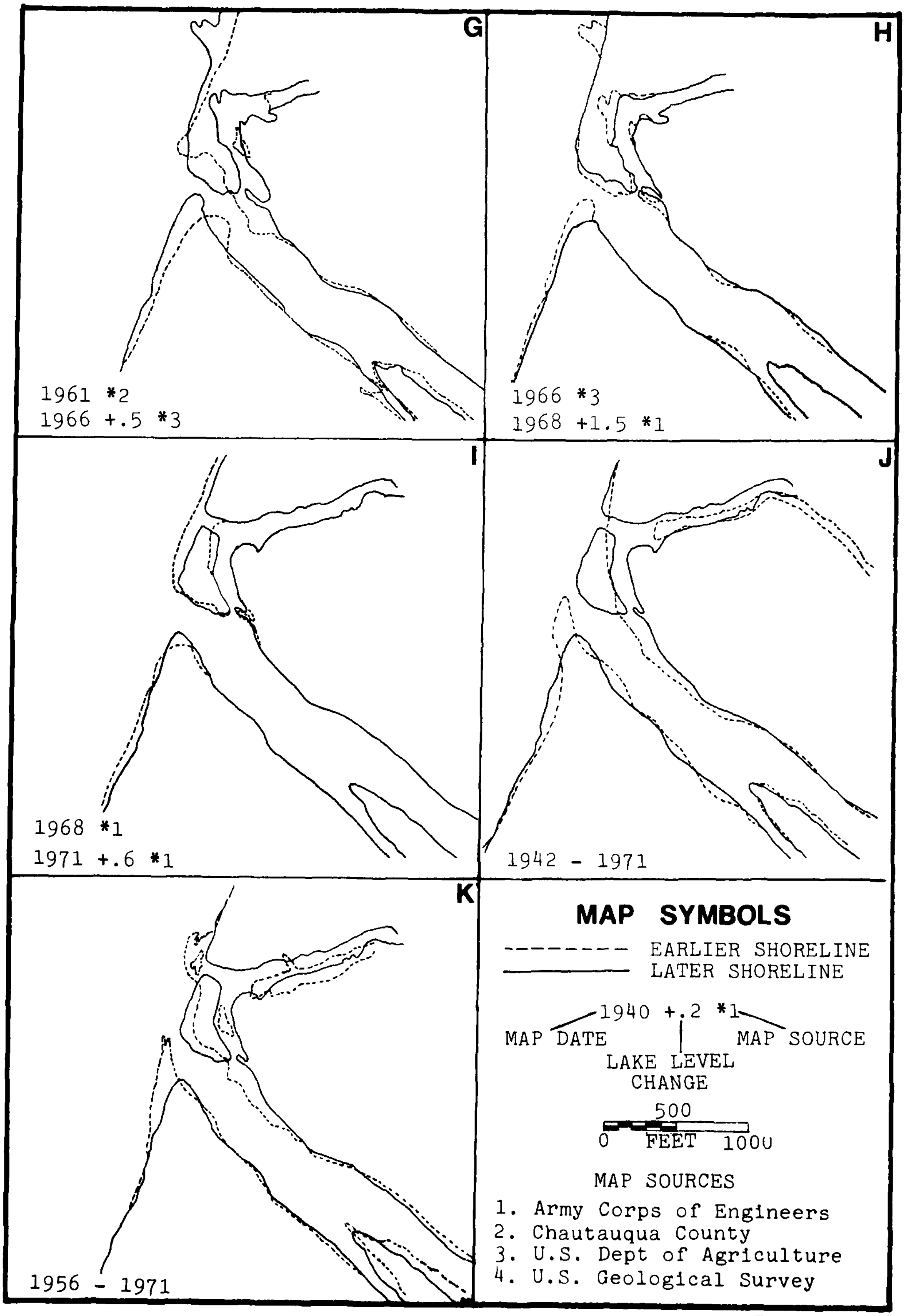

G
1961 *2
1966 +.5 *3
H
1966 *3
1968 +1.5 *1
I
1968 *1
1971 +.6 *1
J
1942 - 1971
K
1956 - 1971
MAP SYMBOLS
EARLIER SHORELINE
LATER SHORELINE
1940 +.2 *1
MAP DATE
MAP SOURCE
LAKE LEVEL CHANGE
500
0 FEET 1000
MAP SOURCES
1. Army Corps of Engineers
2. Chautauqua County
3. U.S. Dept of Agriculture
4. U.S. Geological Survey

FIGURE 45

by 1974 and probably before that. Such openings may develop when the primary mouth of the stream is blocked by ice from the lake or stream or both. The rapid infilling of the breach demonstrates the high rate of littoral sediment transportation on this stretch of beach.

If the map of 1875 can be believed, there was a sand dune more than 30 feet high on the shore south of the creek. Its removal for use elsewhere was probably the sole purpose of the railroad spur shown on the same map.

The long-term stability of the shoreline and the channel may be inferred from Figures 44 and 45 . A comparison with erosion rates of unconsolidated portions of the Ohio shore, which averaged more than two feet per year over the last one hundred years, indicates that sediment losses from the nearshore of the Cattaraugus Embayment must be replaced. The dominant source of sediment is Cattaraugus Creek.

6. LITTORAL PROCESSES

Typically, Lake Erie is ice covered from early December through March. The lake ice is responsible for frequent spring flooding of the lower 3/4 mile of Cattaraugus Creek because an ice jam at the mouth raises the downstream control level of the river (U. S. Army Engineer District, Buffalo, 1972). This problem will be analyzed in some detail later. The ice prevents any active sediment transportation during the winter months, leaving April through November for field measurements of littoral processes. Data from Saville (1953), representing hindcast wave conditions for the three years 1948-1950, indicate that the stormiest conditions are associated with March ice break-up (Fig. 46). May and November are the months with the highest wave action during the ice free period.

In order to cover both the spring storm activity and the transition into typical summer lake conditions, the field data collection program ran from May 7 through June 13, 1974. A brief field period is planned for November to monitor a typical fall storm.

6.1. North American cyclone patterns.

The most severe weather disturbances affecting the Great Lakes region are the extratropical cyclones. The location of fronts or areas of cyclogenesis depends on the general zonal circulation and location of characteristic air masses. Three principal frontal zones generate cyclones affecting the Great Lakes: 1) the Atlantic polar front, 2) the Pacific arctic front, and 3) the Pacific polar front (Petterssen, 1969, p. 222-223). The Atlantic

Figure 46. Annual variation in wave characteristics. Maximum storm activity occurs in March, generally associated with the break-up of lake ice. May and November have about the same storm frequency. Summer thunderstorms may occasionally create high waves. Wave hindcasting, however, does not adequately reconstruct such local phenomena. Data from Saville (1953).

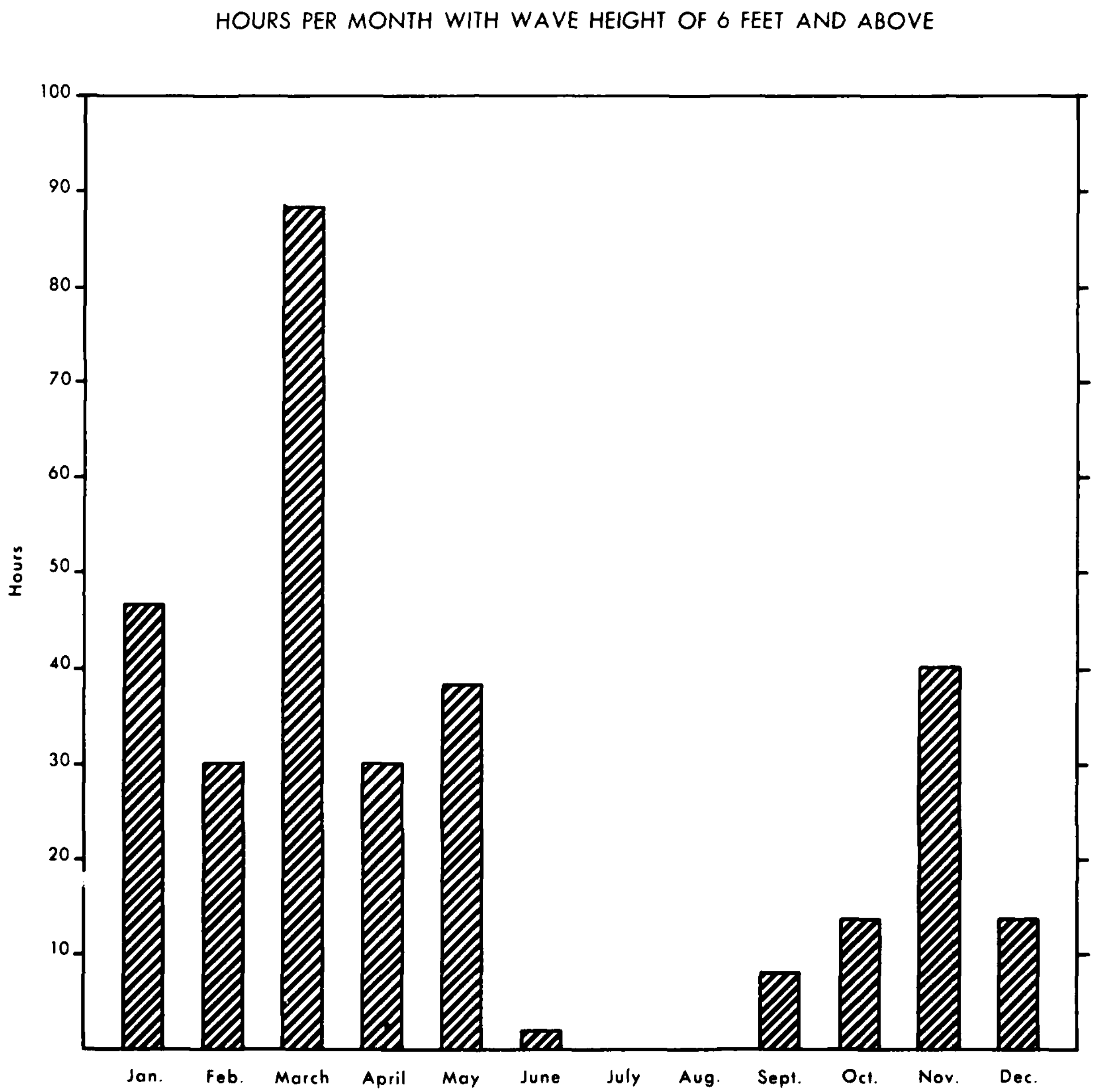

HOURS PER MONTH WITH WAVE HEIGHT OF 6 FEET AND ABOVE
Hours
100
90
80
70
60
50
40
30
20
10
Jan.
Feb.
March
April
May
June
July
Aug.
Sept.
Oct.
Nov.
Dec.

FIGURE 46

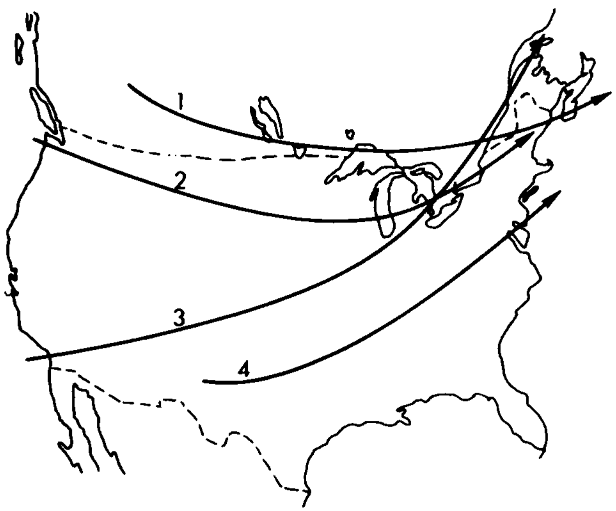
polar front is formed by the temperature contrast provided by the difference in air-mass properties between polar continental and tropical maritime sources. Most of the cyclones affecting eastern North America are generated on this front, and some extend west into the Great Lakes region. The Pacific arctic front often extends itself inland, and storms generated to the east of the Canadian Rockies on this front provide the major disturbances in the Lake region (Alberta lows (1), Fig. 47A). Cyclones developed on the Pacific polar front tend to weaken as they cross the Rocky Mountains, but they frequently redevelop on the east side (North Pacific lows (2) and South Pacific-Colorado lows (3), Fig. 47A) and converge towards the Great Lakes. Texas lows ((4), Fig. 47A) are generated in a similar way and frequently travel into the lake region.

Analysis of weather maps (NOAA, Daily Weather Maps, 1974) revealed that of the storms observed on Lake Erie during the field period, three were Alberta lows, one a North Pacific-Colorado low, and one a South Pacific-Texas low (Appendix I tabulates the relevant information). Four of the five observed storms passed to the north of Lake Erie. Consequently, the observed wind direction on the south shore of Lake Erie rotated from south (offshore) through west-southwest (along the axis of the lake) to northwest during the passage of the storm (Fig. 47C). When the low pressure center is close to the lake, the winds over the lake are generally out of the west-southwest, causing the simultaneous occurrence of miximum wind velocity and maximum fetch. The circulation pattern and frontal locations associated with the most severe storm to hit Lake Erie during the observation period are shown in Figure 48 . By analyzing the charts for a few days prior to June 9, it is

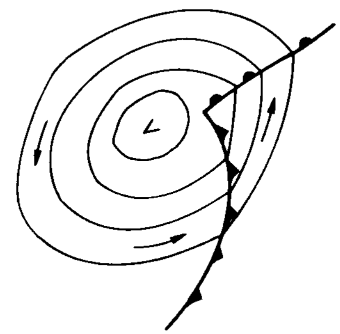
Figure 47. A. Major North American cyclone tracks. Most eastward moving cyclones, regardless of their western area of generation, are focused on the Great Lakes with the most frequent track being to the north of Lake Erie. Data from Goode's World Atlas (1970) and Petterssen (1969).

B. Generalized cyclonic circulation. The geostrophic wind pattern is controlled by equilibrium between the pressure gradient and the Coriolis force.

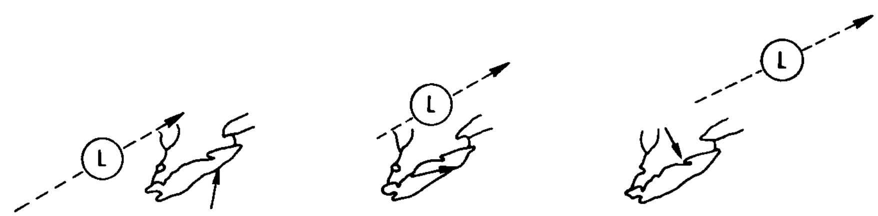
C. Variations in wind direction on Lake Erie with passage of a typical cyclone. The change in wind direction from south through west to northwest is caused by the lake experiencing different sectors of the wind field during the cyclone passage.



A. Major Cyclone Tracks
1. Alberta
2. North Pacific
3. South Pacific - Colorado
4. Texas



B. Generalized Cylonic Circulation



C. Variations in Wind Direction on Lake Erie With Passage of a Typical Cyclone

FIGURE 47

Figure 48. Synoptic charts at 24 h intervals for storm of June 9-June 13, 1974. The storm was generated in Texas and crossed the Great Lakes near Sault St. Marie about 2 days later. The wind direction over Lake Erie typically changes from south through west during passage of the storm. Data from NOAA (1974).

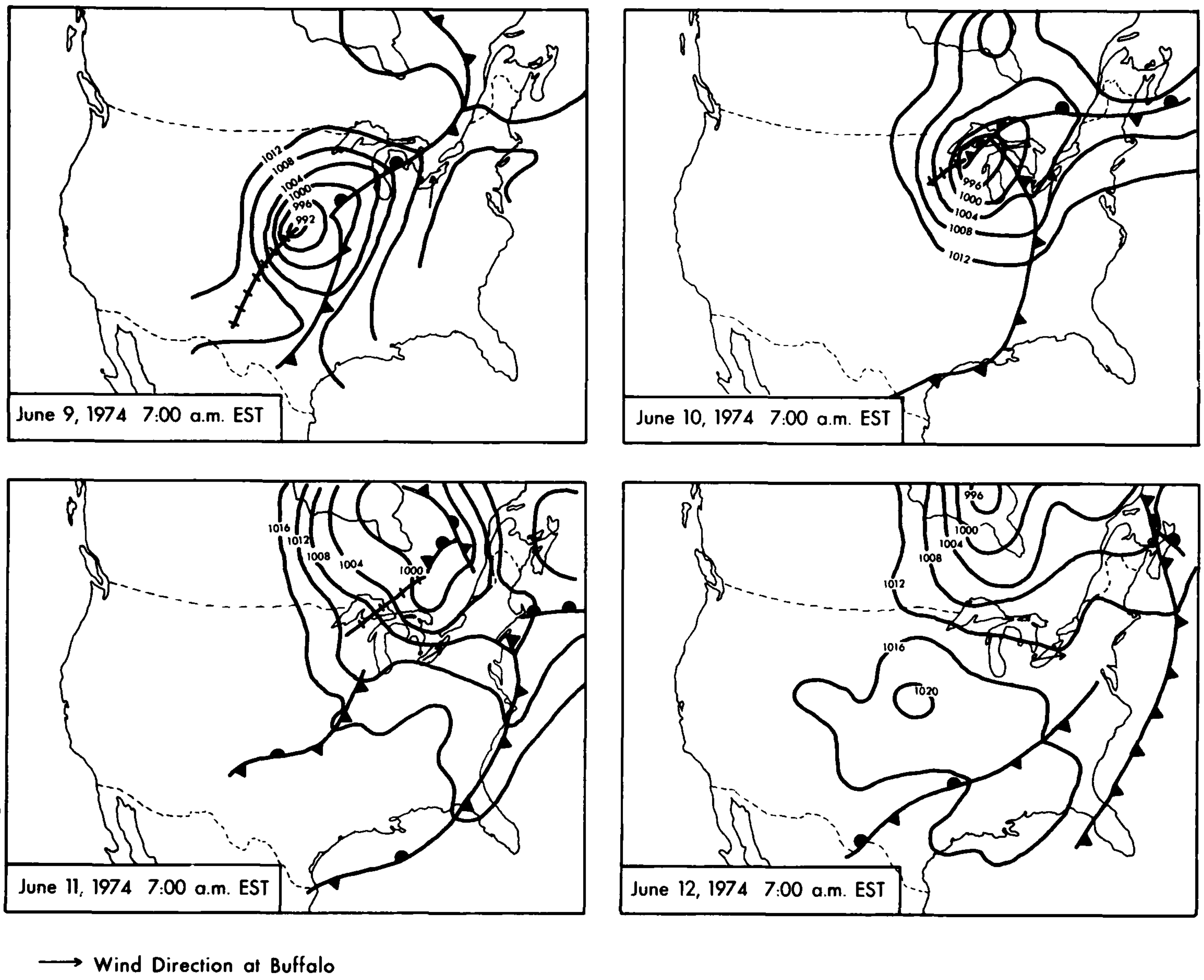

1012
1008
1004
1000
996
992
June 9, 1974 7:00 a.m. EST
996
1000
1004
1008
1012
June 10, 1974 7:00 a.m. EST
1016
1012
1008
1004
1000
June 11, 1974 7:00 a.m. EST
996
1000
1004
1008
1012
1016
1020
June 12, 1974 7:00 a.m. EST
Wind Direction at Buffalo

FIGURE 48

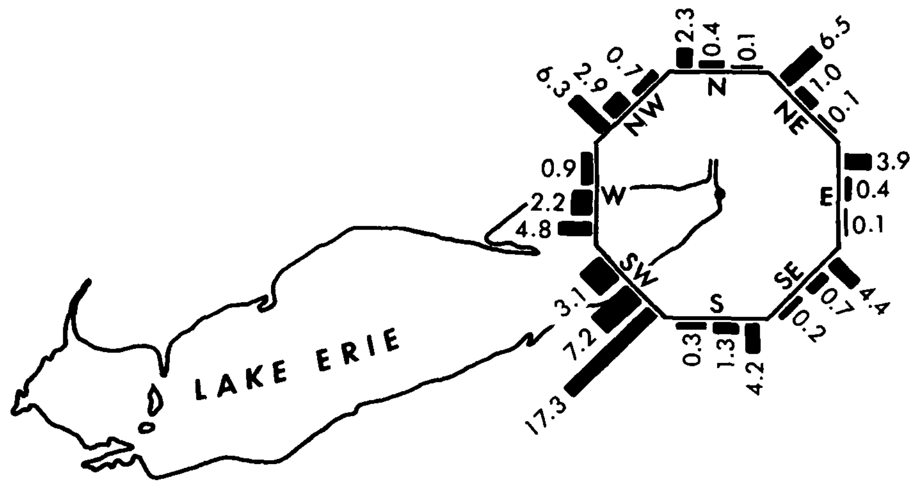
seen that the storm is a typical South Pacific-Texas low. A regenerated low formed in north Texas on June 7 and migrated northeastward to cross the Great Lakes near Sault St. Marie on June 10. Maximum wave height was observed on Lake Erie in the early morning hours of June 11 after a night of westerly winds (map, June 10, Fig. 48) with speeds of 15 to 20 knots. During the passage of the storm the wind changed from south (offshore) on June 7 and 8, through south-southwest on June 9 and 10, to west-southwest during the waning stages of the storm.

Anticyclonic circulation around a high pressure center to the north of Lake Erie occurred on May 11 (high over Ontario) and May 19-20 (high over James Bay). Typically, the wind directions are easterly. The wind velocities are low, however, in comparison to the cyclonic circulation, and longshore current velocities remain small.

6.2. Wind and wave statistics.

The analysis of North American synoptic situations indicated a dominance of westerly winds over Lake Erie. The wind observations at Buffalo Airport (Fig. 49) demonstrate that during 27.6 per cent of the year the wind blows from the southwest over an ice free lake, and for an additional 7.9 per cent of the year winds are out of the west. These figures compare to 35.8 per cent of the year with winds out of any other direction and ice free lake. It should be pointed out that wind conditions over the open lake are not identical to those at Buffalo because of the difference in surface friction over land and water. Reduced friction over the lake will increase wind speed and make the wind more nearly geostrophic, i.e. parallel to the isobars. With the low pressure centers passing north of the lake, this

Figure 49. Wind diagram for Buffalo, New York. The diagram demonstrates the dominance of winds blowing along the axis of the lake from the southwest. The winds over the open lake are more nearly geostrophic because of the lower friction over the water. Consequently, a wind diagram for the open lake would have somewhat stronger westerly and northerly components.



Wind Diagram For Buffalo, N.Y.

0-12 MPH

13-24 MPH

>25 MPH

Velocity Scale

Figures at ends of bars indicate per cent of total wind duration for the ice-free period.

FIGURE 49

implies a stronger northerly component in the lake wind than what is recorded at Buffalo.

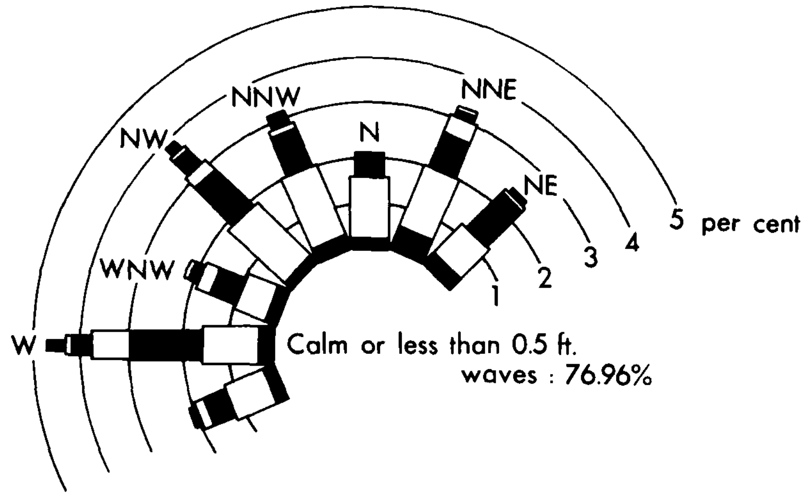
Continuous wave observations of a duration of one year or more are not available for Lake Erie. To evaluate deep water wave approach directions and energies, therefore, one has to resort to wave hindcasting. Of the existing methods, Cole (1967) concluded that the Sverdrup-Munk-Bretschneider wave hindcast method based on surface winds obtained from the geostrophic wind analysis produced the best correlation with observed data on the lakes. Wave hindcasting has been performed for three of the Great Lakes, including Lake Erie (Saville, 1953). Rather than using the geostrophic wind analysis, however, Saville used the recorded surface winds at coastal stations. The additional inaccuracy this introduces into the computations cannot be evaluated. It is the belief of these authors that Saville's approach may underestimate the northerly component in his wave diagrams (Fig. 50) for reasons stated above. The implications will be discussed further below.

Saville hindcast wave conditions for Monroe, Cleveland, Erie, and Buffalo. Wave and wave energy diagrams for Erie and Buffalo are presented in Figures 50and 51respectively. The location of Buffalo at the eastern end of the lake effectively eliminates fetch from any directions but southwest through west. At Erie, on the contrary, substantial fetch exists in all directions from west-southwest through northeast. It is further observed that a fair correlation exists between fetch length and relative annual wave energy from that direction. Westerly waves dominate, however,

Figure 50. Wave diagrams for Erie, Pa., and Buffalo, N. Y. The frequency of waves from each direction is related to the relative fetch length. Erie, therefore, experiences waves from almost a 180 degree sector, whereas Buffalo has significant waves from a sector of about 60 degrees. The highest waves at Erie (76 feet) come out of the west. Data from Saville (1953).

WAVE DIAGRAMS

ERIE, PA.



BUFFALO, N.Y.

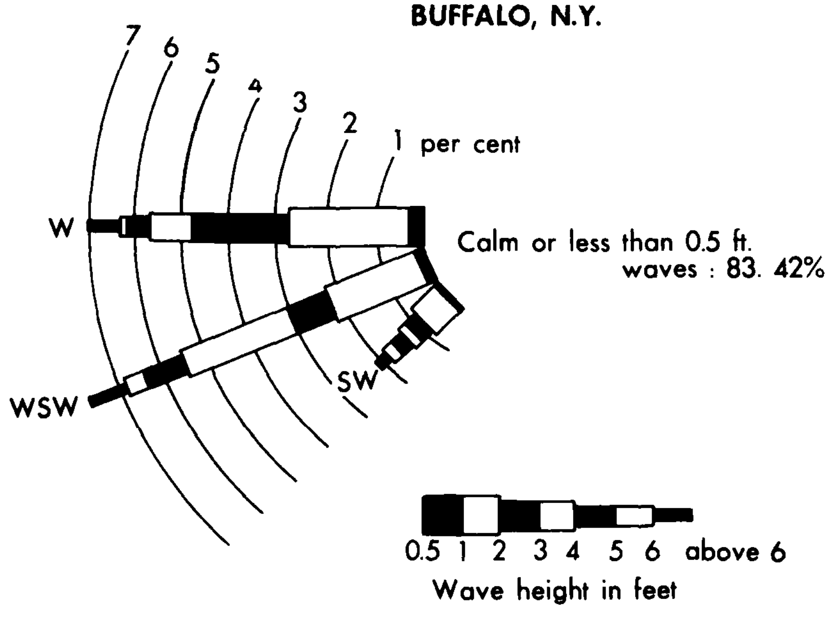


FIGURE 50

Figure 51. Wave energy diagrams for Erie, Pa., and Buffalo, N. Y. Wave energy flux from each direction correlates well with fetch length. Therefore, for any location on the Lake Erie shoreline between Erie and Buffalo an approximate wave energy diagram can be found by constructing a fetch diagram for that location (see Fig. 53B). Data from Saville (1953).

WAVE ENERGY
in $10^8 \ \frac{\text{ft. lb.}}{\text{ft. yr.}}$

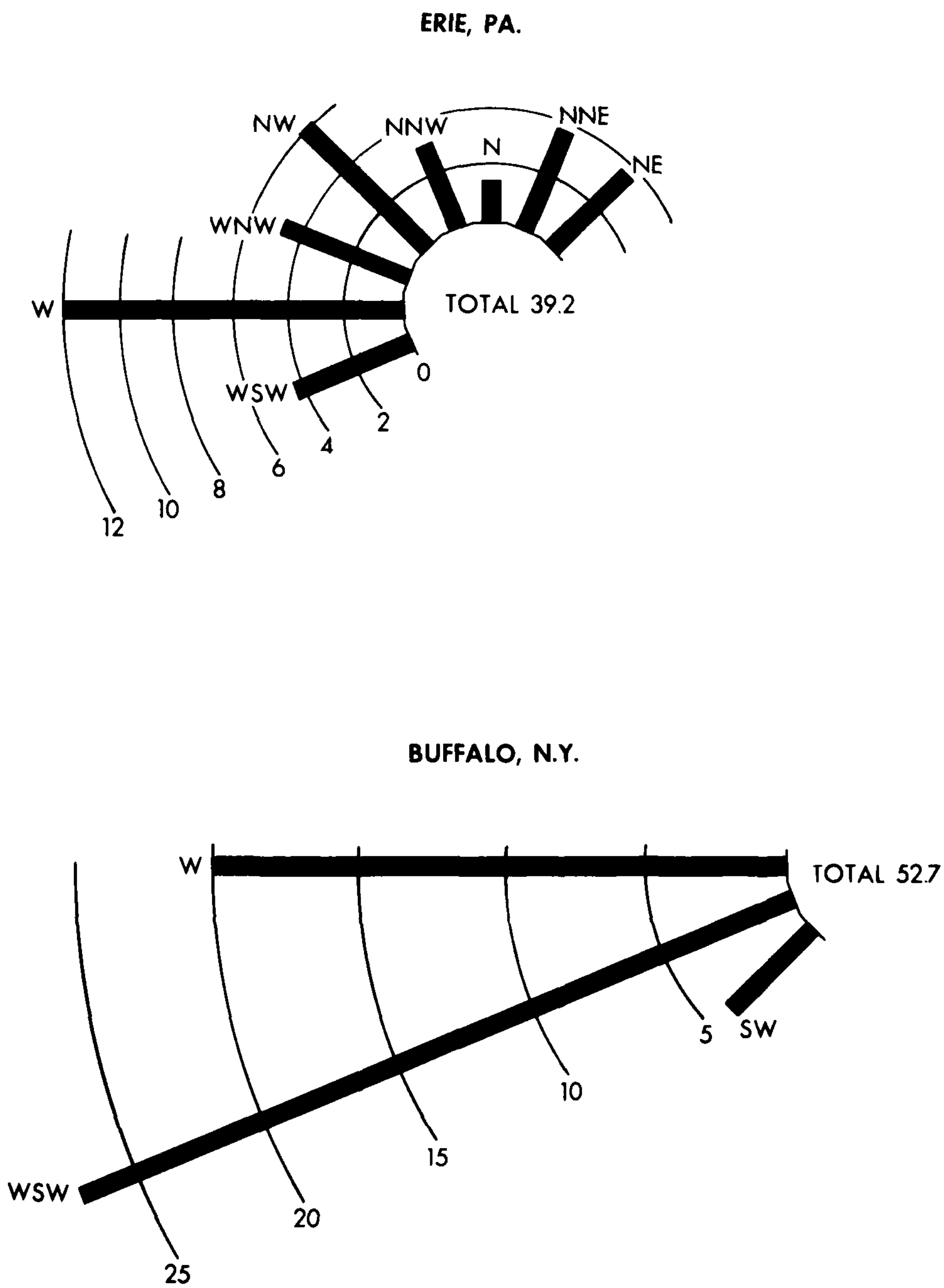


FIGURE 51

more than proportional to their associated fetch length, because of the nature of the cyclone migrations described above.

A wave diagram can be derived for the Cattaraugus Embayment by interpolation of the data in Figures 50 and 51 (Saville, 1953, p. 3). The accuracy of the resultant diagram is unknown. Therefore, only a qualitative interpolation will be attempted. The Cattaraugus Embayment is likely to receive annual wave energies from the west-southwest and west intermediate in value between those at Erie and Buffalo. The northwest fetch is about half of that at Erie, the north fetch about the same, and the northeast fetch is reduced to about one-third. With these approximate interpolations one finds that about 75 per cent of the total deep water wave energy flux approaches the Cattaraugus Embayment from the west and west-southwest. Of the remaining 25 per cent about 10 per cent enters the embayment from west-northwest and northwest and therefore approaches normal to a major segment of the Cattaraugus beach. Only about 15 per cent of the wave energy flux arrives from the north or northeast at an angle sufficient to cause substantial southward oriented littoral currents. The fetch diagram in Figure 53B approximates the wave energy distribution discussed above.

6.3. Littoral processes at Sunset Bay.

Despite the relatively short time coverage of our sampling program, the synoptic situations and consequent wave conditions encountered seem to give a fair representation of year round conditions, with the possible exception of some major fall or early spring storms.

Data on longshore current velocity, angle of breaker crest relative to shore, period and height of breaker, and wind speed and direction were obtained at 12 hour intervals at Station Cat. 3 (see Fig. 53C for location). Station Cat. 3 was judged "characteristic" of the beach south of Cattaraugus Creek for moderate wave energy conditions like the ones observed in May and June of 1974. For high wave energy conditions the site is sheltered by shoals in the southern part of the embayment and off the Silver Creek headland. The data are summarized in Figure 52 and tabulated in Appendix II.

During passage of Alberta lows to the north of Lake Erie, the longshore currents are consistently to the north. The speed of the current correlates more closely with the breaker angle than with the breaker height. A typical example is provided by lake conditions on May 15 and 16. The storm was generated by a cyclone migrating from Wisconsin to James Bay. On the morning of May 15, the longshore current was moving to the north at a speed of 1.7 fps at a wave height of 1.7 feet and a breaker angle relative to shore of 18°. A slight drop in both wave height and breaker angle occurred during the day, reducing the evening current velocity to about 1.4 fps. During the passage of the May 9 storm, the current velocity reached only 1.4 fps for a wave height of 3.3 feet. Because of the increased refraction these higher waves reached the shore at a 5 degree angle, causing the lower current velocity. An even better example is provided by the June 11-13 storm. Wave height decreased from 3.3 feet to 1.2 feet in 24 hours. This was accompanied by an increase in breaker angle from 0 to 12 degrees and an increase in current velocity from 0.2 to 0.9 fps. Wind speed and direction were approximately constant during this time. High longshore current velocities seem

Figure 52. Process parameters at Cattaraugus Beach, Cat. 3, May 7-June 13, 1974. Longshore current velocity is closely correlated with breaker angle, period, and height. Maximum wave energies are encountered during periods of persistent westerly or southwesterly winds. The wind reported here was measured at the same site on the beach where the other process measurements were obtained. Water level was recorded at a staff gage at Keene Marina, about 500 feet upstream of the mouth of Cattaraugus Creek.

PROCESS PARAMETERS AT CATTARAUGUS BEACH, CAT 3
MAY 7 - JUNE 13, 1974

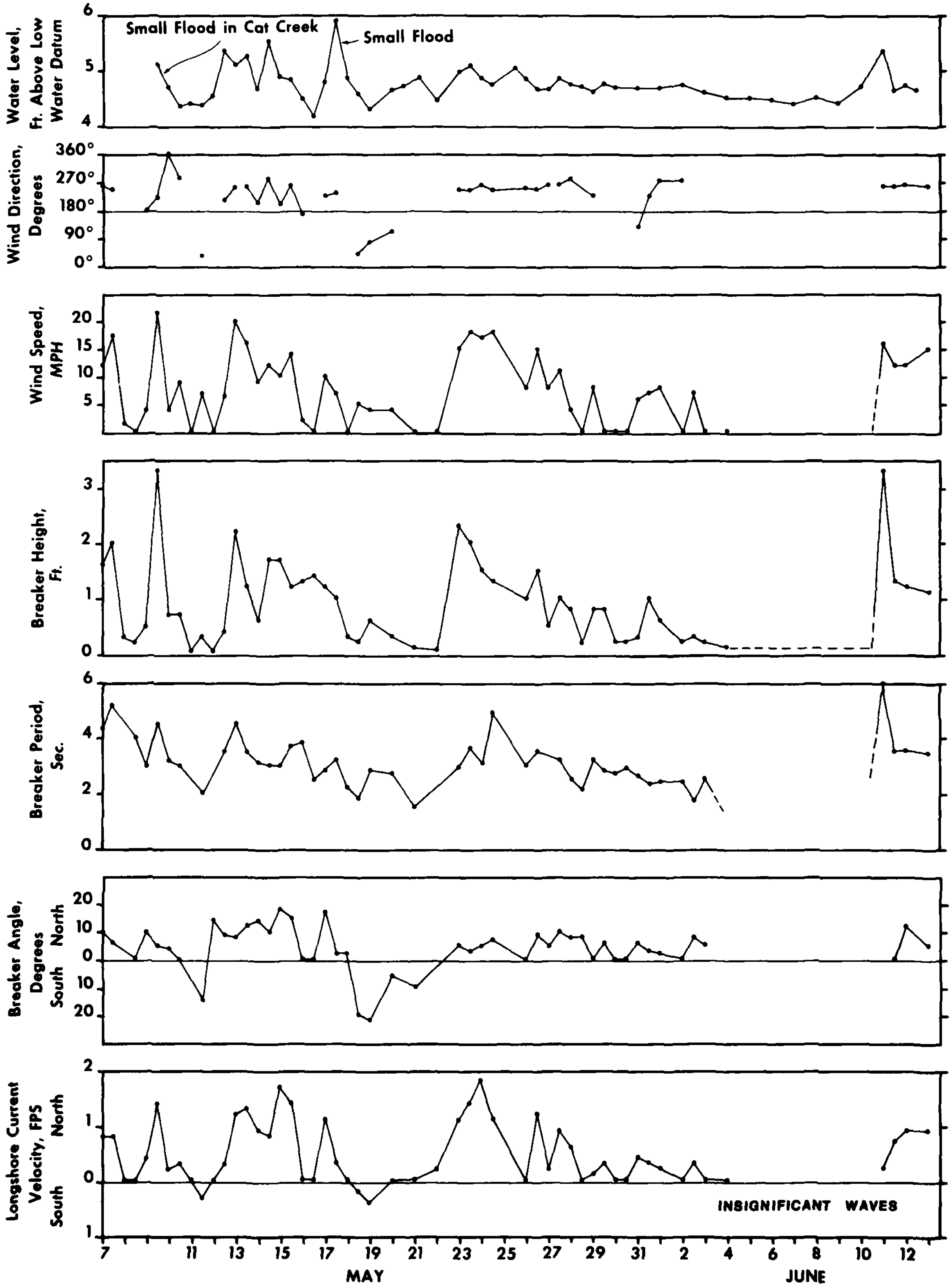


FIGURE 52

to be associated with moderate waves approaching the shore at a steep angle and a period of 3 to 4 seconds. Southerly longshore currents occur, as on May 19 and 20, associated with anticyclonic circulation around a high pressure system north of the lake. Rarely, however, is the anticyclonic circulation strong enough to generate any major waves. Cyclones passing to the south of the lake will also generate southerly currents in the Cattaraugus Embayment, but these cyclones are rare, and none occurred during the field period.

With the passage of a cyclone north of the lake the wind generally rotates from south through west to north, e.g. storm of May 8-9 or June 10-12. Quite frequently, the most intense winds during a storm passage blow parallel to the lake axis, i.e. out of the west-southwest or west. The shear stresses at the air-water interface cause a downwind rise in water surface elevation. Because the deep water return flow is ineffective in the shallow Lake Erie (average depth 50 feet), even moderate storms can produce wind tides of many feet at the eastern end of the lake. Hunt (1959) calculates that 25 mph southwesterly winds may generate a 2 to 3 foot lake level rise at Buffalo (the exact value depends on atmospheric stability). A near maximum difference in recorded water levels between Buffalo and Toledo of 13.2 feet occurred during gale force winds on November 3, 1955. NOAA's Lake Survey Center (1973) has published water level diagrams for recent major storms. These show that a seiche of a period of 12-18 hours and a duration of 2-3 days generally follows a major wind tide. The wind tides in the Cattaraugus Embayment are expected to be similar to the ones at Buffalo (Hunt, 1959, Fig. 10 , p. 29).

The wind tides observed in the Cattaraugus Embayment during the field period were not high, and some coincided with flood discharges in Cattaraugus Creek. This made it difficult to determine the exact wind tide because the staff gage is located in the river channel. The high water levels observed in the period May 13 through May 17 (Fig. 52), however, are primarily wind tides. The 12 hour fluctuations in stage probably reflect lake seiches. The .8 foot rise in water level during the strong June 11 storm is solely a wind tide, as the creek discharge did not increase at all.

The existence of significant tides on Lake Erie creates conditions similar to many oceanic shorelines where astronomical tides of a similar range are operative. These short-term fluctuations in water level superimposed on seasonal and long-term water level variations add to the complexity of the harbor entrance sedimentation patterns as discussed below. Furthermore, high wind tides, often coincident with high discharges in Cattaraugus Creek, will raise the downstream control of the river and increase the hazards of flooding in the Sunset Bay area.

6.4. Wave refraction.

The deep water waves approaching the Cattaraugus Embayment refract with a pattern of change dependent upon bottom topography. Wave refraction computations performed by the U. S. Army Engineer District, Buffalo (1966, Plates D-1 and D-2), demonstrate that 7 second waves approaching from the west start refracting at about 50 feet of depth, i.e. 2 miles offshore, and approach the shoreline almost perpendicularly. The shoal extending lakeward between profiles Cat. 2 and Cat. 3 (Fig. 53C) was found to cause a concentration of wave energy flux at about Cat. 3. The wave orthogonals are also in this

Figure 53. A. Location map of the Cattaraugus Embayment.

B. Fetch diagram. Bar lengths are proportional to the fetch length in that direction. Linear scale in arbitrary units.

C. Wave refraction diagram. 4 second waves out of the west-southwest, typical of the conditions responsible for a majority of the sediment transport, were chosen for study. The refraction diagram is constructed by methods outlined in CERC Tech. Rept. No. 4 (1966). Bathymetry is from USGS 15' quadrangle map, with 6 foot contour.

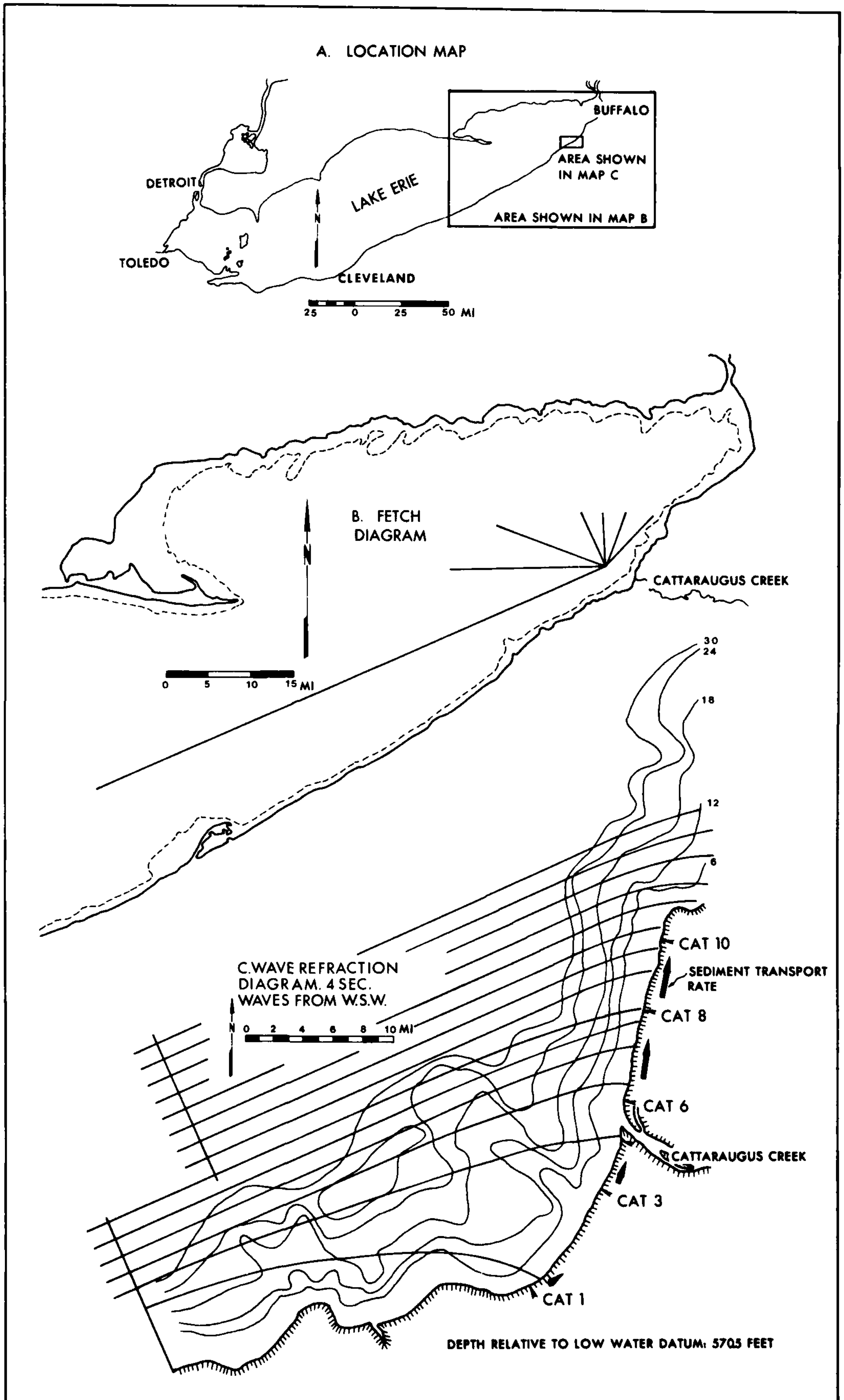

A. LOCATION MAP
BUFFALO
AREA SHOWN IN MAP C
DETROIT
LAKE ERIE
N
AREA SHOWN IN MAP B
TOLEDO
CLEVELAND
25 0 25 50 MI
B. FETCH DIAGRAM
N
CATTARAUGUS CREEK
0 5 10 15 MI
30
24
18
12
6
CAT 10
SEDIMENT TRANSPORT RATE
C. WAVE REFRACTION DIAGRAM. 4 SEC. WAVES FROM W.S.W.
N
0 2 4 6 8 10 MI
CAT 8
CAT 6
CATTARAUGUS CREEK
CAT 3
CAT 1
DEPTH RELATIVE TO LOW WATER DATUM: 570.5 FEET

FIGURE 53

case approximately normal to the shore.

Waves of 7 second period or more out of the west, however, account for only a small percentage of the total annual wave energy flux. Furthermore, their high refraction coefficients make these waves relatively inefficient in longshore sediment transportation. Most efficient are probably the 3 to 5 second waves which occur for a much higher percentage of time and approach the shoreface at a steeper angle because they are subject to less refraction.

To determine a typical pattern of process variability and sediment transportation within the Cattaraugus Embayment, wave refraction was performed on 4 second waves approaching the embayment from the dominant direction, west-southwest. The surface wave rays were traced in accordance with the method outlined in Coastal Engineering Research Center, Technical Report No. 4 (1966, p. 65-67).

Significant wave refraction begins at a depth approximately equal to half of the wavelength. Consequently, the 30 foot contour was chosen for beginning refraction in this study. The principal result of this wave refraction study (Fig. 53C) is the uneven distribution of wave energies along the shoreline of the Cattaraugus Embayment. The steep lake bottom slope off the northern beach causes a relatively small wave refraction, whereas the extensive shoals off Silver Creek cause high divergence of the wave energy flux approaching the southern section of the shoreline. The angle between the arriving wave rays and a line orthogonal to the beach is high at Cat. 8 through Cat. 10 and near Cat. 1, in the former case because of relatively little refraction, in the latter because of the westerly curvature of the beach. At the central section of the embayment, the waves are expected to approach shore almost perpendicularly. The rate of littoral sediment transportation is a function of the product of the wave energy flux and the approach angle. The wave refraction diagram, therefore, predicts that for a moderate storm from the west-southwest a relatively high transport rate exists at the northernmost beach, a low rate at the central section, and an intermediate rate in the Hanford Bay area. The relative length of the solid arrows in Figure 53 intends to portray this pattern.

A wave refraction pattern for a northeasterly storm has not been determined yet, but the process variability within the embayment is expected to be much less because the Silver Creek shoals will play no significant role.

6.5. Observed process variability in the embayment.

Data on longshore current velocity, angle of breaker crest relative to shore, and period and height of the breaker were obtained on a daily basis at six stations representing the entire embayment. The data are tabulated in Appendix II, and the station locations are shown in Figures 53C and 54.

For the three westerly storms studied in detail, May 14, May 24, and June 11, a repetitive pattern is observed (Fig. 54). The angle of wave incidence is relatively high (10-15 degrees) at Cat. 1 and from Cat. 8 to Cat. 10. At Cat. 3, 5, and 6 the waves approach almost perpendicularly to shore. Invariably, the waves are higher on the northern beach than on the southern. An unexpectedly high value was observed at Cat. 6 on June 11.

The consequent variability in longshore current velocity follows closely the general pattern of sediment transport rates outlined in paragraph 6.4. The highest current velocities are observed at the northernmost part of the beach, low current velocities are observed near the creek mouth, and intermediate

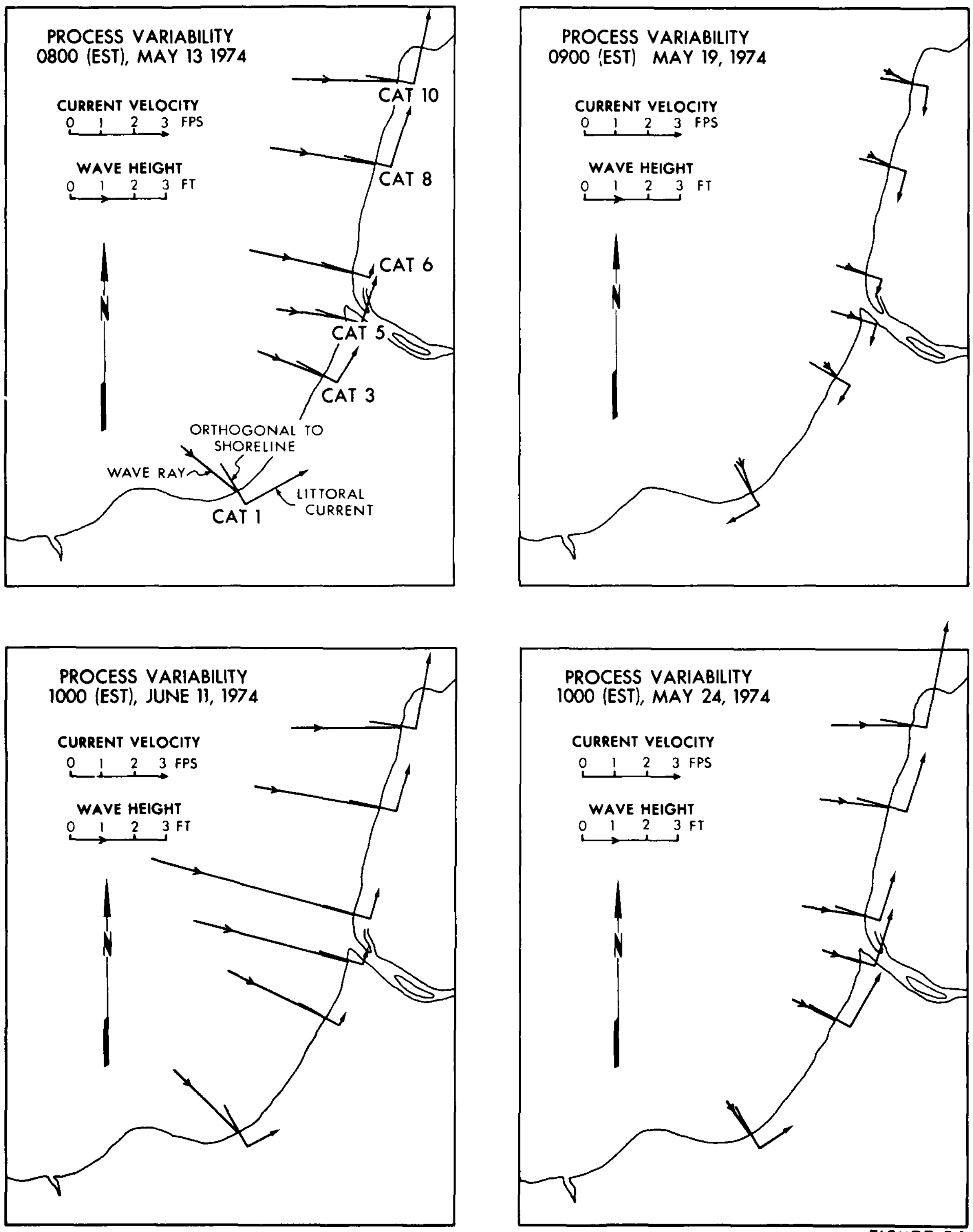
Figure 54. Process variability in the Cattaraugus Embayment. For each of the six stations monitored three process parameters are shown. Wave height is proportional to the length of the onshore arrow, angle of approach is the angle between the orthogonal to the shoreline and the wave ray, and longshore current velocity is proportional to the length of the arrow parallel to shore. Three southwesterly storms and one northeasterly storm are shown.

A. May 13, 1974. Southwest storm.

B. May 19, 1974. Northeast storm.

C. May 24, 1974. Southwest storm.

D. June 11, 1974. Southwest storm.


PROCESS VARIABILITY
0800 (EST), MAY 13 1974
CURRENT VELOCITY
0 1 2 3 FPS
WAVE HEIGHT
0 1 2 3 FT
N
CAT 10
CAT 8
CAT 6
CAT 5
CAT 3
ORTHOGONAL TO SHORELINE
WAVE RAY
LITTORAL CURRENT
CAT 1
PROCESS VARIABILITY
0900 (EST) MAY 19, 1974
CURRENT VELOCITY
0 1 2 3 FPS
WAVE HEIGHT
0 1 2 3 FT
N
PROCESS VARIABILITY
1000 (EST), JUNE 11, 1974
CURRENT VELOCITY
0 1 2 3 FPS
WAVE HEIGHT
0 1 2 3 FT
N
PROCESS VARIABILITY
1000 (EST), MAY 24, 1974
CURRENT VELOCITY
0 1 2 3 FPS
WAVE HEIGHT
0 1 2 3 FT
N
FIGURE 54

velocities are observed in Hanford Bay (Cat. 1). In the application of these data in the structure design (paragraph 10) it will be assumed that, to a first approximation, the rate of sediment transportation is related directly to the longshore current velocity, as has been suggested (Komar, 1971).

Although it is possible at this stage to proceed with a quantitative estimation of volume rate of littoral sediment transportation, this has not been performed. It is our firm belief that the relatively poor state-of-the-art of sediment load computations is likely to produce results that might be orders of magnitude wrong. Consequently, a numerical value of sediment transport rates might introduce bias into the assessment of factors relevant in the structure design.

Surface suspended sediment samples were obtained during the storm of June 11, 1974. The determined sediment concentrations are listed in Appendix VII.

No significant flood was observed in Cattaraugus Creek during the field period. Data which would be meaningful in a quantitative estimate of fluvial sediment supply, therefore, were not available. Suspended sediments were sampled with a depth-integrated sampler (DH-48) during a moderate flood in May, 1974. The data are presented in Appendix VIIB, for comparison with the surf zone sediment concentration data.

7. SEDIMENT SOURCES AND DISPERSAL PATTERNS

7.1. Sediment sources.

Potential sources for the sediment on the beach or in the nearshore of the Cattaraugus Embayment include: 1) Cattaraugus Creek, 2) Silver Creek headland and pocket beaches beyond, 3) Lotus Point and pocket beaches beyond, and 4) offshore sources. To evaluate, independently of the collected process data, the relative importance of each of these sources, the characteristic lithologies of each of the sources were compared to the lithologic composition of the beach gravels.

1) The Cattaraugus Creek drainage basin includes late Devonian and younger shales, siltstones, and sandstones (Tesmer, 1963). From Versailles to upstream of Gowanda the river has cut a gorge, many hundred feet deep, into the Gowanda Shale (Plate 1). This shale is adequately represented on channel bars in the gorge. Because of its loose consistency, however, it does not survive long distance transport. The point bars immediately downstream of the gorge (Plate 2), therefore, are characterized by a very high percentage of siltstone, derived from thin silt beds within the Gowanda Shale, and red sandstone, possibly from outcrops of the Medina Sandstone. Granite and other crystalline rock fragments, as well as quartzite and some chert, are derived both from till units and ancient beaches representing post-Wisconsinan high stands of Lake Erie (Hough, 1958). These components contribute about 80 per cent siltstone and sandstone, 10 to 15 per cent crystalline rocks, and a few per cent dark shale to the gravel bed material of the stream.

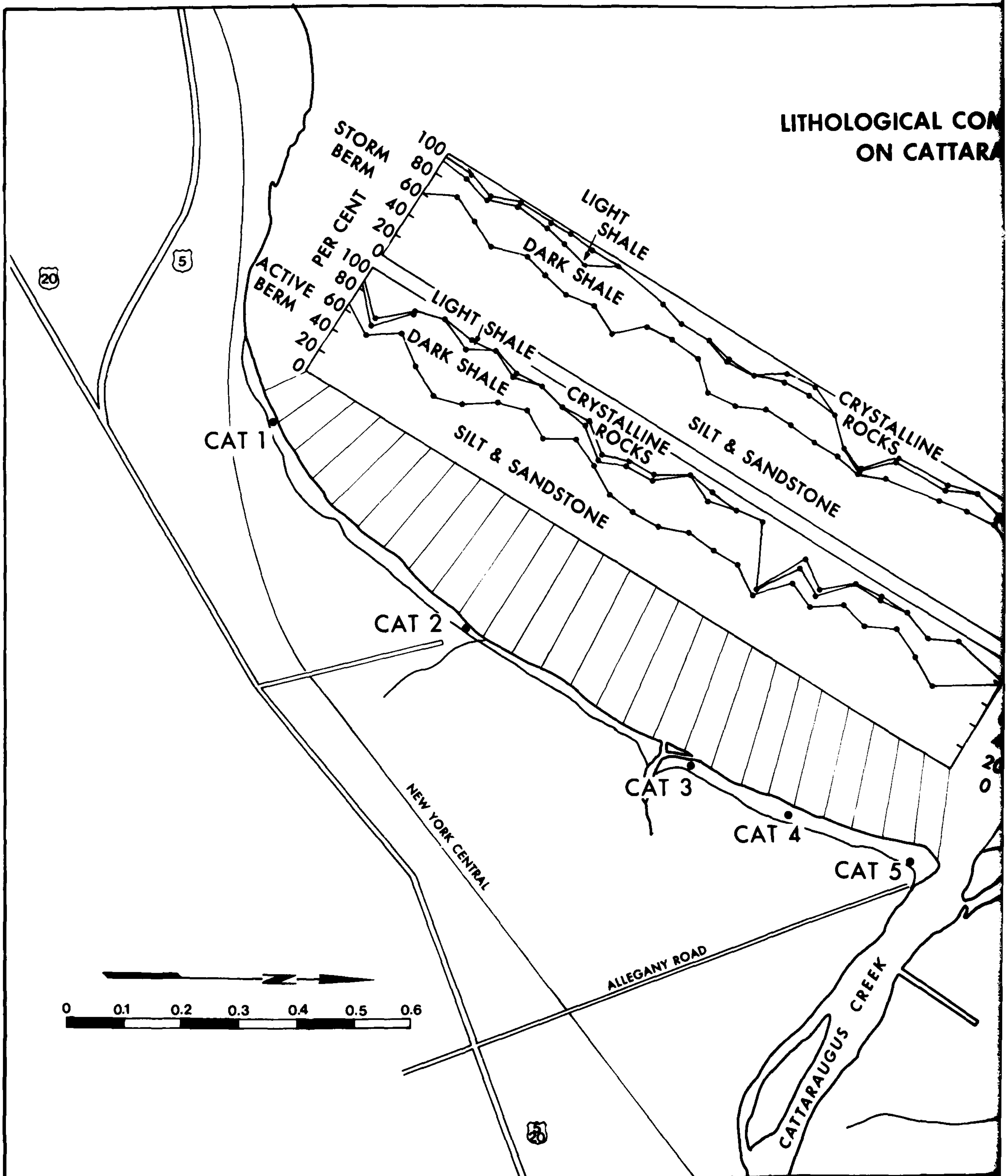
Sampling of the lower reaches of Cattaraugus Creek, between the last point bar at the U. S. 20 bridge and the lake, was done only on a reconnaissance basis, with about 20 samples obtained. This sampling demonstrated that gravel of the size and composition typical of the upstream point bars exists on the bottom throughout the lower channel. The gravel was buried by a few inches of mud during summer slack water in the river. Floods of a few thousand cfs, however, are probably capable of moving this material. It is concluded that Cattaraugus Creek is a prime contributor of siltstone, sandstone, and crystalline rock fragments to the embayment and its beaches.

2) The upland drainage basin of Silver and Walnut creeks, draining into Silver Creek Bay, is much smaller than the Cattaraugus Creek watershed. There are two other important differences. First, Silver and Walnut creeks are cut deeply into the Hanover Shale (Tesmer, 1963) practically all the way to their mouth, in contrast to Cattaraugus Creek, which flows through a broad alluvial valley. Second, the creeks cut through the highly resistant Pipe Creek member of the Hanover Shale, a black shale unit which can survive long distances of littoral or fluvial transportation. In contrast to the mouth of Cattaraugus, therefore, the mouth of Silver Creek and the adjoining pocket beach are dominated by shale, predominantly dark shale (Appendix III, Fig. 55B). The Pipe Creek Shale also outcrops all along the Silver Creek headland west of Cat. 1. From the top of the 20-30 foot vertical shale cliff, about 10 feet of till contributes various crystalline rock fragments, quartzite, and chert into the littoral drift system of the Cattaraugus Embayment.

3) The shale cliffs of Lotus Point are lower and much less extensive than

Figure 55. A. Lithological variations in Cattaraugus Beach gravel. Data based on pebble counting of the active berm and high-level storm berms at each sample station. The lithologies are grouped in categories representative of the sources.

B. Characteristic lithologies of the source materials. Silver Creek headland and the embayment supply black resistant shale derived from the Pipe Creek member of the Hanover Shale. Cattaraugus Creek supplies predominantly siltstone and sandstone, and till-units and high-level beaches supply crystalline rock fragments.



LITHOLOGICAL COM
ON CATTARA
STORM BERM
ACTIVE BERM
PER CENT
100
80
60
40
20
0
LIGHT SHALE
DARK SHALE
CRYSTALLINE ROCKS
SILT & SANDSTONE
CAT 1
CAT 2
CAT 3
CAT 4
CAT 5
NEW YORK CENTRAL
ALLEGANY ROAD
CATTARAUGUS CREEK
5
20
N
0
0.1
0.2
0.3
0.4
0.5
0.6

AL COMPOSITION OF GRAVEL
CATTARAUGUS BEACHES

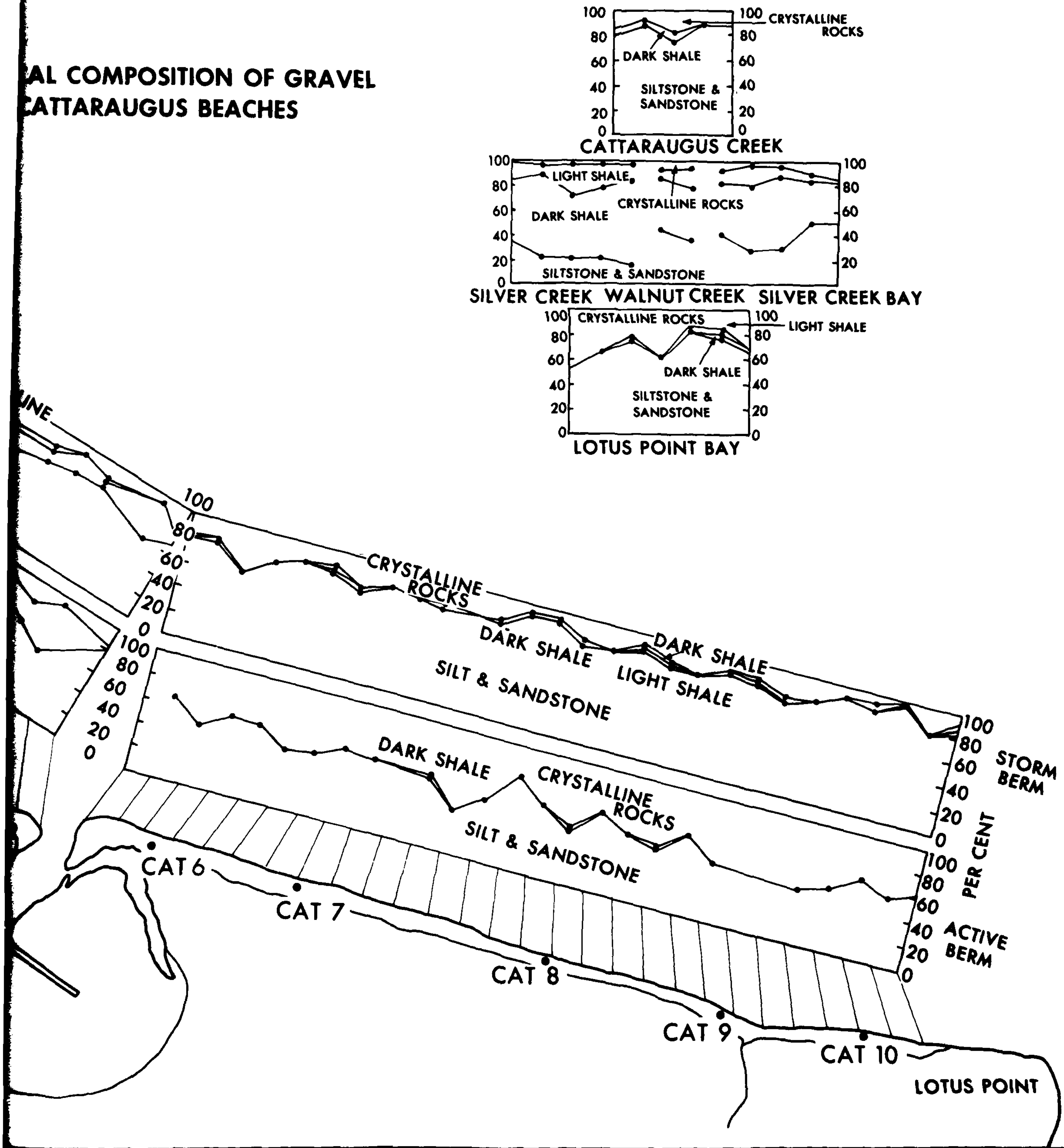


FIGURE 55

the Silver Creek headland. Furthermore, the dark and resistant Pipe Creek member of the Hanover Shale is not exposed at this locality because of the southerly dip of the strata. Consequently, Lotus Point plays an insignificant role in the overall sediment budget of this section of the lake shore.

A shallow (0.5-2 ft deep) gravel bench follows the base of the Lotus Point cliffs all around the headland. Currents of up to 2-3 fps moving north and east around the headland were measured during westerly storms generating 3-4 foot waves at the cliff base. Clearly, this current is fully capable of moving gravel from the northernmost beach of the Cattaraugus Embayment around the point and into Lotus Bay. It is to be expected that the pocket beaches at Lotus Point (Plate 3) and Lotus Bay have the lithologies typical of the north Cattaraugus beach, i.e. 60-80 per cent siltstone and sandstone, 15-40 per cent crystalline rocks and a minor fraction of shale, both dark and light.

4) The contribution from offshore sources is difficult to assess, but it is expected to be small for the following reasons. The only gravel deposit in the embayment is just off the mouth of Cattaraugus Creek (Fig. 57A) and is clearly fluvially supplied. Second, the generally fining offshore sequence from coarse (or medium) sand into lake muds seems not to favor any significant landward sediment transport. Third, there is no observed gravel lithology or sand minerals on Cattaraugus beach which cannot be accounted for by the sources already discussed.

With this knowledge of source materials and locations, the sediment distribution on the Cattaraugus beach and in the embayment should now tell the general pattern of sediment dispersal.

7.2. Beach sediments.

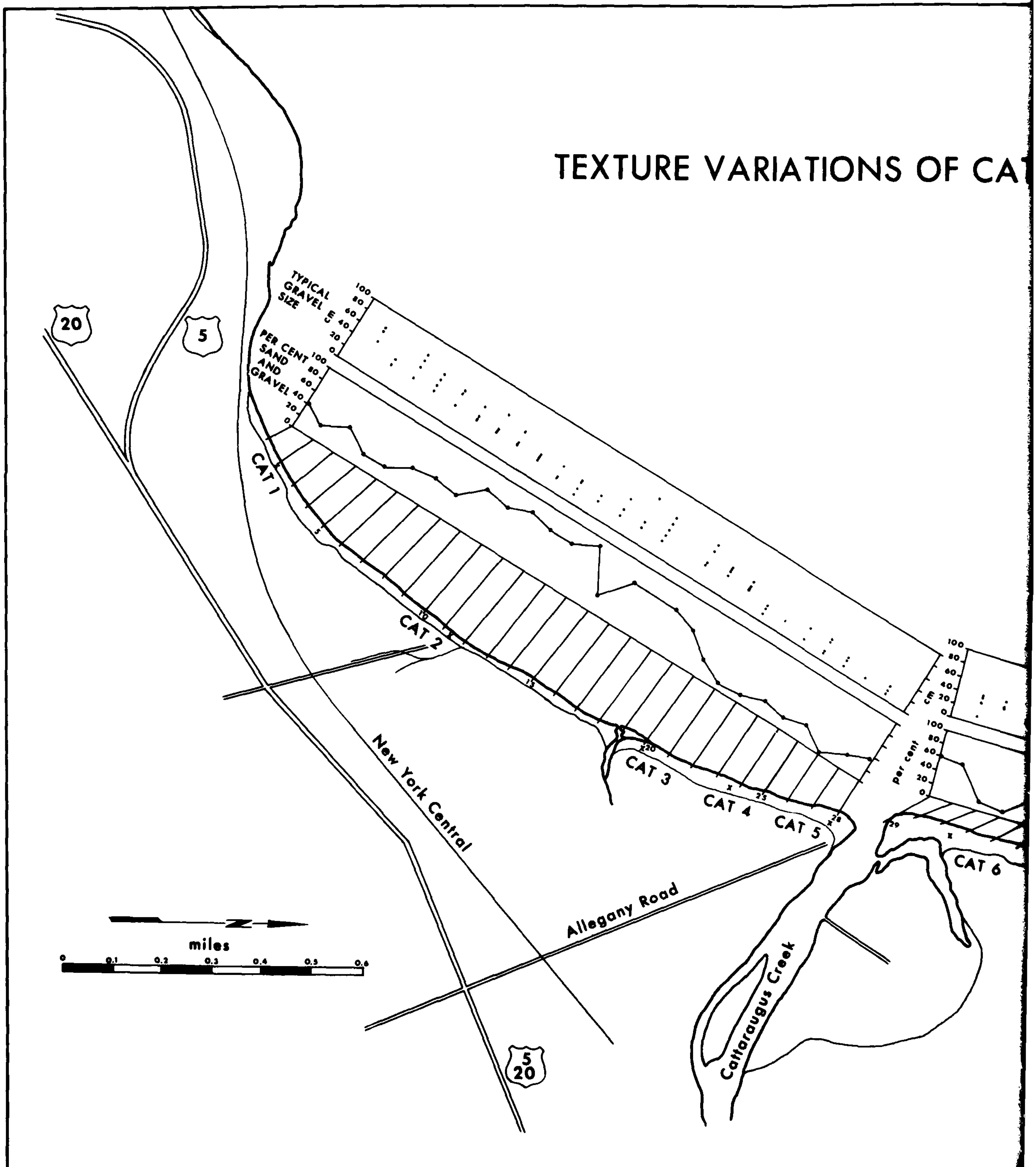
Lithology and texture of the beach sediments were analyzed with the hope of detecting trends that would lead to discovery of dominant transport patterns. The lithological variations in the Cattaraugus beach gravels are tabulated in Appendix III and graphically displayed in Figure 55A. The texture of the beach sediments together with an explanation of the methods used in sampling and computation are listed in Appendix IV and graphically displayed in Figure 56.

The lithological composition of the berm active on the day of sampling or of a high level storm berm was based on a determination of the lithology of each clast which fell exactly on each 20 centimeter mark on a 10 meter long tape laid parallel to the berm crest. Thus, 50 clasts at each berm were sampled at 55 sample stations spaced about 250 feet apart along the entire beach.

The lithological pattern on the Cattaraugus beach shows an interesting relationship to the lithologies of the creek derived material and the lithologies of the western source areas, Silver Creek and Silver Creek headland. The percentage of dark shale at the southern portion of Cattaraugus beach, about 40 per cent, is just a little higher than at the northernmost part of Silver Creek beach, where black shale accounts for 30 to 40 per cent of the gravel. This black shale decreases in significance northward to less than 5 per cent at Cat. 5. Two interesting minima exist at the southern beach. At about Cat. 2 and Cat. 3, the black shale percentage drops to less than five. The crystalline rock category reaches maxima at the same two locations. The

Figure 56. Texture variations in Cattaraugus Beach gravels. The gravel percentage refers to the areal coverage of gravel measured along a narrow strip from the step to the seawall or dune ridge. Typical gravel size measures the size of the most dominant fraction (primary mode) within each homogenous zone on the beach. Se Appendix IV for details.

TEXTURE VARIATIONS OF CA



VARIATIONS OF CATTARAUGUS BEACHES

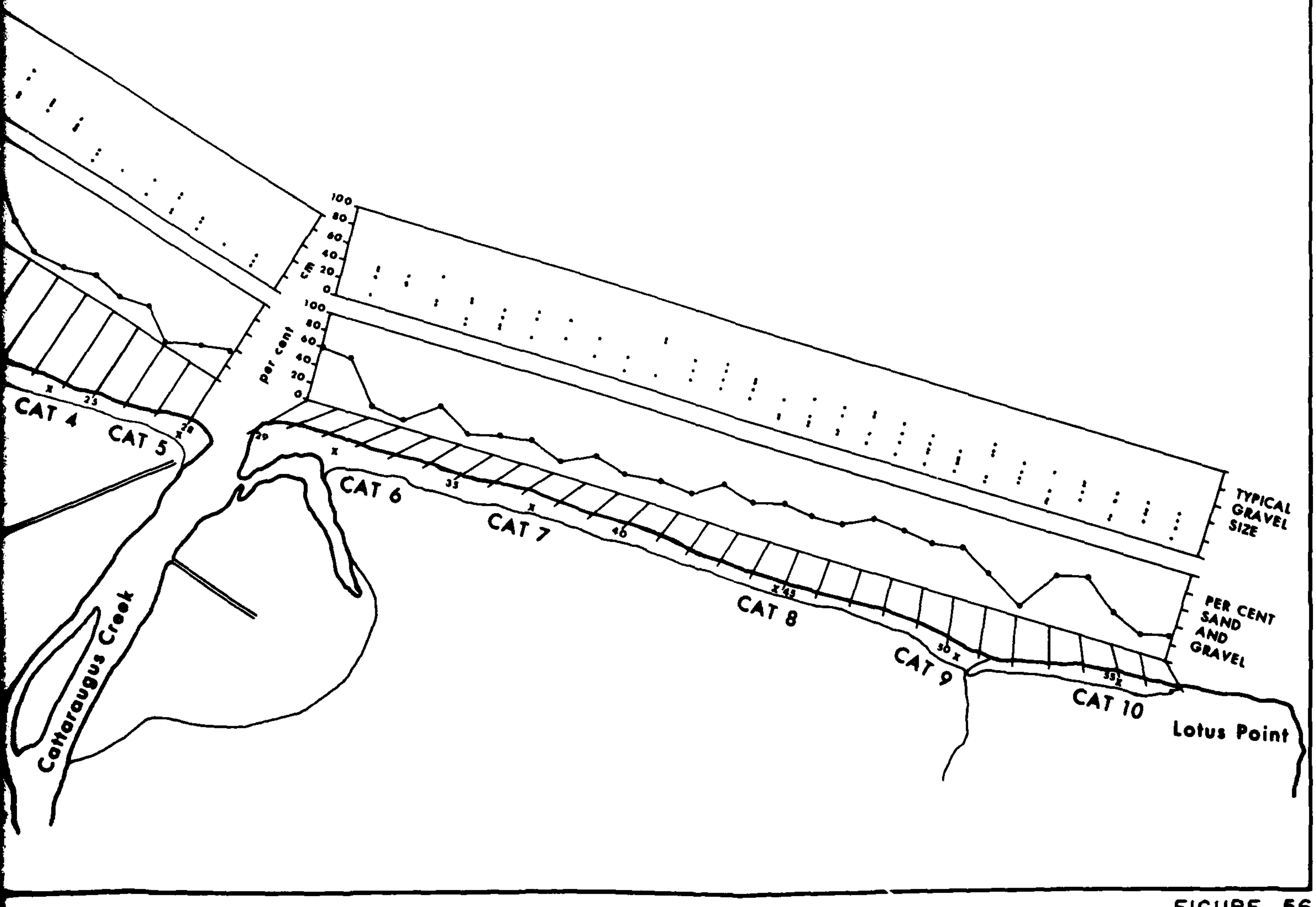


FIGURE 56

siltstone plus sandstone fraction is high all along the beach and reaches its most dominant proportion, about 80 per cent, near the mouth of Cattaraugus Creek.

On the section of beach north of Cattaraugus Creek, the black shale is all but gone, the sandstone plus siltstone fraction remains as high as to the south, and the crystalline rock fraction is very dominant, accounting for 40 to 60 per cent of the total gravel population.

The high level storm berm shows the same general pattern, but the siltstone plus sandstone fraction remains higher throughout. The storm berms sampled undoubtedly represent different time units at different sample stations. Therefore, whether one samples a time unit, as in the case of the active storm berm, or time-transgressive units, as in the case of the multiple storm berms, the pattern remains essentially the same. The sediment, accordingly, represents the long-term average of the processes which have brought it to its sample location. Correlation between the transport patterns derived by process measurements and by lithologic analysis, therefore, provides the best test of the long-term representativeness of the obtained process data.

The sediment patterns described above strongly suggest a dominant transport northward from the Silver Creek headland towards Cattaraugus Creek and further northward towards and past Lotus Point into Lotus Bay. Apparently, shale fragments of gravel size do not pass the creek mouth, but sand undoubtedly does. Cattaraugus Creek is an important source of materials for both the northern and southern beaches, although the largest amount of fluvial sediment feeds the northern beaches. During occasional reversals in transport direction, fluvial material is brought south and ultimately reaches Hanford Bay (Cat. 1). Because of the sheltered location for storms from the west, this area tends to be one of net shoreline accretion. There is no evidence that Lotus Point adds any sediment to the system. During periods of southerly transport, however, local redistribution of sediment on the north beach occurs, causing a net southward displacement of the entire sediment population. Under natural conditions with unrestricted wave impact on the entire north beach, this displacement is quickly reversed during the next westerly storm. The net displacement has to be northward, because there is no northerly sediment source!

The evidence contained in the textural composition of the beach sediments (Fig. 56) is more difficult to interpret. The texture at any one station is a function of the typical wave energies at the station, the distance of transport of the different sediment fractions, and the resistance of each fraction to mechanical attrition. To separate out one of these factors and try to interpret its variability from the aggregate data is difficult. However, some observations seem to be valid. The gravel percentage is relatively low at Cat. 1, increases to a high of 80 per cent at Cat. 2, stays high to about Cat. 3, and then decreases rapidly to the mouth of Cattaraugus Creek. The northern beach shows less dramatic variation in gravel percentage. It is relatively low from Cat. 6 to almost Cat. 8, then remains relatively constant at 40 to 50 per cent to Lotus Point, with the exception of the drop to 10 per cent at the wide beach associated with the creek north of Cat. 9.

The most obvious correlation with gravel percentage is beach width.

The narrow beaches are found between Cat. 2 anb Cat. 3 and relatively narrow beaches at about Cat. 8 (Plate 4). At some of these locations the beach face terminates directly at a seawall. With no back beach present, there is no room for sand storage. The narrow beaches consist solely of gravel berms.

Basically, the factor just discussed is the wave energy. The pattern resulting from another important factor, distance from source, is superimposed on the wave energy pattern. The only clearly recognizable trend here is the low gravel percentage between Cat. 3 and the mouth of Cattaraugus Creek, reflecting the high sand supply to this segment of the beach.

7.3 Nearshore sediments.

Bottom sediments were sampled by a modified Petite Ponar grab sampler[1] at about ten locations on the extension of each beach profile line between the swash zone and the 20-foot contour. A theodolite, positioned at the adjacent beach profile location, determined the boat position at each sample station. The samples obtained were bagged, numbered and subjected to granulometric analysis at the University of South Carolina sedimentation laboratory. The sand fraction was analyzed in a settling tube (Anan, 1972). The less than 62μ fraction was wet-sieved off the original sample and subsequently subjected to pipette analysis (Folk, 1968).

The resultant size distribution pattern is shown in Figure 57A. An inset map of the embayment bathymetry is included for reference (Fig. 57B).

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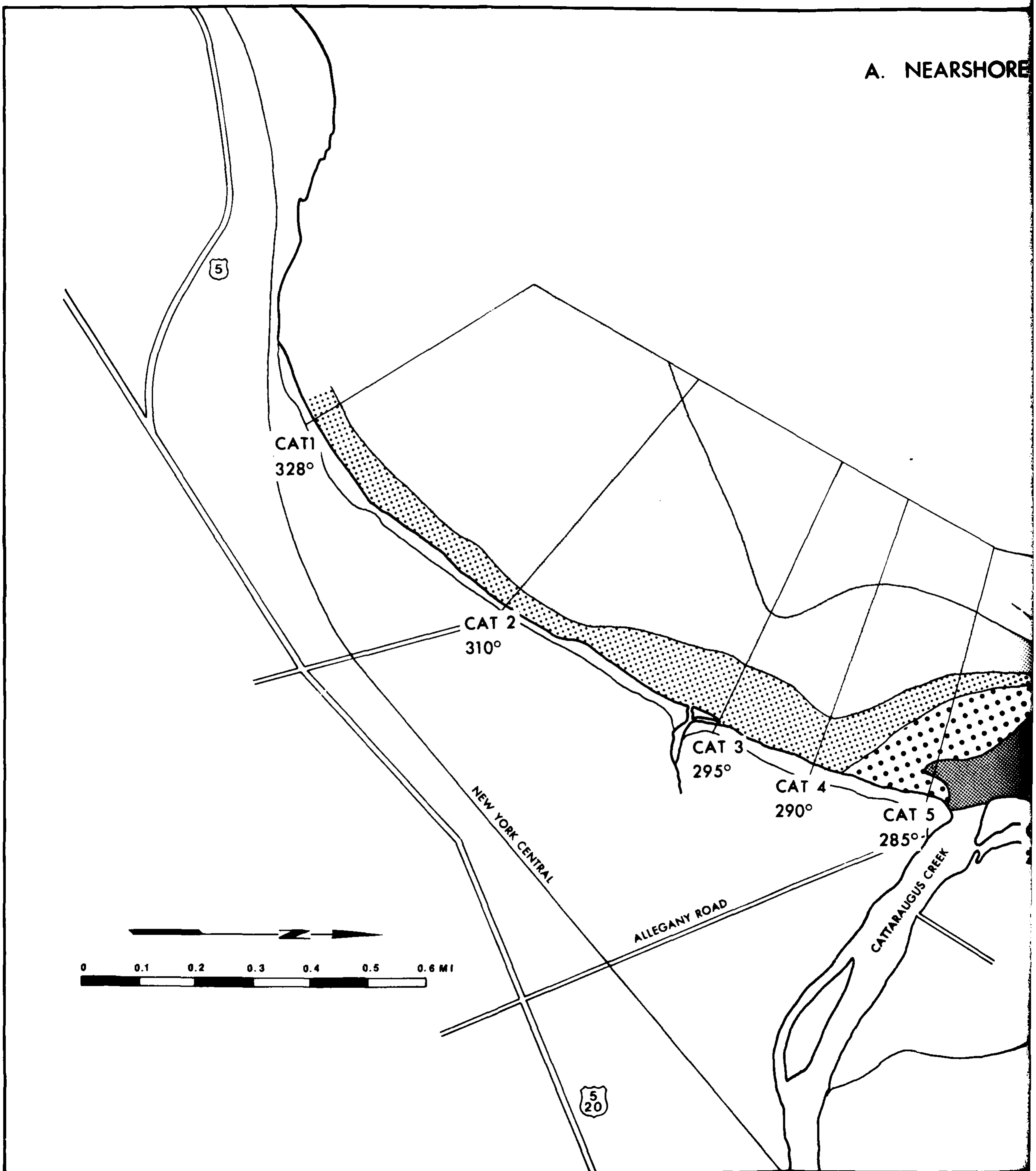
[1]The modified grab retains all fine materials within the sample during transport through the water column.



A. NEARSHORE
CAT1
328°
CAT 2
310°
CAT 3
295°
CAT 4
290°
CAT 5
285°
5
NEW YORK CENTRAL
ALLEGANY ROAD
CATTARAUGUS CREEK
N
0 0.1 0.2 0.3 0.4 0.5 0.6 MI
5
20

NEARSHORE SEDIMENT DISTRIBUTION
JUNE 1974

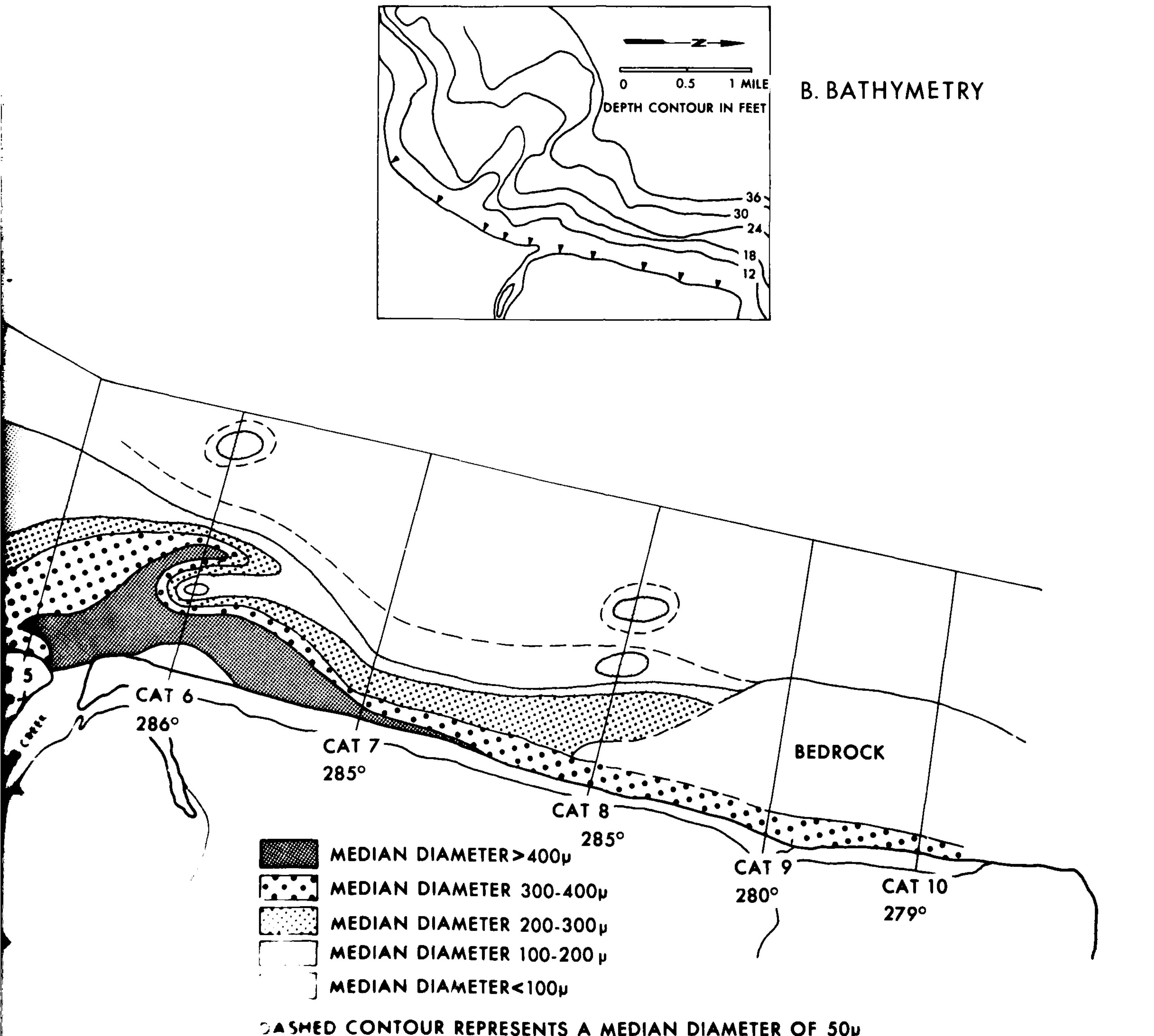


FIGURE 57

The overall trend is a fining offshore sequence from medium sand near shore to lake muds with a median diameter in the coarse silt range characterizing the bottom at the 20 foot depth contour. Great variations in this generalized pattern can be observed. A coarse sediment bulge, deflected to the north, characterizes the lake shore near the mouth of Cattaraugus Creek. Part of this bulge is a major gravel bar trending northwest or north across the creek mouth as a continuation of the southern beach. The nature of this bar will be analyzed in detail in a subsequent section.

At the time of sampling low river discharge and low wave energies had prevailed for about two weeks. Fine grained sediments, generally transported further offshore, had, therefore, been deposited on the lakeward side of the "delta" front. These fines probably form a continuum into the zone of similarly sized materials extending northward parallel to the shore.

The steep gradient of the northern lake bottom is associated with a much more rapidly fining offshore sequence than the flat bottom of the southern embayment.

The distribution pattern of the nearshore sand is somewhat easier to interpret than the beach gravel pattern. Wave energy and directions of the wave generated currents are the controlling factors. Kinetic wave energy, to a first approximation, is a function of water depth. Low wave energies and consequent finer sediment accumulations are associated with the deeper parts of the embayment. Note, for example, the close correlation between the 100μ size contour and the 18 foot depth contour (Figs. 57 A and B).

The deflection of the coarse sediment bulge demonstrates the net northward flux of wave energies capable of transport of gravel and coarse sand. Sand is also transported southward, as the Cattaraugus Creek must have been the ultimate source of the sand in Hanford Bay. The sand must be transported southward close to shore and spread out onto the shallow platform of Hanford Bay, because no sand transport is possible across the steep, north facing escarpment extending lakeward between Cat. 2 and Cat. 3.

8. COASTAL MORPHOLOGY

8.1. Beach profiles.

The shoreline morphology is a direct function of 1) wave energy distribution, 2) nature and quantity of sediment supply, and 3) littoral processes of sediment transportation. In the preceding paragraphs these factors have all been analyzed in some detail. Here we present shoreline morphological data that demonstrate the response of a natural unmodified beach to the dominant littoral processes.

Three sets of morphological data were collected during the field period: 1) beach profiles, for monitoring of changes in beach width, steepness, and micromorphology; 2) maps of the active spit at the south bank of Cattaraugus Creek, for determination of shape and rate of growth; and 3) maps of sediment waves on the northern beach, to delineate their pattern of movement, if any.

Ten profile stations were established along Cattaraugus beach. The profiles were measured bi-weekly except during the first week of June, when wave action remained insignificant for a week. The profiles were measured by a procedure established by Emery (1961). All the recorded profiles are presented in Appendix VI. Profile locations, labeled Cat. 1 through Cat. 10, are shown on most of the preceding maps.

The most noticeable trend in beach character is the drastic steepening of profiles just north of Cattaraugus Creek. Figure 58A shows the profiles at Cat. 5 and Cat. 6 superimposed for May 10 and during the storm on June 11. More typical for the north and south beaches, respectively, are profiles Cat. 7 and Cat. 3, superimposed for the same two days in Figure 58B. Plates 5 and 6 show ground photographs of the two profiles during and after the June 11 storm.

Figure 58. A. Beach profiles Cat. 5 and Cat. 6 superimposed for May 10 and June 11.

B. Beach profiles Cat. 3 and Cat. 7 superimposed for May 10 and June 11.

In both figures the profiles are adjusted to the same water level for easy comparison of steepness. The steep profiles of the northern beach as compared to the southern are apparent, as is the abrupt steepening of the northern beach during the June 11 storm.

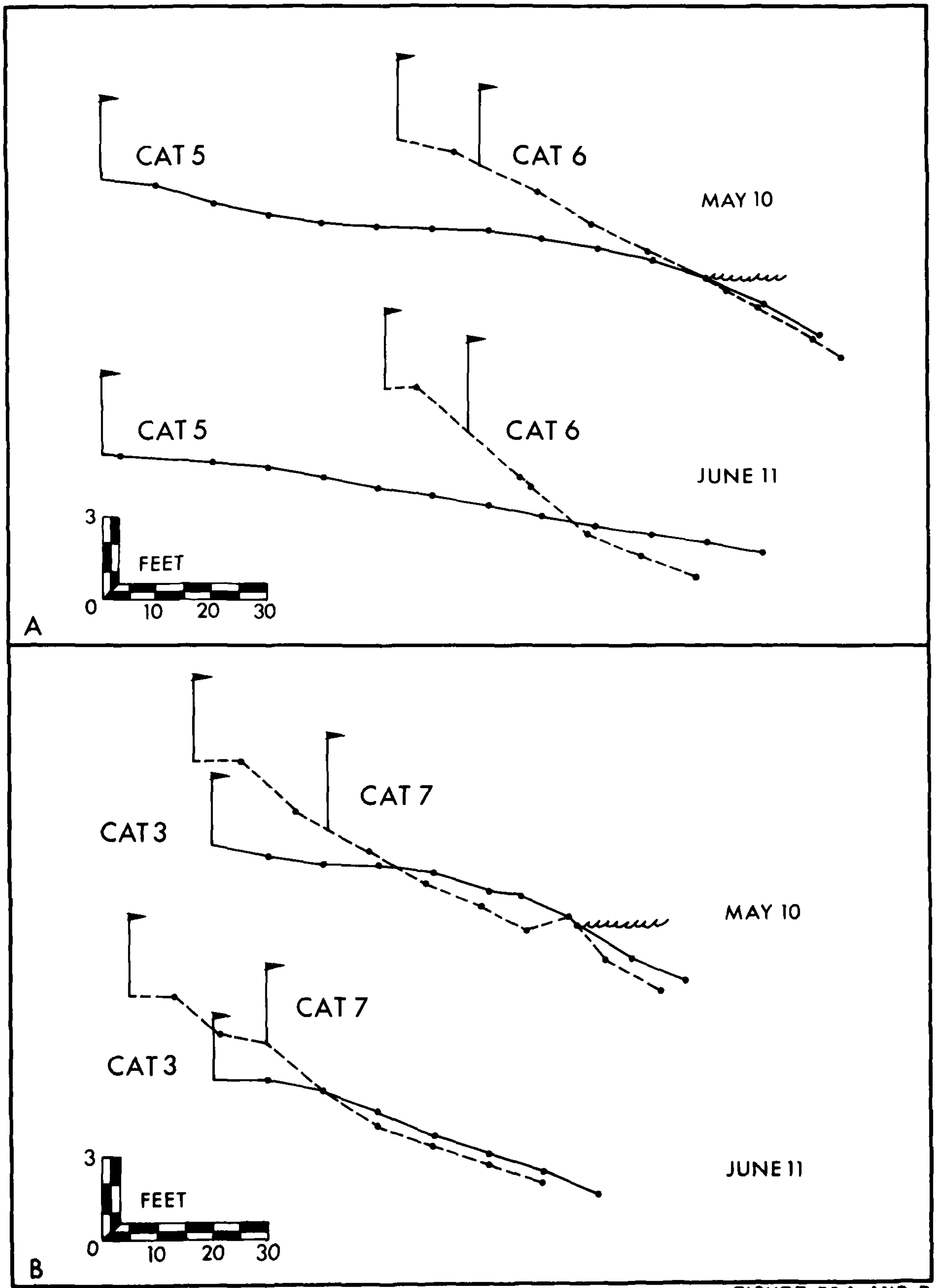


FIGURE 58A AND B

The higher wave energies affecting the northern beach because of the steeper lake bottom profile are thought to be the prime factor causing this difference. Two of the beach profiles, Cat. 4 and Cat. 5, demonstrate significant lateral accretion during the field period (Fig. 59). Upon a close examination of the beach profiles, supplemented by observations while in the field (Plates 7 and 8), this lateral accretion was found to result from the landward migration of nearshore sand bars during constructional wave conditions. During destructional wave conditions the accreted berm is eroded, and the sand is temporarily stored in the nearshore.

The theory has been suggested (Dyhr-Nielsen and Sörensen, 1970) that waves breaking on the nearshore sloping plane will generate secondary bottom currents directed towards the breaker line. This will have an accumulating effect on the sediment particles, moving them towards the breaker line where they build up a bar. Offshore of the bar the current is directed landward; inshore it is directed seaward. The bar height is controlled by maintenance of an equilibrium between the amount of sand transported upward by bottom currents and the amount of sand returned in suspension at the bar crest. "Constructional" waves are those that pass the bar without breaking, causing a net shoreward current. This onshore current erodes the bar crest and provides the beach with material for accretion. The close interaction between sediment transportation and deposition on the nearshore bar system and the beach has been recognized both on oceanic shores (Hayes, 1972) and the shorelines of the Great Lakes (Bajorunas and Duane, 1968; Davis, et al., 1972). The fact that shallow water sand bars exist just south of the mouth of

Figure 59. Beach profiles Cat. 4 and Cat. 5 on May 7, June 11, June 12, and June 13. Each profile has the preceding one superimposed. The dark pattern shows deposition and the light pattern shows the erosion which has taken place in the time interval. Note the characteristic pattern of beach profile change associated with the storm of June 11: deposition on the back beach, erosion of the gravel berms, deposition and progradation at the step.

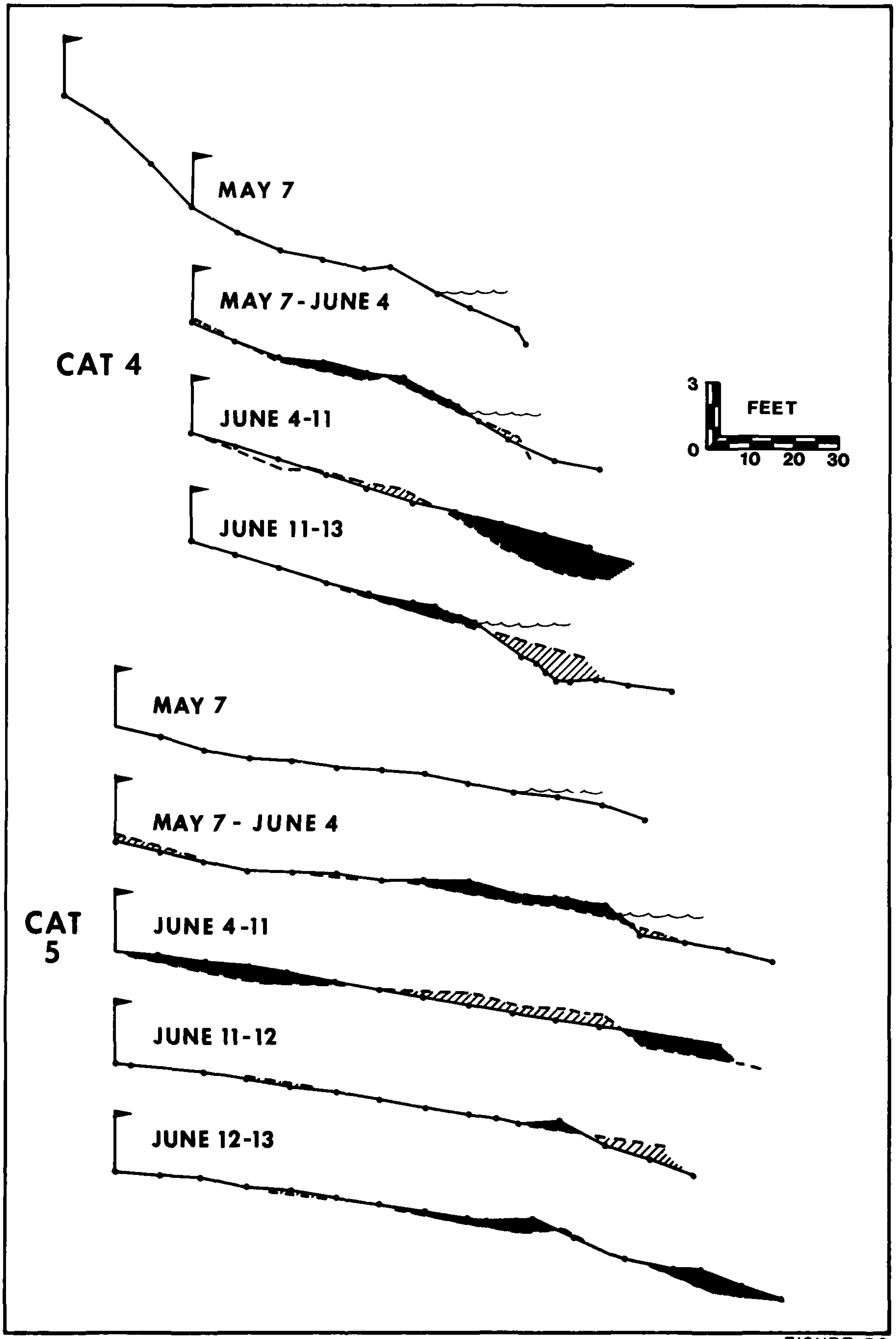

MAY 7
MAY 7 - JUNE 4
CAT 4
JUNE 4-11
JUNE 11-13
3
FEET
0
10
20
30
MAY 7
MAY 7 - JUNE 4
CAT 5
JUNE 4-11
JUNE 11-12
JUNE 12-13

FIGURE 59

Cattaraugus Creek might create additional shoaling problems between the planned harbor breakwaters, both because of the potential lakeward displacement of the bar(s) as a consequence of the erected breakwaters and the high rate of littoral suspended sediment transportation over the bar crest. The severity of the problem will be discussed in the comprehensive structure analysis below.

The dramatic change in beach profile during a moderate storm, like the one observed on June 11, illustrates the very transient nature of the micromorphology of the beach. Because long-term changes are composed of a convergent sequence of almost instantaneous fluctuations, a proper understanding of the dynamics of destruction of a beach during a storm and its post-storm recovery is essential. Figure 59 shows the alterations at Cat. 4 and Cat. 5 during and after the storm. Figure 60 shows similar changes at the steep Cat. 6 profile and the gently sloping Wide Beach at Cat. 10.

The typical pattern of change during the early erosive phase of the storm consists of 1) erosion of the berms with 2) subsequent deposition of the gravel on the lakeward side of the step, causing its progradation, and 3) the deposition of some variable amount of sand on the back beach. The net effect is to smooth the entire beach profile by eroding the central portion (berms) and depositing sediment at the lakeward and landward portions. Gravel is totally removed from the beach face because of the vigorous upper flow regime conditions within the extensive swash zone (Fahnestock and Haushild, 1962).

The swell, which characterizes the waning stages of a storm, typically is constructional. Because of the relatively high waves, often superimposed on a substantial wind tide, the first set of recovery berms is generally

Figure 60. Beach profiles Cat. 6 and Cat. 10 on May 10, June 4, June 11, June 12, and June 13. The pattern of erosion and deposition is similar to the previous figure. Note the enormous erosion at Cat. 6 from May 10 through June 11.

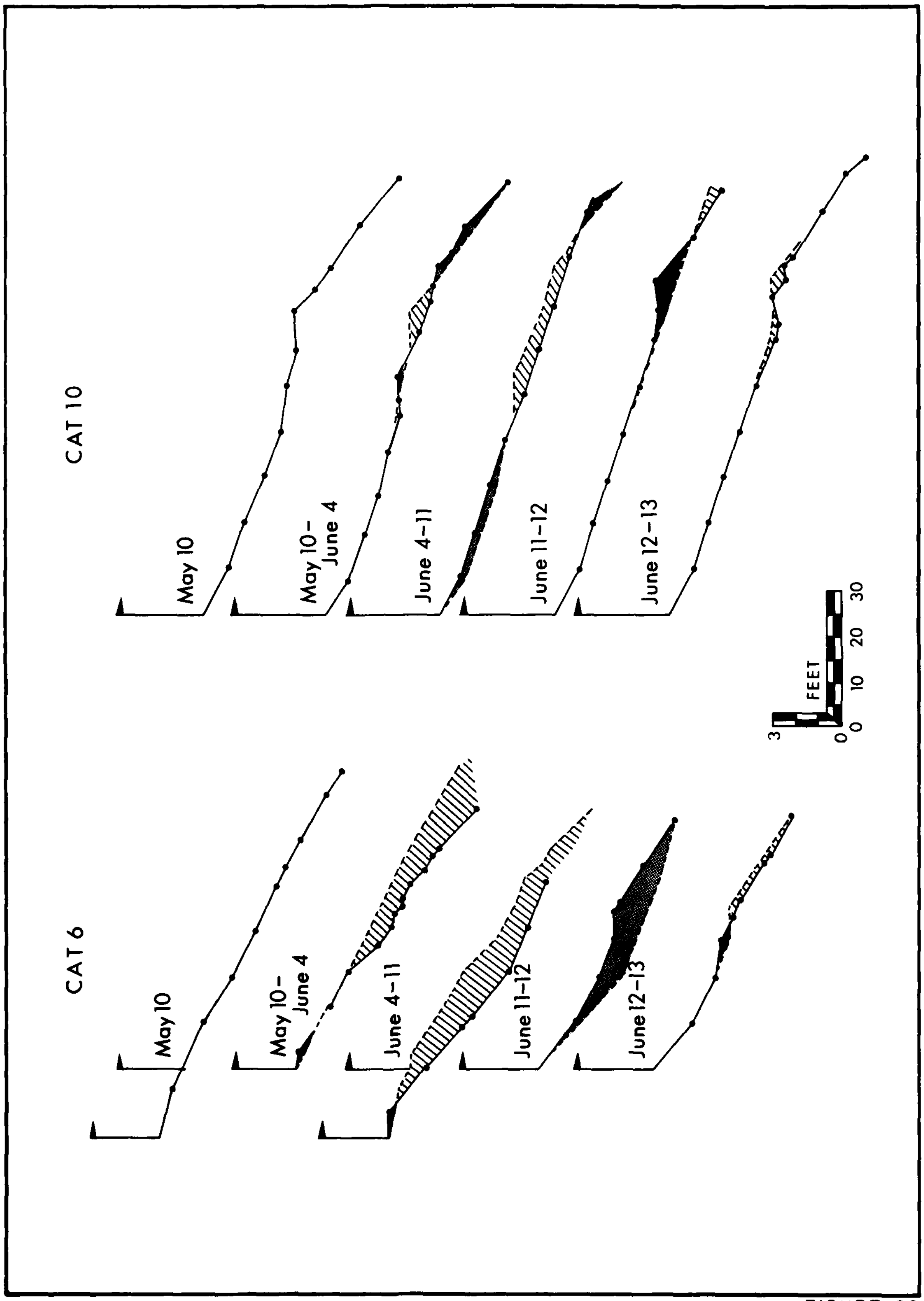

CAT 6
CAT 10
May 10
May 10– June 4
June 4–11
June 11–12
June 12–13
FEET
0 10 20 30
3
0

FIGURE 60

formed high on the beach face, with additional berms forming lower down in response to falling lake level and reduced wave height. Note, for example, at Cat. 3, Cat. 8, and Cat. 10, how the initial berms forming on June 12 were replaced by high level and low level (active) berms on June 13 (Appendix VI).

8.2. River mouth spits.

Figures 61 and 62 show the changes in spit morphology between May 10 and June 6, 1974. The changes in the Brant spit (north side of creek) were minor except for the alteration of some low level gravel berms. Because the zone of drift reversal is located between the creek and Cat. 6 during southwesterly storms (Fig. 53C), sediment supply to the Brant spit was very limited during the observation period.

The Hanover spit (south side of creek) shows rapid morphological changes in response to a changing wave power / stream power ratio. The most noticeable trend from May 10 to June 6 is a growth in spit size, while its alignment remains essentially that of the south bank of the creek. This is thought to reflect the prevalence of constructive wave conditions coinciding with low summer discharge in Cattaraugus Creek, i.e. a dominance of constructive wave power.

The location of a spit slip face is a reliable indicator of short-term sediment transport patterns. The presence of a slip face on the channel side of the Hanover spit on three of the four maps (May 10 and 28, June 6), therefore, demonstrates a net sediment flux from south to north across the spit. This transport pattern shows that littoral sediment transportation is primarily responsible for the development of this spit. On May 18, a few days after

Figure 61. Planimetric maps of the Hanover spit (south side of Cattaraugus Creek). The maps, made by theodolite from a land base on the left bank, show the significant features on the subaqueous portion of the spit, the crest, the slip faces, and the outline of the bar margin. Note the change in slip face location from the lake side to the channel side between May 18 and June 6.

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1974 R F FAHNESTOCK, D MESSINGER, J WALTON DACW49-74-C-0118

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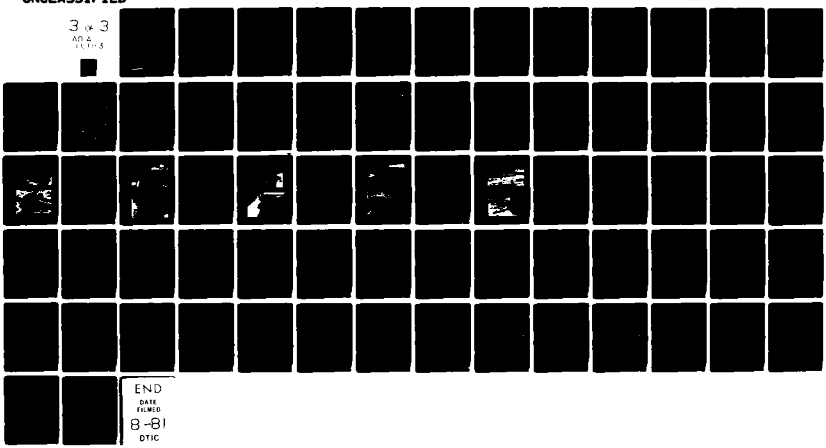

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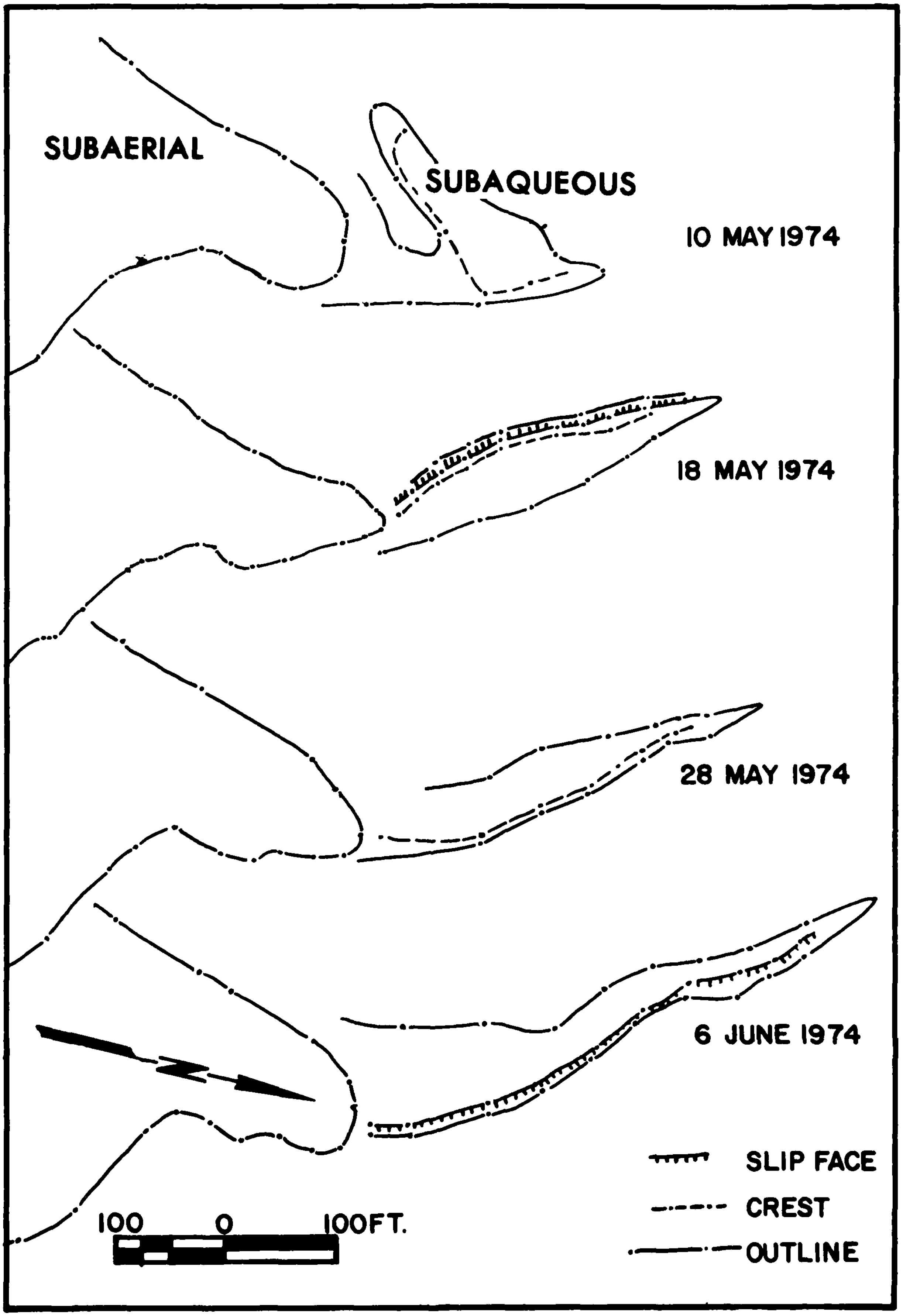

SUBAERIAL
SUBAQUEOUS
10 MAY 1974
18 MAY 1974
28 MAY 1974
6 JUNE 1974
100 0 100FT.
SLIP FACE
CREST
OUTLINE

FIGURE 61

Figure 62. Planimetric maps of both the Brant and the Hanover spits. The Brant spit is all subaerial and shows insignificant change during the time period of observation.

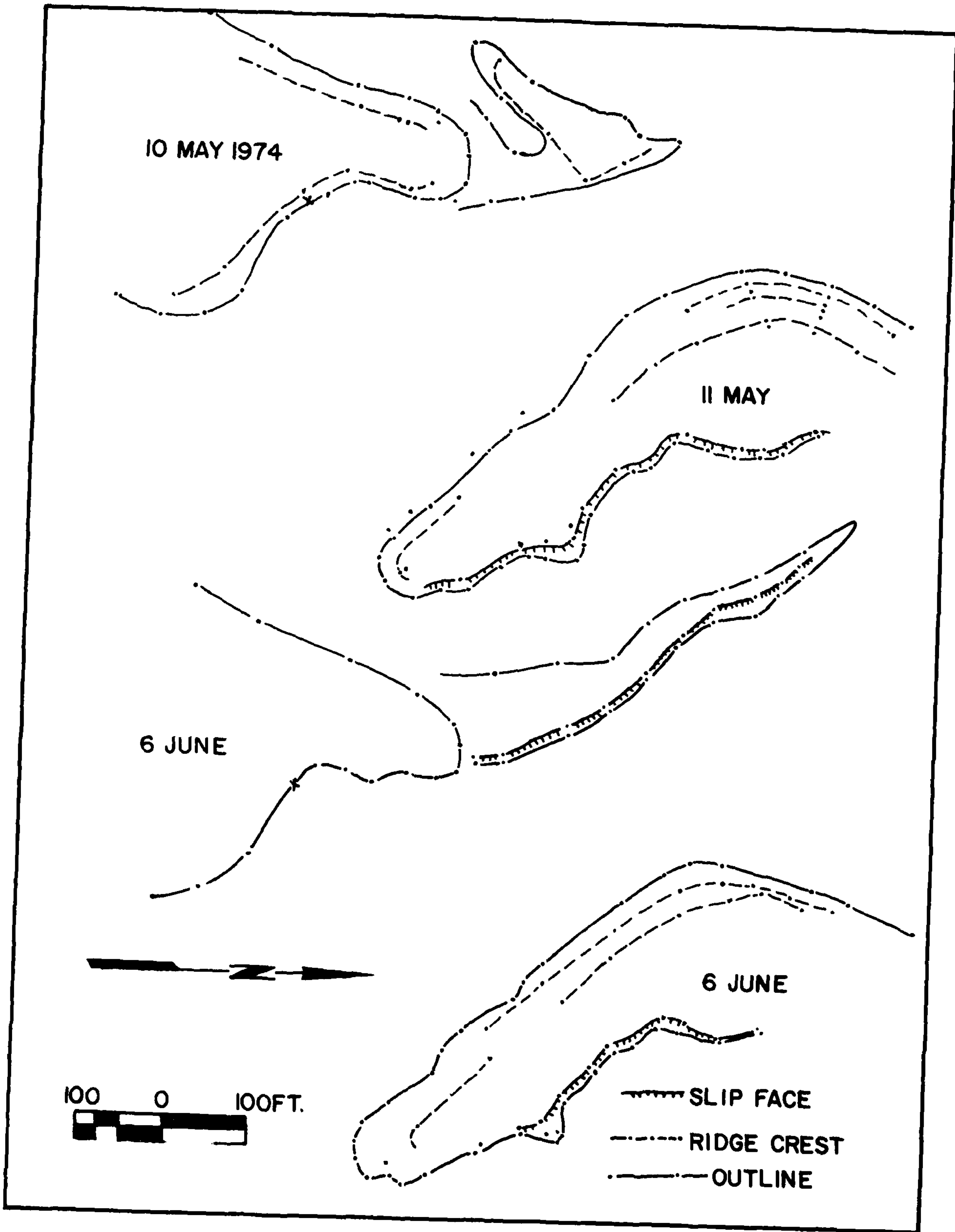

10 MAY 1974
11 MAY
6 JUNE
6 JUNE
N
100 0 100FT.
SLIP FACE
RIDGE CREST
OUTLINE

FIGURE 62

a moderate flood in Cattaraugus Creek (see process data in Fig. 52), the spit slip face was found on the lake side, attesting to the temporary reversal in net sediment flux as a consequence of increased stream power.

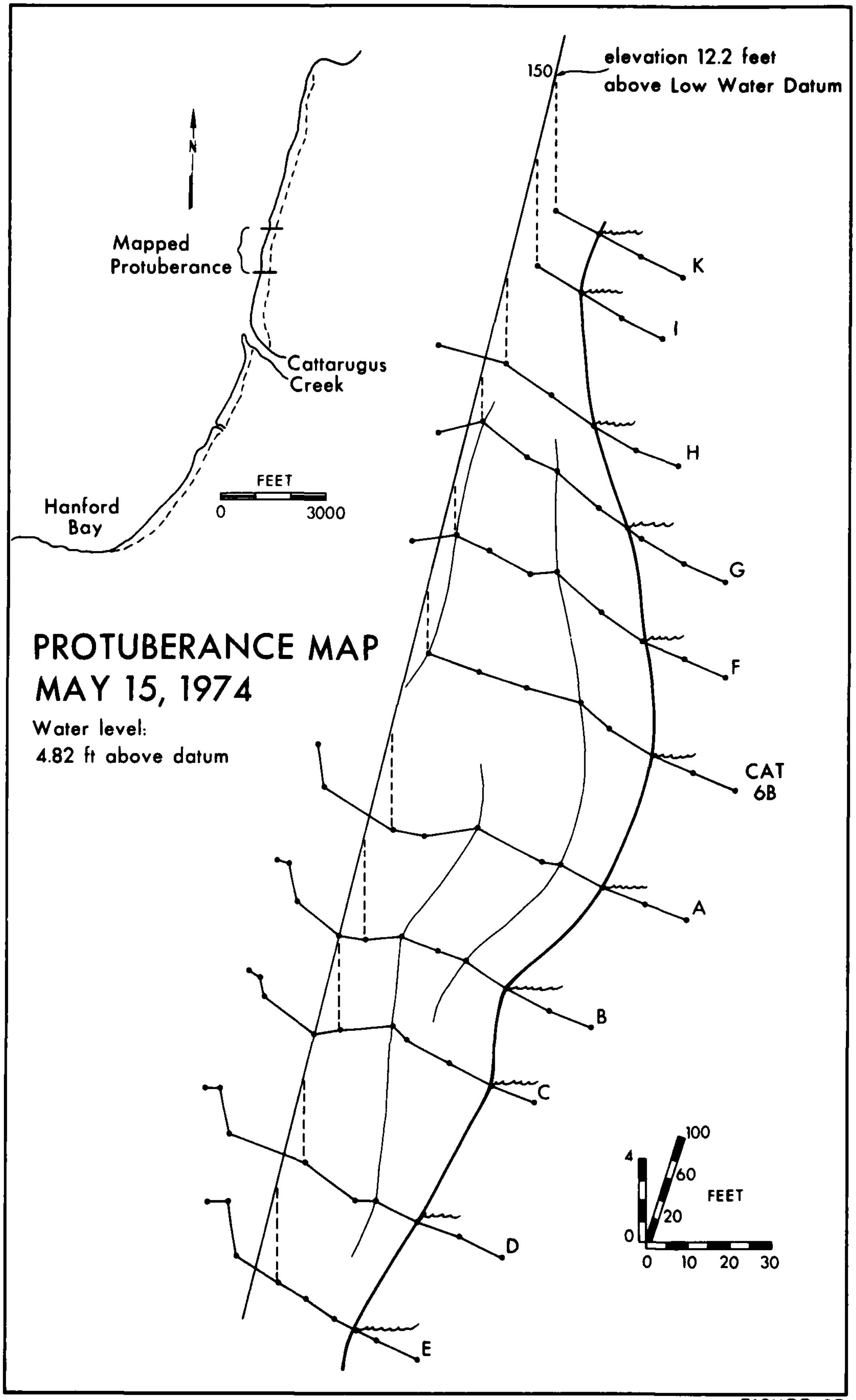
The significance of this sediment transport pattern in the engineering analysis of structure design will be apparent in the discussions presented in paragraph 10.

8.3. Protuberances.

Aerial photographs of the Cattaraugus beach show a series of more or less sinusoidal sand waves of an amplitude of 20 to 30 feet and a wave length of 500 to 1000 feet (Plate 4). As it has been noticed elsewhere that these sand waves, often called protuberances, may move along the beach face as distinct entities, it was decided to monitor the behavior of one of the Cattaraugus features by repetitive topographic mapping.

A major protuberance, located between Cat. 6 and Cat. 7 (Fig. 63) was chosen. The three dimensional map of this sediment accumulation was constructed by running 10 closely spaced beach profiles, covering the beach face from the updrift to the downdrift embayments flanking the protuberance. The protuberance was mapped twice, on May 15 (Fig. 63) and on May 27 (Fig.64). The feature was found not to move laterally in this short time interval. Redoing of this map at the end of the summer and again after a few fall storms, however, may prove it to be less stationary than indicated by these preliminary results. Because of its location just downdrift of the planned northeast breakwater, its behavior pattern can yield significant information about possible detrimental effects of the planned structure on this segment of the beach.

Figure 63. Map of protuberance between Cat. 6 and Cat. 7 on May 15, 1974. The map was constructed by measuring ten closely spaced beach profiles. The berms generally follow the sinusoidal outline of the sand wave but are commonly better developed in the embayments than near the center of the protuberance.



elevation 12.2 feet
above Low Water Datum
150
N
Mapped
Protuberance
Cattarugus
Creek
Hanford
Bay
FEET
0
3000
PROTUBERANCE MAP
MAY 15, 1974
Water level:
4.82 ft above datum
K
I
H
G
F
CAT
6B
A
B
C
D
E
4
0
100
60
20
FEET
0
10
20
30

FIGURE 63

Figure 64. Map of protuberance between Cat. 6 and Cat. 7 on May 27, 1974. By comparing with the previous figure, the lakeward progradation of the protuberance can be clearly seen. The accretion has taken place by multiple berm growth, particularly in the embayments. No lateral movements of the form can be detected.

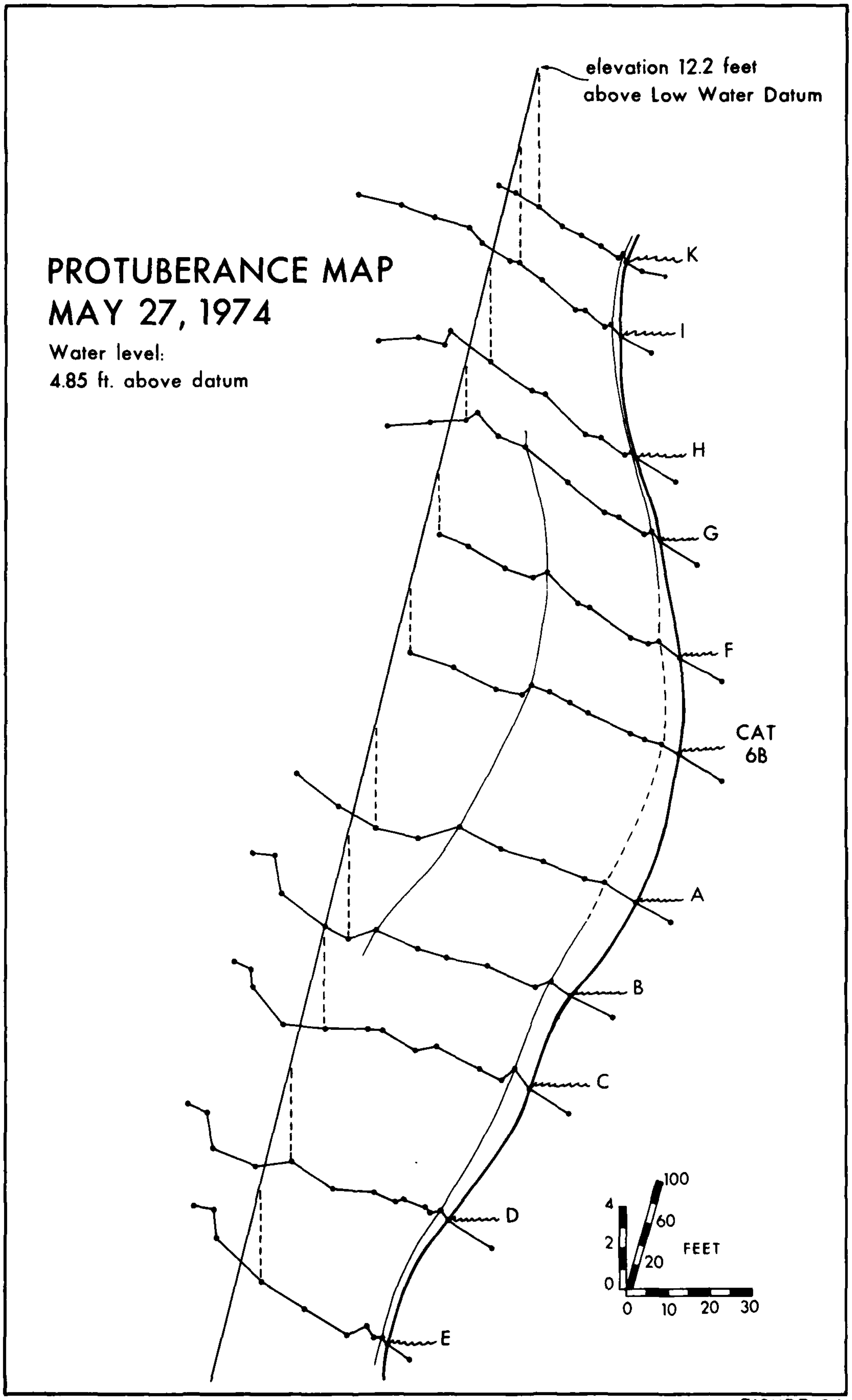

PROTUBERANCE MAP
MAY 27, 1974
Water level:
4.85 ft. above datum
elevation 12.2 feet
above Low Water Datum
K
I
H
G
F
CAT
6B
A
B
C
D
E
100
60
20
FEET
4
2
0
0
10
20
30

FIGURE 64

9. CONCLUSIONS

The objectives of this study were to 1) determine the pattern of sediment transportation and deposition by littoral and fluvial currents and 2) to propose a breakwater configuration that will have the least detrimental effects on the adjacent beaches.

Objective 1 is accomplished by a detailed analysis of littoral processes, sediment sources and distribution patterns, and shoreline morphology presented in the preceding paragraphs. Objective 2 is met in paragraph 10. The aspects of the sedimentary process-response model derived from the preceding analysis which are of most importance in the breakwater design are:

1) Net sediment flux along the southeast shore of Lake Erie, including the Cattaraugus Embayment, is from the west to the east. Sediment accumulations associated with both man made and natural features from Cleveland to Buffalo support this transport pattern. The volume of sediment in the littoral transport depends on the deep water wave energy distribution, the orientation of the shoreline, the nearshore bathymetry, and the conditions of the sediment source. Consequently, the sediment load is highly variable along the lake shore. To establish a meaningful numerical value for the littoral sediment load would require a much more extensive program than what was possible under the provision of this contract.

2) Specifically, within the Cattaraugus Embayment the variations in the sediment dispersal pattern reflect the location of the primary sediment source and the nearshore wave climatology. Details on this follow.

3) Cattaraugus Creek, entering the lake at the center of the embayment,

is the dominant source of sand and gravel sized sediment. Some coarse grained sediment is supplied to Cattaraugus beach from the Silver Creek headland and the pocket beaches beyond. No significant amount is contributed from Lotus Point.

4) Gravel lithology, beach gravel/sand ratio, and textural distribution of nearshore sand support the contention that the net coarse sediment flux within the Cattaraugus Embayment is from south to north.

5) Wave hindcast data show this transport pattern to be in complete accord with the prevailing wave conditions on the lake. Both wind generated current transportation and wave dominated sediment movement in the surf zone will cause a net mass flux northward.

6) Characteristically, during southwesterly storms the littoral current velocities within the embayment are moderate at the southernmost segment of the beach, drop to a minimum near the creek mouth because the waves approach this segment almost perpendicularly to the beach, and increase further northward to reach a maximum near Lotus Point. This is very nearly also the pattern of variation in sediment transport rates.

7) Intermittent reversals in sediment transport direction can occur, however, as evidenced from the extensive sand deposits in the nearshore of Hanford Bay and the southwardly recurved spit on the north side of Cattaraugus Creek. Because the Hanford Bay area is subject to very small wave energies during southwesterly storms, sand brought down there during northeasterly storms is likely to remain.

8) A northward oriented spit forms at the mouth of Cattaraugus Creek as an extension of the beach at periods of low fluvial discharge. Being controlled by the ratio of wave to stream power, the spit grows in extent and aligns itself transversely to the river channel during periods of low fluvial discharge. During periods of high discharge the spit is turned more lakeward and may also be reduced in volume.

9) Shallow water nearshore bars are found to exist, at least intermittently. During periods of constructional wave conditions these bars migrate on shore and weld onto the beach face.

10) During major storms beach berms are eroded and most of the sand and gravel transported lakeward. This leads to a lakeward progradation of the beach step and, possibly, to an increase in the volume of the nearshore bar system. During constructional wave conditions this sequence of events is reversed.

11) Reconnaissance sampling of the lower reach of Cattaraugus Creek showed that gravel is being transported through to the creek mouth during periods of high discharge. During slack water periods the lower river bottom is covered with one to two inches of fine grained lake and fluvial sediments.

10. BREAKWATER DESIGN ALTERNATIVES

Selection of the most suitable design for the structure proposed for the mouth of Cattaraugus Creek has to be based on a thorough analysis of at least three factors:

1) the pattern of sediment transportation and deposition within the area which will be affected by the structure,
2) the pattern of winter and spring ice formation and associated flooding,
3) the effect of the structure on lake conditions within the marina it is built to protect.

Other environmental, technical, socio-economic, and political factors have to be considered in a comprehensive engineering analysis of the project. This, however, is far beyond the authority of this investigation.

Although the data collected for the purpose of this study pertain exclusively to factor 1 above, we feel that recommending a structure based solely on its impact on sedimentation would be unsatisfactory. The constraints set by factors 2 and 3 must also be properly evaluated.

Figure 65 shows five alternative designs discussed in this analysis. 1 and 2 are asymmetric arrowhead breakwaters. 1 is equivalent to the one proposed in the 1966 report on the Cattaraugus Harbor project, 2 is the same structure but turned to have a west breakwater facing the dominant wave approach direction. Structures 3 through 5 are significantly different from the previously proposed structures. Their associated merits and problems will be discussed below.

Figure 65. Alternative structure designs. Conceptual models of five different breakwater designs. The effects of the five structures on littoral and fluvial currents and sediment transportation, lake and river ice jamming, and wave conditions in the harbor are discussed in paragraph 10 of the text.

1. Arrowhead breakwaters, opening to the southwest.
2. Arrowhead breakwaters, opening to the north.
3. Straight arrowhead breakwater.
4. Parallel piers with a detached breakwater.
5. Parallel piers of uneven length.

ALTERNATIVE STRUCTURE DESIGNS

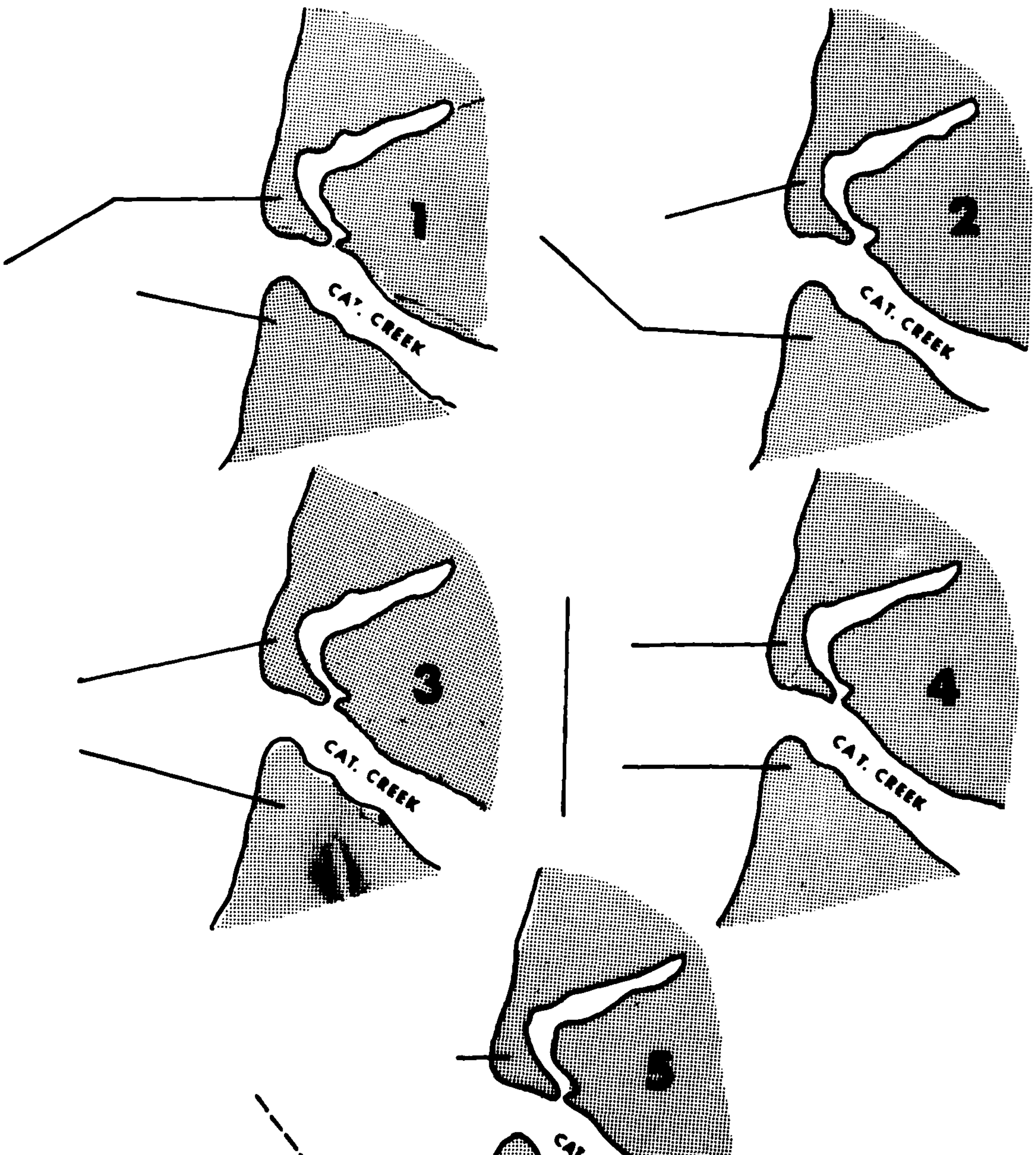


FIGURE 65

In the following sections the effects of each design will be analyzed for specific processes.

10.1. Changes in the updrift beaches.

The dominant transport direction is from the southwest to the northeast. At any one location the rate of transport is likely to be reduced the more northerly the beach face is turned because the longshore component of the wave energy flux will be reduced as the beach becomes more nearly orthogonal to the dominant wave approach direction. Therefore, the updrift sediment accumulation observed at almost every structure seen along the shoreline of lakes Erie and Ontario (paragraph 3) is likely to attain an ultimate shoreline orientation about perpendicular to the dominant local wave approach. With the dominant wave approach direction at the mouth of Cattaraugus Creek being almost orthogonal to the present shoreline, one should not expect a dramatic change in shoreline orientation. The updrift accumulation will affect a wide stretch of beach and a long time will be required before the wider beach will cause any serious increase in sediment transport rates past the south jetty and into the harbor.

Any structure, therefore, is likely to benefit the southern beaches. In order to continue to resupply these beaches, however, it is imperative that fluvial sediment still can reach them. The jetties, therefore, should not terminate in water too deep for removal of materials at their end by wave and wind-generated current action.

10.2. Changes in downdrift beaches.

As suggested by previously reported observations, beach erosion downdrift of a structure, of whatever kind, seems to be an inevitable consequence of the interruption of continuity in the littoral drift system. With no sediment source downdrift of the structure, erosion probably is inevitable. With a sediment source associated with the structure, however, the design should attempt to permit reintroduction of sediment into the longshore transport system. If the source is significant enough, equilibrium transport rates could be reestablished without cost to the downdrift beaches.

Cattaraugus Creek is the only major source of sediment in the embayment. Therefore, by providing for fluvial sediment supply to the downdrift beaches, their erosion can be minimized if not eliminated. These considerations request that fluvial sediment have free path to the north as under natural conditions, a requirement that would favor parallel piers of uneven length (design 5, Fig. 65) or, to a lesser degree, arrowhead breakwaters with opening to the north (design 2). Furthermore, the breakwaters should not terminate in water too deep for effective littoral transport of sand.

10.3. Harbor shoaling due to littoral drift.

Because the net sediment flux is towards the north, any structure with a shorter breakwater on the south side than on the north side is likely to have severe problems with shoaling at the harbor entrance. This seems not to favor the arrowhead breakwaters with opening to the southwest (design 1, Fig. 65) as well as, possibly, the parallel piers with a detached breakwater (design 4, Fig. 65), although the situation here is less clear. Because of wave refraction around the detached breakwater, sediment transported northward between the termini of the jetties and the detached breakwater might accumulate at the jetty mouth.

The most desirable structures in terms of harbor shoaling might be the arrowhead breakwaters with opening to the north (design 2, Fig. 65) and the parallel piers of uneven length (design 5, Fig. 65). In both of these cases, fluvial sediment will have free path to the north and the littoral drift, bypassing the south jetty, is likely also to bypass the northern jetty.

The circulation pattern in lee of such structures, however, is fairly complex and an accurate prediction is impossible. Saylor (1966), studying the currents at Little Lake Harbor in Lake Superior, found that a lee side eddy developed behind an asymmetric arrowhead breakwater during strong westerly wind-driven currents (Fig. 66). This circulation pattern will result in the scour of a relatively deep channel near the southwest breakwater and the possible accumulation of sediment in the middle of the harbor entrance.

10.4. Harbor shoaling due to fluvial sediment supply.

During moderate and low discharge in Cattaraugus Creek, some fluvial sediment will undoubtedly be deposited in the harbor. There is reason to believe, however, that during floods the current velocities are sufficiently high to provide adequate flushing action in the harbor to avoid the formation of a major channel mouth bar. During floods in the present unmodified channel, gravel and sand are transported right through to the open lake,and there is no reason to expect this to change by the addition of the jetties. Designs 2 and 5 might develop a fluvial sediment deposit in the harbor basin to the north of the southern breakwater. This material would partly replenish the northern beach, but it could also be caught in the reverse circulation shown in Figure 66 and be redeposited in the entrance channel to the harbor.

Figure 66. Current pattern near entrance to Little Lake Harbor (Lake Superior) during strong westerly wind with outflow from the harbor. From Saylor (1966).

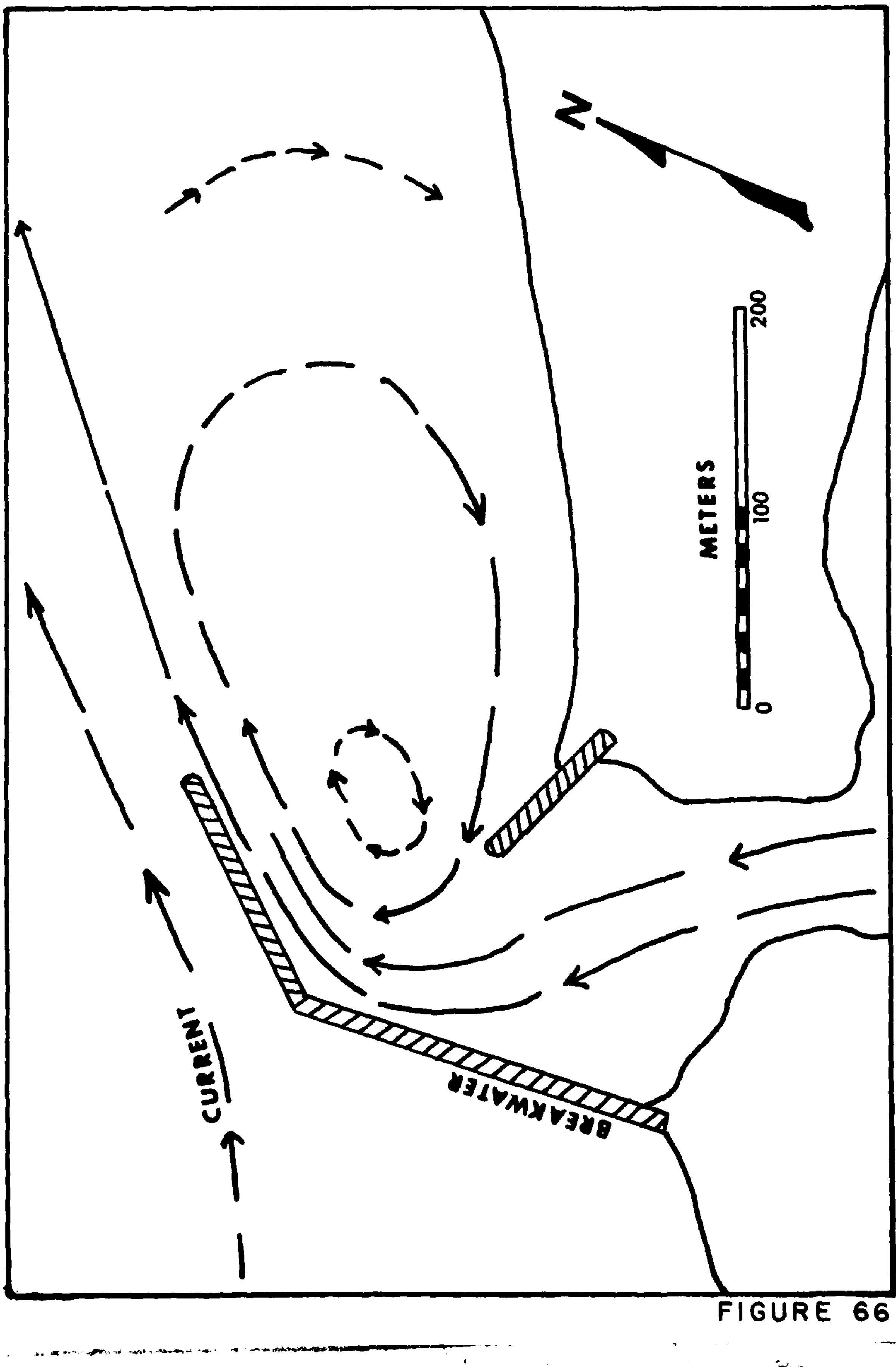


FIGURE 66

10.5. Ice jams and related flood problems.

The most severe flooding of the Sunset Bay area is caused by ice jamming of the creek mouth during periods of high discharge. The jam can be caused by three different ice conditions and the impact of a structure on the ice problem will depend on these conditions.

If solid ice extends from the shore lakeward to beyond the end of the breakwaters at the time of high discharge in Cattaraugus Creek, the flooding is going to be severe irrespective of structure design. Designs 1 through 4, however, are likely to aggravate the situation more than design 5, because the two impermeable breakwaters will have a leveeing effect on the water and raise the downstream control. Creek water flowing onto the lake ice under unmodified conditions is known to build its own "ice-levees," but these are low and somewhat permeable and have relatively little effect on raising the water level in the channel.

Drift ice in the lake tends to be wind rowed parallel to shore in embayments like Cattaraugus during strong westerly winds. An arrowhead breakwater might be effective in providing an unobstructed outlet for the creek water through this ice jam.

Frequently, the creek itself blocks its mouth by ice brought downstream during the flood. This ice is held back by the channel mouth sand spit and jams the creek further upstream. It has been observed to fill the channel completely from the mouth to the New York Central railroad bridge.

Although any of the proposed structure designs probably will eliminate the sand spit problem, it is questionable whether the relatively narrow opening between the arrowhead breakwaters will prove adequate for a rapid discharge of river ice. Parallel breakwaters of unequal length (design 5, Fig. 65) may be the best for this ice condition; an arrowhead breakwater with opening to the north (design 2, Fig. 65), away from the main wave approach direction, may be an acceptable second alternative.

10.6. Wave conditions in the harbor entrance.

For safety, easy maneuverability, and minimum damage to mooring facilities in the marina it is imperative that the breakwaters are designed to receive as little wave energy as possible and to quickly dissipate whatever does arrive at the entrance channel. The entrance should face away from the dominant storm wave approach direction, and multiple wave reflection between the breakwaters should be minimized.

Design 2, and to a lesser degree 4 and 5, are protected from westerly storm waves. The landward divergence of breakwaters with arrowhead design will quickly dissipate any incoming wave energy, as will the parallel breakwaters of uneven length because there is almost no northern breakwater to cause multiple reflection. Designs 1 and 3 might be the least desirable ones in terms of their effect on wave conditions in the harbor entrance.

10.7. Tentative recommendations.

Paragraph 4(2) of the Scope of Work specifies: "Based on his findings (the contractor should) propose a breakwater configuration that will have the least detrimental effect on the regional environment." In the preceding paragraphs, the possible environmental impact of 5 alternative structures has been discussed. It is premature to make any final recommendations based on these analyses. Tentatively, however, it seems that design 5 (Fig. 65), parallel breakwaters of uneven length, has a number of valuable attributes. Design 2, arrowhead breakwaters with opening to the north, might also be acceptable. The remaining three designs seem to be generally less desirable unless some presently overlooked factor should count heavily in their favor.

The alternatives discussed in the previous paragraphs should be thoroughly tested in the movable bed model constructed at the U. S. Waterways Experiment Station at Vicksburg, Miss. If the natural sedimentation processes presently observed in the Cattaraugus Embayment can be adequately reproduced in the model, one should also be able to predict, with some degree of confidence, the post-construction sedimentation patterns.

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PLATES

Plate 1. Aerial view of a section of Cattaraugus Creek upstream of Gowanda. The channel is incised into predominantly shales of upper Devonian age. Photo: June 13, 1974.

Plate 2. Aerial view of a Cattaraugus Creek gravel point bar. The dominant lithologies are siltstone, red sandstone, limestone, and a few crystalline rock fragments. Typical gravel size on the point bar in the picture is 5 centimeters. Photo: June 13, 1974.

PLATE 1

PLATE 2

Plate 3. Wide beach. View northward from profile location Cat. 10 towards Lotus Point. Despite the proximity of the shale headland the lithological composition of the gravel at Cat. 10 is the same as that much further to the south. Note the multiple gravel berms. Photo: May 23, 1974.

Plate 4. Oblique aerial photograph of the Cattaraugus Embayment from 1000 feet. View towards the south. Note the waves breaking over the offshore sand bars and the spit on the south side of Cattaraugus Creek. The protuberance between Cat. 6 and Cat. 7 (Fig. 63) is clearly visible. Rip currents carry sediment lakeward. Photo: May 4, 1974.

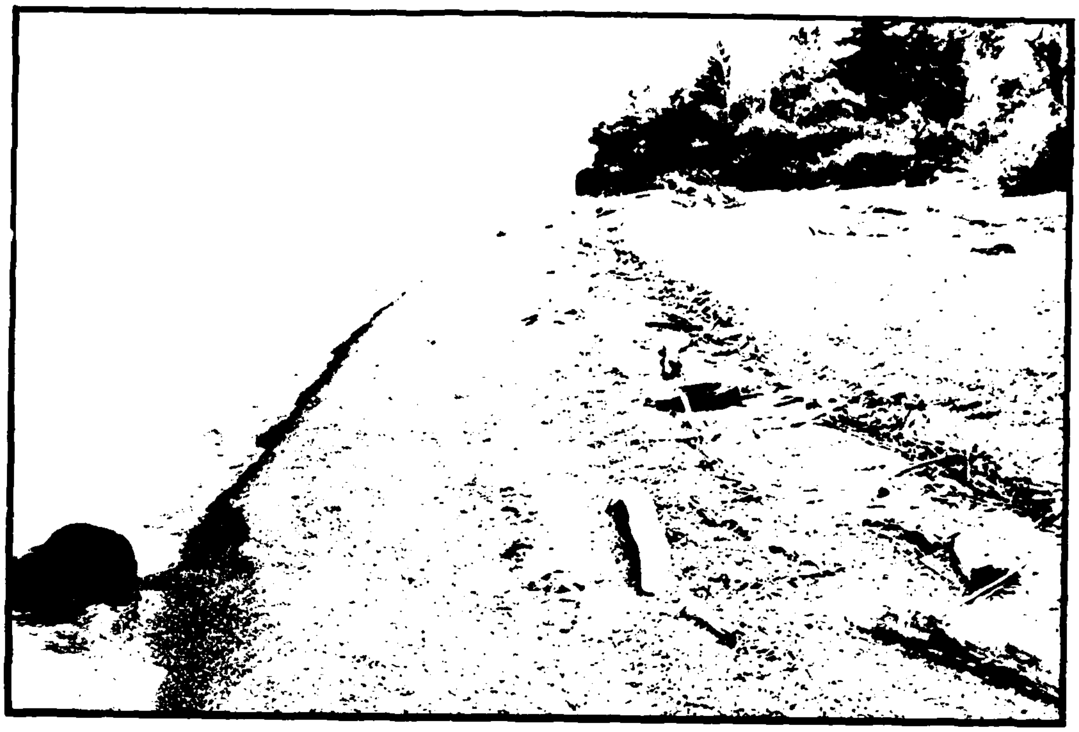


PLATE 3

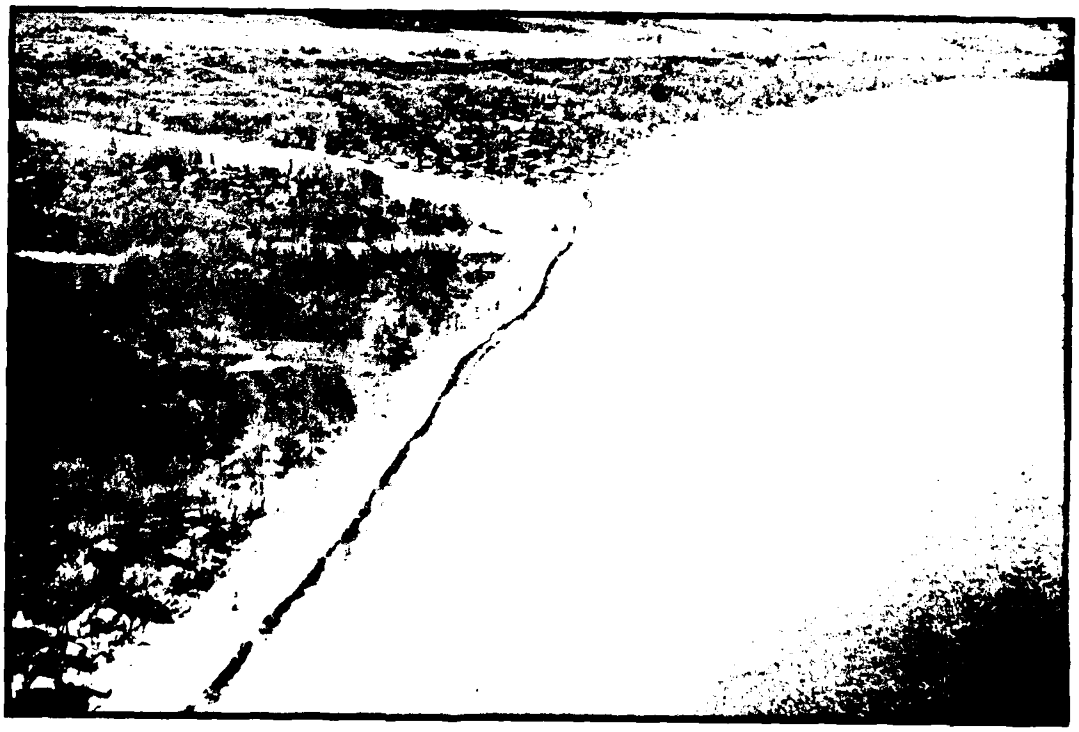


PLATE 4

Plate 5. Beach face at Cat. 6 during storm. The berm is eroded and the gravel deposited at the step which has prograded lakeward during the storm. The breakers are 4 to 6 feet high. Photo: June 11, 1974.

Plate 6. Beach face at Cat. 6. A wide gravel berm becoming more sandy as it grades into the back beach is typical of the constructional beaches in the Cattaraugus Embayment. The change from the previous photo was accomplished in less than 24 hours. Photo: June 12, 1974.

PLATE 5

PLATE 6

Plate 7. View towards the north of the beach at profile location Cat. 5. Note multiple gravel berms and the sandy swash zone. Waves are breaking over the subaqueous spit at the upper left of the photo. Photo: June 12, 1974.

Plate 8. View towards the south of the beach at profile location Cat. 5. Note the wide berm in the foreground which was welded onto the beach face by a ridge migrating landward during the waning stages of the storm. Photo: June 12, 1974.

PLATE 7

PLATE 8

Plate 9. View of the mouth of Cattaraugus Creek during a storm. Note the washover zone on the gentle south beach and the run-up on the steep northern beach. The waves approach almost perpendicular to the shore because of the large refraction. Photo: June 11, 1974.

Plate 10. Aerial photo of the mouth of Cattaraugus Creek right after a storm. Note the washover terrace forming at the neck of the north side recurved spit. View towards the south from about 500 feet. Photo: June 13, 1974.

PLATE 10

APPENDICES

APPENDIX I

Weather data for Buffalo. May 7th - June 13th, 1974. Data from NOAA Daily Weather Maps. All observations of 0700 EST.

Date	Wind Dir. (Az.)	Wind Speed (knots)	Circulation (Type of circulation affecting Lake Erie and location of the associated pressure center).	
May 7	WSW	10	Anticyclonic	High over Indiana
May 8	-	0	Anticyclonic	High over New Jersey
May 9	SSW	15	Cyclonic	Low over Lake Erie
May 10	NW	5	Cyclonic	Low over Ontario
May 11	SE	5	Anticyclonic	High over Ontario
May 12	S	10	Cyclonic	Low over Lake Superior
May 13	W	15	Cyclonic	Low over Labrador
May 14	S	5	Cyclonic	Low over Wisconsin
May 15	S	10	Cyclonic	Low over James Bay
May 16	ESE	5	Anticyclonic	High over Ontario
May 17	SW	15	Cyclonic	Low over New York
May 18	W	5	Straight Isobars	
May 19	E	15	Anticyclonic	High over James Bay
May 20	NE	5	Anticyclonic	High over James Bay
May 21	-	0	Straight Isobars	
May 22	SW	5	Cyclonic	Low over Lake Superior
May 23	SW	10	Cyclonic	Low over Lake Superior
May 24	SW	20	Cyclonic	Low over Quebec
May 25	W	10	Cyclonic	Low over Quebec
May 26	W	10	Cyclonic	Low over Quebec
May 27	SW	5	Cyclonic	Low over Ontario
May 28	SW	5	Cyclonic	Low over Lake Winnipeg
May 29	SW	10	Cyclonic	Low over Ontario
May 30	NE	5	Cyclonic	Low over Quebec
May 31	SE	10	Cyclonic	Low over upper Michigan
June 1	N	5	Anticyclonic	High over South Dakota
June 2	S	5	Anticyclonic	High over Maine
June 3	SW	5	Anticyclonic	High over West Virginia
June 4	SSW	5	Anticyclonic	High over New York
June 5	S	5	Anticyclonic	High east of New York
June 6	S	5	Straight Isobars	
June 7	S	10	Straight Isobars	
June 8	S	10	Straight Isobars	
June 9	SSW	5	Cyclonic	Low over Nebraska
June 10	SSW	15	Cyclonic	Low over Wisconsin
June 11	WSW	20	Cyclonic	Low over Quebec
June 12	SSW	10	Cyclonic	Low over Hudson Bay
June 13	SSW	10	Straight Isobars	

APPENDIX II

Littoral Processes in the Cattaraugus Embayment,
May 7 - June 13, 1974

Station Cat. 1

Date	Time (h)EST	Waves Height (ft)	Waves Period (sec)	Waves Breaker angle rel. to shore	Longshore current (fps)	Wind Dir. (az.)	Wind Speed (mph)
May 7	0835	2.0	4.3	10°N	1.6	270°	12
May 8	0730	0.4	5.0	6°N	0	var.	0-4
May 9	0800	0.4	3.5	12°N	0.05 S	--	0
May 10	0813	0.7	3.0	2°N	0	5°	5-7
May 11	0805	0.1	--	--	0	var.	0-4
May 12	0850	0.3	1.5	38°N	0.6	250°	8-10
May 13	0825	2.3	5.2	20°N	2.1	260°	15
May 14	0745	0.3	3.3	15°N	0	--	0
May 15	0900	0.8	3.3	18°N	1.5	235°	0-8
May 16	0830	0.2	4.3	0°	0	--	0
May 17	0910	0.9	2.5	18°N	1.1	237°	10
May 18	0805	0.2	2.8	6°N	0	255°	5
May 19	0815	1.1	3.0	10°S	0.9 S	58°	8
May 20	0830	0.3	2.7	8°S	0.3 S	27°	5
May 21	1350	0.1	1.5	--	0	--	0
May 22	0907	0.2	1.9	10°	0.1	260°	5
May 23	0925	1.0	2.8	4°	0.6	255°	5
May 24	1000	1.2	2.9	7°	1.1	263°	15
May 25	--	--	--	--	--	--	--
May 26	0810	0.8	2.9	4°	0.6	243°	5
May 27	0820	0.5	2.4	8°	0.2	265°	7
May 28	0925	0.4	2.0	15°	0.6	280°	8
May 29	0822	0.5	3.2	5°	0.3	--	0
May 30	0825	0.1	1.8	0°	0	--	0
May 31	1005	0.3	2.8	3°	0.1	var.	0-3
June 1	0825	0.5	2.1	6°	0.3	274°	8
June 2	0835	0.1	1.8	--	0	var.	2
June 3	0825	>0.1	1.5	12°	0	--	0
June 4	0820	0.1	2.5	0°	0	--	0
June 5-10		No observations, waves negligible.					
June 11	1010	2.6	5.5	15°	1.0	255°	16
June 12	0905	0.7	3.3	10°	0.8	255°	12
June 13	1345	0.7	2.5	10°	1.0	275°	15

Station Cat. 3

Date	Time (h)EST	Waves Height (ft)	Period (sec)	Breaker angle rel. to shore	Longshore current (fps)	Wind Dir. (az.)	Speed (mph)
May 7	0805	1.6	4.3	10°	0.8	265°	12
	1700	2.0	5.2	6°	0.8	245°	15-20
May 8	0710	0.3	--	--	0	var.	0-3
	1700	0.2	4.0	0°	0	--	0
May 9	0735	0.5	3.0	10°	0.4	180°	0-8
	1605	3.3	4.5	5°	1.4	226°	18-25
May 10	0745	0.7	3.2	4°	0.2	0°	4
	1620	0.7	3.0	0°	0.3	285°	9
May 11	0750	<0.1	--	--	0	--	0
	1605	0.3	2.0	15°S	0.3 S	35°	5-9
May 12	0840	<0.1	--	14°	0	--	0
	1700	0.4	3.5	9°	0.3	215°	5-8
May 13	0800	2.2	4.5	8°	1.2	250°	20
	1525	1.2	3.5	12°	1.3	250°	16
May 14	0825	0.6	3.1	14°	0.9	205°	6-12
	1710	1.7	3.0	10°	0.8	280°	12
May 15	0835	1.7	3.0	18°	1.7	204°	10
	1800	1.2	3.7	15°	1.4	255°	14
May 16	0810	0.3	3.8	0°	0	162°	0-4
	2015	0.4	2.5	0°	0	--	0
May 17	0815	1.2	2.8	17°	1.1	230°	10
	1630	1.0	3.0	2°	0.3	240°	7
May 18	0735	0.3	2.2	2°	0	--	0
	1915	0.2	1.8	20°S	0.2 S	40°	5
May 19	0755	0.6	2.8	22°S	0.4 S	75°	4
		No evening observations, May 19-May 22.					
May 20	0805	0.3	2.7	6°S	--	110°	4
May 21	1240	0.1	1.5	10°S	0	--	0
May 22	0830	<0.1	--	--	0.2	--	0
May 23	0855	2.3	2.9	5°	1.1	242°	15
	1700	2.0	3.6	3°	1.4	242°	18
May 24	0910	1.5	3.1	5°	1.8	257°	17
	1750	1.3	4.9	7°	1.1	242°	18
May 25		No observations.					
May 26	0745	1.0	3.0	0°	0	245°	8
	1730	1.5	3.5	9°	1.2	244°	15
May 27	0810	0.5	--	5°	0.2	260°	8
	1730	1.0	3.2	10°	0.9	260°	11
May 28	0845	0.8	2.5	8°	0.6	278°	4
	2110	0.2	2.1	8°	0	--	0

Station Cat. 3 (cont.)

Date	Time (h)EST	Waves Height (ft)	Waves Period (sec)	Waves Breaker angle rel. to shore	Longshore current (fps)	Wind Dir. (az.)	Wind Speed (mph)
May 29	0800	0.8	3.2	0°	0.1	234°	8
	1845	0.8	2.8	6°	0.3	--	0
May 30	0845	0.2	2.7	0°	0	--	0
	1930	0.2	2.9	0°	0	--	0
May 31	0930	0.3	2.6	6°	0.4	130°	6
	1830	1.0	2.3	3°	0.3	225°	7
June 1	0800	0.6	2.4	2°	0.2	273°	8
		No evening observations.					
June 2	0815	0.2	2.4	0°	0	--	0
	1615	0.3	1.7	8°	0.3	275°	7
June 3	0810	0.2	2.5	5°	0	--	0
		No evening observations.					
June 4	0900	0.1	--	--	0	--	0
		No evening observations.					
June 5-10		No observations.					
June 11	0925	3.3	6.0	--	0.2	255°	16
	1730	1.3	3.5	0°	0.7	252°	12
June 12	0835	1.2	3.5	12°	0.9	260°	12
		No evening observations.					
June 13	1250	1.0	3.4	5°	0.9	258°	15

Station Cat. 5

Date	Time (h)EST	Waves Height (ft)	Waves Period (sec)	Waves Breaker angle rel. to shore	Longshore current (fps)	Wind Dir. (az.)	Wind Speed (mph)
May 7	0725	1.3	4.0	3°	0.5	270°	18
May 8	0655	0.5	3.5	3°	0.1	--	0
May 9	0715	0.6	3.0	5°	0.4	170°	0-8
May 10	0825	1.0	4.0	0°	0.3	325°	7
May 11	0735	0.1	2.5	--	0	105°	3-4
May 12	0730	<0.1	--	--	0	--	0
May 13	0800	2.2	4.5	8°	1.2	250°	20
May 14	0900	0.9	2.6	6°	1.5	208°	12-22
May 15	0820	1.3	3.0	17°	2.2	201°	24
May 16	0750	0.7	3.9	1°	0.3	165°	0-4
May 17	0725	0.8	2.5	10°	1.0	215°	10
May 18	0725	0.4	2.5	0°	0	--	0
May 19	0735	0.3	3.2	8°S	0.5 S	70°	8
May 20	0745	0.2	4.0	13°S	0.2 S	100°	6
May 21	1200	0.1	2.0	15°S	0.1 S	--	0
May 22	0815	<0.1	--	--	0.1	var.	2
May 23	0820	1.3	3.2	12°	1.5	240°	18
May 24	0810	1.2	3.1	0	1.6	235°	20
May 25	No observations.						
May 26	0730	0.8	2.8	5°S	1.2 S	238°	10
May 27	0750	0.3	2.2	0°	0.2	275°	5
May 28	0800	0.7	2.6	0°	0.5	245°	9
May 29	0745	0.8	3.4	0°	0.5	245°	8
May 30	0855	0.2	3.2	4°S	0.1 S	270°	3
May 31	0830	0.4	1.5	8°	0.6	190°	5
June 1	0750	0.5	2.3	0°	0.1	270°	7
June 2	0755	0.1	3.3	--	0	--	0
June 3	0800	0.1	1.8	--	0	--	0
June 4	0925	0.2	2.5	--	0	--	0
June 5-10	No observations, waves negligible.						
June 11	0840	5.0	7.0	--	0.5	250°	25
June 12	0805	1.0	3.4	0°	0.9	252°	12
June 13	1200	0.5	3.6	0°	0.6	250°	9

Station Cat. 6

Date	Time (h)EST	Height (ft)	Waves Period (sec)	Breaker angle rel. to shore	Longshore current (fps)	Wind Dir. (az.)	Wind Speed (mph)
May 7	0945	2.3	5.0	0°	--	265°	14
May 8	0805	0.4	5.3	0°	0.1	--	0
May 9	0840	1.0	3.5	4°	0.7	192°	4-8
May 10	0930	0.7	3.5	12°S	0.6 S	335°	10-12
May 11	0905	0.1	--	0°	0	--	0
May 12	0834	0.5	1.6	5°	0.4	210°	5-8
May 13	0900	3.3	5.2	5°	var.	262°	18
May 14	0945	0.7	3.1	10°	0.8	190°	10
May 15	0940	2.3	3.6	12°	1.7	234°	20
May 16	0900	0.3	4.0	0°	0.1	--	0
May 17	1005	1.7	--	14°	1.2	235°	15
May 18	0830	0.3	3.0	2°	0	260°	5
May 19	0850	0.7	3.5	2°S	0.5 S	55°	10
May 20	0910	0.4	3.0	4°S	0.2 S	112°	10
May 21	0900	0.1	--	4°S	0.1 S	var.	4
May 22	0942	0.1	--	0°	0.3	255°	5
May 23	1000	2.0	3.5	8°	1.2	240°	8
May 24	1105	2.0	3.6	10°	1.5	260°	20
May 25	No observations.						
May 26	0830	1.5	3.0	6°S	0.7 S	265°	8
May 27	0900	0.6	2.5	2°S	0.1 S	280°	9
May 28	1005	1.0	2.1	0°	0.5	278°	7
May 29	0902	0.3	3.0	2°	0.4	245°	8
May 30	1005	0.4	2.9	5°	0.1 S	330°	4
May 31	1050	1.2	3.1	3°	1.2	207°	12
June 1	0900	0.8	2.1	0°	0.1	280°	7
June 2	0907	<0.1	--	--	0.1 S	320°	5
June 3	0850	0.3	2.5	0°	0.1	225°	7
June 4	1055	0.1	2.4	0°	0.1	--	0
June 5-10	No observations, waves negligible.						
June 11	1103	6.7	6.5	--	0.9	275°	20
June 12	1005	2.7	3.5	10°	0.9	250°	14
June 13	1425	2.0	3.4	5°	0.8	250°	14

Station Cat. 8

Date	Time (h)EST	Waves Height (ft)	Waves Period (sec)	Breaker angle rel. to shore	Longshore current (fps)	Wind Dir. (az.)	Wind Speed (mph)
May 7	1025	2.3	5.0	5°	1.3	270°	14
May 8	0825	0.6	4.5	5°	0.2	--	0
May 9	0910	1.0	3.0	18°	1.0	195°	0-8
May 10	1005	0.8	3.0	0°	0.3 S	330°	5-6
May 11	0855	0.1	3.5	0°	0	--	0
May 12	0850	0.5	1.6	9°	0.6	235°	8
May 13	0930	3.3	6.1	7°	2.0	255°	14
May 14	1020	1.7	3.3	11°	1.6	200°	12
May 15	0955	2.5	4.0	15°	1.8	235°	16
May 16	0920	0.3	4.3	0°	0.3 S	10°	10
May 17	1035	1.5	4.3	7°	1.2	230°	8
May 18	0900	<0.1	3.2	4°	0.1	240°	4
May 19	0915	0.7	3.1	14°S	0.9 S	30°	10
May 20	0940	0.4	3.5	11°S	0.3 S	--	0
May 21	0750	0.1	--	--	0	--	0
May 22	1002	0.2	1.6	6°	0.3	190°	4
May 23	1025	1.8	3.7	9°	1.3	220°	8
May 24	1200	2.2	4.2	8°	1.8	240°	16
May 25	No observations.						
May 26	0855	1.2	3.1	0°	0	240°	10
May 27	0930	0.5	2.5	3°S	0.1 S	315°	6
May 28	1040	0.7	2.0	7°	0.4	270°	5
May 29	0920	1.2	3.4	6°	0.6	242°	7
May 30	0945	0.3	2.6	6°	0	--	0
May 31	1130	1.2	3.3	6°	1.4	190°	12
June 1	0920	0.7	2.0	0°	0.2	270°	7
June 2	0930	0.2	2.6	--	0.1 S	335°	5
June 3	0905	0.3	3.5	0°	0.2	225°	3
June 4	1023	0.1	2.6	0°	0	--	0
June 5-10	No observations, waves insignificant.						
June 11	1145	4.0	6.0	5°	1.5	225°	14
June 12	1050	2.0	3.3	10°	1.4	245°	12
June 13	1545	1.3	3.5	10°	0.9	250°	9

Station Cat. 10

Date	Time (h)EST	Height (ft)	Waves Period (sec.	Breaker angle rel. to shore	Longshore current (fps)	Wind Dir. (az.)	Wind Speed (mph)
May 7	1100	2.0	5.0	5°	1.4	265°	14
May 8	0843	0.6	5.0	0°	0.3	--	0
May 9	0935	1.2	3.0	15°	0.7	195°	0-8
May 10	1100	0.8	3.5	2°S	0.3 S	348°	5-6
May 11	0845	0.1	3.5	0°	0	--	0
May 12	0915	0.5	2.0	5°	1.2	235°	8-10
May 13	1000	3.3	5.4	9°	2.5	240°	14
May 14	1100	1.8	3.1	13°	2.0	192°	16
May 15	1010	2.8	4.1	13°	2.6	210°	10
May 16	0940	0.8	4.3	0°	0.4 S	6°	6-8
May 17	1100	2.0	4.0	23°	1.7	220°	14
May 18	0945	0.3	3.5	3°	0.1	--	0
May 19	0935	0.9	3.8	15°S	0.9 S	12°	4
May 20	1005	0.3	3.5	14°S	0.3 S	55°	3
May 21	1040	0.1	--	5°S	0.2 S	--	0
May 22	1020	0.5	1.5	13°	0.4	193°	4
May 23	1045	2.8	3.7	20°	2.8	225°	12
May 24	1225	2.5	4.1	10°	3.3	245°	15
May 25		No observations.					
May 26	0915	1.3	3.1	0°	0	240°	9
May 27	0950	0.5	2.5	4°S	0	310°	5
May 28	1105	0.7	2.5	0°	0.3	325°	4
May 29	0940	1.3	2.8	8°	0.8	235°	8
May 30	0930	0.3	3.2	0°	0	270°	3
May 31	1225	1.0	2.9	8°	0.9	185°	10
June 1	0945	0.8	2.3	4°	0.2	265°	7
June 2	0950	0.2	1.8	20°S	0.3 S	340°	4
June 3	0920	0.2	2.7	2°	0.2	230°	4
June 4	0950	0.1	2.5	0°	0	--	0
June 5-10		No observations, waves insignificant.					
June 11	1217	3.3	6.0	10°	2.3	240°	16
June 12	1115	3.3	3.5	7°	2.1	230°	12
June 13	1615	1.3	3.6	10°	1.6	205°	11

APPENDIX III

Lithological Composition of Cattaraugus Beach and Source Materials.

Cattaraugus Beach Active Berm

Sample Station	Siltstone and Sandstone (%)	Dark Shale (%)	Light Shale (%)	Crystalline Rocks and Chert (%)
1	80	4	0	16
2	no gravel	-	-	-
3	50	44	0	6
4	64	18	0	18
5	76	16	0	8
6	64	26	2	8
7	70	18	2	10
8	54	10	6	30
9	64	14	8	14
10	38	4	0	58
11	52	42	0	6
12	52	36	2	10
13	54	30	8	8
14	44	48	2	6
15	44	30	4	22
16	46	28	4	22
17	60	2	8	30
18	70	14	4	12
19	56	30	0	14
20	68	24	0	8
21	60	26	2	12
22	44	50	2	4
23	38	46	8	8
24	50	46	0	4
25	68	18	2	12
26	50	8	8	34
27	66	20	2	12
28	no gravel	-	-	-
29	66	0	0	34
30	50	0	0	50
31	62	0	0	38
32	62	0	0	38
33	48	0	0	52
34	52	0	0	48
35	62	0	0	38
36	60	0	0	40
37	no gravel	-	-	-
38	58	2	0	40
39	38	0	0	62
40	52	0	0	48
41	78	0	0	22
42	60	0	0	40
43	46	2	0	52
44	66	0	0	34
45	56	0	0	44
46	48	2	0	50
47	66	0	0	34
48	50	0	0	50
49	no gravel	-	-	-
50	no gravel	-	-	-
51	44	0	0	56
52	52	0	0	48
53	64	0	0	36
54	56	0	0	44
55	62	0	0	38

Cattaraugus Beach High Level Storm Berm

Sample Station	Siltstone and Sandstone (%)	Dark Shale (%)	Light Shale (%)	Crystalline Rocks and Chert (%)
1	68	6	0	26
2	60	34	0	6
3	no storm berm	-	-	-
4	78	6	2	14
5	76	18	0	6
6	72	10	4	14
7	constructional activity	-	-	-
8	66	16	2	16
9	56	2	2	40
10	64	6	2	28
11	64	30	2	4
12	66	26	6	2
13	62	26	6	6
14	52	28	0	20
15	48	30	2	20
16	68	18	0	14
17	70	12	2	16
18	68	22	0	10
19	46	54	0	0
20	58	38	0	4
21	54	28	14	4
22	58	30	10	2
23	62	30	6	2
24	54	40	4	2
25	64	22	2	12
26	74	18	2	6
27	62	32	2	4
28	82	0	2	16
29	82	2	0	16
30	64	0	0	36
31	78	0	0	22
32	86	0	0	14
33	84	2	2	12
34	74	4	0	22
35	84	0	0	16
36	84	0	0	16
37	80	4	0	16
38	82	0	0	18
39	80	2	0	18
40	94	2	0	4
41	94	2	0	4
42	80	4	0	16
43	82	0	0	18
44	90	2	2	6
45	80	2	4	14
46	80	0	0	20
47	88	2	0	10
48	84	2	4	10
49	76	0	4	20
50	82	0	0	18
51	92	0	0	8
52	86	0	6	8
53	96	2	0	2
54	78	0	0	22
55	84	4	4	8

Sample Station	Siltstone and Sandstone (%)	Dark Shale (%)	Light Shale (%)	Crystalline Rocks and Chert (%)
Lotus Point and Bay				
1	54	0	0	46
2	66	0	0	34
3	76	2	0	22
4	62	0	0	38
5	84	0	4	12
6	78	4	2	16
7	64	2	0	34
Silver Creek Point Bars				
1	34	50	14	2
2	22	66	8	4
3	20	52	26	2
4	20	58	20	2
5	16	68	14	2
Walnut Creek Point Bars				
1	44	42	6	8
2	36	42	16	6
Silver Creek Bay				
1	40	42	10	8
2	28	52	18	2
3	28	60	8	4
4	50	34	6	10
5	50	36	2	12
Cattaraugus Creek Point Bars				
1	80	0	8	12
2	88	0	0	12
3	75	7	0	18
4	87	4	0	9
5	80	5	0	15

APPENDIX IV

Texture of Cattaraugus Beach Sediments

Method. The texture was determined at 57 sample stations evenly spaced along the beach. At each station the beach was divided into texturally homogenous zones from the step to the dune ridge or seawall. For each zone the following parameters were determined: width of zone, w_i; per cent gravel, p_i; typical gravel size, d_i; and typical sand size, s_i.

If the number of homogenous zones is n, the total gravel percentage for the beach at any one station (P) is computed from

$$P = \frac{\sum_{i=1}^{n} w_i p_i}{\sum_{i=1}^{n} w_i} 100$$

South Beach

Sample Station	No. of Zones	Gravel Size Range (cm)	Gravel Range in Per Cent	Sand Size Range, ϕ	Total Gravel Percentage
1	4	1-5	5-100	.50-.75	43
2	5	3-7	3-95	.75	24
3	3	3-4	15-100	1.50	43
4	4	3-7	2-95	.50-1.25	21
5	5	3-6	3-50	.50-1.75	21
6	4	3-5	5-50	.75-1.5	40
7	5	3-5	2-80	.25-1.25	46
8	5	3-5	5-80	.50-1.25	41
9	5	3-5	10-100	-.25-1.25	72
10	5	3	2-95	0-1.75	67
11	3	2-4	2-100	-1.0-(-.25)	81
12	4	1-3	20-100	-1.0-(-.75)	70
13	2	2-3	10-100	1.0	70
14	3	3-5	2-100	.5	89
15	3	2-7	5-100	1.0	26
16	5	2-6	30-100	.25-1.25	70
17	Seawall - no beach				
18	5	3-6	15-100	.50-.75	67
19	5	3-4	20-100	1.25	54
20	4	3-4	15-95	1.25-1.75	28
21	3	2	2-40	1.25-2.00	10
22	2	2	30-100	1.75	12
23	2	3	30-100	1.25-1.75	24
24	5	3-4	5-100	1.25-1.50	18
25	3	2	5-85	1.50-2.25	29
26	2	1-2	5-100	.75-1.50	3
27	4	1-2	2-100	.75-1.75	23
28	2	2-3	30-40	.75-1.00	36

North Beach

Sample Station	No. of Zones	Gravel Size Range (cm)	Gravel Range in Per Cent	Sand Size Range, ϕ	Total Gravel Percentage
29	4	3-5	40-100	.00-.75	60
30	4	3-4	5-90	.75-1.00	58
31	4	3-4	9-100	.25-1.25	12
32	4	2-5	2-100	.50-.75	6
33	4	.5-3	2-100	.75-1.25	30
34	4	2-3	2-40	.75-1.00	8
35	3	3-4	10-100	.75-1.00	17
36	3	2-4	8-100	.50-.75	21
37	3	3-4	5-100	.75-1.25	9
38	3	.5-6	5-100	.75-1.00	26
39	3	1-5	5-100	.50-1.25	17
40	3	2-4	15-80	.75-1.00	22
41	4	2-5	5-60	1.00-.75	19
42	4	2-4	10-90	.75	41
43	3	1-3	5-50	-.25-1.00	33
44	6	1-5	2-95	.50-1.00	39
45	4	1-3	2-95	.25-1.00	35
46	5	1-4	10-100	.75-1.00	35
47	4	.5-4	5-100	.00-.75	49
48	6	.5-4	20-95	.50-1.25	46
49	6	1-3	2-100	.50-1.00	44
50	5	1-5	20-100	.50-1.00	52
51	4	2-4	10-100	.50-1.00	35
52	5	1-4	2-30	.50-1.00	8
53	5	2-4	2-95	.75-1.00	52
54	4	1-4	30-75	.75	64
55	5	1-4	5-95	.50-1.00	34
56	5	1-4	2-100	.75-1.00	20
57	5	3-10	2-95	.50-1.00	26

APPENDIX V

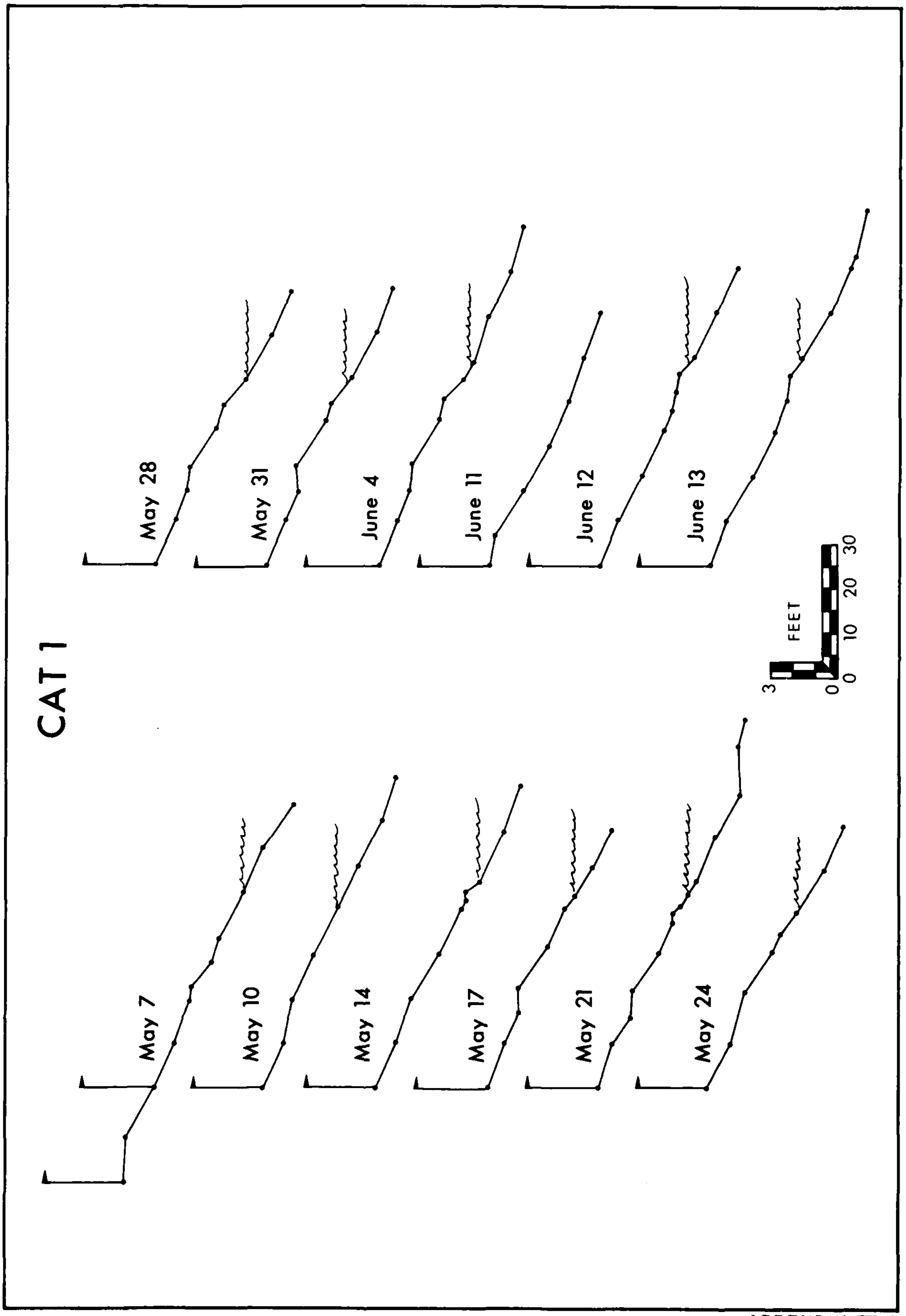
Cattaraugus Creek Stage Readings at the Keene Marina Staff Gage

Date	Time	Stage	Creek Discharge
May 9	1700	5.10	moderate flood
May 10	0805	4.70	moderate flood
May 10	1700	4.34	moderate flood
May 11	0830	4.40	low discharge
May 11	1345	4.38	low discharge
May 12	0830	4.54	low discharge
May 12	1800	5.36	moderate flood
May 13	0815	5.10	moderate flood
May 13	1625	5.26	moderate flood
May 14	0835	4.68	moderate flood
May 14	1240	4.78	waning flood
May 14	1810	5.52	waning flood
May 15	0915	4.88	waning flood
May 15	1910	4.82	moderate flood
May 16	0845	4.48	moderate flood
May 16	2115	4.18	moderate flood
May 17	0820	4.78	increasing flood
May 17	1500	5.68	flood peak
May 17	1730	5.88	flood peak
May 17	1930	5.58	flood peak
May 18	0825	4.86	waning flood
May 18	1610	4.56	waning flood
May 19	0830	4.30	low discharge
May 20	0815	4.64	low discharge
May 20	2245	4.70	low discharge
May 21	1400	4.86	low discharge
May 22	0915	4.45	low discharge
May 23	1205	4.98	low discharge
May 23	1850	5.10	low discharge
May 24	0910	4.85	low discharge
May 24	1845	4.75	low discharge
May 25	1830	5.05	low discharge
May 26	0830	4.85	low discharge
May 27	0850	4.65	low discharge
May 27	1815	4.85	low discharge
May 28	0900	4.72	low discharge
May 28	1400	4.60	low discharge
May 28	2200	4.70	low discharge

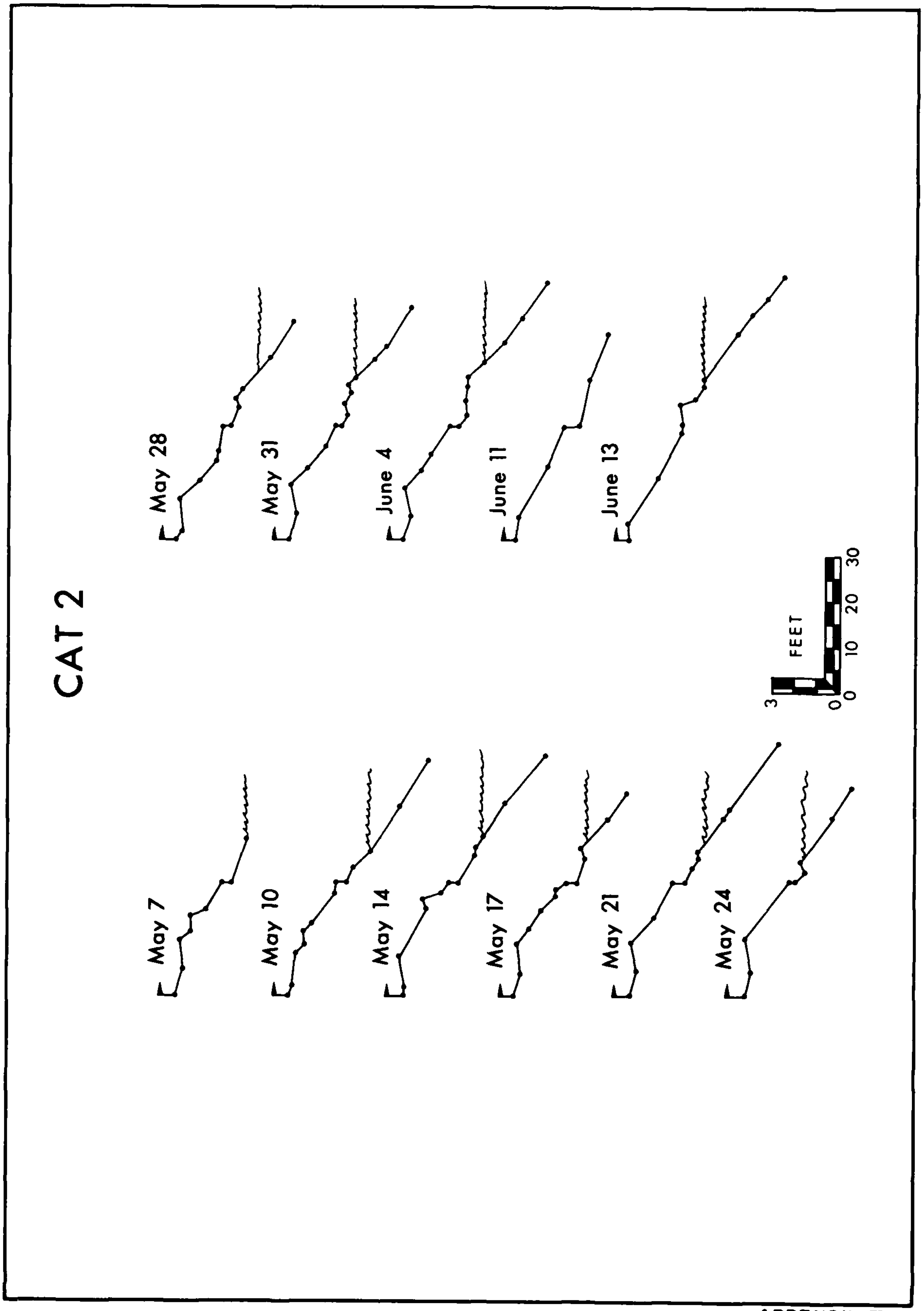
Date	Time	Stage	Creek Discharge
May 29	0830	4.60	low discharge
May 29	0745	4.75	low discharge
May 30	1005	4.68	low discharge
May 31	0930	4.68	low discharge
June 1	0845	4.68	low discharge
June 2	0830	4.72	low discharge
June 3	0900	4.60	low discharge
June 4	1015	4.50	low discharge
June 5	1030	4.50	low discharge
June 6	0835	4.45	low discharge
June 7	1100	4.40	low discharge
June 8	1300	4.50	low discharge
June 9	1230	4.40	low discharge
June 10	1100	4.70	low discharge
June 11	0930	5.35	low discharge
June 11	1820	4.65	low discharge
June 12	0900	4.72	low discharge
June 12	2130	4.64	low discharge

APPENDIX VI

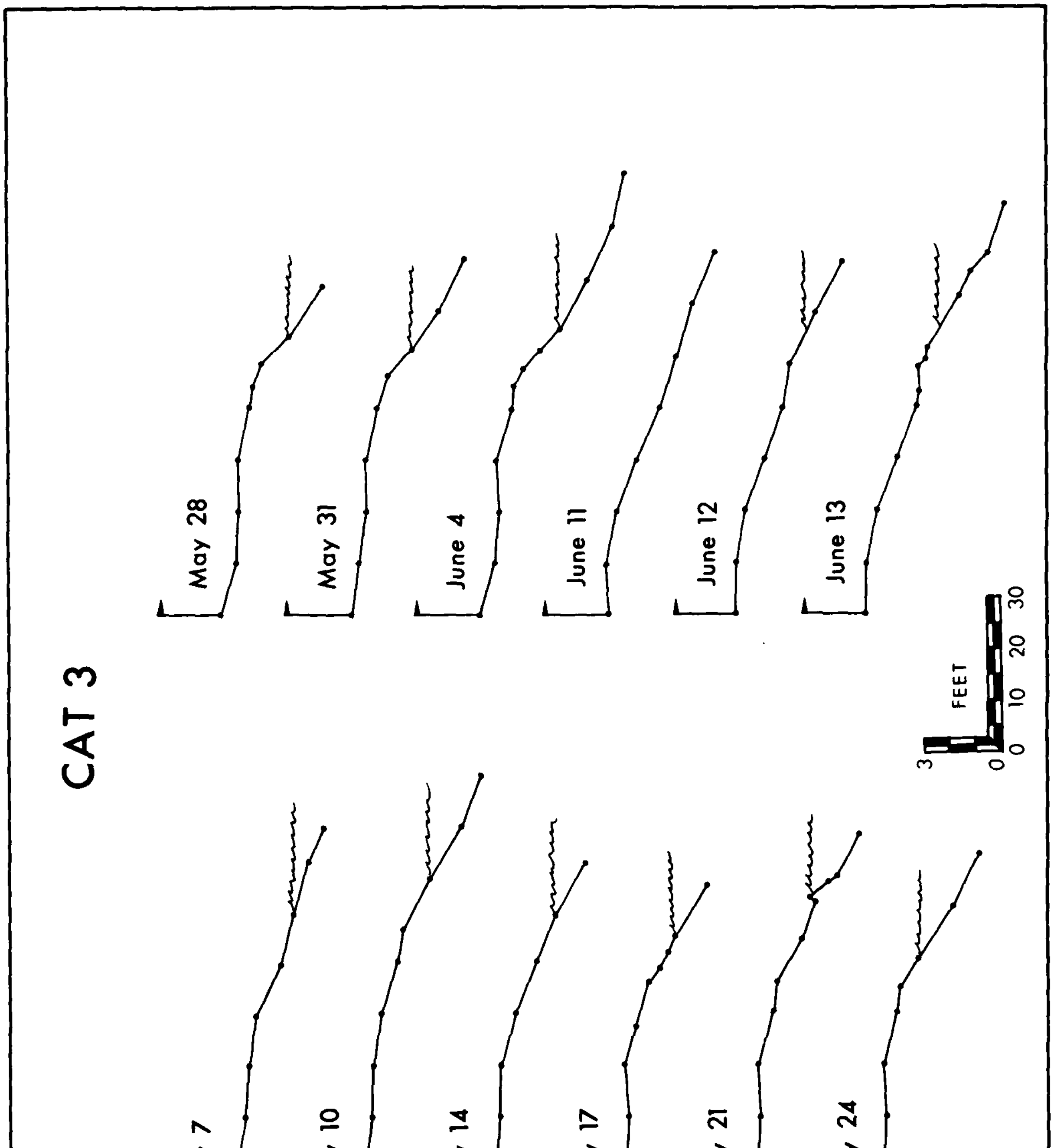
Recorded Profiles of the Cattaraugus Beach



APPENDIX VI A

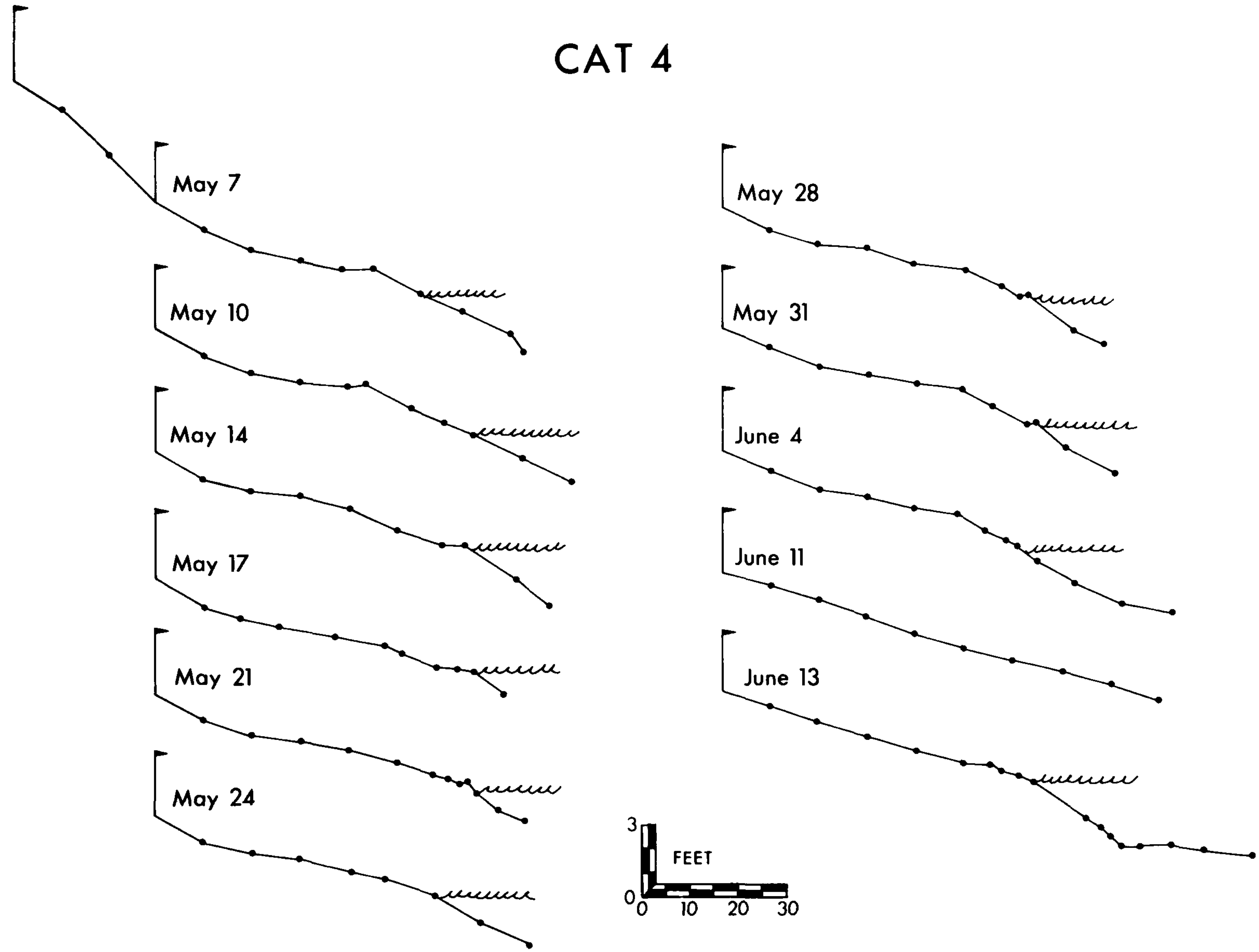


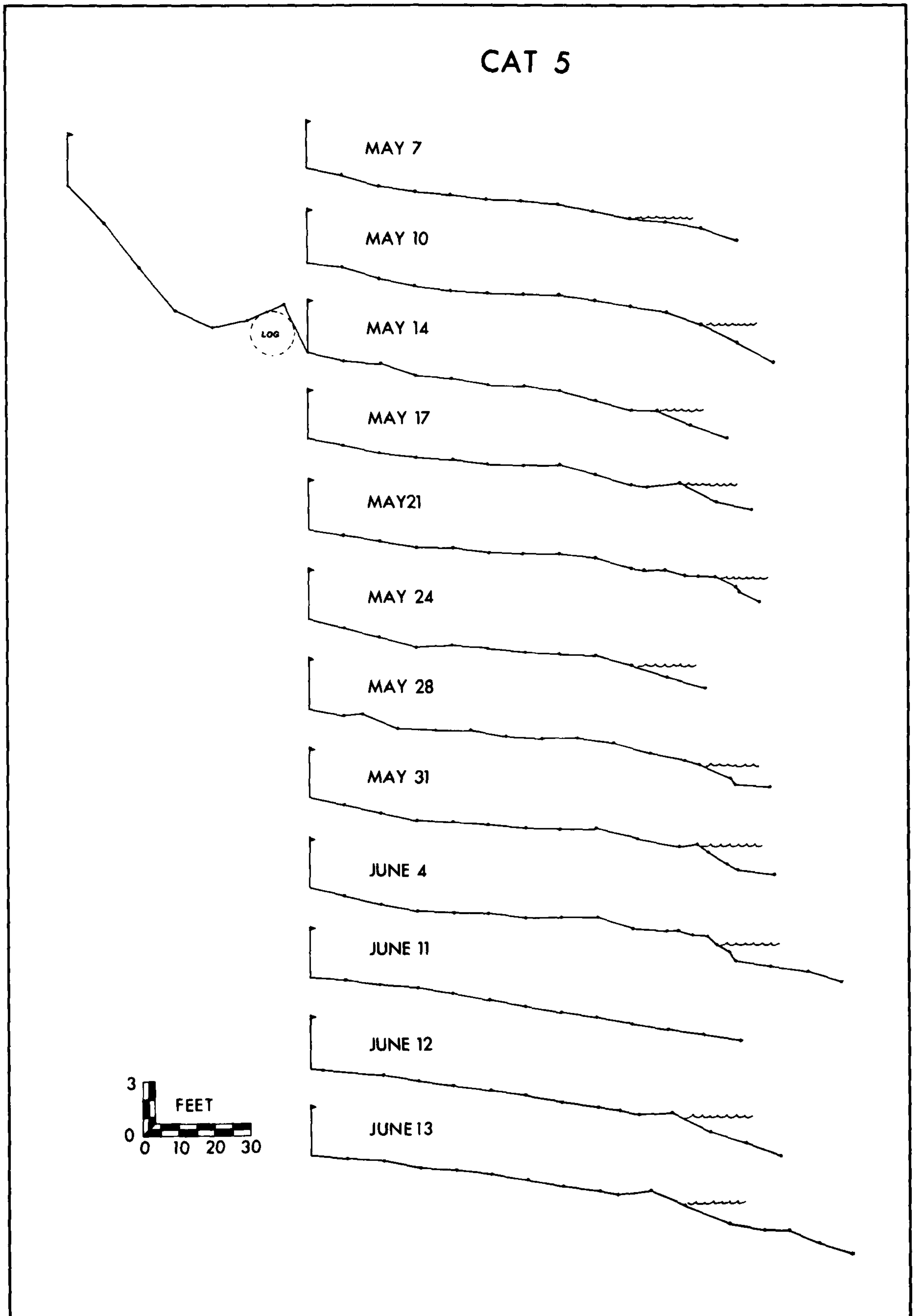
APPENDIX VI B



APPENDIX VI C

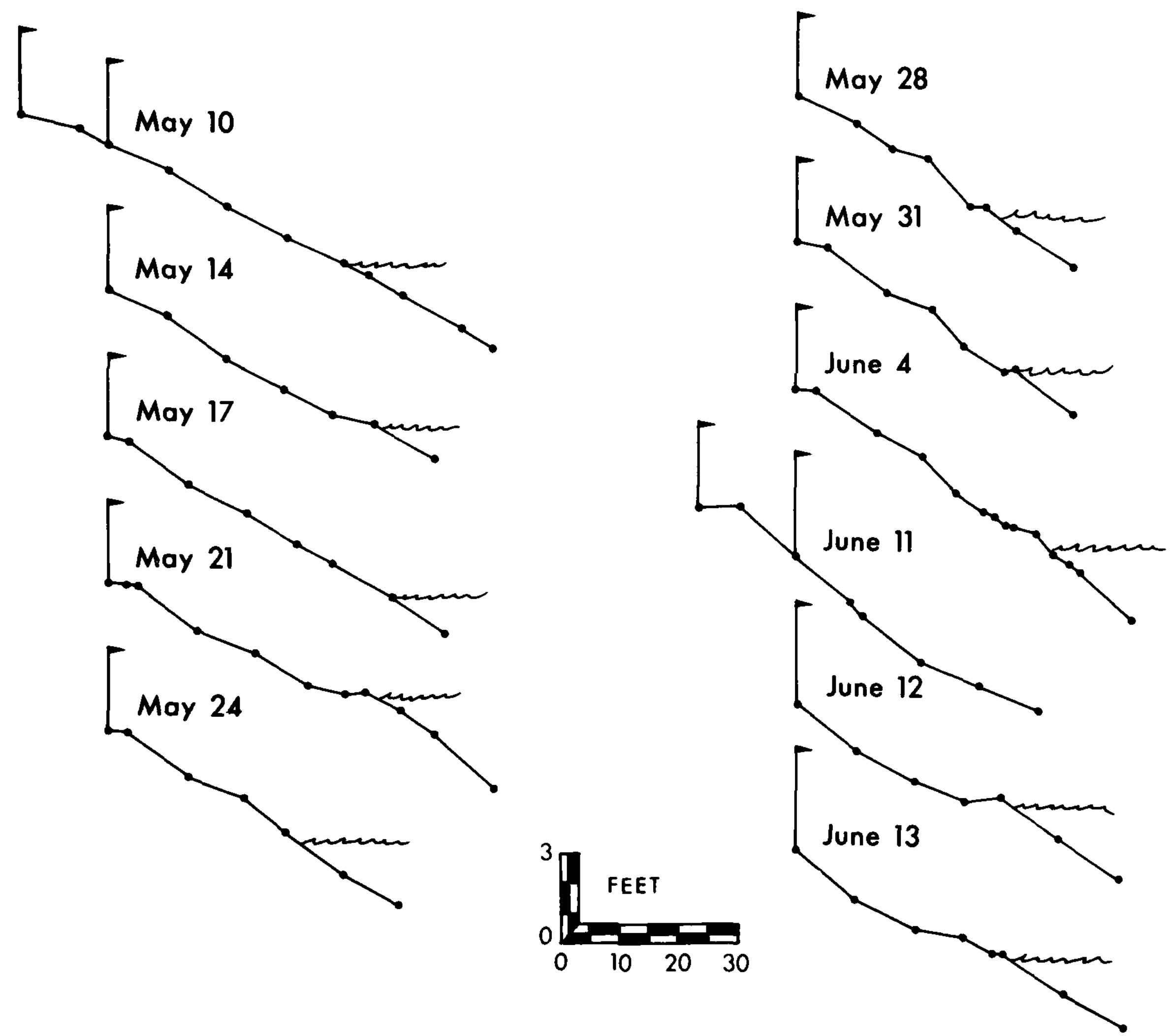
CAT 4


May 7
May 10
May 14
May 17
May 21
May 24
May 28
May 31
June 4
June 11
June 13
FEET
3
0
0
10
20
30



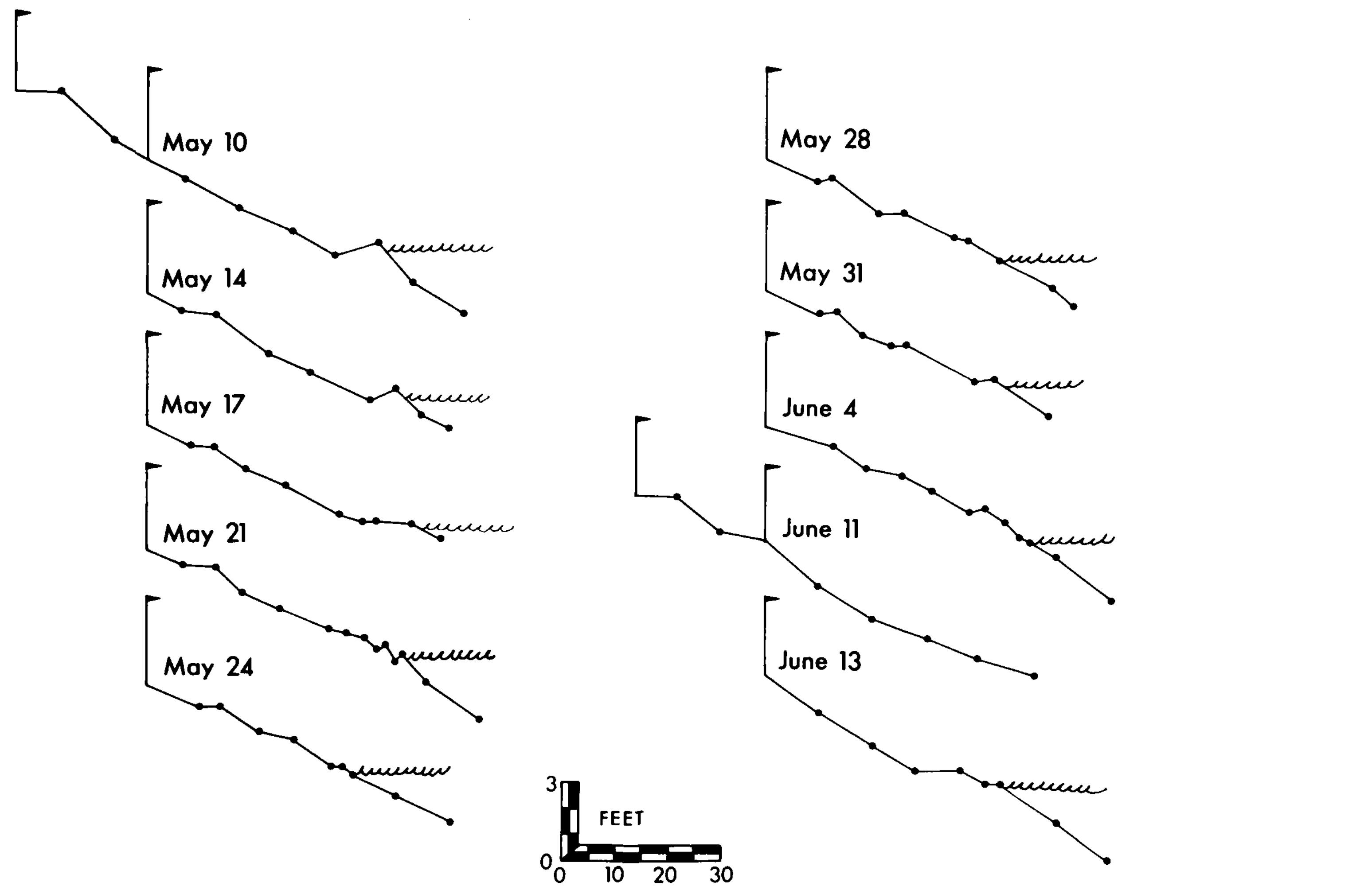
APPENDIX VI E

CAT 6

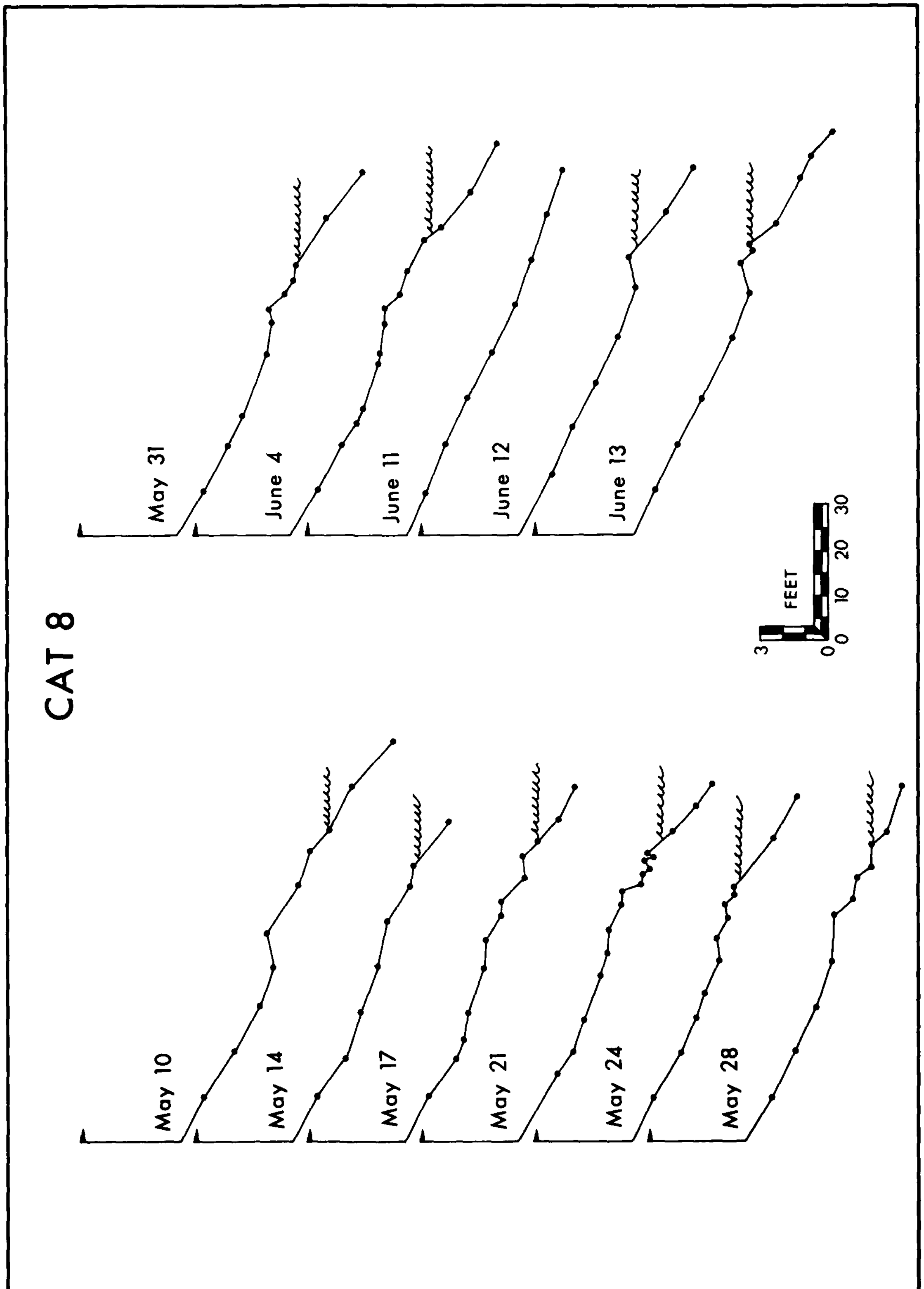


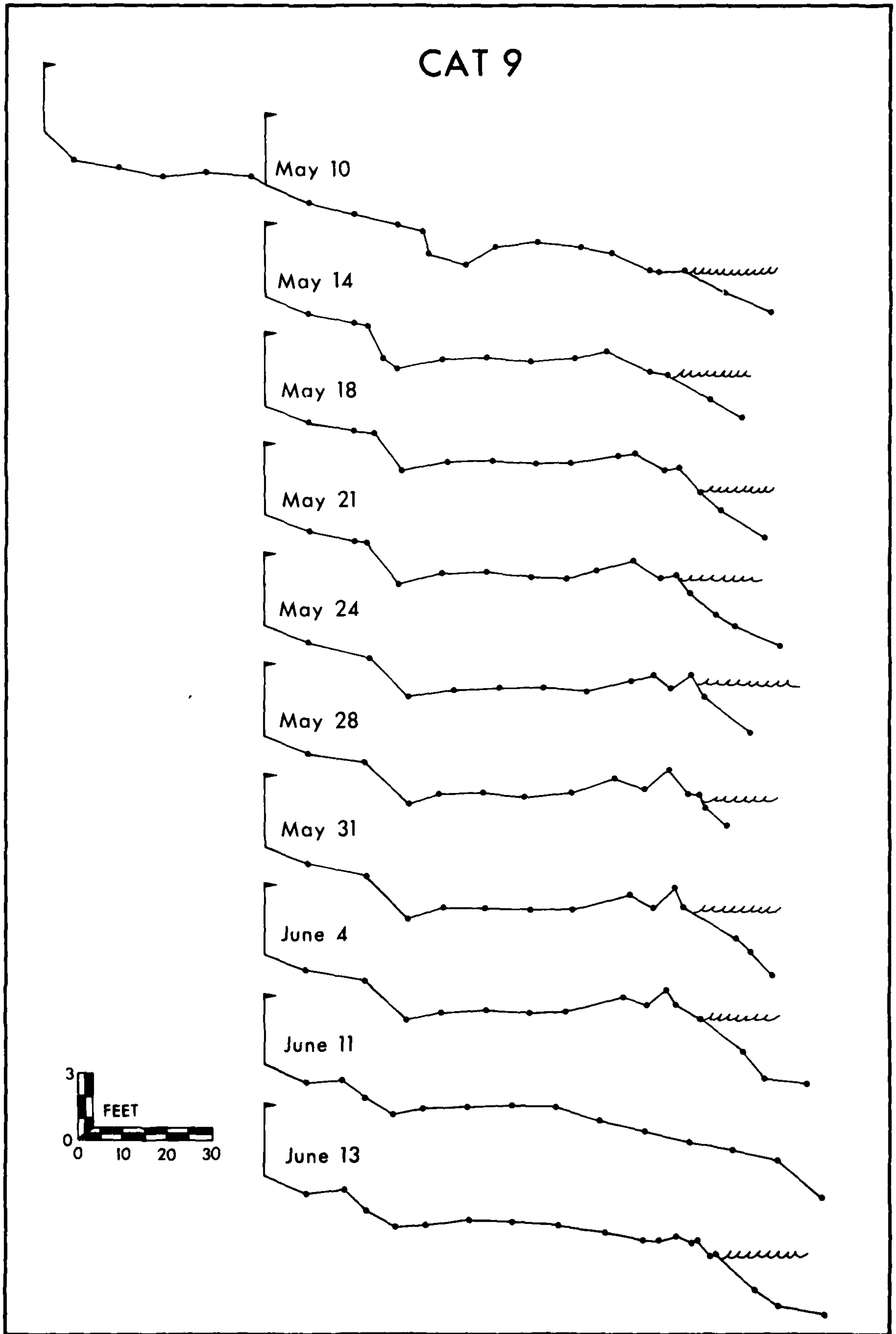
APPENDIX VI F

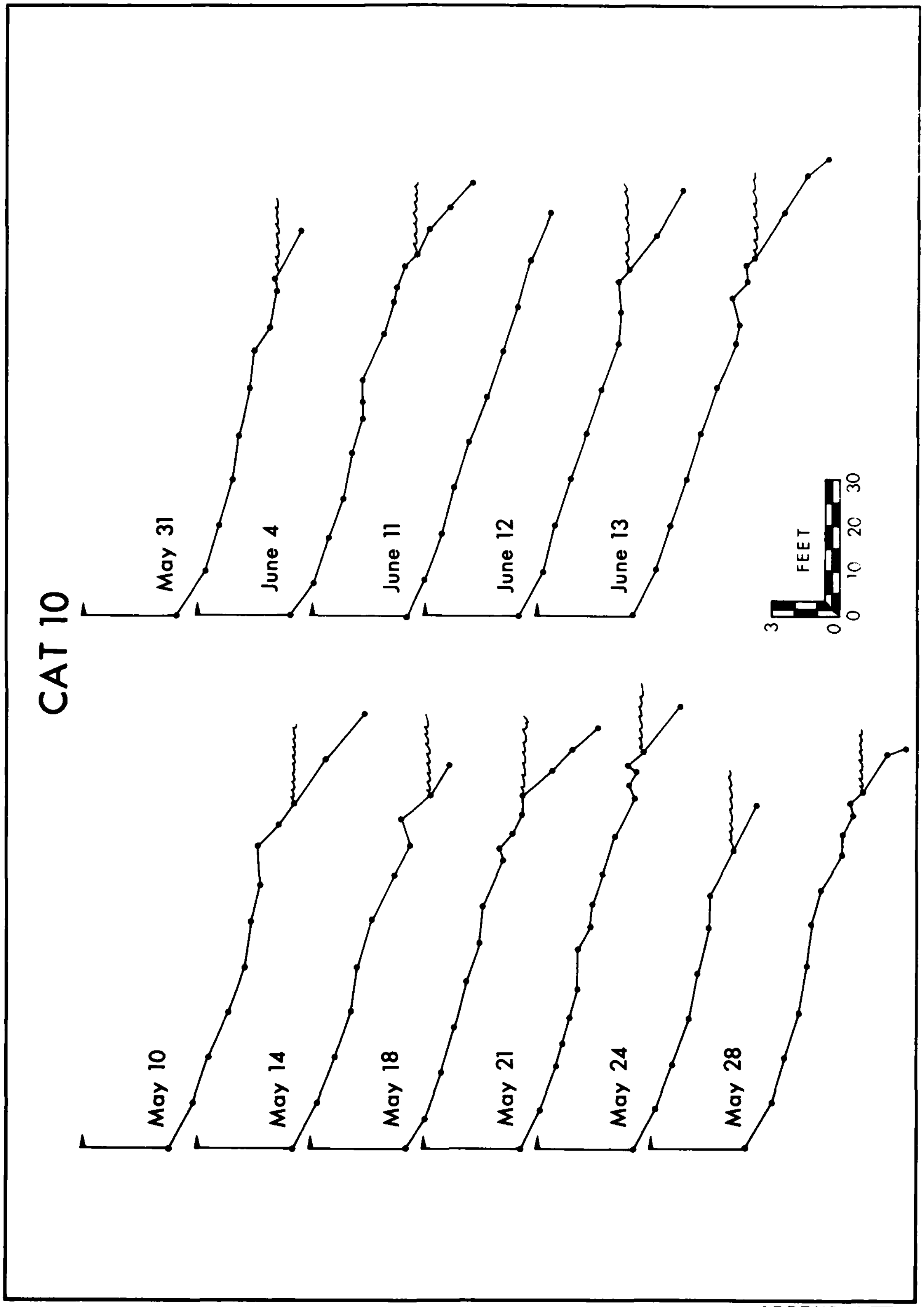
CAT 7



APPENDIX VI G


CAT 8
May 10
May 14
May 17
May 21
May 24
May 28
May 31
June 4
June 11
June 12
June 13
FEET
0
10
20
30
3
0


CAT 9
May 10
May 14
May 18
May 21
May 24
May 28
May 31
June 4
June 11
June 13
3
FEET
0
0
10
20
30


CAT 10
May 10
May 14
May 18
May 21
May 24
May 28
May 31
June 4
June 11
June 12
June 13
FEET
0
10
20
30
3
0

APPENDIX VIIA

Concentration of Suspended Sediment in Surface Samples from the Breaker Zone Obtained during the Storm of June 11, 1974

Sample Station	Concentration (ppm)
Cat. 1	3529
Cat. 3	2601
Cat. 5	124
Cat. 6	2688
Cat. 8	144
Cat. 10	913

APPENDIX VIIB

Concentration of Suspended Sediment in Cattaraugus Creek at the Buffalo Rd. Bridge. Obtained with a Depth-Integrated Suspended Sediment Sampler (DH-48) during a Small Flood in May.

Sample Station	Concentration (ppm)
1	601
2	518
3	606
4	662
5	614
6	505
7	508
8	525
9	510
10	541

APPENDIX VIII

Texture Parameters for Nearshore Sand in the Cattaraugus Embayment.

For computation of textural parameters this report follows Folk (1968, p. 44-47).

Sample Station	Mean Diameter, ϕ	Sorting ϕ	Skewness
Cat. 1A	2.16	0.41	0.50
Cat. 1B	2.33	0.43	0.43
Cat. 1C	2.47	0.52	1.10
Cat. 1D	2.45	0.55	1.24
Cat. 1E	2.44	0.48	0.90
Cat. 1F	2.42	0.55	1.25
Cat. 1G	2.41	0.43	0.30
Cat. 1H	2.41	0.40	0.15
Cat. 1I	2.60	0.56	1.08
Cat. 1J	2.63	0.56	0.95
Cat. 1K	2.58	0.56	1.04
Cat. 2A	2.32	0.40	0.29
Cat. 2B	2.46	0.37	0.24
Cat. 2C	2.41	0.38	0.16
Cat. 2E	2.37	0.35	0.08
Cat. 2F	2.49	0.38	0.06
Cat. 2G	2.56	0.49	0.37
Cat. 2H	2.56	0.53	0.98
Cat. 2I	3.01	1.08	5.88
Cat. 2J	2.57	0.54	1.15
Cat. 2K	2.58	0.54	0.92
Cat. 3A	2.14	0.33	0.23
Cat. 3B	2.28	0.42	0.09
Cat. 3C	2.40	0.53	0.64
Cat. 3D	2.47	0.55	1.02
Cat. 3E	2.98	0.98	3.73
Cat. 3F	4.83	2.20	8.22
Cat. 4A	2.07	0.31	0.13
Cat. 4B	2.38	0.35	0.17
Cat. 4C	2.37	0.36	0.15
Cat. 4D	2.52	0.43	0.25
Cat. 4E	2.64	0.61	0.92
Cat. 4F	2.64	0.61	1.05
Cat. 4G	2.93	0.92	4.37
Cat. 4H	2.69	0.52	0.72

Sample Station	Mean Diameter, ϕ	Sorting ϕ	Skewness
Cat. 5A	1.72	0.70	-2.68
Cat. 5C	2.05	0.44	0.30
Cat. 5D	2.12	0.50	0.47
Cat. 5E	1.75	0.55	0.20
Cat. 5F	2.11	0.51	0.76
Cat. 5G	3.03	1.53	13.58
Cat. 5H	2.98	1.13	4.77
Cat. 5I	3.18	1.28	6.26
Cat. 5J	3.87	1.35	0.63
Cat. 6A	1.55	0.66	-0.39
Cat. 6B	2.08	1.93	19.84
Cat. 6C	5.07	2.03	12.47
Cat. 6D	1.18	0.57	0.49
Cat. 6E	3.88	2.01	8.70
Cat. 6F	5.74	1.85	13.90
Cat. 6G	2.91	1.36	11.28
Cat. 7B	1.90	0.35	0.21
Cat. 7C	2.76	1.13	7.51
Cat. 7D	4.37	2.14	14.28
Cat. 7E	4.39	2.21	11.12
Cat. 7F	5.08	1.97	10.75
Cat. 7G	4.24	1.54	3.83
Cat. 7I	4.54	2.14	11.91
Cat. 7J	4.98	2.12	9.87
Cat. 8A	1.50	0.34	-0.09
Cat. 8C	2.38	0.37	0.12
Cat. 8E	2.65	0.63	1.20
Cat. 8G	3.33	1.51	11.84
Cat. 9A	1.72	0.32	0.10
Cat. 9H	6.89	1.85	4.06
Cat. 9I	6.65	1.83	4.57
Cat. 10A	1.75	0.39	0.43
Cat. 10I	7.30	1.52	5.03

APPENDIX IX

Textural composition of the Cattaraugus Beach sand fraction. For location of sample stations see Figure 56. Cumulative size-frequency curves for all sand samples are available upon request.

Sample Station	5	16	50	84	95	(% Coarser Than)
1	1.00	1.20	1.55	1.90	2.13	
2	1.25	1.45	1.75	2.06	2.27	
3	1.23	1.35	1.60	1.95	2.27	
4	0.15	0.60	1.10	1.68	2.00	
5	0.95	1.20	1.55	1.95	2.20	
6	0.50	0.95	1.40	1.88	2.10	
7	1.10	1.30	1.65	2.00	2.30	
8	0.85	1.15	1.45	1.93	2.30	
9	0.50	0.80	1.30	1.85	2.20	
10	-0.65	-0.25	0.30	1.10	1.60	
11	-0.60	0.00	0.35	0.80	1.10	
12	-0.25	0.60	0.85	1.40	1.85	
13	-0.75	-0.25	0.30	0.80	1.15	
14	0.25	0.65	1.05	1.54	2.00	
15	-0.30	0.15	0.70	1.20	1.60	
16	-0.10	0.05	0.28	0.70	1.25	
17	-0.50	0.00	1.05	1.52	1.85	
18	-0.60	-0.25	0.00	0.25	0.50	
19	-0.55	-0.20	0.20	0.50	0.70	
20	0.15	0.40	0.75	1.25	1.80	
21	0.50	0.75	1.15	1.65	2.25	
22	-0.25	0.50	1.20	1.70	2.15	
23	1.05	1.20	1.50	1.93	2.25	
24	0.20	0.85	1.30	1.85	2.15	
25	1.15	1.30	1.65	2.03	2.35	
26	-0.25	0.20	0.70	1.30	1.70	
27	-0.60	0.00	0.65	1.24	1.63	
28	-0.75	-0.20	0.75	1.30	1.65	
29	0.60	0.90	1.30	1.80	1.95	
30	-0.50	-0.25	0.10	0.65	1.30	
31	0.15	0.55	0.85	1.35	1.95	
32	-0.90	-0.50	0.25	1.05	1.45	
33	-0.85	-o.50	0.60	1.10	1.45	
34	-0.75	-0.40	0.50	1.05	1.80	
35	-0.30	0.55	1.10	1.55	2.05	
36	-0.75	-0.25	0.70	1.37	1.85	
37	-0.75	-0.40	0.20	0.65	1.20	

Sample Station	5	16	50	84	95	(% Coarser Than)
38	-0.25	0.45	1.10	1.57	1.85	
39	-0.50	0.30	1.20	1.60	1.92	
40	-0.85	-0.55	0.90	1.68	2.10	
41	-0.20	0.25	0.65	1.00	1.25	
42	-0.55	-0.25	0.30	1.05	1.45	
43	-0.25	0.00	0.30	0.70	1.05	
44	-0.50	-0.20	0.10	0.50	1.08	
45	-0.50	-0.25	0.00	0.20	0.35	
46	-0.15	0.50	0.75	1.18	1.40	
47	-0.75	-0.40	0.20	0.50	0.70	
48	-0.50	-0.15	0.15	0.50	0.85	
49	0.00	0.35	0.70	1.10	1.30	
50	0.15	0.40	0.80	1.27	1.55	
51	0.35	0.50	0.75	1.10	1.45	
52	0.90	1.05	1.27	1.60	1.87	
53	0.70	0.85	1.15	1.51	1.85	
54	1.05	1.15	1.30	1.60	1.85	
55	0.75	.80	1.00	1.27	1.50	

DAT
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